



**15 YEARS OF PROGRESS
IN RADAR ALTIMETRY
SYMPOSIUM**

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ABSTRACT BOOK

15 Years of Progress in Radar Altimetry Symposium

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Abstract Book

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Session 0:

Thematic Keynote Presentations

Altimetry: Past, Present, and Future

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Modern high accuracy altimetric data sets are now taken for granted by the oceanographic, geodetic, and related communities. Except for a few of the remaining active pioneers, memory is rapidly fading of the very great difficulties, technical, scientific, and political, involved in getting us to the point where useful data can be obtained with the click of a mouse. I will sketch the problems that had to be overcome, and the ones that remain. The problems of the future are also very great, but many of them tend to have a different character---dictated by the fact that altimetry, along with other developments, has transformed oceanography from a small academic discipline into a large community dealing with numerous issues of societal interest in addition to the scientific problems.

Mesoscale Eddy Dynamics observed with 15 years of altimetric data

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Over the last 15 years, great progress has been made in our understanding of mesoscale processes due to the unprecedented space-time coverage of satellite altimetry. The most striking discoveries concern the mid to high latitude band where the historical in-situ data sets are more sparse. This paper will present a brief review of our improved understanding of mesoscale eddy characteristics, including the distribution and seasonal and interannual variations of eddy kinetic energy and eddy momentum flux; techniques for tracking mesoscale eddies and Rossby waves with altimetry and for monitoring their propagation pathways and decay. Using a combination of in-situ data and surface monitoring from altimetry, estimates of eddy heat, salt and momentum fluxes can be made. We examine these eddy fluxes in certain regional sites in the Indian sector of the Southern Ocean where in-situ measurements exist, from repeat hydrographic campaigns or research cruises, or the newly deployed ARGO profiling float array. The interaction

of mesoscale eddies with the mean circulation, and their role in cross-frontal mixing, will also be examined with the combination of altimetry and in-situ data along the Subantarctic Front.

How satellites have improved our knowledge of planetary waves in the oceans

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In this paper we describe the contribution that Earth Observation techniques in general, and 15 years of altimetry in particular, have brought to our knowledge of extra-tropical planetary waves in the ocean, both baroclinic and barotropic.

Early observations with Geosat data showed the presence of a clear baroclinic wave signature in the SSH record; their ubiquity was subsequently demonstrated with the Topex/Poseidon and ERS datasets. These global observations highlighted significantly faster waves with respect to the classical theory of planetary wave propagation, calling for a revision of the theory. In this paper we first review a number of satellite-based studies showing planetary waves and contrast them with the many improvements in the theory that they have triggered, showing how altimetric as well as SST-based observations of planetary waves have contributed significantly to elucidate this aspect of ocean dynamics. Then we illustrate the changes of amplitude of the planetary wave signal in the global ocean, and discuss some hypothesis for the presence of distinct 'waveguides' of enhanced wave activity. We also discuss a number of spectral and statistical techniques that allow an evaluation of the wave features (including their non-zonal characteristics), and the resulting prospects for planetary wave forecast.

Finally, we review the progress in the observation of barotropic waves, which is close to the limit of the sampling capability of the present altimeters' constellation, but

nevertheless has been successfully attempted, at least in some cases.

The Ebb and Flow of Tidal Science, and the Impact of Satellite Altimetry

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In the years immediately preceding the launches of Geosat and Topex/Poseidon, tidal science had lapsed into a period of uncertainty and discouragement, brought about by the failure of once-exciting new ideas that eventually proved overly optimistic. A long list of outstanding problems presented themselves, but progress had reached a "low water mark". What was lacking was a high-quality global dataset of tidal measurements, which satellite altimetry -- and especially Topex/Poseidon -- provided. With these data in hand, a "flood tide" of marked progress resulted. In this paper we review some of that progress.

An important area of progress, with potentially important implications for other areas of physical oceanography, falls under the topic of "energy dissipation." With precise global constraints provided by altimetry -- combined with precise laser tracking of the altimeter, other geodetic satellites like Lageos, as well as the moon -- the planetary energy budgets of both Earth and ocean tides are now well determined. Moreover, the local energy balances, and thus local estimates of tidal dissipation, have now been mapped, although somewhat coarsely, throughout the ocean. This work has pointed to internal-tide generation in the deep ocean as the once missing sink of tidal energy, and has led to a plethora of new observational and theoretical studies of internal tides, and their role in vertical mixing of the deep ocean. The discovery that internal tides, or some part of them, can be directly mapped with an altimeter opens new lines of research on this topic. Low-mode internal tides have been found, at least in some regions, to propagate several thousand kilometers across open ocean. The study of such waves with altimetry gives us a global view heretofore unattainable, allowing strong observational constraints to be placed on possible ocean mixing processes, such as subharmonic instabilities.

ARGO, the Integrated Approach

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An overview of the ARGO programme, which strives to be a mainstay of integrated global observation efforts. Its philosophy, resources, methods, and community will be presented.

Present-day sea level rise: do we understand what we measure?

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Since early 1993, sea level variations are accurately measured by Topex/Poseidon altimetry, complemented for the recent years by Envisat and Jason-1. This >12 years long data set indicates that, in terms of global mean, sea level is presently rising at a rate of ~ 3 . ± 0.4 mm/yr. Such a rate is significantly higher than the mean rate recorded by tide gauges for the past five or more decades (on the order of 1.8 ± 0.3 mm/yr). The higher rate observed during the 1990s may indicate that sea level rise is accelerating due to enhanced land ice melting and/or increased ocean warming. One cannot exclude also that it only reflects decadal variability of the combined thermal and ocean mass change. During the past few years, our group has examined in detail the steric contribution (mainly thermal expansion) to last decade and past 50 years sea level rise. We have computed the thermal expansion contribution using four different global ocean temperature data sets. Results indicate that thermal expansion accounts to about 25% of the observed sea level rise observed over 1950-2000, while for the last decade (1993-2003), it explains about 60% of the rate of rise. For both periods, there is indirect evidence that ocean mass change due to land ice melting accounts to ~ 1 . mm/yr. This magnitude of the land ice melt contribution is confirmed by direct estimates (partly based on remote sensing observations) of ice sheets and glaciers mass balance. These results suggest that the larger rate of sea level rise observed during the 1990s, compared to previous decades, is largely explained by the recent increase of the ocean heat content; a result supported by reanalyses of ocean data assimilation. Satellite altimetry permits also the mapping of the geographical variability of sea level change. Comparison with regional variations in thermal expansion

shows that most of the non uniform sea level change is explained by thermal effects. However some regional differences are observed, in particular in the north Atlantic and austral ocean, with potential implication on other processes such as the isostatic adjustment related to present-day ice sheet melting, change in the thermohaline circulation, etc.

15 years of wave height data assimilation

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15 years of wave height data assimilation are reviewed, along with the progress made in the field and its implications for monitoring, modelling, and forecasting.

Marine Geoid/Gravity/Bathymetry

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Long-term data in radar altimetry have permitted scientists to better describe and understand marine gravity, bathymetry, and the marine geoid. The progress made and its significance for these fields of planetary study is outlined.

The New Vision of the Cryosphere Thanks to 15 Years of Altimetry Observations

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Fifteen years of altimetry have radically changed the way scientists look at the cryosphere. An overview and speculation on how scientists have evolved their vision as a result of advances in altimetry and altimetric data.

Two decades of inland water monitoring using satellite radar altimetry

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The most well-established use of altimetry over land surfaces is the application to measurement of inland water heights. However, this field has evolved rapidly over the past two decades. Initial work over a handful of large targets has now expanded to the current capability to monitor thousands of river and lake heights worldwide. Two factors have been critical to the advances made in inland water monitoring. The first is the inclusion of a designed capability to track rapidly varying land surfaces, deployed on ERS RA-1 and Envisat RA-2. The second is in the analysis of inland water echoes, with the ability to identify and retrack to that part of a complex return corresponding to the underlying water surface.

This paper presents a global overview of the abilities of past and current altimeters to monitor the Earth's changing inland water resources. Utilising a unique database of retracked heights from ERS-1, ERS-2, Envisat, Topex and Jason-1, a 15 year synthesis of the behaviour of the Earth's inland water resources is shown. Together with additional information from the RA-2 I.E. echoes, and a land echo simulator, the unique database of global information captured in the existing datasets is utilised to demonstrate both the requirements of, and potential capabilities for a future hydrology mission.

Session 1.1:

Oceanography: High Frequency

Progress on Dynamics and Thermodynamics in Western Boundary Currents

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Prior to the start of the altimetry missions in the 1990s, ideas about the thermodynamics in western boundary currents (WBC) were simple: the Gulf Stream, for example, carries warm tropical waters poleward while cold air from North America sweeps across it, removing much of its heat and forming 18-degree water in the late winter. While estimates of air-sea fluxes differed substantially, variability in those fluxes was thought to be the result of changing atmospheric conditions. A heat budget for the region was impractical as the currents were too strong to be measured directly and efforts to close the budget would be overwhelmed by ocean eddies.

Early altimetry measurements of sea surface height (SSH) demonstrated that the large ocean signal from WBCs was clearly visible, but the perceived usefulness of SSH anomalies was limited by concerns about the representativeness of surface geostrophic currents for inferring transport, the lack of a mean SSH, the effects of seasonal heating, the sense that the boundary current variability was relatively small-scale, associated with rings, and that that variability was already documented by decades of infrared images.

Statistical analyses of boundary current variability (Kelly, 1991; Qiu et al, 1991) demonstrated that most of the variability in the Gulf Stream and Kuroshio Extension is from the meanders of a constant-width jet, not rings; and that there are relatively large-scale variations in the current structure, which are associated with the recirculation gyres. Sato and Rossby (1995), in comparisons with hydrographic data, demonstrated the large-scale effects on the Gulf Stream of seasonal heating. Imawaki (2001) showed that the Kuroshio transport could be monitored using SSH, but this has not been demonstrated for the Gulf Stream.

Using Geosat data, Kelly and Gille (1990) devised a method for estimating mean SSH that allowed an upper ocean heat budget in a boundary current, using a thermodynamics-only

upper ocean model. The heat budget in the Kuroshio Extension (Qiu and Kelly, 1993) revealed the importance of heat transport by the geostrophic current, compared with the Ekman current. Using TOPEX/Poseidon data, Qiu (1999) showed that large changes in SST were the result of changes in the geostrophic heat advection in the KE, rather than air-sea fluxes. Meanwhile, the relationship between SSH and heat content was probed by numerous researchers demonstrating that SSH was a good proxy for upper ocean heat content, and creating some confusion about the relative roles of thermodynamics and dynamics in the WBCs.

Upper ocean heat budgets for both the Kuroshio Extension and Gulf Stream regions (Vivier et al 2002; Dong and Kelly, 2004) revealed that changes in upper ocean heat content (shown to be nearly synonymous with SSH anomalies) were primarily the result of changes in heat transport by the geostrophic current with time scales of several years or more. Much of the anomalous heat transport is stored in the recirculation gyre regions, where heat accumulates and results in anomalous fluxes of heat to the atmosphere (Kelly and Dong, 2004). Thus, interannual variations in air-sea fluxes in these regions are primarily the result of changes in the ocean, not in the atmosphere. Further, large-scale changes in both the KE and GS heat transport are to some degree in phase, likely the result of large-scale changes in the winds. Motivated by the similarity of the SSH anomaly and the 18-degree (mode) water in the Gulf Stream, comparisons revealed a systematic negative correlation between mode water volume and heat content or SSH (Kwon and Riser, 2004; Dong 2004).

The relatively large local variations in upper ocean geostrophic transport, heat storage, and air-sea fluxes in the WBC regions, along with new understanding of the importance of the shallow wind-driven overturning circulation in meridional heat transport (Boccaletti et al, 2005), suggests that changes in meridional heat transport by the ocean may be dominated by western boundary current variability rather than by meridional circulation changes driven by changes in the thermohaline circulation. A heat budget analysis which spans both the subtropical and subpolar gyres is needed to examine this issue further. Critical to this analysis are both longer time series of altimetric SSH and an improved mean SSH over the larger region as well as an understanding of the influence of salinity and the fresh water budget on the interpretation of SSH. The observationally derived estimates of the thermodynamic budget of the upper ocean are essential for independently evaluating new ocean and climate models, especially for eddy resolving models.

High-resolution statistical analysis of ocean dynamics using ungridded altimeter data and addressing intrinsic difficulties of realistic oceanographic fields

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Many problems of ocean dynamics require field observations at specific sampling rates in both time and space. The fact that the desired spatial or/and temporal resolution of gridded altimeter data products (as well as of most other satellite instruments) is not always sufficient for analysis of certain processes decreases the value of satellite data and leaves such processes outside the scope of altimetry applications. Satellite measurements are always reported at space-time points that hardly form a regular grid. The problem is further aggravated by data gaps. Putting the data onto a regular grid ultimately results in a loss of resolution and a decreased accuracy. The types of processes that are difficult to study using standard altimeter data products are, for example, (i) Fast oceanic motions - including some barotropic waves and baroclinic inertia gravity waves - which have too short timescales to be systematically resolved in altimeter data; (ii) Highly anisotropic and strongly latitudinally-dependent quasigeostrophic motions require high spatial resolution in the meridional direction, although the zonal resolution can be rather coarse; (iii) mesoscale turbulence (with spatial scales under a few hundred km), etc. Our statistical studies yield rather high-resolution results and directly address spatial inhomogeneity in the meridional direction which is crucial for large-scale ocean dynamics.

A systematic review of the statistical techniques developed in the past decade for analysis of altimeter data is presented. Applications include our recent analysis of (predominantly near-zonal) wave fronts for large-scale motions such as baroclinic Rossby solitons and equatorial modons, the detection of vorticity fronts, the three-dimensional high-resolution spectral analysis of mid-latitude Rossby waves and mesoscale turbulence, the statistical analysis of baroclinic inertia-gravity waves (including internal tides), and equatorially trapped eastward disturbances, etc.

Although the development of our statistical approach has been motivated in the past 10 years by the needs of ocean satellite altimetry, these techniques have also been successfully applied to other remote sensing data. In particular, we demonstrate the existence of an internal semi-diurnal tide in the 2D wavenumber spectra of Chlorophyll-a concentration fluctuations, and present analysis of sea surface temperature fluctuations induced by quasi-geostrophic oceanic turbulence.

Temporal Changes in Ocean Eddy Transports

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New estimates from 11-years of altimetric data are made of the global time-average variability kinetic energy and its decadal-scale variability. Making the approximation that the variability reflects primarily eddy motions, a time-mean, but spatially varying, eddy mixing coefficient is then estimated along with its changes over the last decade. With a record length more than twice as long as previously available, the time-mean variability kinetic energy, K_E , is statistically more reliable and smoother in its spatial pattern. Minimum values of K_E are present in the subpolar North Pacific and in the eastern South Pacific (both less than $100\text{cm}^2/\text{s}^2$). In contrast to the North Pacific, the subpolar North Atlantic shows relatively enhanced K_E . Eddy kinetic energy and eddy mixing appears to have declined during the last decade over large parts of the western Pacific Ocean, in some regions by as much as 50% of the time-mean value. Increased eddy variability can be found in the Kuroshio and Gulf Stream regions, as well as in the Agulhas region, east of Australia, and at several locations along the Antarctic Circumpolar Current. Somewhat enhanced eddy variability and eddy mixing are also apparent in the eastern tropical Pacific. A numerical simulation of the ocean circulation at 1 degree spatial resolution over a 10 year period suggests that variations in eddy mixing of this order of magnitude measurably affect the deep temperature field in the vicinity of permanent frontal structures on a timescale of less than 4 years. The meridional overturning circulation also reacts on these time scales. If persistent over longer periods in the ocean, these effects would be important for climate simulations.

Characterizing the variability of the Eastern North Pacific in Time and Space

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Atmospheric indices such as the North Pacific Index, the Southern Oscillation Index, the Northern Oscillation Index

have been used to characterize the ocean's variability on interannual scales. This paper uses the thirteen year AVISO's merged altimetric data set to develop and/or refine a set of indices derived from the ocean's height field to spatially and temporally describe the variability of the Northeast Pacific. Through the use of these indices, the interrelationships between the signals can be analyzed. Disregarding the seasonal cycle, three or four major indices can be defined: 1) a coastal signal - strongly related to the seasonal cycle and Southern Oscillation (ENSO) index, 2) a mid North Pacific gyre signal, 3) a Alaskan Gyre index, and 4) an index associated with small variability west of the California Current. Because the 1997/1998 El Nino dominates the variability, the analysis shows results with and without the inclusion of this event. The event primarily effects the coastal or near coastal region. Finally, the relationship between the atmospheric and oceanic indices are explored.

NCEP SST, the ISCCP-FD surface radiation and the GPCP datasets and by comparing the filled datasets to the original ones.

Main advantages of the method are that the decorrelation scales are unrestricted functions of space and time, only information internal to the flux field is used in the interpolation scheme and the computation cost of the method is low enough to facilitate its use in similar large datasets.

Decorrelation scales of high resolution turbulent fluxes at the ocean-surface and a method to fill in gaps in satellite data products

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In the first part of the paper, a high space-time resolution (1degree latitude/longitude and daily) dataset of the turbulent fluxes at the ocean surface is used to estimate and study the seasonal to annual near-global maps of the decorrelation scales of the latent and sensible heat fluxes. The decorrelation scales describe the temporal and spatial patterns that dominate the flux fields (within a bandpass window) and hence reveal the dominant variability in the air-sea interaction. Regional comparison to the decorrelation scales of the flux-related variables such as the wind stress, the humidity difference and the SST identifies the main mechanism responsible for the variability in each flux field.

In the second part of the paper, the decorrelation scales are used to develop a method for filling missing values in the dataset which result from the incomplete satellite coverage. Weight coefficients in a linear regression function are determined from the spatial and temporal decorrelations and are functions of zonal and meridional distance and time. Therefore they account for all the spatial and temporal patterns on scales larger than 1day and 1degree latitude/longitude and smaller than 1year and the ocean basin scale. The method is evaluated by simulating the missing-value distribution of the GSSTF2 dataset in the

Session 5.1:

Building the 15-Year Altimetric Record/Calibration and validation

20 Years of Improvements to GEOSAT Altimetry

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The U.S. Navy GEOSAT mission provided the first long-term altimetric record for studies of ocean circulation, marine gravity/bathymetry and continental ice. The Geodetic Mission data (GM: 31-Mar-1985 to 30-Sep-1986) were declassified by the Navy in 1995 and released by NOAA together with the Exact Repeat Mission data (ERM: 8-Nov-1986 to 30-Dec-1989) in the 1997 JGM-3 Geophysical Data Records (GDRs). This first complete GEOSAT data set used improved tracking and orbit determination based on the JGM-3 gravity model, and was an update to the previous GDRs based on GEM-T2 orbits (ERM) and NSWC orbits (GM). The radial orbit errors were reduced from the decimeter to meter level down to about 7 cm rms.

We have now completed another major upgrade of the GM data by reprocessing the original Sensor Data Records (SDRs) and Waveform Data Records (WDRs) which were 'separated at birth' by the GEOSAT ground segment at Johns Hopkins/APL. The SDRs were recovered from NOAA archives and combined with the matching waveform data in the WDRs from the NASA/GSFC archive. This has allowed us to retrack all the over-ocean waveforms from the GM to improve measurements of sea surface height and its slope and thereby produce better models of marine gravity and predicted bathymetry. A unique two-pass retracking algorithm is used to further reduce the noise in along-track sea surface slope, and to reduce the correlation in errors between range and SWH from the waveform fitting. The first retracking pass is a traditional multi-parameter least-squares fit of a Brown model to the waveform, fitting pre-

arrival noise, amplitude (AGC), half-power location (range track point), leading edge slope (SWH) and plateau decay (off-nadir attitude) at 10 Hz. The resulting values of noise, amplitude, SWH and attitude are then smoothed along track and a second waveform fitting is performed using these smoothed values with only the range travel time being re-estimated from a one-parameter fit.

The '20th Anniversary GEOSAT Geodetic Mission' data set also includes several improvements compared to the previous GDRs: range data with mm vs. cm precision; measurements of range, SWH, AGC, and all corrections at the full 10 Hz rate; a noise-free Doppler height correction based on orbit height rate and along track mean sea surface gradients; improved time-tagging and ultra-stable-oscillator height correction; and state of the art tide and sea state bias models. The precise orbit determination for the GM data uses the full set of 45 Doppler TRANET tracking stations and is based on gravity models tuned for Geosat Follow-On. The improved corrections and retracking are particularly beneficial to marine gravity and bathymetry, while the new precise orbits yield better estimates of sea level rise from the GEOSAT time period.

Sea state bias – 20 years on

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In the 20 years since the original paper by Srokosz (1986) on sea state bias (SSB), much work has been carried out – theoretical, computational, experimental and observational – on sea state bias. Yet, despite this and the progress that has been made, SSB remains an – possibly the – outstanding problem in the correction of satellite radar altimeter sea surface height measurements. In order to correctly estimate changes in sea surface height at the centimetric level it is necessary to take adequate account of the SSB error. In this paper we will review the last 20 year's work on SSB, discuss the physics of the problem, investigate which sea state parameters best characterise SSB and discuss some new theoretical developments. We will conclude by

summarising the state-of-the art and making recommendations for “where next with SSB?”

Overview of the Improvements Made on the Empirical Determination of the Sea State Bias Correction

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It has long been known that the sea level measured by radar altimeters is lower than the true sea level because the backscattered power per unit area is greater for the wave troughs than for the wave crests (Yaplee, 1971). This effect is known as the electromagnetic bias. Other sea-state-related biases additionally affect the altimeter range measurements (e.g. Chelton et al., 1989). These are generally combined with the electromagnetic bias to form the sea state bias (SSB). This bias ranges from a few centimetres up to a few decimetres and is still one of the main sources of error in satellite altimetry. Its theoretical modelling remains an important challenge (e.g. Elfouhaily et al., 2001, Gommenginger 2003). Therefore, the SSB correction still largely relies on empirical models, calibrated on the altimeter data themselves. The goal of this paper is to summarize all the improvements realised in this field at CLS, for the past ten years.

Early estimations of the SSB correction were performed by fitting an empirical parametric SSB model on altimeter-derived sea surface height (SSH) differences, either at crossover points or along collinear tracks (e.g. Born et al., 1982; Gaspar et al., 1994, Chelton, 1994, Chambers, 2003). The use of SSH differences rather than SSH measurements themselves is a simple way to directly eliminate the poorly known geoid signal from the estimation process. However, Gaspar et al (1998) demonstrated that parametric models based on SSH differences are not true least square approximations of the SSB. The origin of this problem comes from the fact that one has to fit an inevitably imperfect parametric model on SSH differences rather than on SSH measurements themselves. To overcome this artefact, Gaspar et al (1998, 2002) developed and refined a non parametric (NP) SSB estimation technique based on kernel smoothing. It was first applied to TOPEX crossover data, providing a SSB correction of 1 cm accuracy.

Recent works have focused on sensitivity studies of this NP technique. Indeed, Labroue et al (2004) analysed in details the difference between crossover and collinear data sets and

resulting SSB models in order to highlight the most accurate methodology. They also showed the impact on the SSB estimates of several sources of errors affecting the SSH measurements (time-tag bias, orbit error and data filtering...). Additional improvement was found through the use of the high frequency MOG2D correction which removes large barometer errors which were directly assimilated into the previous empirical SSB models.

Thanks to all these efforts, the NP method is now mature enough to provide a valuable tool for the SSB analysis. The latest results obtained for ENVISAT, ERS2, TOPEX, Jason 1, Poseidon 1 and GFO in Ku-band will be presented and discussed in this paper. The main difference between the models lies in the correction magnitude. The results are quite consistent for ENVISAT, Poseidon 1, Jason 1 and GFO, but appear lower for TOPEX and higher for ERS2.

The recent analysis of Jason 1 and ENVISAT SSB models in C band and S band has also been performed. These empirical SSB estimates will certainly help to understand and model more accurately the frequency dependence of the electromagnetic bias.

Calibration of ERS-2, TOPEX/Poseidon and Jason-1 Microwave Radiometers using GPS and Cold Ocean Brightness Temperatures

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Sea-level change studies from altimetric satellites are reliant on range stability of the sea-surface heights computed from the orbital positioning and geophysically corrected data. One such correction, namely the wet tropospheric delay induced by the highly variable atmospheric water vapour content, is provided by radiometers onboard ERS-2, TOPEX/Poseidon and its follow on mission Jason-1. In this study the long-term stability of ERS-2 and TOPEX radiometers are investigated together with radiometer performance to date of Jason-1. Each of the three microwave radiometers is investigated with observed drift in the brightness temperatures approximated by reference to the coldest temperatures over the oceans. For example the TOPEX radiometer investigations show that the dominant drift is about 0.2 K/year in the 18 GHz channel over the first 7-8 years but stabilising and even decreasing slightly thereafter. In contrast, the 21 GHz and 37 GHz channels are comparatively stable. Utilising correction formulae a modified wet tropospheric range is inferred from ‘small-change’ analysis of the radiometric correction given on the

altimetric Geophysical Data Records. This investigation undertakes the validation of the accuracy of this formalism by independent comparison against GPS derived wet tropospheric delays inferred at 14 coastal IGS stations with near continuous data from Sept. 1992 through to the present day. Early comparison between GPS results for ERS-2 and TOPEX shows the ERS-2 radiometer measuring ~ 14 mm long. Additionally for TOPEX, the altimetric range stability is revisited by comparison against time series from the global network of tide gauges.

Keywords GPS, altimetry, radiometers, calibration/validation, sea level

The Altimetric Wet Tropospheric Correction: Progress since the ERS-1 mission

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In order to correct the altimeter range for water vapor path delay over ocean, a microwave radiometer has been embarked on the spacecraft since the early 90's. As any error in the wet tropospheric correction directly impacts the sea level determination, the constraints on the quality and stability of the radiometer products are particularly stringent. In this paper, we present the improvements performed since the ERS-1 mission, the remaining limitations, and the perspectives for the improvement of the wet tropospheric correction for the future altimetry missions. New technologies like the in-flight calibration using injection noise diodes have been used (Jason/JMR). But recent improvements mainly concern the processing of the radiometer measurements at both level 1 (calculation of the brightness temperature) and level 2 (wet tropospheric correction retrieval). Nowadays, the sea level rise is estimated at the mm/year level, so new methods have been developed to detect any drift in order to correct it and so to provide stable products.

Despite the numerous progress achievements made since the launch of ERS1, the uncertainty on the wet tropospheric correction is still today around 1 cm rms and remains a significant contribution in the global uncertainty on the sea level estimation. For the future altimetry missions, the wet tropospheric correction would have to fulfill new constraints on accuracy and spatial resolution. We think that only the combination between new instruments (scanning instruments, higher frequencies, ?) combined with high quality meteorological models should allow to reach this goal.

Session 2:

Cryosphere

Satellite radar altimetry over sea ice - from Seasat to CryoSat

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Sea ice represents one of key uncertainties in the future temperature rise predicted by Global Climate Models (GCM's). However GCM's simulations of future changes sea ice, in particular in ice thickness, vary widely. Satellite altimeters have the potential to provide unique data related to key climatic properties of sea ice related to the extent, thickness and roughness of ice floes.

In this paper we review over two decades of progress in satellite altimetry over sea ice from Seasat though to CryoSat. Early results from Seasat and Geosat demonstrated that the extraction of marine geoid information and sea ice thickness might one day be possible using space-borne altimetry. It was the ERS missions, however, which provided the first altimetric coverage of the high Arctic that allowed the first views of the polar ocean floor and of a highly dynamic sea ice cover to be revealed.

Recent news stories have talked widely of the dramatic retreat of summer sea ice extent during the first years of the 21st century. We will show the most recent results from Envisat and CryoSat with which we hope to answer the question as to whether Arctic sea ice has also undergone an equally dramatic thinning.

Mass Balances of the Greenland and Antarctic Ice Sheets from Satellite Radar Altimetry

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The Earth's ice sheets and ice shelves are of special interest because of the uncertainty in their current mass balance, the direct effect of changes in ice volume on sea level change, and the potential for significant ice changes with climate warming. Since the 1980's, measurement of surface elevation changes (dH/dt) by satellite altimeters and airborne laser surveys has been pursued as a means of directly measuring changes in ice volume and therefore the mass balance. Ice sheet surface elevations have been measured by radar altimeters on Geos-3, Seasat, Geosat, Geosat follow-on, ERS-1 and 2, ENVISAT, and CryoSat. The characteristics of the snow-ice surface that are different from ocean surfaces and significantly affect the elevation measurements include: irregular topography (mean-slope and undulations), variability of surface reflectivity and transmissivity, and variability of sub-surface backscatter. For analysis of elevation data from a single-mission or nearly-identical missions (e.g. ERS-1 and 2), these characteristics are sufficiently well understood to enable construction of reliable time-series of elevation changes $H(t)$. This includes the application of empirically-determined corrections for the dependence of the measured height on the back-scattered signal strength (spatially and temporally variant) and inter-mode and inter-satellite height biases (spatially variant), even though the physical causes of the dependence and biases are not well understood. The most reliable time-series have been constructed for the approximately 11 years of altimeter data from ERS-1 and 2, and new time-series are being constructed from ENVISAT data. However, the effects of the characteristics of the snow-ice surface on the radar signal and the elevation measurement are similar to or are interactive with instrument and satellite properties such as antenna-beam width, range resolution, microwave frequency, tracking parameters, and orbital height. Therefore, most if not all attempts to derive elevation changes by comparing

elevations obtained from different missions (other than ERS-1 and 2) have not been successful. Separate $H(t)$ time-series constructed from ENVISAT data and from ERS-1 and 2 data are evaluated for continuity in elevation change properties between the successive missions.

Combining satellite altimetry (ERS-2 and ENVISAT) with SAR interferometry and SPOT photogrammetry for studies of Austfonna ice cap (Svalbard)

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Glaciers and ice caps are extremely sensitive for detecting global climate variability. We have studied largest ice cap in the Eurasian Arctic - the Austfonna on the Svalbard using combination of various satellite techniques - satellite radar altimetry (ERS-2 and ENVISAT), SAR interferometry (ERS-1 and -2) and SPOT photogrammetry. Though this ice cap has experienced a modest advance during the last 30 years, there are outlet glaciers that have experienced large changes, such as Etonbreen glacier.

We first analyse ERS-2 and ENVISAT altimetry data over the Austfonna since 1995. We present changes of absolute height and height anomalies, as well as backscatter values (depending on the surface roughness, melting and refreezing processes) and the leading edge width (affected by the presence of snow dunes, small-scale undulations, effects of radar penetration in the snow).

We also present results of the combined use of various Digital Elevation Models (DEM) of the Austfonna with ENVISAT and ERS-2 altimetry data. We use historical DEM from the Norwegian Polar Institute, as well as several DEMs from ERS-1 and -2 SAR interferometry (INSAR) and SPOT photogrammetry. DEMs from INSAR and SPOT stereo pairs are able to resolve topography with high resolution but they lack absolute reference and are prone to long-wavelength errors. Radar altimetry produce absolute measure of height with low spatial resolution (several km) with very high precision reference but they are perturbed by small-scale topographic changes. By combining DEMs with altimetric measures we could improve DEMs precision. The DEMs have been used to first simulate the radar return waveform. By comparing the simulated and measured waveform we then estimate the errors associated with the DEM inclination plane (related to the long-wavelength DEM

errors) and correct them using the least square method. Then we again simulate the return waveform and by this iterative approach we assess the application of this particular technique to DEM improvement and to altimeter measurements interpretation.

Using the results obtained, we analyse influence of glacier slope, atmospheric refraction, tides and the state of glacier surface (fresh or wet snow, bare ice, roughness) on the accuracy of altimetry data and estimate necessary corrections. We discuss processing of crossover techniques for processing multi-pass altimetry data obtained over glacier surface and the assessment of expected accuracies.

We have also performed correlation of multitemporal SPOT imagery and INSAR data. While interferometry provide only one component of the speed vector but with high accuracy, while correlation of SPOT imagery (with little time lag and with incidence angles less than 15 degrees) provide estimates of the two component, though with lower precision. These two techniques are highly complementary and both are necessary to establish the best possible assessment of ice movements.

Ice Sheet Topography from ERS Radar Altimetry

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Before the launch of ERS-1, only sparse, terrestrially-derived elevation data, with generally poor accuracy, were available for much of Antarctica and the northern half of Greenland. Elevation errors in excess of 200 m existed for these regions, severely limiting the utility of ice sheet topography for glaciological applications. ERS-1 extended the limit of useful data to 81.5° providing almost complete coverage of Greenland and ~80% of Antarctica. In addition, the geodetic phase of ERS-1, from April 1994-March 1995, provided dense across-track spacing over the ice sheets. As a result, several new digital elevation models (DEMs) of both ice sheets were produced with unprecedented accuracy and spatial resolution. Most recently, ERS-1 geodetic phase data have been combined with ICESat laser altimeter measurements to provide both unparalleled vertical accuracy with high spatial resolution. These DEMs have been used in a wide range of glaciological and geodetic applications and have revolutionised our understanding of many important processes and glaciological features.

Here, I review the development of the new generation of ice sheet DEMs and their use in a range of glaciological problems. Key applications considered include: i) determining the pattern of flow over the ice sheets by

modelling ice particle paths down-slope; ii) determining drainage basin areas for mass balance calculations using interferometrically-derived surface velocities, also known as the flux divergence approach; iii) identification of important glaciological features such as subglacial lakes and previously undiscovered flow features and iv) the use of accurate surface topography in inverse modelling studies to elucidate basal processes and subglacial topography. Finally, I consider what advances CryoSat could offer in terms of our knowledge of ice sheet topography, focusing in particular on the potential improvements in the key marginal areas, where steeper relief has limited the viability of previous radar altimeter systems.

ENVISAT radar altimeter as a sounding radar on the Amery Ice shelf

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An unique advantage of the ENVISAT altimeter system is the acquisition in S band as well as the classical Ku band. This double frequency approach is designed to measure the ionospheric delay to correct altimetric measurements. In contrast to ocean surfaces, over land and ice, the difference in frequency measurement is also influenced by surface properties such as ground slope and penetration into the surface medium. This is particularly the case for the Antarctic snow. Here, we present an original application of the use of these dual frequencies to sound the Amery Ice Shelf snow pack. We used along-track GDR data processed with the Ice2 algorithm to profile various parameters of waveforms for both frequencies and to map the points of interest, where measures in Ku and S differ. Comparison of altimetry data with MODIS image and simultaneous observations from helicopter and airplane, clearly shows that the anomalies between the 2 frequencies correspond to the crevasses identified on satellite image, as S band penetrates much deeper in the firn. The radar waveforms are analysed over space and time to strengthen the detection and better explain the radar behaviour over the crevassed area. Conclusions are drawn on algorithms to be designed to characterise the crevassing.

Session 1.1:

Oceanography: High Frequency

Constraining the mesoscale field

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The history of altimeter sensors provides a valuable opportunity to examine the challenges in observing the ocean mesoscale features and using those observations to constrain a numerical forecast model. A wide range of twin model experiments have been conducted using 1 or more altimeters to gauge accuracy in reconstructing ocean sea surface height. Many of these involve optimal interpolation systems that are inherently linear. However, the ocean dynamics are nonlinear, and small errors grow in time. Additionally, numerical models often have biases in circulation or energy of the mesoscale field. These pitfalls are avoided in this study by using direct satellite observations. To evaluate the accuracy with which multiple altimeters can constrain the nonlinear growth of the mesoscale field, we first use a 3 year assimilative 1/32 degree resolution global ocean model assimilating Jason-1, ENVISAT and GFO observations from 2001-2003. The model is the NRL Layered Ocean Model (NLOM) forced by NOGAPS surface stress and heat fluxes. Additional assimilation experiments are performed using only GFO observations and then only GFO and ENVISAT observations. Finally, a third experiment is performed assimilating all three altimeter data sets. The key difference between the two experiments assimilating 3 altimeter data sets is that they start from slightly different initial conditions. Due to the nonlinear behavior of the mesoscale flow, small perturbations grow in time. One of the three altimeter assimilation experiments is declared "truth". The difference between the two experiments using 3 altimeters provides a measure of the ability of these systems to constrain the mesoscale.

Individual snapshots or spatial plots of the RMS error indicate the largest errors occur in the western boundary currents and the associated eastward extensions. The error variance to signal variance is examined spatially for the 1 through 3 sensor assimilation cases. With only one altimeter, the unresolved variability is in the typical range of 75% to 100%. With 3 altimeters, the results are much improved, particularly in mid latitudes. Zonal average error statistics

reveal the improvement from of additional sensors as well as the importance of the observations. There are instances in time and areas in the world where a non-assimilative wind forced model has higher skill than the experiment using 1 altimeter. In these areas and times the dominant processes are wind driven deterministic variations and occur primarily in the equatorial regions.

The Interaction Between the Mesoscale and Gyre-Scale Variabilities of the Argentine Basin

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The ocean is a turbulent fluid characterized by interactions among a wide range of spatial and temporal scales. The Argentine Basin of the South Atlantic Ocean is an ideal region to study the interaction between mesoscale eddies and gyre-scale waves and currents. The confluence of the Malvinas and Brazil Currents creates mesoscale meanders and eddies with energy levels ranked at the top of the world's oceans. Surrounded by the energetic mesoscale variability is a gyre of anticyclonic barotropic circulation, superimposed by rapidly-rotating, gyre-scale, high-frequency waves (25-day period). Decade-long altimetric observations of sea surface height have provided a unique opportunity to study the relationship between the mesoscale and gyre-scale variabilities of the region. The high accuracy and temporal sampling of TOPEX/Poseidon (T/P) and Jason data have allowed the detection of the high-frequency gyre-scale waves, whereas the enhanced spatial resolution provided by the merging of T/P and Jason data with ERS-1 and -2 data enables the synoptic analysis of the mesoscale variability. Some interesting properties of cross-scale interactions were discovered. The amplitude of the high-frequency gyre-scale waves is highly intermittent with dominant periods in the range of 110-150 days. Within this period band, the wave amplitude is coherent with the energy level of the mesoscale variability: When the mesoscale energy level goes down, the wave amplitude goes up, and vice versa, suggesting an exchange of energy between the two scales. The time-lagged correlation of the mesoscale variability reveals a pattern of anticyclonic movement of eddies and meanders, suggesting an interesting relation

between them and the mean circulation of the Argentine Basin. These findings provide motivations for further theoretical and modeling investigations of the nature of the interactions and the role of mesoscale variability in determining the general circulation of the region.

Eddies and Mean Flow in the Antarctic Circumpolar Current

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The Antarctic Circumpolar Current (ACC) is a multi-jet flow that encircles Antarctica, providing a Southern Ocean connection between the Atlantic, Indian, and Pacific Ocean basins. Exact repeat altimeters are highly successful at identifying eddy variability, and in the Southern Ocean they have clearly demonstrated that strong eddy variability is associated with the ACC. Altimeter observations by themselves do not distinguish the time invariant geoid from time invariant features of the dynamical ocean circulation, so efforts to study the mean flow of the ACC have proved more difficult than studying the eddies themselves.

Since the first altimetric studies, a number of strategies for studying mean circulation have been explored. One strategy is to assume that the ACC consists of meandering jets with Gaussian velocity profiles and to use an iterative process to reconstruct an estimated mean flow. This method can work well near large meandering jets but fails in places where jets do not meander and cannot capture large-scale background mean flows. A second strategy is to infer the mean sea surface height from hydrographic atlas data by determining dynamic topography relative to a known "level of no motion". This method can prove problematic in the Southern Ocean where recent in situ estimates have suggested that bottom velocities are as large as 2 to 4 cm/s. New satellite geoid observations (from GRACE) and new dynamic topography estimates developed from autonomous ALACE and ARGO floats now offer alternate strategies for assessing the large-scale mean flow of the ACC and its interactions with eddies, although these means offer coarser spatial resolution than meandering jet models. Thus merged sea surface height maps may ultimately need to combine aspects of a variety of different strategies. Altimeter-derived estimates of the mean ACC have shown the current to be strongly steered by topography with enhanced eddy variability in regions of strong topography. Newer data will allow these analyses to be refined to demonstrate more completely the interactions between eddies and mean flow in the ACC.

Dynamics of the Near-Uniform Basin-Wide Wind-Driven Sea Level Fluctuation of the Mediterranean Sea

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Dynamics of the recently identified basin-wide oscillation of the Mediterranean Sea is analyzed using sea level observations from the TOPEX/POSEIDON satellite altimeter and a numerical ocean circulation model.

More than 50% of the large-scale, non-tidal, and non-pressure driven fluctuation of sea level can be attributed to this oscillation that is nearly uniform in phase and amplitude across the entire basin. The oscillation has periods ranging from 20-days to several years and has a magnitude as large as 10 cm. The fluctuation is due to variations in net mass flux through the Strait of Gibraltar driven by winds in the Strait and its vicinity including the Alboran Sea and the Atlantic Ocean immediately to the west of the Strait between the Iberian Peninsula and Africa. The Mediterranean Sea adjusts almost uniformly across the basin with depth independent pressure perturbations.

A dynamic balance is established in the vicinity of the Strait between wind and sea level difference between the Mediterranean Sea and the Atlantic Ocean. The amplitude of this basin-wide wind-driven sea level fluctuation is inversely proportional to the Strait's depth but is insensitive to its width. The wind-driven fluctuation is coherent with atmospheric pressure over the basin and contributes to the apparent deviation of the Mediterranean Sea from an inverse barometer response.

Recent advances on the characterization of mesoscale vortices from altimetric maps

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Satellite altimetry has proved to be a very valuable tool for the study of the ocean mesoscale. At these scales the ocean is characterized by the presence of coherent vortices, which make it resemble two-dimensional turbulence. Such

similarity has been exploited to analyze altimetric data using ideas and techniques developed in the domain of turbulence with very successful results (e.g. Stammer 1997, Gille and Llewellyn Smith 2000). One of these ideas is the view of coherent vortices as the basic building blocks of the flow. Indeed, ocean vortices are known to play a key role in the ocean dynamics due to their effectiveness in moving energy and matter through the ocean and their impact on mixing.

In order to be successful in this approach to the dynamics of the ocean a robust vortex detection algorithm is necessary. A possible choice of such a criterion is one based on the sign of the Okubo-Weiss parameter (Okubo 1970, Weiss 1991), which measures the relative contribution of deformation and vorticity. Then, a coherent vortex can be defined as the simply connected region with negative values of the Okubo-Weiss parameter. Besides this definition only captures vortex cores, it has been shown that this method is adequate to detect marine eddies in altimetric maps and when the geometry of streamline contours in Sea Level Anomalies (SLA) maps is unclear it appears to work more consistently (Isern-Fontanet et al. 2002, Isern-Fontanet et al. 2004).

When a vortex, or its core, has been identified it is possible to estimate the individual properties of the vortex such as size, mean kinetic energy and amplitude and then analyze its statistical distribution. Initially, this criterion has been applied to SLA maps that combine TOPEX and ERS data (Le Traon et al. 1998, Larnicol et al. 1995) of the Mediterranean sea produced by CLS (France) for the period October-1992 to October-1999 produced by CLS (France). The distribution of such properties for the vortices in the Mediterranean, suggests an heuristic criterion to extract and select very coherent and long lived vortices from the whole set of structures identified in altimetric maps. An algorithm to systematically locate and track such vortices provides for the first time a general picture of their preferential paths in the Mediterranean basin (Isern-Fontanet et al. 2005a) and at global scale. Furthermore, it has been shown that these very coherent vortices are the principal responsible for the non-Gaussian behavior of the Velocity Probability Density Functions having a great impact on the dispersion and mixing processes (Isern-Fontanet et al. 2005b). Indeed, a wavelet decomposition of the vorticity field from SLA maps shows that an important fraction of the global properties of the flow dynamics as total energy and enstrophy is retained by the contribution of a small fraction of such coherent structures (Turiel et al. 2005).

Session 5.1:

Building the 15-Year Altimetric Record/Calibration and validation

Lessons Learned for Science Processing

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Based on the development of the TOPEX Science Data Processing System and the related development of the NSCAT and SeaWinds ground systems a number of important lessons in system design, development, and calibration have been accumulated. Specifics in the areas of

Science Team participation

Algorithm development

Use of a Testbed system

Calibration of data

Cross calibration of systems

Data quality monitoring

will be presented.

The success of TOPEX/POSEIDON and the continuation of these data by Jason-1 are prime examples of the best practices in these areas.

Three Decades of Precision Orbit Determination Progress, Achievements, Future Challenges and its Vital Contribution to Oceanography and Climate Research

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Although satellite altimetry has been around for thirty years, the last fifteen beginning with the launch of TOPEX/Poseidon (TP) have yielded an abundance of significant results including: monitoring of ENSO events, detection of internal tides, determination of accurate global tides, unambiguous delineation of Rossby waves and their propagation characteristics, accurate determination of geostrophic currents, and a multi-decadal time series of mean sea level trend and dynamic ocean topography variability. While the high level of accuracy being achieved is a result of both instrument maturity and the quality of models and correction algorithms applied to the data, improving the quality of the Climate Data Records produced from altimetry is highly dependent on concurrent progress being made in fields such as orbit determination. The precision orbits form the reference frame from which the radar altimeter observations are made. Therefore, the accuracy of the altimetric mapping is limited to a great extent by the accuracy to which a satellite orbit can be computed. The TP mission represents the first time that the radial component of an altimeter orbit was routinely computed with an accuracy of 2-cm. Recently it has been demonstrated that it is possible to compute the radial component of Jason orbits with an accuracy of better than 1-cm. Additionally, still further improvements in TP orbits are being achieved with new techniques and algorithms largely developed from combined Jason and TP data analysis. While

these recent POD achievements are impressive, the new accuracies are now revealing subtle systematic orbit error that manifest as both intra and inter annual ocean topography errors. Additionally the construction of inter-decadal time series of climate data records requires the removal of systematic differences across multiple missions. Current and future efforts must focus on the understanding and reduction of these errors in order to generate a complete and consistent time series of improved orbits across multiple missions and decades required for the most stringent climate-related research. This presentation discusses the POD progress and achievements made over nearly three decades, and presents the future challenges, goals and their impact on altimetric derived ocean sciences.

Geographically correlated errors – problem solved?

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It is known that gravity field errors map differently to ascending and descending passes of a satellite – either by the sum or by the difference of a ‘mean’ (geographically fixed) error and a ‘variable’ error component. In satellite altimetry, mean or geographically correlated errors are of particular concern, because they directly map into the sea surface heights. They are, however, not visible in single satellite crossover differences, because they cancel each other. Thus, with a single altimeter satellite there is no way at all to assess this type of errors – except by a retrospective comparison between old and new orbits, the latter reprocessed with improved gravity field models. 14 years ago – with the launch of TOPEX/Poseidon – a period began with two or even more altimeter satellites operating simultaneously. Subsequently dual-satellite crossovers could be used to estimate the mean orbit error – above all for those satellites whose orbits were considered to be less precise. This way ERS- and GFO-orbits have been adjusted to TOPEX, taken as reference. Long-term means of dual satellite crossover have also been used to invert the crossover and to estimate errors for the gravity field harmonics which in turn implies knowledge about the geographically correlated error. Dual satellite crossovers have been used to evaluate the spectral accuracy of the gravity field models which required to harmonize as far as possible the altimeter data and to use orbits based on the same gravity field. Dual satellite crossovers have been even used for a successful tuning of the Earth gravity field model (e.g. DGM-04) which in turn was taken to reprocess satellite orbits. Later on the quasi continuous tracking with GPS allowed to follow a “reduced dynamic” orbit determination procedure – minimizing gravity field induced orbit errors. With new generation gravity field models derived from the CHAMP and GRACE missions, the gravity field has now dramatically improved (and will further improve with the

GOCE mission). Again, new (GPS-based) orbits reveal significant geographical error pattern – even for TOPEX which has been considered as a reference for other altimeter missions. Gravity field induced orbit errors are now minimized. If geographically correlated error pattern are still discovered they are governed by other error sources. Multi-mission satellite crossovers, computed – in all combinations – from two or more contemporaneous altimeter systems, perform a dense network with high redundancy. A common analysis allows to estimate errors of the radial component of all altimeters and to verify if there are still geographically correlated error pattern.

15 years of improvements in ocean altimetry performance: a review

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From the ERS-1 and TOPEX/Poseidon launches in the early nineties, Oceanography was radically changed thanks to global and precise observations from satellite altimetry. Since then, a tremendous number of improvements in a wide variety of domains have been brought by extensive studies in different teams all over the world. All these efforts allowed the current situation of high precision multi-mission altimetry. In the same time, studies, applications such as operational oceanography and new fields of investigation have developed and put new requirements on altimetry missions in terms of data availability, accuracy and stability.

A review of the main improvements in altimetry is given, with quantification in terms of performances and identification of the major impacts on applications. Indeed, great breakthroughs have been achieved in several domains, such as instrument processing, precise orbit determination, geophysical algorithms and corrections, data availability and coverage, but also calibration, cross-calibration and merging techniques. Thus it is important to estimate to what extent each subject contributed (and still contributes) to the overall performance and error budget. Moreover, it is interesting to identify, depending on the nature of each improvement, which cause motivated the change and by which means it was achieved. The impact on the end user applications is of course essential, since it drives the loop between improvements in altimetry, development of new applications and new requirements for altimeter systems. Finally conclusions are also inferred from this 15 year experience about the efficiency of including validation and performance assessment at each step, and about the great collaborative work that has been set up between operation engineers, project managers, specialists in each domain, scientists and users, each doing his utmost for the same goal in an integrated concept.

Estimating Altimeter Drift from Tide Gauges: Past, Present and Future

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In the past 15 years methods have been developed to make precise estimates of altimeter drift rates using the global tide gauge network, and at present we are able to determine drift rates for the TOPEX/Poseidon/Jason-1 missions to better than 0.5 mm/yr. A review of these methods will be presented, with an emphasis on what limits the accuracy of the estimations. We will then turn to a brief description of the present status, presenting drift estimates for all currently available altimeter datasets. Based on this assessment of past and present results we will conclude with a discussion of what is required in the coming decade to insure that our present and future altimetric datasets are drift-free.

Session 2:

Cryosphere

Hydrological networks beneath Antarctica: New signals from altimetry

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While much of the base of the East Antarctic ice sheet is melting, as is evident from 145 subglacial lakes, little else is known about the basal hydrology of this huge ice mass. Such knowledge is critical to understanding the flow of ice, the rate at which water stored beneath an ice mass may be transferred to its margin, the development of glacial landforms and the habitats of subglacial lakes. In addition, little attention has been given to the possibility that the very existence of subglacial lakes may determine the mode of basal drainage through intense outburst flooding. Here we record an outburst flood from a subglacial lake within the Adventure Subglacial Trench in central East Antarctica, the most stable part of the ice sheet. We show that, in 16 months, some 1.8 cubic kilometres of flood water was transferred 290 km to at least two other subglacial lakes. While the presence of the ice roof may moderate flooding, the intrinsic instability of pressurising subglacial lakes makes such events, occurring at intervals of 10 to 1000 years, a normal mode of subglacial drainage. If large lakes, such as Lake Vostok or Lake Concordia, are presently pressurising, substantial floods may be foreseen, and these may reach the coast. Our observations are also in contrast to expectations that subglacial lakes are characterised by long residence times and slow circulations; indeed entire subglacial drainage basins may be flushed at regular intervals. The rapid transfer of water from one lake to another will result in the large-scale relocation of solute and microbes between lakes, and the contamination of significant portions of drainage systems from future in situ exploration is a distinct risk.

Historical understanding of ice sheet dynamics versus evolution of topography

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The ice sheet topography is one of the pertinent parameters related to the processes acting on ice sheet. Because it is a free surface, its description strongly helps in ice modelling. From the global scale to the km-scale, the topography hides the signature of the physical processes as well as the one of external forcing. The aim of this paper is to review the historical evolution of our ice modelling understanding with respect to the evolution in the altimetric sensors, in the mission orbits, in our comprehension of bias and in the data processing. At the large scale, the first well described by the altimetric observations, it is mostly the validity and the parameter values of the Glen law that were looking for. As the topography evolves, the so called Glen exponent were found to be 1, then 3, then varying from 1 to 3 depending on the temperature. The first unexpected surprise offered by the altimetric observations was the discovery of large subglacial lakes, the first one the Astrolabe with the Seasat altimeter, then the Vostok one very soon after the ERS launch, before the discovery of numerous lakes around dome C and Vostok areas. At the 100-km scale, two different undulations networks were pointing out. The first one, in the flow direction, is related to the propagation of anomaly from the outlet glacier up to the dome and exhibits that the flow direction does not always follow the surface slope direction. The second one, parallel to the flow with a wavelength of 250 km is still to be understood, as the regular pattern of the outlet anomaly mapped with the help of the first network. Even if the 10-km scale undulation were quickly well described, the evolution of the sensors, of the mission orbit, of our understanding of the altimetric bias and of the data processing yields to a better small-scale features description with the help of waveform shape. Thus, we are now able to characterize and describe km-scale. At this scale we observe the anisotropy of surface undulations related to the ice properties, we describe the effect of the longitudinal stresses or we detect the hydrological subglacial networks

Arctic Ocean geoid, ice thickness and mean sea level – the ArcGICE project

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Satellite altimetry from ERS, Envisat and ICESat may be used together with updated geoid models based on surface, airborne and satellite gravity field data to derive estimates of Arctic Ocean mean dynamic topography (MDT) as well as sea ice free-board heights. In the paper we use a mean sea surface (MSS), based on ICESat lowest-level filtered laser altimetry and retracked radar altimetry, combined with an improved Arctic geoid model based on terrestrial gravity data and GRACE, to make a consistent estimate of Arctic Ocean MDT. We compare results to oceanographic models, showing that an overall absolute consistency is possible at the dm-level. Arctic Ocean sea ice freeboard heights (and thus thickness) are an integral part of these investigations, and ICESat-derived freeboard heights show a good correlation to multi-year ice distribution as determined from Quikscat. The sea ice presence, which may bias altimetry sea level measurements, as well as the inhomogenous distribution of gravity data and tidal model errors, are limiting factors in the precise MDT determination. We study the characteristics of errors in both space and spectral domains, and outline optimal methods for joint processing of altimetry and gravity for MSS and MDT recovery. The investigations are the core of an ongoing ESA project “ArcGICE”, aimed a.o. at providing a practical algorithm for the estimation of sea surface heights and its associated error covariances, to be used, e.g., as reference for Cryosat measurements of sea ice freeboard.

Satellite altimetry over ice shelves: tides and grounding lines

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The floating ice shelves are the areas of the Antarctic ice sheet that are most susceptible to the effects of climate change, justifying recent intense efforts to determine trends in ice-shelf mass balance terms including thickness and velocity. However, ice shelves move vertically with the underlying ocean tide, and any errors in predicted tide displacement can be aliased by the satellite orbits into apparent trends, seasonal cycles, and other periods. There are two factors making tide removal more challenging for Antarctic ice shelves than for the bulk of the global ocean. First, tide models for Antarctica are not as accurate as they are in mid-latitude oceans. This is because basic model inputs such as coastline/grounding-line locations and sub-ice-shelf bathymetry are poorly known, and the tide-resolving TOPEX/Poseidon and Jason radar altimeter missions only extend to 66 degrees S. Second, shelf ice within the grounding zone (GZ), a band a few kilometers wide adjacent to the grounding line, is not in hydrostatic equilibrium with the underlying ocean tide, but shows a reduced amplitude response.

Here, we review work we have done to help resolve this significant problem, including methods for improving the accuracy of Antarctic tide models through assimilation of multi-mission satellite altimeter data (ERS and ICESat) and in situ data from ice shelf GPS and ocean moorings. We also present early results of a technique which uses repeat-track ICESat data across the GZ to determine the location and flexure characteristics of the GZ. Since ICESat covers all of the ice shelves, by analyzing ICESat data around the perimeters of the RIS and FRIS, we can significantly improve the GZ definition relative to existing estimates. By defining the flexure characteristics of the GZ, including width and curvature, it will be possible for the first time to apply tidal corrections within the GZ, which is frequently a region of intense basal melt and thus a significant focus of shelf-ice mass balance studies. Our studies will also contribute to tide removal for GRACE by improving not only the prediction of ocean tide but also the associated ocean load tide, whose influence extends over the entire Antarctic continent.

Application Of Radar Altimetry To Estimate Sea Ice Extent and Thickness East of Greenland

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This study investigates the use of space borne radar altimetry to estimate the sea ice conditions and the sea ice thickness in the sea east of Greenland.

The data analyzed are ENVISAT radar altimeter (RA-2) data.

In order to investigate sea ice extent, the shapes of the waveform are studied as they are an indicator of the surface properties depending from the surface roughness. Three parameters are extracted from the shape of the waveforms in order to analyze sea ice conditions: -backscatter coefficient - peak power of the waveform -pulse peakiness parameter Furthermore the sea ice freeboard height are measured by the spaceborne radar altimetry by discriminating the specular waveforms from the diffuse and thereby sea ice thickness estimates are derived.

The RA-2 data used in this analysis spans a whole year: from the 15th of March 2004 until the 4th of April 2005. Four repeated tracks (sampling period 35 days) are analyzed over the eastern Greenland sea in order to point out changes in the data originating from the sea ice changes over the seasons, e.g. accumulation of snow, and meltwater.

Session 1.3:

Oceanography: Low Frequency

The seasonal cycle of the South Indian Ocean from model and altimeter data

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The seasonal cycle of the South Indian Ocean has been investigated using the results of numerical simulations and altimeter information. In the first portion of our research we investigated the seasonal response of the South Indian Ocean circulation to the wind stress forcing from a series of process-oriented numerical experiments. According to these experiments the topographic ridges that run south of Madagascar regulate the variability in the south Indian Ocean. These topographic features isolate the western boundary region from the subtropical gyre seasonal timescales. To confirm the conclusions from our process studies we also analyzed the results of an eddy-permitting global simulation (POCM_4C) and altimeter data. The conclusions drawn from the analysis of POCM were consistent with those obtained from our regional model and further revealed that seasonal changes of the Agulhas Current transport are linked to the large-scale circulation in the tropical region (not the subtropics). According to this model, the Agulhas Current transport has a seasonal variation with a maximum at the transition between the austral winter and the austral spring and a minimum between the austral summer and the austral autumn. Regional and basin-scale mass balances indicate that although the mean flow of the Agulhas Current has a substantial contribution from the Indonesian throughflow, there appears to be no dynamical linkage between the seasonal oscillations of these two currents. Instead, we found evidence that the seasonal cycle of the western Indian Ocean is the result of the oscillation of barotropic modes forced directly by the wind. The analysis of altimeter data confirmed that the influence of the Indonesian throughflow on the seasonal cycle appears to be confined to the easternmost portion of the basin, while the influence of the wind stress forcing is important everywhere. Our analysis indicates that seasonal variations of tropical origin propagate to the subtropics in the central portion of the basin and in the western region. In the central region, there is strong evidence of an annual wave that propagates southwestward between $\sim 105^{\circ}\text{E}$ and 75°E in a lapse of ~ 4 months. The connection between the tropics and subtropics in the western region is less robust. Preliminary calculations using Pathfinder data, however, appears to

confirm the propagation of seasonal variations of tropical origin through the Mozambique Channel.

Rossby wave and eddy in the North Pacific Subtropical Countercurrent

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Since the earlier study of low-frequency large-scale oceanic Rossby waves using 3 years of TOPEX/POSEIDON data by Chelton and Schlax (1996), some new features of the oceanic Rossby wave have been found with more and more available observational data including Sea Surface Height Anomaly (SSHA), ARGO and other data in the North Pacific Subtropical Countercurrent (STCC) area. There are two branches of the STCC in the North Pacific: the North STCC located in the Northwestern Pacific ($20^{\circ}\sim 26^{\circ}\text{N}$ to the west of 170°W) and the South STCC extends from 145°E to the west of the Hawaii Islands (158°W) along $19^{\circ}\sim 20^{\circ}\text{N}$. In both STCC regions, the SSHA exhibits remarkable intraseasonal oscillations with period of 80-120 days, corresponding to westward propagation of free Rossby waves. The amplitude of those intraseasonal Rossby waves appears larger in the west end of the North STCC than that in the east end of the North STCC, seemingly due to the stronger baroclinic instability in the North STCC. As a result, the intraseasonal variation of SSHA appears to be stronger than its annual variation in the west end of the North STCC, and the transport of the Kuroshio in the east of Taiwan also exhibits strong intraseasonal variation with a period of about 100 days. Eddies in the STCC associated with the intraseasonal Rossby wave move westward at an average speed of approximately 0.098 m/s and with an average radius of about 200 km. These eddies from the interior North Pacific seems not to be able to enter the South China Sea through the Luzon Strait. The transport of the Kuroshio in the east of Taiwan, however, can be affected by these eddies with a high correlation with the SSHA ($22\sim 24^{\circ}\text{N}$, $121.75\sim 124^{\circ}\text{E}$). During the period of Oct. 1992~Jan. 1998, two northwestward propagating cyclonic SSHA converged to the Kuroshio and caused a substantial reduction of the Kuroshio transport as a contrast to the normal westward propagating cyclonic SSHA. Although the lower Kuroshio transport event can be generated in different ways, the intraseasonal Rossby wave plays a dominant role in

the 100-day period oscillation of Kuroshio transport in the east of Taiwan. In addition to those eddies, there is also a vortex pair with the orbital period of 10-11 days and the radius of 58-68 km in the west of Hawaii Islands. The average T/P SSHA shows general distribution of the vortices in a region broader than that covered by the trajectories. The T/P SSHA clearly demonstrates two symmetrical arrays of cyclonic and anticyclonic vortices that are similar to the pattern of the vortex street.

Dynamical and thermodynamical signatures of Rossby waves in presence of mean flow and topography

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A major achievement of satellite altimetry has been to reveal the ubiquity of westward propagating planetary wave features at nearly all latitudes. Such signals have been interpreted as first mode baroclinic Rossby waves, but the standard theory for such waves appears to underestimate the speed of the observed signals by a factor of two to three at mid and high latitudes, and to overestimate it in the equatorial regions. This has prompted many theoretical investigations aimed at understanding the physical mechanisms affecting the dynamics of Rossby waves. Probably the two most important effects are the background mean flow and the topography. With regard to the mean flow effect, a puzzling result is that the net effect on the speed of the waves is the difference between two large terms which nearly cancel each other: the doppler shift effect on the one side, versus the modification of the background planetary vorticity gradient. Although the mean flow effect is often held to account for the observed "too-fast" propagation, the large uncertainties generally accompanying the estimation of the large-scale circulation raises questions as to the reality and statistical significance of the net speed-up found in the published literature. On the other hand, it can be shown that the topography always produce a Rossby wave mode that is systematically faster than the standard first baroclinic mode, and whose speed closely match the observed wave speeds. Furthermore, the topography is found to generically led to the split-up of Rossby wave modes, implying a scattering of wave energy near the top of ocean ridges which could potentially explain the observed increased wave activity westward of major topographic features in the ocean. Finally, an important property of oceanic Rossby waves is that they possess a thermodynamic signature in the surface temperature field, by which they may have some climatic impact. The thermodynamic signature of Rossby waves can be caused by several processes, including the advection by Rossby wave velocity

field across mean temperature gradients, and the coupling with the mixed layer. This paper will summarize the theoretical results achieved by our work over the past 10 years on the above issues.

Causes of large-scale sea level variations in the Southern Ocean: Analyses of sea level and a finite element barotropic model

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We analyze a decade of sea surface height (SSH) measurements in the Southern Ocean from the TOPEX/Poseidon and ERS altimeters, with a focus on the variability at timescales shorter than two years. Among the different processes contributing to large-scale SSH variations, the barotropic response to the winds dominates poleward of 50°S, while thermocline processes dominate equatorward, except for resonant basins for the barotropic modes and regions of intense eddy activity. A finite element barotropic model has been developed to analyze the vorticity budget. The SSH from the model agrees well with observations. The leading barotropic mode, which is annular, is confined near Antarctica, and is responsible for most of the barotropic circumpolar transport. The barotropic transport associated with this mode is coherent with the zonally integrated eastward wind stress consistent with a free mode response. Although previously evidenced in bottom pressure data, this mode is only partially seen in altimeter data because of ice coverage. It nevertheless distinctly appears above the Pacific ridges where it expands meridionally up to midlatitudes. In the rest of the domain, several regions coherent with the local wind stress curl are found. These are regions isolated by f/H contours, mostly deep basins. An analysis of the vorticity budget shows that, generally, topographic Sverdrup balance is the leading process for periods larger than 50 days, but in some regions (resonant basins), diffusive and nonstationary terms are important. A model experiment shows that transients redistribute energy along f/H waveguides, contributing to drain resonant regions, as was hypothesized in previous works.

On the low-frequency variability in the Indian Ocean

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The satellite altimetry data available today, since the launch of TOPEX/Poseidon in August 1992, covers a time interval of more than 13 years. Such a long time series opens up new opportunities for analysing low-frequency processes in the ocean with periods of more than one year. In this work we present results for the Indian Ocean using spectral analysis and band-pass filtering of 1992-2004 sea surface height anomalies (SSH) from satellite altimeter data sets. Four dominant frequencies are identified at frequencies corresponding to a 6-month period and longer, separated by significant spectral gaps. Two of these frequencies constitute the well known semi-annual and annual signals, while the other two frequencies correspond to 18-20 months and more than 24 months. For each of these frequencies, the spatial distribution of the power spectral density of the SSH field is analysed. The results show westward and eastward propagation suggestive of Rossby and Kelvin waves; however, they also point to potentially new phenomena. The spatial distributions of the power spectral density provide important clues to the physics of the corresponding variability modes, such as where the signals are strongest. The spatial/temporal structure of identified variability modes is identified by inverse Fourier transforms of the sets of harmonics belonging to a particular band. One of the most interesting results of this analysis is the discovery of strong 18-20 month variations to the south-west of Sumatra that are opposite phase with sea level near the Cocos Islands. Another interesting phenomenon is propagation of the greater than 24 month signal from the Pacific to the Timor Sea and around Australia as far as the Great Australian Bight.

Seasonal and interannual variability of the North Pacific Ocean: modeling results and their validation through altimeter data

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Altimetric measurements have allowed significant validation

of hypotheses, based on modeling results, concerning the functioning of two relevant aspects of the variability of the North Pacific Ocean: (a) the wind-driven seasonal variability in the eastern tropical ocean and (b) the decadal variability of the Kuroshio Extension.

As for the first dynamical aspect, the wind-driven seasonal variability in the tropical North Pacific is analyzed by means of an ocean model implemented in an idealized North Pacific and forced by an analytic seasonally varying wind stress field derived from ECMWF winds. The oceanic response in the tropical region is found to be mainly in the form of annual beta-refracted baroclinic Rossby waves radiating from the eastern boundary, and generated by the passage of northward propagating coastal Kelvin waves which are, in turn, produced remotely by seasonally varying winds in the equatorial wave guide through a mechanism known to play a major role in the El Niño dynamics. These modeling results suggest, therefore, that the annual Rossby waves observed in the eastern tropical North Pacific may be mainly generated remotely in the equatorial band rather than by varying winds along the eastern coast, as considered in other studies. Validation of these results with TOPEX/Poseidon altimeter data is carried out. Zonal x-t diagrams of sea surface height anomalies and zonally integrated meridional transports computed from T/P data and from the winds through the Sverdrup relation by Stammer (1997) are compared with the corresponding quantities obtained from the model results. Such comparison shows that the model does capture the essential features of the wind-driven seasonal variability in the eastern tropical North Pacific.

As for the Kuroshio Extension dynamics, a model study in which forcing is provided by a time-independent climatological wind yields an internal decadal variability of the jet in significant agreement with the altimeter observations for the period 1992-2004 presented by Qiu and Chen (2005). A reduced-gravity primitive equation ocean model is implemented in a box spanning the whole North Pacific, including a schematic coastline at the western side, and the wind, though idealized, is chosen according to the ECMWF and COADS climatologies. The low-frequency variability (due to intrinsic nonlinear mechanisms) is found to be a chaotic bimodal oscillation between an energetic meandering state and a much weaker state with a reduced zonal penetration. These high and low energy states are found to be very similar to the “elongated” and “contracted” modes of the Kuroshio Extension detected through altimetric measurements, and also the period (of around 10 years) and transition details of a typical bimodal cycle are in good agreement with the above mentioned altimeter observations. A dynamical mechanism supporting this self-sustained oscillation of the modeled Kuroshio Extension is then proposed, and its strict connection with the bimodal behavior of the Kuroshio south of Japan is analyzed. On the basis of these modeling results and of their significant altimetric validation, it can be hypothesized that the observed bimodal decadal variability of the Kuroshio Extension is basically due to a self-sustained internal oscillation related to the barotropic instability of the

Kuroshio south of Japan without any crucial intervention of wind-driven Sverdrup transport fluctuations and of topographic interactions, although such effects certainly play an important role in shaping the finer structure of the jet variability.

Antarctic Circumpolar Transport Variability from a combination of precise altimetry and GRACE 'bottom pressure' data

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Efforts at monitoring the transport of the Antarctic Circumpolar Current (ACC) have intensified in recent years, as the ACC's important role has become more apparent. The ACC has the strongest bottom pressure signal of the world's oceans (together with N. Pacific), which makes it clearly detectable in GRACE data, interpreted as bottom pressure variability. When using precise altimetry, however, surface-intensified eddy variability acts as noise when trying to construct an index of ACC transport. Furthermore, while the barotropic horizontal transport across an arbitrary vertical cross section is proportional to the difference in bottom pressure between the two ends of the section, the southern boundary of the ACC is much better defined than the northern one, and there are physical reasons to believe that the fluctuations in the southern boundary's pressure are more important in determining the pressure gradient. However, the southern data alone are more sensitive to quantities that are still poorly defined by the GRACE data. Here we construct an index using both the GRACE data, which only exists after mid 2002 and whose quality increased at the beginning of 2003, and precise altimetry, which permits us to extend the time series to 1993-2005.

Session 5.1:

Building the 15-Year Altimetric Record/Calibration and validation

Fifteen years of ERS satellite orbits and altimetry: an overview

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In fifteen years much has changed in the field of satellite altimetry. Only three altimeter satellites preceded ERS-1, two of which were only active for a few months. ERS-1 was the first to provide wind and wave information operationally to meteorological institutes. Much was expected from the sea height measurements it would provide, but few expected it would do so well that it marked the beginning of a new era of high-precision satellite altimetry, ahead of TOPEX/Poseidon, which was exclusively built for this purpose.

Since then orbit errors have been reduced by nearly two orders of magnitude, tide models have improved by a factor 10 as well, and high-resolution gravimetry was made possible by ERS-1's geodetic mission.

By the time ERS-2 was launched it became clear that the ERS satellites could also contribute to the assessment of global sea level rise, both by gauging the oceans as well as ice surfaces. And in the last decade many unforeseen applications have been added, including the measuring of sea ice thickness, lake level monitoring, and hurricane forecasting.

This presentation highlights some of the key developments in satellite altimetry and orbit determination that demonstrate the important contributions of ERS-1 and ERS-2 to the field.

High Rate Waveforms Analysis: 10 years of geophysical applications

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High rate altimeter waveforms (10 Hz for Topex, 20 Hz for Jason and Envisat) contains a wealth of information on the variation of the Normalized Radar Cross section (NRCS) at scales smaller than the altimeter footprint. However, the complexity of their analysis and the quantity of data to be processed have limited their use and very few studies involving their analysis for geophysical studies (other than tracking) have been published. Over the past 10 years, the Laboratoire d'Océanographie Spatiale of IFREMER has developed several applications based on the analysis of the high rate waveforms, i.e. the determination of rain cells characteristics, the detection of surface slicks (associated with sigma-0 bloom) and the detection of ships, small islands.

The presence of small scale phenomena within the altimeter footprint, such as rain cells which attenuate the signal, surface slicks that enhance it, or above sea level objects (light house, ships, etc.) leads to characteristic V-shaped patterns in the waveforms fields. They result from the relative movement of the satellite above the surface phenomena. Specific models of waveforms based on the Brown model and on the modulation of the surface NRCS within the altimeter footprint have been developed to explain and characterise the signatures of these different processes. The models and methods have been validated by data/model comparison. In this paper, we describe these three main applications of high rate waveforms analyses and present what operational use could be foreseen as the computing capabilities improved.

ENVISAT S-Band Altimeter Calibration and Validation

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As a principal investigator for the Envisat RA-2 Altimeter the Navigation Office at ESOC has been actively involved in the Calibration and Validation phase of the Altimeter. After the Cal/Val phase ESOC has continued monitoring the performance of the altimeter as a member of the Quality Working Group (QWG) of the ENVISAT Altimeter. All the major effort during the Cal/Val phase and the ensuing routine monitoring phase has focused on the Ku-Band of the Altimeter. Very little work so far has been done to correctly estimate the S-Band range and time bias of the Altimeter. This paper will describe the results of the detailed study performed on the S-band range and time bias. Further the impact of the range bias on the dual-frequency ionosphere correction as it is currently present on the GDR product will be illustrated.

The Calibration of ESA Altimeters from ERS-1 to CryoSat

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The first ESA altimeter on-board the first ESA Environmental satellite, ERS-1, was launched on 17 July 1991. Since ERS-1, ESA has launched another 2 altimeters, ERS-2 RA on 21st April 1995 and EnviSat RA-2 on 1st March 2002; and is about to launch the 4th ESA altimeter on-board CryoSat, in October 2005. In order for the scientists to achieve consistent and sensible results, the need of building a consistent time series (over these 15 years) is required. And to do that, all these altimeters need to be calibrated both in absolute terms, and among them.

Different calibrations have been performed over these years to these altimeters, driven by the scientific needs of the particular moment. The ERS-1 altimeter range was absolutely calibrated over the Venice tower (Francis, 1992). The ERS-2 altimeter was cross-calibrated against ERS-1 and TOPEX/Poseidon altimeters (Benveniste et al. 1997). The EnviSat RA-2 was calibrated in absolute terms for both: its range over the Mediterranean sea with a regional calibration (Roca et al. 2002) and, for the first time in altimetry, its backscatter using an ESA transponder (Roca et al. 2002).

The SIRAL altimeter, on-board CryoSat, calibration of

range and sigma-0 will be based in the comparison of its measurements against other altimeters. The primary scientific objectives for the CryoSat mission (Wingham et al. 2004) are to improve the accuracy of measurements of ice sheet elevation and sea-ice thickness and thus enhance understanding of cryospheric dynamics. Over sea-ice this is to be achieved by the use of a radar altimeter with synthetic aperture forming capability to improve the along track resolution. In addition, over ice-sheet margins the direction (along and across track) of the leading edge of an echo is retrieved through the use of a second receiving antenna recording chain allowing interferometric capability. This new design of an altimeter also implies that new calibrations shall be performed. In particular the calibration of the interferometric baseline. For this particular purpose ESA has located a transponder in the Svalbard station. We will then use the transponder for the calibration of the angle of arrival, and also to estimate the datation error. Although the project will perform an indirect calibration of the range and sigma-0 by comparing its measurements with other altimeters, we will also use the ESA transponder for the calibration of range and sigma-0.

This paper will present the calibration performed over all ESA altimeters for 15 years, from ERS-1 to CryoSat.

Authors of this paper should include all the ERS-1 calibration team lead by R. Francis, all ERS-2 calibration team lead by J. Benveniste, all EnviSat RA-2 Absolute Calibration team lead by M. Roca, all EnviSat RA-2 Cross-calibration and Validation team lead by J. Benveniste and all CryoSat calibration team lead by R. Francis.

Session 5.3:

The 15-Year Altimetric Record/Long time series

History of Altimetry, 1960–1992

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We will review the history of the various strands leading to the successful development of the Topex/Poseidon altimeter mission, the first of a series of satellite altimeter missions jointly developed by CNES and NASA. The strands include: 1) The development of altimeter technology through a series of missions—Skylab, GEOS-3, and Seasat. 2) The ability to calculate accurate satellite ephemerides by groups at the Centre National d'Etudes Spatiales Precise Orbit Determination Department, Toulouse; University of Texas Center for Space Research; and NASA Goddard Space Flight Center Geodynamics Branch. 3) An understanding of the influence of the ocean surface and the atmosphere on the altimeter signal. And, 4) The political decisions in France and the USA leading to funding of the mission, including the role of 1) national space policies and the development of a Memorandum of Understanding that led to a long-term relationship between CNES and NASA, 2) the Topex Science Working Group, 3) the Topex/Poseidon Science Definition Team, 4) the Topex/Poseidon Science Working Team, 5) the World Ocean Circulation Experiment/World Climate Research Program, and 6) the Earth System Science Committee.

Building a Record of Surface Elevations of the Continental Ice Sheets from Satellite Radar Altimetry

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Obtaining surface elevations over the continental ice sheets from satellite radar altimetry includes special challenges caused by the specific nature of the ice sheet surfaces in contrast to ocean surfaces. Special algorithms are required to account for the surface slopes and undulations, variations in surface reflection, and penetration of the signal into the snow surface. This presentation addresses these unique challenges and how we have overcome them to create a consistent record of ice sheet elevations from satellite radar altimetry. Specifically this will address the effect of the slope-induced error and our methodology for correcting the measurement; the effect of penetration and sub-surface volume scattering, the evolution of waveform shape fitting and retracking algorithms to determine the location of the surface return, and inter-mission biases calculated using both the ERS-1 and 2 tandem mission data and ICESat time-coincident laser altimeter measurements. Using consistent methodologies, NASA/GSFC has built a database including all ice sheet elevations retrieved from radar altimeters on Seasat, Geosat, ERS-1, ERS-2, and Envisat.

EKE and circulation variability in the Labrador Sea and the North Atlantic subpolar gyre

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The eddy field from 1993 to 2001 in the Labrador Sea was calculated from sea level anomalies (SLA) measured by TOPEX/Poseidon and ERS-2 altimeters. Correlation between in-situ measurements in the Central Labrador Sea and eddy kinetic energy (EKE) calculated from altimeter data was improved using a quadratic correction with respect to significant wave height. The mean EKE field comprises maxima within the main boundary currents and in the Central Labrador Sea. The annual cycle is most distinctive in the Central Labrador Sea. A southward propagation of EKE from the West Greenland Current (WGC) into the Central Labrador Sea can be seen with a propagation speed of about 3 cm/s. The EKE Maximum in the Labrador Current stays well separated from the one in the Central Labrador Sea. Distinctive interannual variability is seen in the WGC and in the Central Labrador Sea. The WGC shows strong EKE maxima in early winters 1993 and 1997-1999, while in the Central Labrador Sea the strongest maxima are found in March/April 1993-1995 and 1997. The WGC shows continuously high levels of EKE during 1994-1996 and a seasonal cycle with minima in summer and maxima in winter during 1997-2000. Results from altimetry are compared with in-situ observations and results from a eddy-resolved model. Along-track altimeter data from TOPEX/Poseidon, Jason-1, ERS-2, Envisat, and GFO acquired over the North Atlantic subpolar gyre are compared using EOF analysis and, after adjusting their respective means, merged together providing a continuous time series from 1993 to 2005. The interannual variability of the SLA is analysed and shows a decreasing strength of the North Atlantic subpolar gyre. A similar analysis of EKE is performed. The SLA and EKE variability as obtained from altimetry is discussed with respect to different forcing mechanisms represented by large-scale indices like, e.g. the North Atlantic Oscillation.

Session 4:

Hydrology and Land Processes

Global analysis of multi-mission echoes over the earth's land surface from 15 years of altimeter missions

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A vast quantity of radar altimeter echoes have been collected over the earth's land surfaces by the series of missions flown over the past fifteen years. Although primarily designed for operation over ocean, a significant part of the earth's continental land mass has also been sampled, even by those missions specifically configured for ocean operation (Topex and Jason-1). The additional mode of operation of ERS-1 and ERS-2 altimeters enabled sampling over much of the earth's land surfaces, whilst the multi-mode capability of the Envisat RA-2 has given us the first almost universal surface echo database (except for very extreme terrain such as the highest reaches of the Himalayas). The totality of these missions has resulted in a unique global database of echoes, containing information not only on the elevation but also on the surface characteristics.

This paper presents the results of a global analysis of echoes from all these missions, interpreted using a rule-based expert system, and discusses the information which can be extracted, both from the spatial distribution and from the temporal changes. A series of examples is presented, illustrating the characteristic signatures of different terrain types, and discussing the impact on echo shape of roughness on different spatial scales. The key role of surface water in temporal change is highlighted, including the sporadic effects from ephemeral events, and the seasonal and interannual changes of inland water and snow. The results demonstrate the unique contribution of this global dataset to measurement and monitoring of the earth's land surfaces.

Use of Topex-Poseidon and Envisat Dual-Frequency Radar Altimeters Data over Continental Surfaces

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Initially developed to operate over ocean surfaces and make precise measurements of the sea surfaces topography, the satellite-altimeter radars, which are nadir-pointing active microwave sensors, rapidly exhibited on strong capabilities to provide information over continental surfaces. At this time, radar altimetry mainly shows its capabilities over ice caps with the construction of precise topography or the characterisation of the snow surface roughness and snowpack structure. In parallel, the development of altimetry to monitor continental water surfaces and measure their stage elevation makes this sensor a powerful tool to study regional hydrological systems. Many other particularities of radar altimeter over continents are newly exploited, like the opportunities to use all retracked waveform parameters, to use the dual-frequency measurements or to develop a synergy with passive microwave data obtained by the radiometer that operated simultaneously on altimeter platform. The capability of Topex-Poseidon and Envisat radar altimeter data for land surface studies at regional or global scale are so investigated. The analyzed data, available since mid-1992 for Topex-Poseidon consist of dual-frequency backscattering coefficients measurements (Ku and C band) estimated along the satellite tracks. The processing of Envisat data available since 2002 (Ku and S band) using the ICE-2 algorithm enables now the study over continents with all the wave forms parameters. It first shows, at a global scale, the capabilities of dual-frequency altimeters to monitor forests, deserts, boreal regions... and their seasonal variations. At the regional scale, radar altimeter backscatters was successfully used to recover snow depth evolution through winter over the snow covered areas of the Northern Hemisphere. It also enables to determine the duration of the snow period, within the beginning and the end of the winter snow pack. Topex-Poseidon data are also used to develop a synergetic method using active and passive microwave measurements to study the sea ice variability of the Caspian and Aral Sea. This work was also enlarged to Antarctic Ocean to recover snow depths over sea ice. Recently,

Topex-Poseidon 10 year-span dataset were successfully used to recover wetlands extent over the Boreal Regions. These works were used for the calibration/validation phase of the dual-frequency radar altimeter on board ENVISAT over land surfaces and ice sheets. ENVISAT dual frequency radar altimeter offers now for the first time to the scientific community a dataset processed with an algorithm entirely devoted to continental surfaces studies and offers new capabilities to retrieve parameters, such as inundated areas extent on the global scale or accumulation rates over the ice sheets.

Two decades of land altimetry – achievements and challenges

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Studies of altimetry over land began with data from SeaSat and Geosat. Since this initial work, huge advances have been made both in instrument design and in interpretation of the complex and rapidly varying echoes returned from topographic surfaces. This paper presents an overview of the achievements in land altimetry, drawing on the vast database of echoes returned by Geosat, ERS-1, ERS-2, Topex, Jason-1, Envisat and GFO, including an assessment of the key contribution over rough terrain of the RA-1 and RA-2. Data collected over the earth's land surfaces have been used for a range of applications, primarily for topographic mapping and measurement of inland water heights. In mapping, data from the ERS-1 Geodetic Mission allowed the derivation of a new Global Digital Terrain Model, ACE. More recently, data from all altimeters have a key role in assessment and correction of the Shuttle Radar Topographic Mission dataset. Over inland water, the different orbit repeat patterns, combined with the instrument designs, have given access to data over a huge range of targets. Land radar altimeter data have a range of further applications, from identification of temporally changing information such as snow cover and flooding, to derivation of detailed backscatter models for calibration of both existing and future altimeters, including instruments optimised for measurement of clouds. The range of applications continues to grow, with potential additional applications such as soil surface moisture.

The unique continuous time series of echoes still contains information not yet identified and extracted; the RA-2 I.E. capability and the CryoSat mission have the potential to give further new insights, not only enabling data from these missions to be utilised fully, but also permitting the identification of further information encoded within the continuous database of altimeter echoes.

Although an instrument originally designed for operation

over the earth's oceans, the radar altimeter has made a huge contribution to our understanding of the earth's land surfaces and climate related processes. With the only planned future altimeter mission currently being Jason-2, there is a very real prospect that the continuity of this valuable time series may be lost.

Altimetry landed - Digital Elevation Data from ICESat, SRTM and Surveying

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NASA's laser altimetry mission ICESat launched in 2003 has provided high-accuracy and high-resolution elevation data over all surface types including land. Due to its small footprint of about 70 meters, ICESat waveform processing resulted in accurate elevation retrieval over multiple land types (e.g. bare rock, vegetation, mountainous areas) and even over steep terrain. While such data is too sparse to derive a digital elevation model (DEM), its high accuracy allows for the calibration of independent DEMs. The Shuttle Radar Topography Mission (SRTM) has provided homogeneous and highly accurate data for Digital Elevation Models (DEM) in February 2000. The accuracy of the resulting DEM depends on various factors including the roughness and slope of the terrain, type of land cover and the determination of the antenna positions on-board the shuttle. Both C-band and X-Band DEMs show intrinsic errors of about 5-15 meters, limiting the accuracy of absolute height determination in numerous applications. A comparison and a potential calibration using more precise, but point-wise, height information is conducive to improve the SRTM derived DEMs. Survey control monuments (SCM) situated across Canada are used as an independent data source for comparison. The analysis focuses on both data and datum issues which must be addressed in order to provide a realistic comparison and assessment of the achievable accuracy. The discussion highlights the seasonal considerations that account for changes in vegetation and snow cover over time. Preliminary results suggest that laser altimetry provides an excellent means to calibrate less accurate DEMs (e.g. SRTM DEM) after the differences due to penetration depth have been accounted for. Ultimately, ICESat can potentially be used to derive error maps of the published SRTM DEM worldwide.

Global Assessment of Multi-Mission Radar Altimeter Performance Over Land

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Radar Altimeters have collected much useful data over the Earth's land surfaces during the past two decades. However, interpretation of the complex and rapidly varying echoes is problematic, especially when components are present from multiple facets within the pulse-limited footprint. One very effective way of analysing these data is to utilise a rule-based expert system approach using a suite of retracking algorithms tailored for the multitude of echo shapes encountered.

The extent to which each altimeter can contribute to our knowledge of the Earth's land surfaces is dependent on both the orbit pattern and the onboard tracking used. ERS-1 and 2 sampled the majority of land in 'ice-mode' which increased the window size at the expense of vertical accuracy. This fact, particularly when combined with the ERS-1 Geodetic Mission orbit configuration has provided an invaluable legacy of land height data. The ENVISAT RA-2 further improved the acquisition of land data through the use of a mode-switching technique which dynamically adjusts the window size in order to maintain lock over more rapidly varying terrain whilst sampling moderate terrain at the highest available resolution. Despite being optimised for operation over the ocean, TOPEX, Jason-1, Geosat and GFO have also obtained significant amounts of data over land, particularly in flat to moderate terrain.

This paper presents an analysis of the performance of ERS-1, ERS-2, ENVISAT, TOPEX, Jason-1, Geosat and GFO over land using a unique global multi-mission database of land heights obtained by retracking all echoes for which a leading edge is present. The extent to which each altimeter has contributed to the mapping of land heights is quantified. Particular improvements in acquisition caused by the tracker design are examined.

The results clearly demonstrate that all the altimeters included in this study have provided valuable height data over land, and have made a unique contribution to mapping of the Earth's topography.

Geosat Follow-On Waveforms: Retracking for Hydrology Applications

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Geosat Follow-On is a Navy altimetry satellite whose primary mission is to monitor sea level, wind speed, and significant wave height for fleet operations. Additionally, for measurements of continental ice sheets, altimetry waveform data are collected for five passes per day that cross Greenland and portions of Antarctica. Fortunately, these passes provide near total coverage of the African and N. American continents (ascending and descending portions, respectively) as well as parts of Asia and Europe. However, the waveform data are rather noisy, in particular because the onboard tracker used to fit the leading edge of the waveform to determine range is not suited to radar echoes reflected back by continental waters (rivers and lakes). We have processed all the available GFO waveform data using different trackers in order to improve the height values over continental waters. We present examples of hydrological time series so obtained, and an absolute comparison of retracked altimetric heights vs. GPS in-situ measurements over the Issyk-kul Lake (Kirghizstan).

Lake Level Monitoring Based on Satellite Altimetry

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Accurate and continuous monitoring of lakes and inland seas are available since 1991 thanks to the of satellite altimetry missions (Topex-Poseidon, GFO, Jason-1 and Envisat). Global processing of the data of these satellites could provide temporal and spatial times series of lakes surface height from 1993 to 2005 on the whole Earth with a sub-decimeter precision. The Legos laboratory is involved in this field of analysis since many years. The response of water level to regional hydrology is particularly marked for lakes and inland seas of semi-arid regions. Altimetry data can provide invaluable source of information in hydrology sciences, but in-situ data (rivers runoff, temperature, or

precipitation) are still strongly needed to study the evolution of water mass balance of each lakes. Moreover, sea level variations that result from variation of hydrological parameters such as river discharge, precipitation and evaporation, are very sensitive indicators of regional climate variations. Special focus on the Central Asian lakes will be presented, in particular which type of hydrological informations can be deduced from a combination of in-situ and altimetry data.

Session 1.1:

Oceanography: High Frequency

Variation of Sea Surface Height in the South China Sea

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The dominant forcing mechanisms of Sea Surface Height (SSH) variations in the South China Sea are the variations of the sea surface wind and buoyancy flux as well as the impacts of the Kuroshio. Analysis of the seasonal variation of the SSH using TOPEX/POSEIDON-ERS altimeter data along with Levitus steric height, COADS wind stress curl, and POM model result indicates that the pattern of the SSH anomaly in winter is dominated by a negative SSH anomaly with two centers in the deep water basin. The north center (16°N, 115°E) corresponds to the Luzon Cold Eddy, while the south one (10°N, 112.5°E) corresponds to the cyclonic eddy east of Vietnam coast. Geostrophic current calculated from the SSH anomaly indicates a basin wide cyclonic gyre with strong southward western boundary current. The latter leads to the cold tongue of the SST on the Sunda Slope. In summer, the SSH pattern changes to positive SSH anomaly with two centers in the deep water, located in the northwest of the Philippines and the southeast of the Vietnam coast, respectively. Between both positive centers, there is a negative SSH anomaly due to the upwelling induced by the southwesterly monsoon and the cyclonic wind stress curl east of Saigon. Dynamical analysis shows that the seasonal variation of the SSH mainly depends on the wind stress curl of monsoon in the south of the 18°N, because the annual baroclinic Rossby waves cross the basin in less than a few months and the upper ocean is in a quasi-steady Sverdrup balance in seasonal or longer time scale. Unlike the forced variation of the SSH by the wind in central SCS, the SSH variation north of 18°N is more complicated in the SCS. About 30% or more of the variation of the SSH in the north SCS is forced by the Kuroshio. The Kuroshio bends into the SCS through Luzon Strait, forming anticyclonic eddies quasi-periodically around 119.5°E and 120°E with a frequency of 70-90 days. The eddy shedding is not a product of the local wind stress curl but rather the intrinsic dynamics of the Kuroshio bending. The frontal instability in the south of the Kuroshio bend fosters the growing up of a cyclonic eddy which cleaves Kuroshio bend and triggers the separation of the anticyclonic eddy. As there are generally four or five eddies shed within a year, the mass or momentum transport into the SCS by these eddies may play a very important role in the intraseasonal, seasonal, or even interannual variation of the SSH in north SCS. Future

studies are needed to assess these impacts. With the accumulation of the TOPEX/POSEIDON, ERS-1 and Jason-1 altimeters' observation, inter-annual, even decadal variations of the SSH in the SCS can be studied in the future. With the improved observation of the Geoid, the mean structure of the circulation in the SCS can also be obtained, that will help the study of the Kuroshio and the western boundary current in the SCS.

Combination of NOAA/AVHRR Images and Topex/Poseidon Data to Analyse the Mesoscale Phenomena in the Algerian Basin (in the Western Mediterranean Sea)

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Even though the circulation of the various water masses in the Western Mediterranean Sea can now be considered as roughly described, several features are not reproduced by the numerical models. Therefore, the functioning of the whole sea is certainly not well understood yet. The major questions concerning the Gulf of Lions and the Algerian Basin are as follow. In this project, we are interested to study the physical structure of mesoscale phenomena resulting from the instability of coastal current has still to be specified, significant results have been obtained about the Algerian Current system. Obviously, the interaction of an event with the topography at the channel of Sardinia entrance, and its transformation into an open-sea eddy isolated from its parent current, are complex problems that cannot be solved with the available data sets (NOAA/AVHRR images). The dynamic topography of the sea surface is directly related to the oceanic currents. In order to obtain details of circulation, it is interesting to use the altimetric data of the satellites altimeters, such as for example TOPEX/POSEIDON, to obtain a denser space-time sampling. The combination of two types of satellite data made it possible to observe, for the first time by altimetry, the principal characteristics of circulation in the western Mediterranean sea and in particular the seasonal variations. The cartography of the Sea Surface Height (SSH) highlights the intensification of oceanic circulation. Nevertheless, the anticlockwise circuit

of the Algerian eddies in the eastern Algerian Basin is definitively demonstrated. The essential goal of this study is to establish a cartography of a high degree of accuracy of the average surface of the Algerian basin in the Western Mediterranean sea, and also to observe the space and temporal variability surface marine, precisely, the anticyclonic eddies through short and long-term.

Improved description of the mesoscale variability by combining four altimeter missions

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In this work we combine the data of four satellite altimeters [Jason-1, ERS-2/ENVISAT, Topex/Poseidon interleaved with Jason-1 and Geosat Follow-On] with the aim of improving the representation of the mesoscale variability in the global ocean. All the missions are intercalibrated and weekly gridded maps are produced. In areas of intense variability, the rms differences between a classical configuration of only two altimeters and the scenario merging four missions can reach up to 10 cm and 400 cm²/s², in SLA and EKE, respectively, which represents an important percentage of signal variance. In other areas of moderate activity, like the Mediterranean Sea, which is characterized by relatively small structures, the combination of Jason-1 + ERS-2/ENVISAT fails to reproduce some relevant mesoscale signals. On the contrary, when T/P and GFO are added, these features are well recovered and the EKE does not show significant discontinuities due to sampling effects. The merged Jason-1 + ERS-2/ENVISAT + T/P + GFO maps yield EKE levels 15% higher than Jason-1 + ERS-2/ENVISAT. We carry out an external validation with surface drifters covering the global ocean, and it is shown that the four altimeter scenario resolves better some mesoscale structures that are not properly recovered with Jason-1 + ERS-2/ENVISAT. A comparison with 86 tide gauges reveals an improvement of about 25% in the estimation of sea level in coastal areas with 4 satellites compared to the errors obtained with 2 altimeters. Unfortunately, the future of satellite altimetry is uncertain. At the moment (September 2005), only one altimeter mission (Jason-2) is planned and approved. There is an urgent requirement to fly a post ENVISAT altimeter mission but, as demonstrated in this paper, higher resolution will be ultimately needed.

Seasonal and Interannual Variability of eddy field and surface circulation in the Gulf of Aden

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The circulation in the Gulf of Aden is inferred from three different data sets: historical ship drifts, hydrography, and satellite altimeter derived sea level (Topex/Poseidon, Jason and ERS). The circulation in this semi-enclosed basin is marked with strong seasonality with reversals in the direction of flows twice a year following the reversal in monsoonal winds. During the winter monsoon (November - February) there is an inflow from Arabian Sea; an extension of Arabian Coastal Current (ACC). During southwest monsoon (June - August) the flow is generally towards east especially along the northern coast of Gulf of Aden. The geostrophic currents also show that the circulation in the gulf is embedded with mesoscale eddies. These westward propagating eddies appear to enter the Gulf of Aden from the western Arabian Sea in winter. The relative contributions of mesoscale eddies, annual signal and interannual signal to the circulation in the gulf were estimated using altimeter derived SLA for the years 1993 to 2003. In the absence of interannual variability, the mesoscale eddies and the annual variability caused by the monsoonal winds appears to be the only contributions to the circulation in the gulf. The contribution from the mesoscale eddies is equal to that from the annual signal. The effect of these mesoscale eddies extend over the entire water column. The vertical structure of density and the geostrophic currents derived from the hydrographic data confirms the presence of eddies at deeper levels (~400 m). The propagation speeds, of these eddies, estimated using weekly spaced altimeter for winter season (2002 - 2003) is ~ 4 cm/s. The propagation speeds of Rossby waves due to first and second baroclinic modes (estimated using the Brunt-Vaisala frequency profiles derived from the hydrographic data for the winter season) works out to be 8 cm/s and 2.5 cm/s respectively and the speed of westward flowing current during winter was 1.3 cm/s. The vector sum of the speeds of second mode Rossby wave and the mean current (3.8 cm/s) matches with the propagation speeds of eddies estimated from the altimeter data (4 cm/s). Hence, second mode baroclinic Rossby waves are responsible for the westward propagation of eddies in the Gulf of Aden. The presence of these eddies in the temperature-salinity climatology confirms that they are not transient features.

Formation process of the Kuroshio Large Meander in 2004

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The Kuroshio south of Japan exhibits remarkable bimodal features, namely, the large meander (LM) path and the non-large meander (NLM) path. In 2004 summer, a LM event occurred for the first time in 13 years, and the LM path is maintained for about one year. We looked into the formation process of the LM event in 2004 using the MRI Multivariate Ocean Variational Estimation (MOVE) System, an ocean data assimilation system. Three-Dimensional Variational (3DVAR) method with vertical coupled temperature-salinity Empirical Orthogonal Function (EOF) modal decomposition is used in the MOVE-System. The western North Pacific model with a resolution of 0.1 degree (MRI.COM: MRI Community Ocean Model) is used for the dynamical model. The altimeter data (TOPEX/Poseidon, ERS-1/2, Jason-1, ENVISAT) and in-situ (ship and AGRO float) temperature and salinity data are assimilated. The assimilation results reproduced well the formation process of the Kuroshio large meander occurred in 2004 summer. In 2004 spring, a cold eddy corresponding to the small meander can be seen southeast of Kyushu, located south west of Japan. At the middle of May, a warm eddy located south of the cold eddy interacts with the cold eddy. As a result of the interaction, a deep anti-cyclonic eddy is induced between the warm and cold eddies, and propagates eastward along the Kuroshio path. At the middle of August, the small meander develops into the LM under this phase relation of upper and lower layer eddies. Thus, the formation process of the LM path can be understood as a growth of the baroclinic instability. The relation with the Kuroshio transport or the large scale field will also be presented.

Satellite altimetry research at the Institute of Ocean Sciences

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An overview of close to 30 years of research in satellite altimetry at the Institute of Ocean Sciences in Canada and its applications in oceanography is presented, from early work with GEOS-3 and Geosat altimeters up to more recent use of

altimeter data from TOPEX/POSEIDON (T/P), ERS-1,2, Jason-1 and Envisat satellites. The subjects covered include: (1) comparison of wave heights from GEOS-3 with observations at Station Papa and of wave and wind data from T/P with moored buoys off the West Coast of Canada; (2) tracking and modelling of Haida and Sitka eddies, of their formation and effects on ocean productivity using data from Geosat, T/P, ERS and Jason-1; (3) calculation of seasonal circulation and of changes in sea level from T/P and ERS; (4) assimilation of T/P-derived tidal constituents in high-resolution tidal models and calculation of tidal dissipation and resonances in enclosed seas; (5) observations and modelling of internal tides from T/P-derived constituents; (6) studies of high-latitude transports through Arctic channels, such as Bering Strait; (7) modelling the first leading principal component for the NE Pacific circulation and using it to monitor the low-frequency variability; and (8) detection of tsunami waves using altimeter data from Jason-1, T/P and Envisat satellites.

Satellite Altimetry for Indian Ocean Studies

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Satellite altimetry has given an ample opportunity to study a wide varieties of oceanographic phenomena, particularly, over the otherwise data sparse Indian Ocean region. Sea surface height anomalies (SSHA) have been extensively used to study the mixed layer dynamics and the oceanic eddies. Initially, Geosat altimeter observations have been used to infer the vertical motion of ocean waters in the equatorial Indian Ocean (EIO), in connection with the slopes in SSHA and the associated changes in mixed layer depth (MLD) slope. By analysing the SSHAs, a phenomenon similar to El Nino was observed in the EIO. However, this phenomenon of reversal of the sea level is present every year with different intensities depending upon the intensity of the southwest monsoon. Since the MLD in the EIO is dominated by the changes in SSHAs, MLD could be estimated using the altimeter observations alone and the associated changes could be studied. Similar to the atmospheric phenomena, altimeter observations could reveal a 40-60 day oscillations in the SSHAs. As a part of the ERS-1 AO project on the study of eddies, SSHAs have been estimated from GDRs and eddies were detected. Statistical analysis of the ERS-1 measurements revealed that all the corrections given in GDRs were sensitive. This experience has been used to prepare an atlas of the oceanic eddies, jointly with NOAA, from TOPEX/POSEIDON observations. The presence of eddies have been confirmed with the in situ measurements of temperature profiles. Unlike in the other parts of the oceans, Bay of Bengal eddies propagate slowly. Comparison of SSHA and the dynamic

height obtained from in situ temperature and salinity profiles indicated that salinity observations were not critical for detection of eddies. Since the SSHAs represent the subsurface thermal structure, TOPEX/POSEIDON observations, in conjunction with the XBT measurements, have been used to generate another atlas of the XBT thermal structures and TOPEX/POSEIDON SSHAs, jointly with Ohio State University. This study helped to infer the subsurface thermal structure where in situ measurements are not available. SSHAs were also used to study the current variability and the inter-annual variation of eddy kinetic energy in the Indian Ocean. Statistical analysis of the SSHAs reveal that the RMS sea level variability was high in regions of Rossby wave propagation. FFT analysis was also used to identify the eddy regions. Inter-annual and seasonal variations in slope of the thermocline was studied using Jason observations in conjunction with the Argo temperature profiles.

Velocity statistics inferred from the TOPEX/POSEIDON-JASON Tandem Mission Data

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Using a parallel-track approach to estimate geostrophic surface velocities, an estimate of the statistics of ocean geostrophic surface currents and momentum stresses is provided on a 10 km along-track resolution from the first 49 repeat cycles (16 months) of the JASON-TOPEX/POSEIDON tandem altimetric sea surface height (SSH) data. Results are compared with estimates obtained in a traditional way from along-track SSH data at cross-over points and with in situ ADCP measurements obtained on board the VOS Oleander along a nominal path connecting Bermuda with the US mainland. Agreements with the Oleander data are reasonable when simultaneous (in space and time) sampling is available. However, amplitudes of parallel-track geostrophic velocity variances are about 25% lower as compared to Oleander measurements which represent geostrophic and ageostrophic flow components. Estimates of velocity variances show clear signs of an anisotropic eddy field in the vicinity of all major current systems. At the same time estimates of Reynolds stresses and eddy momentum fluxes show a convergence of eddy momentum in all those regions, suggesting a forcing of the mean flow by the eddy field there.

The eddy fields of the Leeuwin and East Australian Currents

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The warm-core eddies shed by the Leeuwin and East Australian Currents have been conspicuous features of Sea Surface Temperature imagery for nearly three decades. Altimetry reveals that these anti-cyclonic eddies are only half the story. The cyclonic, cold-core eddies are equally abundant and are not just mirror images of the warm-core eddies. Australia is unique in having poleward-flowing boundary currents on both her western and eastern margins, and the fascinating asymmetries of eddy polarity are of much more than academic interest. Indeed, these ocean eddies are the ocean 'weather' of the Australian ocean environment, and their behaviour is of principal importance to all marine life.

Variability of the MAW vein branching, in the Central Mediterranean, estimated by altimetric data

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Three years of JASON-1 altimetric data (2002-2004) are analysed to shed lights on spatio-temporal variability of mesoscale structures that occurs in the Central Mediterranean, off the Tunisian coasts. This region is considered as a key area for the whole Mediterranean Sea dynamics (Astraldi, 1999). It includes the Sardinia Channel, the Strait of Sicily and the Gulf of Gabes, particularly known for the relatively high amplitude of its tides. In this study, attention is specially paid to the branching of the Modified Atlantic Water (MAW) vein, east of the Sardinia Channel. The classical scheme of the circulation in this area (called T2S: Tunisia- Sardinia-Sicily) consists on the separation of this MAW vein into two branches: one is flowing northward into the Tyrrhenian Sea, the other is crossing the Sicily Strait to flow into the Eastern Mediterranean (Astraldi et al., 1996, Herbaut et al., 1998). The latter branch is variable in time and space and seems to be itself subject to additional branching. Recent studies (Lermussiaux and Robinson, 2001, Molcard et al., 2002, Mercator Group) are often referring to two sub-branches: the Atlantic Tunisian Current (ATC) flowing along the Tunisian shelf and the Atlantic Ionian Stream (AIS) reaching the Sicilian shelf, north of Malta, and then flowing towards the Ionian Sea. However, because the lack of a dedicated

monitoring, several questions remains concerning the dynamical behaviour, the path, the spatial extension, the temporal scale involved in the variability of these two branches, that, furthermore, have not been pointed out in previous studies using altimetric data (Ayoub et al., 1998, Larnicol et al., 2002). We show that JASON1 along-tracks Sea Level Anomaly data are very suitable to address some of these remaining questions, especially concerning the ATC and the AIS. The analysis allows us to obtain a more accurate identification of these mesoscale structures, a quantification of the branches strength, variability and spatial extension and to suggest some hypothesis on the dynamical equilibrium involved in.

The greater Agulhas Current System: Intercomparison of altimetry and model results

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The Agulhas Current flows polewards along the South African East Coast, before retroflecting near 40 S and between 16 - 20 E. With average and peak velocities of approximately 1.36 m/s and 2.45 m/s, and volume transport estimated to lie between 60-65 Sv, it has been described as one of the strongest western boundary currents in the world's ocean. The Agulhas Retroflection describes a loop with a diameter of up to 340 km, and is associated with frequent ring shedding, or eddy formation, events. These eddies may have diameters exceeding 200 km and are thought to contribute to the Indo-Atlantic heat and salinity exchange, and thereby to the global thermohaline circulation and the South Atlantic overturning. Following the Retroflection the Agulhas Return Current flows eastward between 38 and 40 S with surface velocities of up to 2 m/s. Semi-permanent geographically trapped meanders have been observed associated with the flow around the Agulhas Plateau. The dynamics and characteristics of the greater Agulhas Current System exhibit strong spatial and temporal gradients, which makes the region particularly suitable for observations from satellites, in particular measurements from radar altimeters. The analysis of along-track sea level anomaly (SLA) data from Jason-1, shows that the Agulhas Current system dynamics seem to remain fairly stable over a 10-day orbital repeat cycle. A comparison of the repeat-track SLA analysis to gridded merged SLA maps for the region shows that the two data are well correlated, with seemingly no significant loss, or smoothing of information from the production of the 7-day merged maps and subsequent monthly mean calculations. This suggests that the mesoscale variability of

the system is fairly well captured in the merged SLA maps, making these a powerful tool for assessing ocean current dynamics and variability. Furthermore, they provide a very good spatial picture of the flow regime and basis for comparison to modelling studies of the region. We compare results from a regional hybrid coordinate ocean model (HYCOM) for the Agulhas Current system to the aforementioned SLA data. As the merged (7-day / monthly mean) SLA data product captures the mesoscale dynamics of the system quite accurately, it becomes a powerful data source for model validation.

Geostrophic Turbulence and Mechanical Energy Budgets from Satellite Altimetry

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Utilizing over a decade of satellite observations of sea surface height we are studying the World Ocean's kinetic energy cascade of the surface geostrophic flow. This has allowed for the first direct confirmation of one of the most fundamental predictions of geostrophic turbulence theory, but also challenged other aspects of the theory. It's also providing new insight into the oceanic mechanical energy budget and sources of diapycnal mixing.

The last 38 years have seen considerable development in the theory and phenomenology of the geostrophic turbulence, the turbulence that governs large scale atmospheric and oceanic flow. Numerical simulations of simplified equations in idealized domains have remained the primary tool of investigation. While laboratory experiments helped to ground ideas in reality, questions of the applicability to real geophysical flows inevitably remained. Before the advent of satellite altimetry, there simply was not sufficient observational data to test these theories in the ocean, one of the major systems they're supposed to describe. Using satellite altimeter data, we estimated the spectral kinetic energy flux, i.e. the flux of energy from scales with total horizontal wavelength greater than λ to scales with wavelength less than λ , for λ from several thousand km to less than a hundred km. Some of our key results are summarized below:

1) A near universal shape of the spectral kinetic energy flux was found that provides direct evidence of a source of kinetic energy near to or smaller than the deformation radius, consistent with linear instability theory. This suggests baroclinic instability is a ubiquitous source of kinetic energy everywhere except the equatorial region. 2) No inertial range was found, implying inertial range scaling, such as the established K-5/3 slope of spectral kinetic energy

density, is not applicable to the surface geostrophic flow. 3) We also found a net inverse cascade (i.e. a cascade to larger spatial scale), consistent with strictly two-dimensional turbulence phenomenology. But stratified geostrophic turbulence theory predicts an inverse cascade for the barotropic mode only while energy in the large scale baroclinic modes is predicted to undergo a direct cascade towards the first mode deformation scale. Thus if the surface geostrophic flow is predominately the first baroclinic mode, as expected for oceanic stratification, then the observed inverse cascade contradicts geostrophic turbulence theory. Furthermore the inverse cascade arrest scale does not follow the Rhines scale, as one would expect for the barotropic mode. A revision of theory was proposed that resolved these conflicts. Subsequent idealized modeling experiments have confirmed the revision, providing an example of where satellite altimetry has successfully guided geostrophic turbulence research.

The measurement of the kinetic energy cascade and its interpretation in terms of geostrophic turbulence theory is finding its most immediate application in quantifying the mechanical energy budget of the World Ocean, and uncovering the pathways from large scale forcing to small scale dissipation. Key quantities, such as the conversion rate from gravitational potential to kinetic energy and the ratio of kinetic energy cascading to small scales versus large scales, that could not previously be measured, are now being estimated using satellite altimetry. This information is of great interest to understanding the source of diapycnal mixing responsible for driving the thermohaline circulation.

What do we know and what can we predict about the timing of Loop Current eddy separation?

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The ability to accurately predict the time that a Loop Current eddy (LCE) will ultimately separate from the Loop Current (LC) has become a grail of sorts in Gulf of Mexico oceanography, and for good reason. Approximately 30% of the crude oil and 20% of the natural gas produced in the U.S. comes from the Gulf of Mexico, much of it from the continental slope and deepwater of the north-central Gulf. Strong LC and LCE currents affect day-to-day operations during offshore oil and gas exploration activities, frequently shutting down operations and making planning and scheduling difficult for this very expensive enterprise. The LC and LCEs also play an active role in the rapid intensification of Gulf of Mexico hurricanes. This was the case in Hurricanes Katrina and Rita, both of which intensified over the intruded LC and reached Category 5

before making landfall along the northern Gulf coast. Clearly if LC intrusion and eddy separation could be predicted a year or even just months in advance there could be significant socioeconomic benefits. Efforts along these lines, using operational data-assimilative nowcast/forecast ocean models, have not been very successful. This is because the LC is an inherently unstable current system in which the dominant processes affecting intrusion and separation are not clearly understood, making accurate forecasting using numerical models very difficult. A review of the 15-year altimetric record of LC metrics and comparisons with the LC penetration and eddy separation cycles, however, suggest that there may be a more fundamental controlling influence on LC eddy separation. The statistics show a clear relationship between the LC retreat after eddy separation and the time that a large LC eddy will ultimately separate during the next LC intrusion cycle. The 15-years of LC intrusion LCE separation statistics and a proposed statistical approach to predicting the timing of subsequent LCE separation based on LC retreat after eddy separation will be discussed, as well as potential applications to operational planning and hurricane forecasting.

Investigation of the oceanic currents and fronts in the Southeastern Pacific Ocean using satellite altimetry data

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Sea level anomalies (SLA) charts, based on the merged TOPEX/Poseidon and ERS-2 altimetry data for 1992-2003, as well as corresponding charts of sea surface dynamic heights (constructed by the superposition of SLA distributions over the climatic dynamic topography calculated from mean temperature and salinity data of WOA-1998 Atlas relative to 1000 m depth) were used to study main oceanic currents and fronts in the region 45-20°S, 110-70°W. Spatial and temporal variability of the South Pacific Current, Peru/Chile Current, Subtropical Front has been investigated basing on the charts of dynamic heights gradients, calculated maps of occurrence of mesoscale features (e.g., frontal eddies) and calculated geostrophic current velocities. The analysis allowed to distinguish zones with different degree of the currents position and intensity variability. The main features of the seasonal and temporal variability of the currents and front were revealed. This study has demonstrated efficiency of the analysis of the satellite altimetry data in the investigation of the structure and spatial and temporal variability of the main

surface currents and oceanic fronts in the Southeastern Pacific. In view of the fact of the lack of regular oceanographic observations in the Southeastern Pacific the proposed approach may give a high advantage and improve our knowledge about seasonal and interannual variability of the currents and fronts in this region. This work was partly supported by the Russian Fund of Basic Research, Grant No. 06-05-65061-a.

Session 1.2:

Oceanography: Coastal

Advances in Coastal Altimetry over the Northwestern Mediterranean

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In this paper we describe the motivations and outcomes of 10 years of research into applications of altimetry to the area of the Corsica Channel in the Northwestern Mediterranean. This area is highly relevant from an oceanographic point of view, as the flow through the Channel links the overall circulation in the Ligurian and Tyrrhenian Seas, and its variations and trends play a key role in establishing the ocean dynamics in the two sub-basins.

The research activities had two specific and complementary purposes: a) to contribute to the oceanographic knowledge of the area and b) to assess the applicability of altimeter techniques in coastal/marginal systems. The Corsica Channel is a perfect site for such investigations, in virtue of the favourable location of altimetric tracks and cross-over points, combined with the availability of long-term in-situ observations from a number of instruments including currentmeters, tide gauges and bottom pressure recorders. As such, it has been chosen as a site of cal/val activities and hydrographic campaigns in the framework of the joint French-Italian ALBICOCCA (ALtimeter-Based Investigations in COrsica, Capraia and COntiguous Areas) project.

One important oceanographic issue that has been addressed with the help of altimetry is what drives the flow along the channel, which exhibits a marked seasonal and interannual variability. We describe how along-track Topex/Poseidon (T/P) data have confirmed that the contribution of the steric

level difference between the two interconnected basins is predominant.

A significant part of the research activity has been devoted to assessing the extent to which altimetry data can be applied in the area, and devising any possible improvement in the data processing chain and in the retrieval of the geophysical parameters, which may increase the applicability of altimetry in coastal seas. A comparison between XBT data and T/P altimetry shows that the altimeter is capable to detect the overall spatial and seasonal pattern seen in the circulation; an ad hoc processing strategy based on local corrections has been attempted and the results compared against in situ sea level anomalies and surface velocity anomalies from moorings, showing a good level of agreement. We conclude by discussing further improvements on the processing scheme, including the use of 20 Hz data, which should allow a better match between altimetric and in situ observations, and hopefully promote the 15-year sea surface height from altimetry to the rank of operational record for the coastal areas.

Altimetric data to monitor the seasonal and year-to-year variability of the upwelling intensity along the West Africa coasts

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At present standard upwelling indexes for the monitoring of coastal upwelling are based on estimate of the wind intensity or wind stress intensity (Ekman transport) along the coast. More complex indexes include the estimate of the Sea Surface Temperature (SST) and/or the wind-driven vertical turbulence. The actual intensity of the Ekman-like upwellings circulation can be modulated by e.g., the interaction with large scale circulation and the coastal wind, changes in the vertical stratification induced by anomalies in coastal freshwater discharge (runoff). A more direct estimate of the circulation could therefore be useful. Among the several satellite-based remote sensing of the ocean

circulation, altimetric data are the most suitable to monitor the variability of the surface circulation. In particular for the upwelling phenomenology, (wind-induced) geostrophic coastal currents could be a priori monitored. Here we investigate the possibility of improving our monitoring capability of the upwelling intensity via the inclusion of altimetry-based informations in the definition of upwelling indexes. An upwelling index based on the difference between near-shore and off-shore sea level slope has been defined and applied to altimetric data of the West African Coast. The 15 years time series of Altimeter data together with the corresponding SST time-series has been analyzed to and to investigate the role of local and remote forcing on the upwelling seasonal and interannual variability. The analysis reveals the presences of a strong interannual and coherent signal in both altimetric SLA and SST indices and suggest that only part of the signal induced by local winds

A description of the currents off the eastern and southern boundaries of Australia from fifteen years of Altimetry

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We use an integrated dataset of satellite (both altimetry and SST) and in situ observations to characterize the main current systems off the eastern and southern boundaries of Australia. A high-resolution in situ climatology provides the mean flow and the time-variability is determined from the satellite time series, coastal tide gauges and repeated XBT sections. The Australian continent divides the south Pacific and Indian Ocean subtropical gyre circulations. Off the eastern side the gyre inflow bifurcates to form a northward flow and a southern component which provides the source waters of the East Australian Current (EAC), the main poleward flow of the Pacific gyre. The EAC has a relatively weak mean flow but is highly variable, being dominated by mesoscale eddies. Altimeter time series show that these eddies are influenced by both remotely forced Rossby waves from the east and the complex topography in the southwest Pacific. The EAC system follows a complicated seasonal pattern which is well represented in both the altimeter and SST observations. The poleward boundary flow is strongest in summer associated with an intensification of the cross-shelf pressure gradient. A summer pulse of warm, salty water penetrates as far south as Tasmania while a limited number of eddies reach the Indian Ocean from the Tasman Sea around southern Tasmania. The variability of SLA is dominated across southern Australia by seasonally reversing alongshore winds which produce Ekman fluxes which alternately increase and decrease the coastal sealevel. An eastward shelf-edge winter flow, representing the

continuation of the Leeuwin Current, reaches the west coast of Tasmania. Instabilities in the coastal build-up of sea level separate and propagate westward. Finally the altimeter, SST and XBT time series show the distinctive interannual and multi-year variations of these current systems.

Coastal altimetry and sea level change in selected test areas along the European coast

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The accuracy of satellite altimeter measurements instantaneous sea surface heights is lower in coastal regions than in the open ocean, due to contamination of land in the radar altimeter and in the radiometer measurements, that causes the sea level height and wet-tropospheric correction from on-board radiometer to be less accurate.

The accuracy of the some of the standard corrections applied to the satellite altimeter measurements is lower in coastal areas. This is true for the ocean-tide correction and for the classical inverse barometer corrections, that is inaccurate in semi-closed seas.

The land contamination in the footprint is here investigated at selected locations along the European shelf.

Alternative environmental corrections for ocean-tide, wet-troposphere and inverse barometer corrections are investigated and a dedicated waveform processing is used to improve the quality of the altimeter measurements.

The resulting sea level height variability is checked using both in-situ data and local models. A high resolution coastal hydrodynamics model is used to account for the tidal amplification between the satellite trace and the tide gauge. Both variability and absolute height of sea level are investigated at tide gauge stations where GPS measurements are available. Residual bias and drift between the multi-mission altimeter data are estimated from quasi-simultaneous measurements from altimeter and tide gauge stations. Two regions are selected for their different and complementary characteristics: the western Mediterranean Sea near Toulon and the Gulf of Biscay near La Rochelle.

Temporal and spatial sea surface height variability in the North Sea - Baltic Sea system from altimetry, tide gauges, and 3D modelling

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The water exchange between the North Sea and the Baltic is controlled by the Danish Straits, where the flow is governed by sea level differences and hydrological control. Due to coastal effects, it is challenging to use satellite altimetry in this area, but altimetry shows a large potential because of the basin wide data coverage.

In this study, the sea surface height of the North Sea - Baltic Sea system is analysed by the use of satellite altimetry and coastal water level recorders. In these near-coastal areas altimetry measurements from the TOPEX/POSEIDON and Jason satellites are obtained by careful selection of correction methods and a state of the art local geoid. By combining the two types of observations, high temporal and spatial resolution can be gained, and thereby dynamical processes in the North Sea - Baltic Sea system are revealed in new detail.

Regions with different characteristics are identified based on statistical analysis, and the benefits and challenges of satellite altimetry will be discussed for each region. A near-real time statistical water level model is set up for the area, and the performance is compared to the Danish Meteorological Institute storm surge model.

Estimation of model error covariance in a nested coastal model for multivariate data assimilation system

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The control of coastal circulation using data assimilation techniques is still an open problem. This is due to the

complexity of the non-linear phenomena characterizing the coastal circulation and the difficulty to acquire appropriate sets of accurate observations. In this work, we are developing a reduced order Kalman filter (a variant of the SEEK filter) to control a regional model of the bay of Biscay. The model is a HYCOM configuration between 14.80°W-1.04°W and 43.21°N-50.82°N with a 1/15° resolution, covering the Biscay abyssal plain and a large part of the Celtic continental shelf. It is nested in a 1/3° HYCOM configuration of the North Atlantic basin.

In order to use a Kalman filter for controlling such a complex dynamical system, it is of primary importance to identify the main sources of error and to provide an accurate parameterization of the corresponding error covariance matrices. In our system, two important sources of errors are the atmospheric forcing and the open sea boundary conditions. Firstly, the dynamics of coastal models is strongly constrained by the turbulent heat, fresh water and momentum fluxes imposed at the air/sea interface. Such fluxes are known to be affected by important errors, and the problem is amplified in coastal regions, where the atmospheric fluxes are usually derived from global reanalyses without specific tuning near the coast. Secondly, the dynamics of coastal models is also strongly dependent on the data imposed at the open boundaries. The low resolution model error feeds the high resolution model with imperfect data. Moreover, an imperfect nesting protocol can lead to inconsistency between the low resolution and the high resolution dynamics at the open/sea boundaries.

The purpose of this contribution is to address the problem of the parameterization of these two main sources of error in a low rank Kalman filter. The structure of the model error due to the atmospheric forcing and to open sea boundary conditions is estimated from ensemble experiments. We build an ensemble of atmospheric forcings and an ensemble of boundary conditions that represent the error probability density on these two sources of information, and we fulfill an ensemble of simulations forced by these two ensembles of forcings. From the resulting ensemble of simulations, we can study the structure of the error that is generated in the system. We focus on the two first moments of the resulting error probability distribution: the mean and the covariance.

As a first result, we show that even by using zero mean error probability density on the forcing, we can obtain a biased error structure on the model state. This is the consequence of the nonlinear processes in the model, and can be of significant importance in the setup of a Kalman filter, which is not originally conceived to deal with biases. As a second result, we have computed representers associated to the resulting error covariance. The representers show the influence that an observation would have if analysed using that covariance matrix to parameterize the background error on the ocean state. The study of the representers allows us to anticipate the behavior of the assimilation system. We can evaluate in particular the impact of the vertical coordinate (z coordinate vs hybrid coordinate) on the statistical analysis, the impact of various features of the circulation on the error structure, and hence, the impact of various observation

systems such as altimetry, sea surface temperature, or in situ profiles, according to their location in the open ocean or on the shelf.

Towards using satellite altimetry for the observation of coastal dynamics

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Today, because of land contamination on the altimeter and radiometer signals and poorly adapted corrections, the use of standard satellite altimetric products in coastal zones is challenging. Moreover, the space-time sampling of the satellites is generally too low to capture the variability of coastal ocean processes. In the future, a new generation of altimetric missions will better fulfill the requirements of coastal domains. In parallel, we need to develop improved post-treatment altimetric data for coastal purposes and to analyse how best to combine information from altimetry with other coastal observations (tide gauges, coastal radar data, ...). The objective of this study is to determine to what extent coastal processes can be observed with satellite altimetry. Therefore, we have used a new data processing approach developed in the context of the ALBICOCCA project (ALtimeter-Based Investigations in COrsica, Capraia and Contiguous Area). This approach uses improved local modelling of environmental corrections (MOG2D solutions), new experimental editing criteria and an inversion method to derive the mean sea surface. It substantially increases the number of valid data in the coastal domain and their accuracy. So far, we have used this original approach to reprocess all the TOPEX/POSEIDON altimetric data in three experimental areas: the NW Mediterranean Sea, the North Indian Ocean and the region of the Humboldt current system. We present the validated results and show some analyses of the kind of coastal information contained in these datasets.

Influence of Barrier Layer on Sea Surface Height Variability in Bay of Bengal

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Studies have documented that the barrier layer formation may have significant impact on air-sea interactions. The advancements in the ocean in-situ observations, satellite based observations and ocean modelling provides us an opportunity to investigate the influence of barrier layer formation on the SST and heat content variability on seasonal and intrannual time scales. The satellite altimetry has opened a new dimension for monitoring the variability of the Sea Surface Height (SSH) without the assumption of level of no motion. SSH can be used as a proxy to understand the upper ocean heat content variability. Bay of Bengal is typically marked with fresh water flux and heavy rainfall and also convective mixing due to surface cooling cause the fresh water to mix down to the top of thermocline, thus disturbs the barrier layer. Due to the formation of barrier layer we can observe changes in the subsurface temperature and salinity on intraseasonal to seasonal time scales.

Hence we made an attempt to understand importance of barrier layer formation on SST variability. To study these features on various scales we have analysed Topex/Poseidon derived Sea Surface Height (SSH), TMI derived SST and satellite derived precipitation. Along with the above data we have used high resolution OGCM simulations for the years 1997-2004. In this study we have observed that the barrier layer significantly affects SST and the heat flux. These results are validated with few ARGO observations.

Observing the short scale ocean variability in the Western Mediterranean Sea by using a coastal multi-satellite altimetry product and models

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Thanks to the space and temporal resolution of satellite altimetry, the sea surface topography is commonly accessible for the deep ocean. However, the coastal oceanic dynamic is much more complex and is characterized by a wide range of spatial and temporal scales rendering its observation difficult in the classical altimetric product.

A coastal, multi-satellite (Topex/Poseidon, Jason1, Envisat, GFO) altimetric dataset at a 10-20 hz sample rate is processed in the Western Mediterranean Sea. In addition to coastal-dedicated instrumental and environmental corrections, orbit errors have been minimized with a linear regression method. The high frequency response of the ocean to the tidal and atmospheric forcings has been corrected using a high resolution barotropic hydrodynamic simulation (Mog2D model).

In order to validate this multi-satellite altimetric data set, sea level anomalies time series are compared with tide gauges records and with a 3D circulation simulation (Symphonie model). The comparisons exhibit coherent patterns and differences in both temporal and spatial scales. In addition, the combined use of the improved altimetric data set and hydrodynamic modelling permits to produce noise level charts for the different altimetric missions.

This preparatory work emphasizes the potential of multi-satellite altimetry to observe meso-scale dynamics and contributes to the configuration toward assimilation of multi-satellite altimetric data in coastal hydrodynamical models.

Satellite altimetry of the Caspian Sea

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The oscillations of the Caspian Sea level represent a result of mutually related hydrometeorological processes, which proceed not only in the sea catchment area but also far beyond it. The regime of the Caspian Sea level is mostly controlled by the proportions of the cyclonic and anticyclonic activity in the basin of the sea (mainly, in the Volga River region) and the related precipitation regime. The change in the tendency of the mean sea level variations that occurred in the middle 1970s, when the long-term level fall was replaced by its rapid and significant rise, represents an important indicator of the changes in the natural regime of the Caspian Sea. Therefore, sea level monitoring and long-term forecast of the sea level changes represent an extremely important task. The aim of this presentation is to expound the experience of application of satellite altimetry methods to the investigation of seasonal and interannual variability of the sea level, wind speed and wave height in different parts of the Caspian Sea and Kara-Bogaz-Gol Bay, and the Volga River level. The work is based on the 1992-2004 TOPEX/Poseidon and Jason-1 data sets. The process of the filling of the Caspian Sea and Kara-Bogaz-Gol Bay and its acquisition of the new climatic regime is well traced in the satellite altimetry data with high spatial (5-6 km) and temporal (5-10 days) resolutions. The high efficiency of this method for the purposes of sea level monitoring (seasonal and long-term variabilities) and for the studies of the water dynamics of enclosed seas and lakes, in particular, of the Caspian Sea is proved by the results of recent investigations.

Evaluation of tandem TOPEX/Poseidon-Jason data in the Newfoundland offshore

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We have investigated sea level and surface currents features over the Newfoundland Shelf and Slope using the tandem TOPEX/Poseidon (T/P) and Jason altimetry data (2002-2003). The consistency and error characteristics of T/P and Jason measurements are examined not only in terms of sea level and cross-track current anomalies but also with respect to current anomalies at crossovers and the Labrador Current

transport. Nominal absolute currents are constructed by adding the altimetric geostrophic current anomalies to an annual-mean model circulation field. The comparison of the sea level and cross-track current anomalies from January to July 2002 shows overall good agreement between T/P and Jason, with correlation coefficients different from zero at the 5% significance level at almost all locations for sea level and at most locations for currents. Errors are estimated to be 2.5 cm for sea level and 10 cm/s for cross-track current anomalies. Analyses of the current variability at crossovers indicate approximate agreement of T/P and Jason measurements, except for the Northeastern Newfoundland Shelf and Slope probably due to the ice presence during the period. Model-altimetry combined absolute currents are used to estimate near-surface transport associated with the shelf-edge Labrador Current, showing good correlation between T/P and Jason estimates and strong seasonal changes. The cross-track geostrophic current anomalies from September 2002 to December 2003 are used to calculate the root-mean-square (rms) current variability at crossovers and to derive the shelf-edge Labrador Current. The interleaved T/P and Jason observations can better capture the spatial distribution of shelf and slope circulation variability.

Session 1.3:

Oceanography: Low Frequency

Steric sea level variations inferred from combined Topex/Poseidon altimetry and GRACE gravimetry

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We have combined observations of global mean sea variations from Topex/Poseidon altimetry with averaged gravity variations over the oceans determined from the GRACE satellite data to estimate thermal expansion of the oceans over a 2-year plus period (March 2002 through July 2004). In effect, altimetry-derived global mean sea level change results from steric (thermal) effects and ocean mass change due to water exchange with atmosphere and continents. On the other hand, GRACE data over the oceans provides the ocean mass change component only. The paper first discusses the corrections to apply to the GRACE data as well as the ability of GRACE to measure the total water mass budget by comparing GRACE ocean data with non steric mean sea level variations. Then the steric contribution to the global mean sea level is estimated using GRACE and Topex/Poseidon data. Comparison with available thermal expansion estimates is performed.

Interannual and annual variations in the Mediterranean Sea from satellite

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Since its launch in 1992, TOPEX/Poseidon altimeter satellite has collected more than a decade of high-quality Sea Level Variation (SLV) measurements. We have used

these SLV data to study the inter-annual variation in the Mediterranean Sea, whose behavior is found to be rather different from that of the global ocean. An interesting abrupt change of linear trend in mid-1999 is observed in the Ionian, Adriatic and Aegean seas and in the Levantine basin. This event coincides in time with the restoration of the Adriatic Sea as the main source of deep water in the Eastern Mediterranean, that is, the end of the Eastern Mediterranean Transient (EMT), although the possible connection is still unclear. On longer timescales we estimated the linear trends of the altimetric SLV versus that of the tide gauges along the northern coast of the Mediterranean. The difference of the two slopes is an estimate of the vertical motion (in mm/year) of the ground at each tide gauge site, presumably due to tectonic movements modified by any post-glacial rebound signals. Interesting regional patterns of such vertical movements emerge as a result, and can be used as data source for regional tectonic studies.

We have also examined the annual SLV cycle in the Mediterranean. Thus, the SLV was corrected for the steric height variations, or the dilatation/contraction of the column of water due to salinity and temperature changes, for which we adopted the profiles from ECCO ocean circulation model. The resultant non-steric altimetry is an indirect measurement accounting for water mass variations. In parallel with this estimation, we use the GRACE data for a direct measurement of the Mediterranean water mass budget variation. The GRACE satellite mission was launched in 2002 to measure time-variation gravity (TVG) of the Earth system, which can be converted into surface mass variations. The comparison between those direct and indirect estimations of water mass variations in the Mediterranean shows a good agreement and a similar annual signal with an amplitude between ~40 and ~50 cm, which is lagged ~4 months with the apparent SLV from altimetry. We can conclude that the Mediterranean SLV is mainly driven by steric height variations which are offset by water mass variations.

Inverse estimate of the North Atlantic Circulation:n Influence of the fine resolution GOCINA dynamic topography

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The circulation in the North Atlantic subpolar gyre and the Nordic seas has been improved by assimilating GOCINA altimetry into inverse finite-element ocean circulation model. The inverse model seeks for the density field which minimizes the distance between model and observations subject to stationary dynamic equations.

A series of model experiments has been conducted to improve the circulation by including altimetry data. It turned out to be necessary to add information about the deep ocean circulation to obtain a realistic solution. We chose to require closeness of the deep pressure gradient to that of a forward solution.

The work also gives estimates of transports across the Denmark Strait.

Mechanism of Interannual Variation of Meridional Overturning Circulation of the North Atlantic Ocean

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The low-frequency variability of the meridional overturning circulation (MOC) of the North Atlantic Ocean has important climate implications because it is the main carrier of the meridional heat transport in the ocean. Previous studies suggest that, on decadal time scales, the variability of the MOC is primarily caused by buoyancy forcing, and that sea level can be used as an indicator of the changes in MOC. In this study, we investigate the nature of the interannual variability of the MOC and its relation to sea level using an ECCO assimilation product in which TOPEX/Poseidon and JASON-1 altimeter data have been assimilated. The time series of the 1st Empirical Orthogonal Function (EOF) of the

MOC are found to be coherent with the North Atlantic Oscillation (NAO) index. To decipher the processes associated with such interannual variation in the MOC, we decompose the MOC variation into the contributions by (1) the Ekman flow and its depth-independent compensation, (2) the vertical shear flow, and (3) the external mode associated with the barotropic gyre. The latter is caused by meridional barotropic currents flowing in different longitude bands over different depths and give rise to an apparent meridional overturning circulation upon zonal average. For example, when the Gulf Stream travels over shallower depths in the west and its interior return flow goes over much great depths in the east, the resulting meridional transport stream function is characterized by an apparent "overturning" with northward flow in the upper ocean and southward flow at depths. The vertical shear component is found to explain much of the variability of the MOC at mid-latitudes. The contributions by the Ekman component and external mode are important in the tropics and at high-latitudes, respectively. By thermal wind relation, the variation in geostrophic vertical shear is proportional to east-west density difference across the basin. This relation is used to diagnose how the local and remote wind forcing generate the east-west temperature difference across the basin to drive the anomalous MOC. The relation of the east-west density difference to sea level is also addressed.

Interannual variation of sea level in the South Atlantic based on satellite altimetry

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11 years of altimeter monthly sea level are used to further explore interannual variability of the South Atlantic. The strongest variability outside the eastern and western boundaries is trapped to relatively narrow zonally oriented band between 35S and 25S, the Agulhas eddy corridor. On their way across the South Atlantic the Agulhas eddies gain energy on the southern flank of the eddy corridor via the barotropic conversions by decelerating the South Atlantic Current. On interannual time scales the sea level in the corridor fluctuates out of phase in the west and east revealing noticeable variations of 10 cm at 4 to 5 year cycle.

Inertannual and Seasonal Variation of Axis Position and Intensity of the Antarctic Circumpolar Current by Satellite Altimetry

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The Antarctic Circumpolar Current (ACC) develops to area of convergences and divergences of the Southern Ocean, which is confined of Subantarctic Front (SAF) and Polar Front (PF). Position of the SAF and PF were constructed from Multi-Channel Sea Surface Temperature (MCSST) gradients based on satellite AVHRR data. According to the SAF and PF average annual position the ACC northern and southern borders was determined as 60 and 100 cm isolines in Rio and Hernandez (2003) combined mean dynamic topography (CMDT), which calculated by in situ measurements relative to 1500 dbar. The ACC axis was defined as location of geostrophic surface speed maximum along meridian between stated isolines on the synoptic dynamic topography (SDT), which are constructed by superposition of sea level anomaly altimetry data with corresponding CDT. Value of surface speed on the ACC axis was determined as intensity of this current. Along ACC axis seven local maximum of geostrophic surface speeds (more 20 cm/s) are observed. The ACC axis position changes near latitude 50°S in the Atlantic and the Indian Oceans, and between latitude 55–60°S in the Pacific Ocean. Thus average geostrophic surface speed along the ACC axis makes 16 cm/s, and it changes from 10 to 15 cm/s on ACC borders (SAF and PF). In spectral density seasonal variation of the ACC axis and intensity are looking good independently of longitude. However interannual changes are various for different part of the Southern Ocean. For example they are insignificant in Drake Passage, but near Kerguelen Plateau position of the ACC axis dislocates to south with rate about 0.02 deg/yr, while the ACC intensity isn't change almost. The research was undertaken with partial support from the Russian Basic Research Foundation (Projects 06-05-64871 and 06-05-65061).

Coexistence of the Antarctic Circumpolar Wave and a Southern Annular Type Mode in the Southern Ocean?

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We examine the time evolution over a 13 yr time series of the dominant modes of variability in sea level anomalies (SLA) from TOPEX/Poseidon and ERS-1/2 in the Southern Ocean (35–60°S). We use Hayashi's classical space-time spectral analysis and a newly developed method combining a Gabor analysis with Hayashi's method. Zonal wavenumbers 3 and 2 emerge unambiguously with null corresponding meridional wavenumber meaning that both associated modes have no meridional propagation. Their power spectrum density (PSD) is maximum within 50–55°S. The 2/0 pair is characterized by a ~4.4 yr period and exhibits a clear eastward propagation, with a maximal PSD just after the 1998 El Niño peak. It corresponds then probably to the Antarctic Circumpolar Wave. The discernible zonal wavenumber 3 pattern of variability in the SLA signal displays a westward propagation associated with a 1.04 yr period, and may be related to the atmospheric Southern Annular Mode (SAM). Simultaneously, we have investigated the presence of these two modes in the surface chlorophyll concentrations derived from the SeaWiFS sensor over the 1997–2004 period. It is delicate to resolve the 2/0 mode due to the limited temporal extent of the ocean color archive. Results show high correlation coefficients (up to 54%) between the power spectrum density of the ocean color signal and that of the altimetric signal associated to the 3/0 mode related to SAM. Links between the SAM index, the biological and the physical signals at the interannual scale will be discussed.

Kelvin waves activity in the eastern tropical Atlantic

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Ocean Kelvin waves have long been considered as processes able to communicate subsurface stratification perturbations from the equator to higher latitude coastal regions. In the Atlantic, it has been argued that they could this way remotely control upwelling activity and SST variability, in particular in the Gulf of Guinea and the Benguela upwelling systems. Few studies though have been able to provide evidences of this happening in nature, maybe due to the weakness of Tropical Atlantic sea level anomalies relative to measurement errors. Continuous lessening of this error encouraged us to address this question using the Aviso Ssalto/Duacs SLA gridded data set in parallel with the output of an Ocean GCM and SSM/I SSTs over the period 1993-2003. Both SLA datasets show uninterrupted and clear equatorial propagations at intra-seasonal scale along the equator as well as along some parts of the coasts, when appropriately filtered. The speeds are consistent with those of first mode Kelvin waves. We evidence interannual stronger signals which appear capable of propagating from the equator to the coast towards north and south. The study of the coastal signals reveal large changes in the speeds at certain fixed key points possibly due to stratification changes. We finally present quantitative analyses of other ocean and atmosphere variables like wind, SST and subsurface stratification in order to better assess the physics and the impact of these signals.

Session 1.4:

Oceanography: Tropics

The Atlantic North Equatorial Countercurrent

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More than ten years of sea height anomaly fields are used in combination with climatological hydrographic data to investigate the spatial and temporal variability of the North Equatorial Countercurrent (NECC). Results obtained here are compared against those derived from temperature sections obtained from the high density XBT transect AX08 and of the depth of the 20°C isotherm derived from PIRATA moorings. A marked shift to the north was observed in the location of the core of the NECC in 1997, which coincides with a similar shift previously observed in the location of the North Brazil Current retroflection. The location of the NECC is observed to have a strong annual and semiannual component with maximum northerly locations in February and August. The geostrophic transport exhibits a predominant annual cycle with maximum values occurring during November.

Tropical Pacific long waves for the 1997-1998 El Niño-La Niña event from an altimetric data assimilation experiment

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A forced Ocean General Circulation Model simulation of the tropical Pacific in which combined TOPEX/POSEIDON and ERS altimetric data over January 1994-July 1999 are assimilated, is used to investigate equatorial wave

characteristics during the intense 1997-1998 El Niño-La Niña event. The assimilation results in an increased contribution of the higher-order baroclinic modes in the eastern basin and a decreased contribution of the first baroclinic mode in the western Pacific for the zonal current variability. Kelvin and first meridional Rossby waves are then derived for the first two more energetic baroclinic modes. The Kelvin waves of both modes contribute constructively to the strong warming observed in 1997, with the first (second) baroclinic mode being more energetic than the (first) second baroclinic mode in the early (mature) stage of the warming. Kelvin waves of both modes reflect as first meridional Rossby waves at the eastern boundary (reflection efficiency of ~ 95%) and contribute to push back the warm pool westward. From January 1998, the reversal of the warming is apparently initiated by the second baroclinic mode contribution which controls the position of the 28°C isotherm at the surface. At the western boundary, reflection of Rossby waves takes place for both modes, but a ~50% reflection efficiency is derived at 165°E. This suggests that the delayed oscillator theory is not applicable for explaining the reversal from warm to cold conditions during the 1997-1998 El Niño-La Niña, while the zonal advective feedback was at work. This study suggests that it is necessary to take into account the vertical structure of the ocean when interpreting altimetric data, which can be done through assimilation experiment.

Short description: The results presented in this paper illustrate the benefit in using altimetric data in ocean model to infer information on the vertical structure variability.

Application of Satellite Altimetry to Tropical Climate Prediction

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Application of satellite remote sensing to climate study is still in its infancy, largely due to the limitation of data record being too short. Now that the combined TOPEX/Poseidon and Jason altimeter data set has become more than a decade long, we should be able to evaluate the impact of these data on a large range of time scales and in a systematic and

quantitative manner. More importantly, we should explore the possibility of applying these high-quality, high-resolution observations to real-time ocean modeling and climate prediction.

Our focus has been on the tropics for two reasons: first, there are large interannual-to-decadal fluctuations in the tropical oceans which have strong influences on regional and global climate; and second, altimetry data are likely to have a major impact here because of the important role of sea level in tropical ocean dynamics and climate variability.

This paper reviews our efforts at Lamont-Doherty Earth Observatory in applying altimeter observations to predicting tropical climate variations, especially ENSO. Here we examine the impact of sea level data assimilation, elucidate the theoretical basis and the practical procedures that lead to such impact, and discuss the current status of our forecast system and the potential for further improvement.

varying latitudinal extents. The other ranges from 10deg S-9deg S to 9deg N-10deg N, with 20 latitudinal belts each with 1deg extent. Monthly sea surface slopes along 50-95deg E for the 30 latitudinal belts have been obtained for the entire altimeter period by fitting a linear regression between the sea surface elevation and longitude. The jet propagation has been studied in detail during various seasons using 14 years of the altimeter sea surface height .

Equatorial Indian Ocean Sea surface slope changes (Wyrтки Jet extent) using altimeter data

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Equatorial Indian ocean (EIO) behaves uniquely compared to the other oceans because of the monsoonal wind features prevailing over this region. The current direction also changes because of the wind reversal. Since the Coriolis force vanishes near the equator the surficial water is pushed downwind in the wave guide via Yoshida Jet/Kelvin wave. This jet is sometimes referred as the "WYRTKI JET". The presence of the Sumatra coast and the adjoining islands piles up the water there at the east (Wyrтки, 1973). This results in change in the zonal slope of the mixed layer (O'Brien and Hulbert 1974, Ali 1993 etc). Studying the extent of this type of jet in the open ocean over a better temporal and spatial scale is practically impossible with conventional measurements from buoys/ships. The advent of satellite altimetry thus gave an opportunity for such a study. In this study we have analysed 14 years of the altimeter data (1990-2004) over the Equatorial Indian Ocean (EIO) (10 deg S-10deg N, latitude and 50-95E longitude) to study the latitudinal extent and the interannual variations of the Equatorial Jet. To study the propagation of the jet, monthly mean sea surface elevations have been constructed using sea surface height (derived from altimeters) for different latitudinal belts spanning the EIO. Two latitudinal belts have been considered for this study. One ranges from 1deg S-1deg N to 10deg S to 10 deg N in total having 10 belts with

Session 1.5:

Oceanography: Tides

Tidal Energy in the Bering Sea

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Tidal harmonics computed from TOPEX/POSEIDON altimetry are assimilated into a barotropic, finite element model of the Bering Sea and used to estimate energy fluxes through each of the Aleutian Passes and Bering Strait, and to construct an energy budget for the major tidal constituents. Though the M2 constituent is estimated to have the largest net energy flux into the Bering Sea at 28.9 GW, K1 is not far behind at 27.1 GW, and the sum for the three largest diurnal constituents is found to be greater than the sum for the largest three semi-diurnals. A significant portion of the diurnal energy is seen to exist in the form of continental shelf waves trapped along Bering Sea slopes. The effect of the 18.6-year nodal modulation is estimated to cause basin-wide variations of approximately 21% in the net incoming tidal energy flux and larger variations in subregions, such as Segum Pass and south of Cape Navarin, that are strongly dominated by the diurnal constituents. These variations should correlate with tidal dissipation and mixing and may have important consequences to biological productivity, similar to those previously found for Pacific halibut recruitment.

Session 1.6:

Oceanography: Marine Meteorology

On the combined assimilation of RA-2 and ASAR wave data for the improvement of wave forecasting

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The increasing number of wave observations from satellites related to sea state represents a stimulating challenge for wave modelers in order to improve operational wave forecasting. It is now well known that a better estimate of the sea state has an important contribution to a better description of the physical processes at the ocean surface, such as currents circulation, air-sea heat fluxes and surface stress. Improving the wave forecast is also an essential need for several activities at sea (off-shore activity, ship navigation and coastal survey). The RA2 altimeter provides the total wave height at the free surface, while the imaging radar ASAR gives the directional wave spectra limited to azimuthal wavelength cut-off. The use of these two wave observations conjointly is well appropriate to the correction of both wind sea and swell parts of the sea state. As their orbit tracks are separated with an average distance of 200 km, the coverage of observations over sea points is also improved. In our previous studies, it was found that the use of spectral information improved the estimate of wave parameters, in particular for swell (Aouf et al. 2004). This work presents the impact of using continuously the combined assimilation of RA2 and ASAR data in the wave model WAM for long period of two months, in February and March 2004. To remove corrupted ASAR data, quality controls depending on the retrieved parameters from ASAR (wind speed, the ratio of signal to noise and the normalized variance of images), are performed in a prior procedure before assimilation. The validation of the assimilation results with independent wave observations is performed for the periods of analysis and forecast. An important point related to the choice of optimal wavelength cut-off for the ASAR wave spectra is well discussed by investigating different test cases. The results showed that the assimilation system works correctly and the estimate of mean wave parameters is significantly improved. The impact of the assimilation stays effective for more than three days after the end of assimilation. The filtering procedure seems to work

efficiently for the rejection of spurious ASAR data. In other respects, statistical analysis in comparison with Jason-1 altimeter and buoys data has clearly indicated a significant positive impact for the significant wave height and mean period of waves. Further, the analysis for specific ocean areas (intertropical and high latitudes areas) exhibited the benefit of using both RA2 and ASAR wave data. Longer period of assimilation and validation is still needed to prepare the assimilation system for operational use.

The impact of dynamic topography on the intensification of hurricanes

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Satellite altimeter data show the intensification of wind speed and wave heights associated with the recent hurricanes Katrina and Rita that ravaged the U.S. Gulf Coast. At the same time, wind surges of up to 90 cm were observed near the coast.

The correlation between the intensification and the crossing of regions of higher dynamic topography is evident. Those regions harbour more heat in the upper layer (with a thickness of approximately 100 m) than surrounding areas and can thus release more energy to the storm.

This perception is contrary to the general agreement that hot surface waters are responsible for the intensification. We will show that the intensification has a stronger correlation with dynamic topography (and thus total heat content) than with sea surface temperature (which applies only to the very top centimeter of the ocean).

Operational satellite altimeter data are therefore a more effective tools for hurricane forecasting by indicating pools of warm water than infrared sensors.

This presentation will highlight several examples of North Atlantic hurricanes, their intensification and the correlation with sea surface temperature and sea level anomaly.

Satellite significant wave height observations in coastal and shelf seas

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Significant wave height (SWH) observations from the Topex/Poseidon and Jason-1 satellites are compared against buoy observations and a spectral wave model for the North Sea/Baltic Sea region. The comparisons span several years of data and thus give a valuable interannual validation of the satellite observations in coastal areas. The satellite observations in general show good agreement with the wave model and the buoy observations. However, a significant bias is seen in the northern part of the North Sea where the satellite SWHs are substantially lower than both the model and the observations. The scatter index reveals enhanced errors in the danish straits and in parts of the Baltic Sea. Detailed error statistics will be presented for different regions and the probability of obtaining erroneous satellite SWH observations will be determined for the near coastal areas. Based on the detailed comparisons, the applicability of the satellite SWH observations for operational coastal and shelf seas forecasting will be assessed. Finally, the potential for near-real time use of these observations will be discussed.

Altimeter dual-frequency observations of surface winds, waves, and rain rate in tropical cyclones

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Extreme weather events such as tropical cyclones are difficult to observe with conventional means. Satellite-based observations provide essential measurements of key parameters governing tropical cyclones. They are critical for short term forecasting. Radiometers onboard the DMSP satellite series, WindSat and TRMM , scatterometers onboard the ERS, ADEOS and QuikScat satellites, offer unprecedented synoptic observations of surface wind and atmospheric liquid water content, revealing the storm structures with good accuracy. However, satellite estimates don't provide direct measurements of geophysical parameters and can suffer from limitations linked to the sensors characteristics, such as the signal wavelength and

polarization or the measurement incidence angle. For example, measurements at Ku-band are strongly affected by rain. Still, each observing system can offer specific information which can be combined with the others. In particular, we highlight the capabilities of dual- frequency altimeter to provide very high resolution measurements of rain rate, surface

wind speed and wave characteristics. A method is proposed to obtain continuous along track 5 km resolution measurements of these parameters in tropical cyclones. The results shows that dual-frequency altimeters can provide useful information to complement and validate the operational fields provided by the atmospheric numerical models and by the other observing systems.

Wind speed retrieval by altimeter data: evolution of algorithms

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The cross section of a radar signal backscattered from the ocean surface depends upon the ocean state, which turn depends upon the wind speed, fetch and swell. The first our result devoted to this problem was presented in 1995 (Biarritz, Operational oceanography and satellite observation). To understand better the dependence radar cross section (RCS) on sea state we initiated a new investigation based on the theory of the scattering of electromagnetic waves from a statistically rough surface, using a model spectrum for the sea surface. The main factors affecting the RCS within the framework of our ocean model were established and investigated. The next step was the transition from the solution of the direct problem of the electromagnetic wave scattering by the water surface for considering the inverse problem, i.e. the retrieval of wind speed using altimeter data. The new two-parameter algorithm was developed and presented in the 1999 (Saint-Raphael, Topex/Poseidon and Jason 1 SWT meeting). The improvement of wind speed retrieval algorithms allows to increase the precision of wind speed retrieval due to taking into account the significant wave height. However, these researches show also that even the use of a two-parameter algorithm does not completely remove regional effects. Evidently, the same wind speeds may corresponds to different sea states: developing wind waves, fully developed

wind waves and mixed sea (wind waves plus swell). Also, every region has local features of sea states, for example, mixed sea is a dominant sea state near Hawaii and developing wind waves is a dominant state in Caribbean sea. These regional features will be reflected in radar cross section and, hence, in retrieved wind speed. Therefore, using of single retrieval algorithm for all regions gives errors. To improve the precision of wind speed retrieval the new approach was suggested. The main idea is to use measured by altimeter a significant wave height and a retrieved wind speed (conventional algorithm) to determine the sea state. For description of sea surface was introduced 12 sea states. The wind speed correction was calculated for every state. The new approach was submitted in 2002 (Biarritz, Jason 1 SWT meeting). Before now we have used the Topex/Poseidon data. The appearance of the new altimeters (Jason and Envisat) gives the possibility to check our algorithm. In this report the review of the wind speed retrieval algorithms on altimeter data is executed and the analysis of efficiency of existing algorithms is carried out. The aim of research is to generate an improved altimeter wind speed retrieval algorithm, which will be able to work with data of all altimeters. The existing two-parameter algorithm was used at the first stage. The data correction has shown that develop for a altimeter TOPEX the two-parameter algorithm effectively works with the data of the new altimeters. The data processing has confirmed that the new algorithm allows to reduce an error deal with regional features of wave climate formation.

Numerical modelling of the 2004 Indonesian tsunami: methodology and results

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The Indonesian tsunami has been triggered by the vertical deformation of the ocean bottom due to the earthquake. The modelling of the tsunami wave generation, propagation and dissipation is a challenging task as the dynamic of the tsunami wave is highly complex, and the realistic numerical modelling of such phenomenon would require huge computer power. Nevertheless, it can be seen, at least at the first order, as a gravity wave problem by many aspects, especially for the wave propagation, and thus be partially treated using a barotropic model with the adequate grid resolution. Such an approach has been carried out at LEGOS, using mog2D model and thus the finite element variable resolution capabilities. Sensitivity on the initial conditions, hence the realistic knowledge of the ocean bottom deformation in terms of location, amplitude and timing, was found to be determinant for the simulation accuracy when comparing to existing observations like

altimetry and arrival time along the Indian ocean's coastlines. Methodology and results of the simulations are discussed, as well as the need for further improvements.

Comparison of altimetry wave and wind data with model and buoy data

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A quality controlled dataset of significant wave heights (SWH) and wind speeds based on ERS-2 and Topex/Poseidon (T/P) altimetry from the period 1999-01-01 to 2000-02-29 has been compared with buoy observations of significant wave height (HS) and model forecasts of HS and wind velocity. The examined area covers four sub-areas: : the western part of the North Sea, the eastern part of the North Sea including the Skagerrak, the Kattegat and the western part of the Baltic Sea. The wave models are OSW (a commercial product of DHI Water&Environment based on the WAM model) and Wave Watch III (WW3 of H. Tolman, NOAA/NCEP). Both models have been run with a standard parameterisation and both are forced by the forecasted 10 m wind. For the wind forecast the first 6 hours of the model Hirlam E15 of the Danish Meteorological Institute have been used. The buoy observations have been performed near the west coast of Jutland and the north-west coast of Germany. Small correction algorithms have been applied to satellite SWH data, while satellite wind data are uncorrected.

The analysis shows that SWHs and wind speeds from ERS-2 and T/P are consistent and may be merged together in the comparison with model data and buoy observations.

Wave heights of the satellites agree well with the WW3 model, and the WW3 wave heights agree well with the buoy observations. OSW wave heights tend to be about 20% higher than satellite wave heights. These results are independent of the sub-area in consideration, but varies slightly over the seasons.

Satellite winds are about 9% lower than Hirlam winds (15-20% for high wind speeds). This result is slightly dependent on the choice of sub-area (for the Kattegat Hirlam forecasts and altimetry winds differ more than for the other areas). There are seasonal variations in the wind comparisons, especially for the low wind speeds.

Based on these observations it is concluded that altimetry SWH and wind speeds from the two satellites support each other well in any comparison with other data types. Satellite SWHs may be a valuable source for wave model validation and/or assimilation, while the wind speeds derived from

satellite altimetry differ systematically from the wind model.

Session 2: Cryosphere

Extraction of Arctic Sea Ice Thickness from Envisat Altimetry Data

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Radar altimetry data from the ERS-1 and ERS-2 satellites has been used to obtain a continuous time series of Arctic sea ice thickness to 81.5 degrees North going back to 1993. Since its launch in March 2002, the radar altimeter on board the Envisat satellite has continued observing Arctic sea ice from space and this poster shows how the method of extracting ice thicknesses from altimetry data was extended to Envisat data.

The poster shows how the Envisat results have been cross-calibrated with those from ERS-2 by comparison of sea level anomaly, ice elevation and freeboard maps. It also includes some preliminary validation results with in situ data as well as a comparison of Envisat derived elevations with GPS over the Salar de Uyuni.

Altimetric Constraints for Parametric Geocoding of Glacier Interferograms

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This paper describes the background to geocoding and mosaicking spaceborne ERS-1/2-SAR interferograms (1995-1996) of the largest European glaciers and reports on the most recent results achieved in the CryoSat AO research project No.2611 "SIGMA". The research objective was to establish a unified control network serving as a framework for detecting, measuring, interpreting and mapping glacier changes on the Main Ice Sheet in north Novaya Zemlya, Tyndall Ice Cap in Franz Josef Land, Austfonna and Hornbreen glaciers in Svalbard. Up-to-date topographic maps and digital elevation models of these tidewater glaciers

are either nonexistent or of limited quality and extension. In this circumstances, the glacier height constraints needed for precise interferometric modelling of active glaciers were derived, without the use of surveyed control points, from the ICESat-GLAS altimetric transects obtained over test glaciers in 2003.

Straightforward and rigorous procedure for the "absolute orientation" of SAR interferograms making the use of spaceborne altimetry data, sensor-specific imaging models and least squares adjustment techniques includes the following basic operations: 1)co-registering altimetric transects with standard interferograms ("compilation & identification of control points"), 2)estimating phase distortions and removing phase or/and height offsets, height ambiguity control and spatial baseline refinement ("levelling, scaling, adjustment"), 3)determining glacier heights at specific target points between altimetric transects ("measurement"), 4)parametric geocoding and mosaicking of INSAR models ("orientation to available control").

Radar penetration effects were ignored, and monotonous and homogeneous character of elevation changes over the test glaciers during the period of 1995 - 2003 was assumed. It has been demonstrated that the arbitrary height and velocity of each specific point on the glacier surface characterised by a high coherence value can be derived from single geocoded SAR interferograms without complex processing artifices such as phase unwrapping and differential interferometry. In geocoded INSAR products, all geometric effects at precipitous glacier fronts can be accounted for, thus allowing precise glacier change detection in multitemporal data sets. Several orthoimages and glacier map series representing elevation changes in different glacier environments were produced.

Absolute topographic validations and map quality control were performed during concurrent D-GPS surveys in the Austfonna test site in 2003 and 2004. Maximum height errors were estimated as being nearly 5 times smaller than those in standard INSAR products. It has been concluded that the combination of satellite radar interferometry and altimetry offers a particularly potent solution to the topographic modelling of large glacier complexes in the case of insufficient ground control. In similar manner, radar altimetry data, e.g. that to be obtained by RA-2 and SIRAL altimeters, can be applied to geocoding SAR interferograms. In this case, the results might be even more stable due to the alikeness of backscattering effects and, probably, lesser impact of the snow accumulation between the instants of interferometric and altimetric surveys.

Along track repeat altimetry for ice sheets and continental surface

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Satellite altimetry is the unique possibility for continuous and extensive survey of the large polar ice sheets volume change. With ERS1 it became possible to measure the surface topography of 80% of the antarctic and quite all of the greenland ice sheets with an unprecedented accuracy. The accuracy of the classical radar altimeter measurements over continental surfaces is however limited by a number of factors of which the first is the topographic induced error (commonly called slope induced error). In addition volume echo induce penetration effect on the altimeter waveforms. The temporal survey of the surface height is classically made using crossover points differences in order to limit the topographic induced errors. However the measurements show difference as to volume echo induced errors between ascending and descending tracks. A method has been developed at LEGOS to survey along track by taking into account the fluctuations across track of both the height measurement and the waveform shape parameters. This method has the advantage to avoid the ascending/descending difference in echoing and also to lead to around 100 times more measurements available to survey the evolution. It also helps to look at the time evolution of the ice sheet surface at small scales of the order of few km in regional or local studies. In this presentation, we'll show the principle and aspects of the methods and the impact in terms of accuracy and local signal on 2 regions, one with very small expected fluctuations (Vostok lake area) and another one with large fluctuations expected (Pine island glacier basin). We'll discuss the interest of the method in various aspects and its applicability on other land surfaces.

Validation of altimeter measurements over ice.

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We've been investigating the altimeter measurements from ENVISAT satellite over ice sheets of greenland and antarctica. The measurements are mapped on the ice sheet scale on both Antarctica and Greenland for every cycle. The result shows an overall good behaviour of the radar altimeter with most of the time high resolution measurements over ice

apart from strong transitions. The crossover difference of the height, backscatter, leading edge width and trailing edge slope show characteristic behaviour. This behaviour stays stable from cycle to cycle and compare well with ERS1 and ERS2 series. We investigated the difference between ERS2 and ENVISAT along track. Although few measurements are available on common cycles and many of the tracks show large across track distance after ERS2 attitude difficulties, the results on the small safe dataset will be shown. In addition to these global analysis, we made survey on smaller identified targets. One target is the lake Vostok area where the time variations of the signal are supposed to be small, the surface is very flat and shows little undulations, the accumulation is very small as well as the wind, the atmosphere stays clear most of the time and we have extremely fine topography issued from revised ERS1 geodetic data and controlled with ICESAT data. The other target of interest is on the Amery where we designed a spiderweb around an ENVISAT crossover point. The web has been surveyed in 2003-2004 by roving GPS and the tides have been investigated to validate an adapted ocean tide model. The GPS roving has been processed to produce a local very high resolution topography and statistics of the surface roughness. This crossover point will be again surveyed in 2005-2006. We will show results on the data analysis for those targets and on altimeter echo modelling to improve the analysis of the altimeter data. Emphasis will be done, based on these analysis, on the quality of the data, on the best operational modes of the altimeter and on the routine survey of altimeter data over ice.

Simulation of radar altimeter waveforms over ocean and ice covered regions

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Initially satellite altimeters were developed to measure ocean surface heights. But they also provide measurements over continental ice sheets and sea ice covered regions. Radar altimeters operating over ice covered regions are subject to additional error sources. The return scatter depends on the surface slope and surface roughness and is also affected by the extinction coefficient and the reflection inside the snow and ice layers. Therefore these parameters have to be well known for interpreting the power and the signal of the pulse response. Since it is almost impossible to determine the parameters continuously at the surface, the computational simulation of the waveform is a suitable tool to get a better understanding of the impact of the surface conditions on the reflected signal. For this purpose a waveform simulator has been developed which takes into account prominent topographic features due to the

discretisation of the surfaces. We will present the results of various simulations of waveforms for different states of the surface and for several topographic features like shelf ice edges and ice floes. Using the waveform simulator will allow us to develop adapted retracking functions and will lead to a better estimation of sea surface heights in sea ice covered regions.

Session 3:

Marine Geodesy, Gravity, Bathymetry

Determination of the Earth Gravity Field Components in the Persian Gulf and Oman Sea with Satellite Altimetry Data

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Satellite altimetry provides continuous, accurate, and homogenous data series in marine areas. The Sea Surface Heights (SSH) extracted from altimetry data was used in a method searching for the least squares of the sea surface topography to simultaneously determine the geoidal height and the sea surface topography as well in the Persian Gulf and the Oman sea. This is contrary to the methods which require the knowledge of one parameter to estimate the other. The North and East components of the deflections of vertical were also estimated by differentiating the derived geoidal heights in the corresponding directions, and finally the free-air gravity anomalies were computed utilizing the inverse Vening-Meinesz integral.

the marine science community has made only modest progress in acquiring new seafloor mapping data. Indeed, the pace of acoustic mapping of new seafloor areas has actually dropped.

The situation will probably get worse before it gets better. For example, in the USA the recent jump in fuel costs puts even more stress on vessel operations, which were already threatened by declining budgets. It is not uncommon for vessels to be laid up for 3-5 months this year, due to lack of funds. At the same time, the number and quality of proposals for sea going science continues to grow. Programs that are lucky enough to be funded are being postponed 1-2 years to fit into reduced schedules. Programs that target a localized objective, including repeat visits, are more likely to be funded than broad reconnaissance and exploration cruises. There is a continuing demand for site surveys to support the Integrated Ocean Drilling Program, but fewer resources are available to accomplish the work. Little progress has been made in obtaining commitments to replace the aging fleet of global research vessels. This is a troubling scenario for young researchers, as they consider embarking on a career in the marine sciences.

While satellite altimetry will never replace detailed acoustic investigation of the seafloor, a higher resolution system can help to overcome roadblocks in many areas, such as support for oceanographic expedition planning, the identification of patterns of tectonic fabric, and the modeling of regional phenomena such as tsunamis and ocean mixing. Unfortunately now, more than ever, there is a need for a high resolution altimetry mission.

Progress Toward a Comprehensive Map of the Seafloor

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During recent years, a number of global efforts have succeeded in allowing data from altimetry missions, shuttle radar, and shipboard echo sounding to be merged, catalogued, and disseminated online to a wide audience. Progress at the Scripps Institution of Oceanography and other organizations will be summarized. However, despite the best intentions and efforts of many, in the last five years

An overview of spectral methods for the optimal processing of satellite altimetry and other data

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This paper summarizes the results obtained and the improvements achieved during the last fifteen years of satellite altimetry research by spectral combination methods at the Universities of Calgary and Thessaloniki. In particular, a review of the principles and characteristics of the FFT-based multiple input-output system theory method is presented, with applications in marine gravity and geoid, sea surface topography, and bathymetry modeling by an optimal combination of satellite altimetry and other (e.g., shipborne gravity, bathymetry, etc.) data. The main focus is placed on the contributions of geodetic mission altimetry from ERS1, as well as from multi-satellite altimetry data processing, with and without the use of additional data, including error propagation. Furthermore, a comparison to the least squares collocation method, and the results obtained by it, is made from both the theoretical and practical point of view. Numerical results are shown for the areas offshore Canada and in the Mediterranean Sea. Finally, conclusions are drawn on the improvement in the determination of various gravity field related quantities in terms of accuracy and resolution by combining altimetric and other observations.

Accuracy of the 2500 m Isobath from Satellite Bathymetry

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In December 1994, ESA extended the ERS-1 Mission Phase F to collect complete geodetic coverage of the oceans with an 8-km ground track spacing. In 1995, the U.S. Navy released all the previously classified Geodetic Mission Data from Geosat. New maps of global ocean tectonics and seafloor topography were made possible thanks to these satellite missions.

Locating the 2500 m isobath is a crucial component of a

Coastal State's efforts to lay claim to its Juridical Continental Shelf under Article 76 of the United Nations Convention on the Law of the Sea. We compare depths from the altimetric bathymetry grid of Smith and Sandwell to depths surveyed by ships with multibeam acoustic echosounders to assess how accurately satellite bathymetry maps the 2500 m isobath. We find the satellite isobath meets IHO S-44 vertical accuracy standards 90% of the time in areas of smooth topography with good acoustic survey control, but only 31% of the time in a rugged, poorly surveyed area. A horizontal displacement of the satellite isobath with respect to the NGDC Coastal Relief Model offshore of New Jersey, USA, is due to the underlying depths being uncorrected for the velocity of sound in seawater in the Model and corrected in the satellite-derived bathymetry data.

Generation of a high resolution grid of gravity anomalies by inversion of altimetric data from Geosat, Topex/Poseidon, ERS1/2 and Jason-1 in the Azores region

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Stacked data from Geosat, Topex/Poseidon, ERS-2 and Jason-1 are used to define a precise reference frame of satellite tracks, where data with very dense coverage from geodetic missions of Geosat (18 months) and ERS-1 (10 months) are adjusted, allowing a very detailed recovery of the marine gravity field. A remove restore procedure is used to obtain residual sea surface heights by removing the low and high frequencies (the global geopotential model EGM96 is used as reference field and the effect of the topography/bathymetry is computed using the RTM correction with the local accurate bathymetric model AZDTM98 and the global model JGM95E. A validation procedure is applied using a least squares collocation, followed by a grid generation of residual geoid undulations, that are inverted using an efficient method based on Fast Fourier Transform to obtain residual gravity anomalies. After adding the contributions to the gravity field from the global model and from the topography/bathymetry, the results are compared with adjusted gravity data obtained from gravimetric surveys.

A Mean Ocean Dynamic Topography Derived from Altimetry and the Latest GRACE Geoid Model

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The determination of a precise mean ocean dynamic topography for the estimation of oceanic transports and the assimilation into ocean circulation models is still a challenge. For this study we have compiled a new mean sea surface height model from reprocessed and harmonized altimeter data (TOPEX, ERS-1 and ERS-2) and combined it with the latest static satellite-only GRACE geoid model from GFZ Potsdam (EIGEN-GRACE_03S). It can be shown that the resulting mean dynamic topography resolves signals down to 400-500km wavelength. For this resolution the derived geostrophic surface currents are still reliable - even for the more noisy meridional component. The mean dynamic topography is further validated using the WOCE hydrographic climatology. The two data sets show a very good agreement for the resolved spatial scales. This includes the absolute ranges as well as the position of the main current systems. In addition, the satellite-derived data resolve details even on currents of smaller scale like the Gulf Stream Recirculation and the Azores Current. The differences between the two estimates help to identify regions with strong barotropic currents as well as regions where the geoid is not yet adequately determined.

Simultaneous Improvement of Large Scale Geoid Height and Mean Sea Surface Topography

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In physical oceanography the slope of the large scale dynamic sea surface topography can be used to calculate a surface geostrophic velocity as a reference for the general circulation and its associated transports. The dynamic topography is the elevation of the sea surface from the equipotential surface, i.e. it is identical with the difference between the sea surface height as it is measured by satellite altimetry and the geoid height. Therefore we calculate a mean dynamic topography (MDT) by combining altimetry

and gravity data. A first guess MDT is calculated from a dynamical ocean model into which measurements of temperature, salinity, property fluxes and sea surface height anomalies have been assimilated. The large scales of this surface are subsequently improved by adding information about the mean sea surface height from satellite altimetry and a 'satellite only' geoid model. Simultaneously we estimate large scale corrections for the respectively used geoid models. The combination takes into account full covariance matrices and considers the different error structures of the three sources of data. The results show that it is possible to use satellite altimetry not only for oceanographic purposes but also to validate existing and new geoid models. Comparing the corrections of different geoid models makes it possible to verify the improvement of 'satellite only' gravity models by current satellite missions.

How Satellite Altimetry Contributes to the Vertical Datum Problem

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Over the past several decades, the definition of a global vertical datum and the realization of such a system has been a topic of great research and debate. Many different methods for defining a vertical reference system to be implemented all over the globe have been presented. The definition of such a global vertical reference system is further complicated by accuracy and spatial coverage limitations with traditional techniques. The purpose of this study is to provide a detailed account of the major efforts conducted over the years for defining a vertical datum in Canada. Both theoretical developments and practical aspects will be discussed, based on research conducted at the University of Calgary over the past ten years. The paper will emphasize the contributions of altimetric satellite measurements to the vertical datum definition issue. The Canadian situation will be studied in the context of existing problems and complications for defining a regional vertical datum, including the expected improvements by the use of data from the new satellite gravity missions. Since one of the major problems with the definition and subsequent acceptance or adoption of a globally defined datum is dealing with existing regional datums, a case study on the status of the Canadian vertical datum will be useful for understanding the topic.

The DNSC05 high-resolution global marine gravity field.

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The latest version (DNSC05) of the formerly KMS global marine gravity fields is presented. This gravity field has a resolution of 1 minute by 1 minute and covers all marine regions of the world including the Arctic Ocean up to the North Pole. By starting out from the original waveform data and retracking the entire ERS-1 GM mission using a highly advanced expert based system of multiple retracers the return time from both the open sea surface and from all ice-covered regions within the coverage of the ERS-1 can be derived with higher accuracy than presently available. This presentation describes the combined effort in improving the ERS-1 GM dataset through retracking and regression to 2 Hz (3 km) and its effect on gravity field modeling close to the coast. Extensive comparisons carried out at the National Geospatial-Intelligence Agency are also presented to document the findings.

High resolution coastal gravity anomalies from retracked Geosat/GM and ERS-1/GM altimetry

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The paper presents the high resolution (1 minute by 1 minute) gravity anomalies using corrected sea surface heights (SSHs) derived from non-repeat Geosat and ERS-1 Geodetic Missions (GMs) in the Australian coast. The SSHs have an along-track resolution of ~3 km (2 Hz) and are obtained from retracking the altimetric waveform data. Retracking algorithms are developed to reduce the noise effect and improve the accuracy of the range estimate (and thus the SSHs). The retracking technique also estimates the parameters of the off-nadir angle and significant wave height. These estimates are then analysed to find their error characteristics. Different retracking algorithms applied to coastal regions are also analysed. The SSH profiles derived

from retracking waveforms of Geosat and ERS-1 GMs are now more accurate and much closer to the coast than those without a retracking procedure, thus providing optimised data sources for gravity field and mean sea surface recovery in coastal regions. Finally, the recovered gravity anomalies are compared with ship-borne gravity observations.

Satellite altimetry and marine gravity data: toward a consistent knowledge of the gravity field.

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Since the sixties, marine gravity measurements are done in the oceans and the oceanic area was gradually covered by the gravity marine surveys. The launching of the first altimetric satellites in the eighties had a great impact on the global marine gravity knowledge. The global models of mean sea surfaces or of the free air anomalies were universally used and lead to a lot of results in oceanography or earth geophysics in the oceans. Nevertheless, these models don't answer all questions especially in the study of the short wavelengths of the free air anomaly or bathymetry. From few examples the case of mixing derived altimetric free air anomaly grid with marine measurements will be studied. We will show in this paper the own contribution of satellite altimetry and marine gravity in the knowledge of marine gravity disturbances. The use of satellite altimetric data to homogenize the gravity measurements will be described. To recover the high frequencies of the gravity, a new method of enrichment of global gravity model by bathymetric information will be presented. The results show that the merging of these data conducts to precise gravity modelling at high spatial resolution. In the future, the GOCE data allow to obtain better referenced altimetric data due to the very precise geoid and to improve our model.

Comparing the use of ship and satellite data for geodynamic studies

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The availability for scientists of global data sets on satellite free air anomalies and predicted bathymetry changed

considerably the research on marine geology and geophysics. These data sets allowed for the first time to have a global view of the morphology of the ocean floor. Geodynamic studies which were hindered by the lack of good quality regional morphology data especially benefited from these new data sets. Marine gravity studies also benefited from a more homogeneous coverage since most of the marine surveys are localized, with gravity data being acquired along ship tracks.

Although satellite derived free air anomalies and predicted bathymetry are very useful for regional and global studies, they lack the fine scale quality required for detailed studies. Moreover, predicted bathymetry is the result of a model calculation and, although constrained by real bathymetry data, for many studies it cannot fully replace it. In this short paper, I will present some studies done with both ship and satellite data and discuss the advantages of using merged data sets for regional studies. However, detailed local studies require the fine scale features that can only be acquired by good quality ship data. It is certain that the arrival of a new generation of satellite data will improve the quality of the global grids and allow the use of these grids for more detailed studies.

ESA's Earth Explorer gravity mission: GOCE

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ESA's first Core Earth Explorer mission within the Living Planet Programme is the Gravity field and steady-state Ocean Circulation Explorer (GOCE). GOCE will play an important role in this 'geopotential decade' by acquiring a high quality, high spatial resolution gravity field and geoid for future scientific applications. GOCE combines an innovative new three-axis gravity gradiometer (EGG) instrument (comprising three x, y, z pairs of accelerometers with a baseline separation of 0.5 m) with a drag-compensating ion-propulsion system to measure for the first time the full gravity gradient tensor along its orbit at 250 km altitude. GOCE will carry a GPS satellite-to-satellite tracking navigation system for 3-dimensional positioning, star trackers for precise pointing knowledge, and a laser retroreflector for ground laser tracking. GOCE is specifically designed to make accurate and precise measurements of the stationary gravity field and gravity anomalies (to 1 mGal) at high spatial resolution (100 km). The data will facilitate the computation of a high spatial resolution (100 km) global geoid model to 1-2 cm accuracy. Applications of these products will be illustrated using examples of applications in oceanography, solid-earth physics and geodesy. After a successful completion of the design consolidation phase, the construction phase for the

GOCE satellite is presently underway, with an anticipated a launch in late 2006.

Satellite Derived Predicted Bathymetry: Essential Tool for UNCLOS 'article 76' on the extension of the legal continental shelf beyond 200 nautical miles

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Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS, Montego Bay, 1982) allows coastal states to claim a legal continental shelf extending beyond the 200 nautical miles that presently limits their exclusive economic zone (EEZ). As part of a claim submitted to the UN Commission on the Limits of the Continental Shelf (CLCS), coastal states have to demonstrate natural prolongation of their landmass and fulfill certain geomorphological and geological criteria. A number of geophysical and geological observations, needed to respond to these criteria, are laid out in Article 76, and further explained in the Scientific and Technical Guidelines published by the CLCS in 1999. Although these requirements present a tremendous opportunity for the acquisition of bathymetric, seismic (both reflection and refraction) and other data, the costs of such operations may be prohibitive, in particular for developing countries. Also, the time lines for data acquisition are relatively short as coastal states have a nominal 10 year period after ratification of the convention to complete their claims for an extended continental shelf. In fact, for a large number of states, the deadline is 2009, but others have more time. Satellite derived bathymetric data is therefore an essential tool for any outer continental shelf program: Firstly, due to its uniform coverage, it is a more coherent data set than those derived from ship tracks only (e.g. Gebco). For a preliminary study of potential extension, Etopo-2 provides results that are quite acceptable, and allow for an accurate planning of additional data acquisition. Secondly, given the hydrographic standards required by the CLCS, it may well be that for the determination of the foot of the slope in relatively deep areas (deeper than ~3000 m), the existing satellite derived bathymetric data approaches the quality needed to substantiate a legal shelf claim. A higher resolution satellite altimeter mission will surely help a significant number of countries in constituting their submission to the UN, in an efficient and cost-effective manner.

Intraplate seismicity, oceanic basement topography and marine gravity

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The intraplate seismicity that affects the ocean seafloor is poorly known, while it is of critical importance to study the thermal structure of the oceanic lithosphere and assess the peculiarities - if any - of the earthquake generation processes in submarine environments. T-waves generated by submarine earthquakes can propagate almost without attenuation in the SOFAR (Sound Fixing And Ranging) channel, as far as a few thousands kilometers away from the epicenter. Hydrophones arrays have thus been recently used to detect small-magnitude earthquakes (typically $3 < M_s < 5$) that are undetectable or imprecisely located by land-based seismological networks, providing unprecedented data and new insights on the low-level seismicity of the oceanic lithosphere, over areas extending over a few millions square kilometers.

However, to fully interpret data from hydrophone arrays, it is necessary to recognize the tectonic environment near the epicenter, using structural maps of the seafloor. Marine gravity and bathymetry derived from satellite altimetry are, to date, the only means to improve this knowledge at a global scale, especially in the remotest areas of the world's oceans, for at least two reasons : 1) deep seafloor areas will not be covered by shipboard multibeam systems in a foreseeable future ; 2) some areas, such as for instance, the Central Indian Ocean Basin, where a very active intraplate seismicity occurs, are thickly covered with sediments. Marine gravity thus remains the only way to map the structure of the rough igneous at a basin scale. Here, we present some examples from the Pacific, Atlantic and Indian Oceans, showing the benefit that would be gained from improving the resolution of satellite derived models of marine gravity and bathymetry to optimize the use of hydrophone arrays and to study intraplate seismicity.

Session 4:

Hydrology and Land Processes

Ice and snow cover on lakes from radar altimetry and radiometry: case of the lake Baikal

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The state of ice cover, and the freeze-up and break-up dynamics of lakes are good indicators of large-scale climate changes. We demonstrate the potential of multi-sensor data fusion for studies of ice and snow cover for lake Baikal in Siberia. We show the synergy of the combined use of passive and active microwave satellite data - simultaneous active and passive observations available from the recent satellite altimetry missions (TOPEX/Poseidon, Jason-1, ENVISAT and Geosat Follow-On), as well as passive data from SSM/I sensor. All altimetry platforms have two nadir-looking instruments: a dual-frequency radar altimeter and a passive microwave radiometer that operate simultaneously. Though the primary mission of satellite altimeters was to measure sea level, we have found that the combination of active and passive microwave measurements could be successfully used for the sea, lake and river ice cover studies. This information was complemented by long time series from the SMMR side-looking radiometer.

We propose a methodology for ice discrimination and estimation of snow height and we discuss the drawbacks and benefits of each type of data. The resulting satellite-derived series of dates of ice cover formation and break-up and snow height estimations are analysed together with existing observations at coastal stations and other satellite and in situ data. These time series show pronounced regional, seasonal and interannual variability and for the first time provide continuous time series of modern ice cover variability in lake Baikal at the lake-wide scale. Comparison of historical data with satellite observations shows that fusion of multi-sensor data is able to reliably extend existing time series of ice cover parameters and provide new information for regions not previously covered by observations.

Seasonal fluctuations of water storage in the Ob River basin from satellite altimetry and SSM/I measurements

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Remote sensing offers new opportunities to monitor and better understand hydrological cycle of major river basins. Satellite radar altimetry is currently used to monitor the water level of large lakes, rivers, floodplains and wetlands, while satellite imagery (microwave and visible/infrared) can delineate flood extent over large river basins. Various studies demonstrate the possibility to combine observations from radar altimeters and satellite imagery to determine spatio-temporal variations of water volume over inundated areas located in large river basins. We apply a similar method to estimate surface water volume variations over the Ob river basin for twelve years of Topex/Poseidon, ERS-2 and ENVISAT altimeters and Special Sensor Microwave/Imager (SSM/I) data. These results are then compared to discharge measurements of the Ob river, snow depth estimated by global hydrology models (LaD, WGHM, ORCHIDEE, GLDAS) and derived from SSM/I data.

Cross-comparisons of radar and laser altimetry, GPS measurements and hydrological modelling for the slope determination of the Rio Negro and Rio Branco

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River morphology, which is both a control and consequence of fluvial processes, has received growing recent interest, for the prediction of flood wave propagation, sediment transport, or empirical estimates of discharge. Hydraulic slope is one of the parameter generally used and it is perhaps the most difficult to measure in the field. We present estimations of river slopes in the Negro drainage basin (Amazon basin) from different data sources: radar altimetry from Topex/Poseidon and ENVISAT RA-2, laser altimetry from ICESat, GPS measurements campaigns, leveled in-situ gauges and results from hydrological modeling.

Inundated wetlands and floods dynamics from remote sensing: the use of the Topex-Poseidon dual-frequency radar altimeter and its application over the Boreal Regions.

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Monitoring wetland and flood dynamics and their climate-sensitive processes is crucial to better understand their influence on future climate through their role in the global carbon cycle, as well as their role in the prediction of inter-annual and longer-term climate variations or their role in

local or regional hydrological studies. In that context, satellite observations provide a unique means of monitoring wetlands and their dynamics at global and regional scales over long time periods. Initially launched to operate over the ocean satellite radar altimeter exhibited soon a high potential for the study of continental surfaces, especially to accurately estimate the topography of ice-covered regions such as Antarctica or Greenland or to monitor large continental water surfaces and measure their stage elevation for hydrological applications. Recently, the altimetric response was investigated over land surfaces using dual-frequency backscattering coefficients from the French-American Topex-Poseidon satellite or the new ESA ENVISAT satellite, demonstrating new capabilities to characterize and monitor vegetated areas, deserts, semi-arid, or boreal regions at global scale. The Topex-Poseidon altimeter was also successfully used to retrieve snow depth evolution over the Northern Great Plains. This study presents a first attempt to quantify extend and seasonality of northern wetlands using radar altimeter satellite observations, as a new complementary technique to the ones previously developed for that purpose, such as passive microwave observations. We propose to analyze the altimetric observations from the CNES/NASA Topex-Poseidon (T-P) launched in August 1992. The NASA Radar Altimeter (NRA) on board this satellite is the first dual-frequency active microwave sensor, with nadir measurements at Ku (13.6 GHz) and C (5.4 GHz) bands. The sensibility of Topex-Poseidon dual-frequency radar altimeter to detect inundation is firstly investigated including a comparison of passive and active microwave satellite measurements along with land surfaces in-situ database. The C band backscatter altimeter signal is clearly in accordance with passive microwave emissivity observations above wetlands and is thus more able to detect small local flooded areas. Because of the nadir looking angle, the radar altimeter shows also more capability to detect wetlands than C band scatterometer. Monthly flooded areas are then calculated by estimating pixel fractional coverage of flooding using the altimeter C band backscatter magnitude and a linear model with dual-frequency altimeter backscatters difference C-Ku to account for vegetation cover. Because of Topex-Poseidon satellite cover, the results are given for northern hemisphere wetlands from 40° to 66° of latitude that represent more than 30% of world's global inundated surfaces during the summer period. Radar altimetry estimations, comprising natural wetlands and river/lakes, indicate a maximum inundated area for July 1993 and 1994 with 1.86*10⁶ km² to be compared with 1.31*10⁶ km² from passive microwave technique and ~2.10*10⁶ km² from independent dataset. Wetlands seasonal variability from altimeter or passive microwave technique is clearly in accordance. These promising will soon be confirm with the Topex-Poseidon 10-year span dataset and the use of the ENVISAT dual-frequency radar altimeter which better spatial cover will allow to survey world's global inundated surfaces.

Improvement of the Topex/Poseidon altimetric data processing for hydrological purposes (CASH Project)

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Satellite altimetry technique and products are primarily designed for open ocean studies. The same technique has been progressively applied to inner seas, lakes and large rivers. Early results have highlighted the potential contribution of this technique to the monitoring of continental water bodies levels, and the gains than can be expected in measurement quality (accuracy, frequency) through better definition of ground track location, improved algorithms for waveform retracking, improved methods to quantify tropospheric propagation delays. Actually, over non-ocean surfaces (wet or dry), the accuracy of the altimetric measurements is degraded to several cm or tens of cm, mainly because of the heterogeneity of the reflecting surface (a mix of water and emerged lands). Another important source of error lies in the propagation of the signal through the atmosphere. This study focuses on these 2 issues.

In the framework of the CASH project (Contribution de l'Altimétrie Satellitaire à l'Hydrologie) founded by the French Ministry of Research, it has been decided to initiate a global re-processing of the Topex/Poseidon data (1992-2005) that is dedicated to the constitution of an hydrology-oriented altimetric data base.

Over the open ocean, only water is present within the radar footprint. Over continental water bodies, emerged lands within the footprint generate complex radar echoes (waveforms) over which the height retrieval process is not as accurate as it is for oceanic echoes. As a first step, we applied to the Topex waveforms the same 4 retracking algorithms that are routinely applied to the ENVISAT measurements. Consequently, Topex/Poseidon products become coherent with ENVISAT Geophysical Data Records. These retracking algorithms are known as "Ocean", "Ice1", "Ice2" and "SeaIce" in the ENVISAT processing. Although not specifically dedicated to the large variety of waveforms that can be found over continental waters and therefore not fully optimized for hydrological purposes, these algorithms nevertheless provide, over water bodies, promising results in terms of accuracy improvement and recovering of data that are missing in the Topex/Poseidon MGDRs. Several examples showing the resulting gain are presented.

Simultaneously, we investigated the correction of the propagation delay induced by the water vapour within the troposphere. This correction can amount 50 cm, with an

annual cycle amplitude of up to 20 cm, and is usually computed over oceans with simultaneous radiometric measurements. Such measurements generally default over non-ocean surfaces and may be superseded by a correction computed from meteorological model outputs (usually the ECMWF model). We first show that the model correction included in the widespread altimetric data sets is not reliable over non-ocean areas because the changes in the altitude of the reflecting surface (and thus the thickness of the atmosphere column) are not taken into account. Then, we demonstrate that a computation based on the use of a gridded Digital Elevation Model is not adequate. We finally propose a new method where the altitude of the reflecting surface is deduced from the altimetric measurement itself. This method is applied (with the NCEP Reanalysis model outputs) and is evaluated via comparisons with radiometric measurements acquired over a selection of large inland water bodies.

Assessment and Correction of the Global 3 arc-second SRTM DEM Using Multi-mission Radar Altimetry

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The release of the Shuttle Repeat Topographic Mission (SRTM) C-band data set provides a near-global 3 arc-second resolution DEM. Global scale validation of these data is problematic since available ground truth are patchy and of variable quality. Using a unique database of heights derived from ERS-1, ERS-2, ENVISAT, Topex and Jason-1 radar altimeters, including over 54 million height measurements obtained from the ERS-1 Geodetic Mission, a global validation of the SRTM data set has been performed. The results show that these data sets are generally in very good agreement over much of the Earth's land surface. However, geographically correlated patterns of differences between the two data sets have been observed. Many of these anomalies are caused by differences in the acquisition technique of the instruments, for example the SRTM is sensitive to vegetation where as the Radar Altimeter is not.

This paper presents the results of the continued work on the assessment of the differences between these two data sets, and the use of the altimeter data where appropriate to correct the SRTM derived heights. Of particular note is the ability of the RA-2 to maintain lock over extreme terrain and thus allow assessment and correction of SRTM data obtained over mountainous topography. The results demonstrate the effectiveness of the altimeter data in assessment, validation and error-correction of space derived DEM data sets.

The Envisat Burst Mode Echoes– a new look from satellite radar altimetry

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Over the past two decades, the series of radar altimeter missions flown has gathered a huge amount of useful data over the earth's land surfaces.

Enhancements to the instruments for acquisition of non-ocean data have greatly increased the capability of altimeters to make useful measurements over rough terrain, and advances in retracking the complex echoes returned from land surfaces has allowed height measurements to be made even over mountainous topography. However, the onboard averaging applied to the individual echoes prior to telemetering these data to ground has severely restricted the measurement of high frequency changes in the underlying surface, even when only a part of the returned signal is retracked to improve the spatial resolution.

The ability of the Envisat RA-2 to store and transmit the individual echoes has given a first glimpse into the full potential of satellite radar altimetry over land. This paper presents results from retracking these unique echoes. The unexpectedly low noise in these data allows the echoes to be utilised with minimal averaging, whilst the ability of the RA-2 to maintain lock even over mountainous terrain by dynamically adapting the range window is generating a huge database of burst echoes over all terrain types. This allows, for the first time, a full investigation into the information which is gathered by a radar altimeter over land, and illustrates the huge potential of these instruments to measure and monitor land surface processes.

Altimetric data in hydrological models

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Hydrodynamical models are aimed to describe the flow propagation in river channels. Such models are highly demanding in data input, including water height, channel geometry (cross-sections and bed slope). In large basin such as the Amazon, the hydrodynamical modelling was coming up against such a need of data. Above all the lack of gauge levelling and the scarcity (relatively to the size of the basin) of the gauging stations have precluded until now the modelling in most of the network contributors. In the Amazon, another drawback is the un-channelized flow, derived in numerous and large inundation plains.

Satellite altimetry data can solve part of these problems. First, for gauge levelling, we present some examples of stations that we levelled using various satellite data, T/P, ENVISAT and ICESat. We discuss the accuracy of the method, by comparison with GPS levelling. Second, we used the slope derived from these levelling to run a model based on diffusion-cum-cinematic wave propagation (Muskingum-Cunge formulation). Third, we have combined the modelled discharge with altimetric heights to produce rating curves at satellite-river crossings.

Concerning the inundation plains, altimetric data are not, as are the gauging stations, limited to channelized rivers. Thus, it is possible, by combining the water elevation variations from various radar altimetric data sources with the inundation spatial extension mapping from radar images as the JERS mosaic, to quantify the volume variation of water storage in the inundation area. These estimation are very useful for hydrodynamical modelling of the exchanges between the river channel and the floodplain.

Analysis of Radar Altimeter Waveform Retracking Algorithms for Geodynamics Studies

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This study tests the potential use of NASA's radar altimeter TOPEX/POSEIDON to potentially detect solid Earth geodynamic deformation signals such as the Glacial Isostatic Adjustment (GIA). Our study region covers a relatively flat land area where the maximum solid Earth crustal uplift of ~1 cm/yr due primarily to the GIA occurs near the Hudson Bay. We choose to conduct collinear analysis along a single TOPEX track using data from TOPEX's 10-day repeat cycles over the study region. A mean ground track has been generated using TerrainBase global DEM. Even though TOPEX can maintain lock over moderately smooth land surface, the return waveforms over different surfaces/conditions, including ice, land and vegetations are complicated and therefore the accuracy of topographic recovery will typically be at the meter level. To obtain more precise radar altimeter measurements over land, we first categorized each waveform according to its shape and number of ramps and interpreted the corresponding distinct surface features, and then applied several waveform retracking algorithms to assess their respective appropriateness. These algorithms include the NASA V4, the surface/volume scattering model, the ESA/UCL COG, the threshold method, the cross-correlation technique and ESA's ICE2 algorithms. We have generated a mean height profile using each of the available retracking algorithms, and then calculated deviations to determine which methods agree with each other. We found most of the returned waveforms are more or less specular and contain a pre-leading edge bump which is likely due to the topography. There is no way a model-based retracker such as S/V model can account for this problem since the algorithm assumes a flat surface. Since NASA V4 fits a waveform to a function whose variables are estimated to achieve the best fit, it performed well on these topographically noisy waveforms and waveforms with fast decaying trailing edge. Unlike the 10% threshold algorithm which has been used to calculate ice-sheet height change at cross-over points, a 20% threshold level has been proven to be adequate since it reduces the effect of this pre-leading edge noise. Another model-independent cross-correlation technique calculates retracking differences from the non-zero-lag of the correlation function between a pair of waveforms. Optimal cross-correlation coefficient and spread value have been determined to reject dissimilar waveforms. The advantage of this algorithm is that it can work for any pair of similar waveforms. After retracking each radar altimeter measurements, we chose a relatively flat area to perform spatial averaging and 3-sigma editing to reduce the effect of data outage. Finally, we will present preliminary results using the retracked TOPEX waveform data for potentially

measuring the deformation near the Hudson Bay due primarily to the Glacial Isostatic Adjustment.

Application of Radar Altimetry in Detecting the Changes of Wetlands and Lakes in the Prairie Pothole Region

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The influence of climate change and climate variability in the Prairie Pothole region (PPR) of North America has emerged as a problem of particular concern in recent years, given two scale of the region, satellite remote sensing has emerged as a critical technology for the investigation of hydrology, ecology, geology and climatology. The severe drought in 1988-92 led to tremendous shrinkage of the lakes and wetlands. This extreme was followed by the most significant wet period of the century in the middle to late 1990s. Although imagery satellite sensors have been widely applied in hydrological studies, the large-scale space/time syntheses were prohibited by cloud coverage and limited availability of the repeatable scenes. Fortunately, Radar altimetry, e.g., NASA/CNES TOPEX/POSEIDON (T/P) mission, with relatively short measurement cycles (weeks), a diminished atmospheric influence (at Ku-band radar frequency) and a longer than 10 years observational span (1992 to present), provides an excellent tool to assess hydrological changes, e.g., the extents and their changes of potholes, in the PPR. New techniques are developed using backscatter data from radar waveforms to develop a practical classification approach to examine how the numbers and general size of pothole lakes and wetlands change, representing the water body extent changes, on a seasonal and interannual basis. Imagery data from Landsat and Terra/ASTER satellite sensors are processed to evaluate the water abundance on ground surface and the results are also used to validate radar altimetry observations. The results indicated that the classification scheme developed in our study is capable of quantifying the water proportion of land surface by the analysis of the backscattering coefficient and waveform data from T/P, towards studying of hydrological processes in the PPR of North America. Based on statistic analysis, trend and seasonality of Topex data over our testing sites are significantly correlated to simultaneous hydrological variation of wetlands.

Using Altimetry Waveform Data and Ancillary Information from SRTM and LANDSAT to retrieve River Characteristics

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Spaceborne radar altimeters are shown to have the potential for monitoring the height of large rivers with accuracies of approximately 1 m. However, the need for a better height accuracy and the observations of smaller continental basins have led to studies on how to improve and extend the use of nadir altimeter data. Conventional retracking techniques over land are limited to the examination of altimeter waveforms on a case by case basis. Due to the arbitrary geometry which may be present at altimeter river crossings, this approach may be limited to large rivers, which approximate ocean crossings. To overcome this limitation, we introduce a waveform fitting method which uses the entire set of waveforms associated with a water crossing, rather than individual waveforms. By using ancillary data, such as a digital elevation model (obtained from SRTM) and classification maps (obtained from Landsat), it is possible to recast the retracking problems as a maximum likelihood estimation problem. Theoretical power returns based on the a priori knowledge of the observed scenes are generated resulting in a parametric library of waveform histories, which is then used to constrain the estimation. For demonstration, we concentrate on the river Meuse in Northern Western Europe. This river has important social impact, since it has flooded in the past and better real time predictions of its changing stage may improve flood forecasting skill. Furthermore, it presents a challenge to conventional nadir altimeter waveform retracking. We will present both theoretical performance results and demonstrate the feasibility based on real altimeter data. Keywords: altimetry, waveform, hydrology, Europe

The WatER Mission in Europe: how can it help science?

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The Water Elevation Recovery (WatER) mission, which was recently submitted by an international team to the Earth Explorer Core Mission of ESA, is dedicated to the determination of surface water extent, height, and slope. The WatER instrument consists of a Ka band Radar Interferometer (KaRIN) coupled with a nadir Ka altimeter (AltiKa) for filling the nadir gap and for risk reduction in the KaRIN calibration. There is a strong need to determine the value added science that can be attained from various spatial and temporal samplings of surface water storage and movement. A Virtual Mission has been implemented for a while and helps to answer this question. Recent large floods that occurred in 1995 on the river Meuse in Northern Western Europe have led to heightened interest in flood forecasting systems in this region. The VM concept has been applied to this river. Simulated WatER data are brought to a global forecasting model involving meteorological, landuse and DEM data. The validity of the forecasts and their improvement are then examined in specific cases. Keywords: interferometry, hydrology, forecast, Europe

Session 5.1:

Building the 15-Year Altimetric Record/Calibration and validation

Oceanic Water Vapor Derived from TOPEX Microwave Radiometer: Climatology and Variability

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Using the newly available TOPEX microwave radiometer (TMR) data spanning 1993 through 2003, a 11-year climatology of oceanic water vapor (OWV) is constructed, of which the distribution and variation at various spatial/temporal scales are investigated. The new dataset confirms most of the well-known OWV features, and yields a number of interesting findings, due to its high quality, long duration, and unique orbit.

1) The TMR-derived climatology compares well, in both overall pattern and general statistics, with similar results based on radiosondes and other satellites. Climatological comparisons with sea surface temperature and oceanic precipitation suggest that the western Pacific warm pool is “mirrored” in the atmosphere as a “wet pool”, whereas the meteorological equator is reflected in OWV as a trans-ocean equatorial wet belt.

2) It is found that El Niño (La Niña) events are accompanied by a significant increase (decrease) in the amount of OWV between 10°S and 10°N with a somewhat unexpected southern hemisphere dominance. This is particularly evident during the 1997-98 El Niño when the interannual variability of OWV reaches a record high. Composite maps of annual OWV anomalies disclose a dipole-like pattern in the western equatorial Pacific with a phase opposition between El Niño and La Niña years.

3) The annual amplitude of OWV is characterized by six cross-continent wet belts located largely in the subtropics of both hemispheres. The phase patterns of the annual and semiannual variations are hemispherically divided, and climatologically correlated, respectively. North (south) of the ITCZ, a majority of the oceanic areas have their water vapor maximum in August (February). Early peaks in July are found over a few continental shelf regions of the Northern Hemisphere (NH), while late peaks in March in the

tropical oceans of the Southern Hemisphere (SH).

4) Our results suggest that El Niños (La Niñas) can weaken (strengthen) the seasonality of OWV by decreasing (increasing) the annual amplitude. The change of amplitude is usually slight but significant, especially for the six most dynamic seasonal belts across the major continents at midlatitudes. The ENSO impact on the annual phase of OWV is seen to be highly systematic and geographically correlated. The most striking feature is a large-scale advancing/delay of about 10 days for the midlatitude oceans of the northern hemisphere in reaching their summer maxima during the El Niño/La Niña years.

5) In addition, an alternative scheme for estimating the mean position of the ITCZ based on the annual phase map of OWV is proposed. The so-obtained ITCZ climatology agrees with existing results in that the mean position meanders from 2°S to 8°N oceanwide, and stays constantly north of the equator over the Atlantic and eastern Pacific, but differs in that it favors 4°N in latitude rather than 6°N as previously concluded.

In view of these encouraging results, further exploration of present and future “altimeter-borne” radiometer data will no doubt lead to an improved and complementary understanding of the OWV system in many aspects.

The ENVISAT/MWR : Improvements in the Processing, Calibration/validation and Long-term Survey of the Products.

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In order to correct the altimeter range for water vapor path delay over ocean, a nadir-looking microwave radiometer has been embarked on the spacecraft. As any error in the wet tropospheric correction directly impacts the sea level

determination, the constraints on the quality and stability of the radiometer products are particularly stringent. The uncertainty on the wet tropospheric correction is today around 1 cm rms (Ruf et al, 1994, Eymard et al, 1996) but remains a significant contribution in the global uncertainty on the sea level estimation (around 4 cm rms, Fu and Cazenave, 2001). In this paper, we present the improvements performed in 1) the processing, 2) the retrieval algorithms, 3) the calibration/validation and 4) the long-term survey of the ENVISAT Microwave Radiometer with respect to other altimetry missions (ERS2, TOPEX, Jason), to minimize this error.

1) The particular position of the microwave radiometer on the ENVISAT platform, induces strong contamination of the main measurement by the side lobes. An algorithm dedicated to the correction of this contamination has been proposed and represents actually an improvement with respect to the classical side lobe correction algorithm implemented in the processing of other altimetry missions.

2) Retrieval algorithms for wet tropospheric correction are developed using a database of geophysical parameters (from ECMWF fields) and corresponding simulated brightness temperatures by a radiative transfer model. This database is used to determine statistically the relation between the brightness temperatures and the wet tropospheric correction. The quality of the retrieval algorithm depends therefore on the representativity of the database, the accuracy of the radiative transfer model used for the simulations, and finally on the quality of the inversion model. The development of the retrieval algorithms for the ENVISAT/MWR follows the methodology used for the ERS2 mission, but has benefit from a higher quality meteorological model, a more accurate radiative transfer model and particularly of neural network techniques to take into account the non-linearities in the relation between the brightness temperatures and the wet tropospheric correction.

3) After launch, the major difficulty lies in performing the in-flight calibration of the microwave radiometer, because there is no natural blackbody target, which could help to control the measured brightness temperatures. The method we used to calibrate the ENVISAT/MWR is therefore a combination of comparison with its predecessor ERS2/MWR flying on the same orbit with a time lag of about half an hour, and simulations over sea using ECMWF fields and a radiative transfer model. The use of the same tools (ECMWF analyses, radiative transfer model) to formulate the retrieval algorithm and to perform the in-flight calibration ensures the consistency in the processing to provide at the end a high quality product.

4) The sea level rise is estimated at the mm/year level, so an accurate survey in time is necessary to provide stable products. The methods developed these last years (survey over hot and cold continental targets, survey of the coldest ocean brightness temperatures, comparison with other instruments) allows the detection and the evaluation of weak instrumental drifts, and therefore to propose suitable

corrections to users.

Envisat Altimetry Mission Status

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The Envisat satellite was launched on March 1, 2002. It carries on-board a new generation Radar Altimeter (RA-2), a Microwave Radiometer (MWR) and a DORIS receiver. The RA-2 instrument provides improved measurement performances and many new capabilities, which benefits the science and application community. With almost two decades of altimetric measurements acquired by ESA, long-term evolution of parameters playing a key role in climate change can now be addressed. This requires homogeneous data sets inter-calibrated at the millimetre level, supported by an accurate and permanent monitoring of the sensor performances and product quality. Over the last ~4 years of operations, the Altimetry system (RA-2, MWR, DORIS) has been nominally operational, providing the user community with an altimetric data set of highly valuable quality. The status of the Altimetry mission in terms of sensors performances, algorithm and product evolutions shall be addressed.

Cross-calibration of multi-mission altimeter and TRMM PR sigma0 over natural land targets

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In order to utilise fully the record of sigma0 measurements from the series of altimeter missions flown over the past 15 years, the data have to be cross-calibrated to remove individual biases, and checked for measurement stability over time. The technique generally employed is to cross-calibrate over the earth's oceans, which requires both spatially and temporally coincident measurements. An alternative approach is to utilise the earth's land surfaces. Prior work has already shown that natural land calibration sites provide a temporally stable region for the monitoring of altimeter sigma0 over the mission lifetime, and for cross calibration between instruments.

Using a series of natural land targets previously identified as suitable calibration zones for ERS-1 and ERS-2, precise calibration models have been derived by analysing the

waveform data using a rule-based expert system. This work has now been extended to permit a full analysis of multi-mission sigma0 including data from Envisat, Topex and Jason-1.

This paper presents the results from analysis of multi-mission sigma0 over both primary and secondary calibration zones. The work includes an analysis of the behaviour of TOPEX sigma0 over the mission lifetime, made possible by the inclusion of Jason-1 data in the calibration models.

In addition to measurement and monitoring of nadir-pointing altimeter sigma0, the application of this technique to other instruments is illustrated by the inclusion of sigma0 data from the Tropical Rainfall Monitoring Mission Precipitation Radar. The further extension of this technique to multi-frequency sigma0 is discussed, including the development of detailed models at a range of frequencies. One goal of this work is to enable calibration and monitoring of instruments such as the forthcoming EarthCare Cloud Profiling Radar over natural land targets.

RA-2 Bias Determination Using a Transponder

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The usual technique of the radar altimeter range calibration is to compare the altimeter-observed sea surface height with the accurate ground truth referred to as in situ data sets, observed independently by tide gauges and GPS buoys.

The use of a transponder is a different and convenient technique to determine the altimeter bias. A transponder is a device that receives the signal from the satellite, amplifies it and re-sends it back. In contrast to the ocean surface, a transponder represents a stable and very precise reflective reference point (few millimeters in height), which allows a very precise determination of the vertical distance between the satellite and the transponder. The accuracy of such determined ranges depends on the ability to estimate the path delays caused by the atmosphere, the precision of the orbit and the GPS height positioning of the transponder.

When deployed within the footprint of the altimeter and if the altimeter range window set to the estimated range, the transponder will appear in the data with a significant waveform power. Also, the corresponding waveforms differ both in power and shape from the other waveforms caused by natural targets. By means of transponder signature

analysis, the time of the closest approach of the satellite to the transponder is determined and the range is hence calculated and further used to determine the altimeter bias.

Corsica: an experiment for long-term altimeter calibration and sea level monitoring

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The Corsica site, which includes Ajaccio-Aspretto site, Senetosa Cape site, and Capraia (Italy) in the western Mediterranean area has been chosen to permit the absolute calibration of radar altimeters. Thanks to the French Transportable Laser Ranging System (FTLRS) for accurate orbit determination, and to various geodetic measurements of the local sea level and mean sea level, the objective is to measure the altimeter biases and their drifts.

The expected outputs of this on site verification experiment are dedicated obviously to the determination of the calibration bias of TOPEX/Poseidon and Jason-1 but has been extended to other radar altimeters (ERS, EnviSat, GFO). On the other hand, it is also an opportunity to contribute to the orbit tracking of oceanographic and geodetic satellites and to the analysis of the different error sources, which affect altimetry. In the field of positioning, we expect to contribute also to the decorrelation between the possible vertical displacements of our site (Earth crust) and the Mediterranean mean sea level.

The double geodetic site in Corsica (Aspretto, near Ajaccio and Senetosa Cape 40 km south under the Jason-T/P ground track N° 85) has been used to calibrate the TOPEX/Poseidon altimeters from 1998, and the Jason-1 ones since the beginning of the mission. Permanent and semi-permanent geodetic equipments are used to monitor these calibrations. Concerning the Aspretto site, a permanent GPS station and an automatic tide gauge have been installed since 1999 (close to an EnviSat ground track). Two dedicated tracking campaigns of the French Transportable Laser Ranging System have been realized in 2002 and 2005.

At Senetosa cape, permanent geodetic installations have been installed since 1998 and different campaigns have been conducted in view of Jason-1 mission. Four tide gauges are

installed at the Senetosa Cape and linked to ITRF using GPS and leveling. In parallel, since 2000, a GPS buoy is deployed during overflights at Senetosa (10 km off-shore). Besides, two GPS campaigns (1998 and 1999) have been performed to measure the marine geoid slope from the coast to 20 km off Senetosa cape - in this area the geoid slope can reach 6 cm/km. Moreover, since 2003, a permanent GPS has been installed to monitor possible vertical displacements of our site. In addition, using a local weather station, we derived the wet tropospheric path delay from GPS measurements which are compared to the Jason Microwave Radiometer ones at the overflight times.

The extension of this calibration experiment includes now Capraia island where a dedicated GPS campaign has been realized in 2004 to measure the geoid slopes under Jason-1, EnviSat and GFO tracks around the island. In a near future (October 2005), a similar campaign will be realized for the Envisat ground track close to Ajaccio.

Our semi-permanent experiment is planned to last over several years in order to detect any drift in the space borne instruments.

GPS-equipped buoys – Sea Level Measurements with cm-accuracy

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Various analyses of radar altimetry missions (RA) have shown that performance degradation of the satellite range measurements can result in an apparent sea level change. Comparisons of RA with in situ measurements of the instantaneous sea level at Harvest Oil Platform have been used to monitor the absolute sea level measurements of T/P, but not for other missions.

As shown for ERS past RA missions and cal/val-campaigns, a GPS-equipped buoy, anchored beneath a sub-track, can be used as a height reference for monitoring the stability and long-term behavior. Since GPS-derived coordinates are ITRF-referenced, an absolute calibration is possible.

In May 2002 a ruggedized toroid GPS-buoy was deployed in the North Sea in the context of a large German sea level monitoring project. After an initial phase, the second deployment was made in 2004. Currently a new system is being developed, integrating the past technical experience.

A close intersection of ERS-2/ENVISAT, TOPEX/Poseidon, Jason-1 and a GFO sub-track near the German coast gives

the unique possibility to monitor all active RA missions. The lifetime of the new buoy is expected to be several years; therefore, a long-term calibration, drift monitoring and inter-calibration of different missions will be possible. In addition, the buoy is equipped with supplementary sensors, like a dynamic motion sensor and meteorological devices, allowing a broader use for calibration, e.g. of wind speed or significant wave heights.

Results of the buoy measurements will be shown.

Ocean-bottom pressure measurements for radar altimetry calibration

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GFZ is operating several bottom-mounted pressure gauges and a wave tide recorder in the North Sea near the German coast. They are closely located to an intersection of ERS-2/ENVISAT, TOPEX/Poseidon, Jason-1 and a GFO sub-track, giving the unique possibility to directly compare tidal information with all active RA missions.

While the gauge measurements give only relative values, corrections for air pressure changes using a nearby surface platform give direct relative sea surface heights. With a sampling rate of 10 minutes resp. 30 minutes, the instantaneous sea surface height (iSSH) for each radar altimetry satellite track can be interpolated with high accuracy. Additionally the wave tide recorder gives information about the significant wave height.

In order to achieve a height-stable tidal record, the relative depth stability of each tide gauge sensor can be achieved by the intercomparison between the individual sensors. This allows monitoring the stability of the RA missions with a sufficient accuracy.

The results of the comparison between the RA measurements and the tide gauges will be shown.

The IGS Tide Gauge Benchmark Monitoring Project

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Sea level is a very sensitive parameter to natural and human-driven climate related changes. For more than a century tide gauges (TGs) have been the most important measuring devices for the sea level. Today radar altimetry (RA) gives highly precise global measurements of the actual sea level and sea level changes. However, TG measurements remain a valuable tool, e.g. as a time series by itself or as a reference data set for RA monitoring.

One limiting factor for using TGs is the globally uneven distribution of TG measurements and the stability of the TG benchmark (TGBM). Both are accuracy-degrading for sea level studies. For RA calibration this fact will map in a global uncertainty and geographically correlated errors, especially in the long-term and for older missions.

The International GPS Service (IGS) plays a significant role in promoting, establishing and the densification of a global reference system by GPS. Moreover, coordinates published and distributed by the IGS are used in numerous scientific applications, ranging from plate tectonic studies to atmospheric sounding. In contrast, since the beginning of the GPS era several studies have revealed the uncertainty in the GPS height component. Especially when studying sea level changes, where the GPS height of the benchmark is used for defining an absolute sea level datum, problems occur when correcting the time series for height changes of the TGBM.

To overcome this problem and to demonstrate IGS's capability to provide products also for the sea level research, in 2001 the IGS Tide Gauge Benchmark Monitoring Pilot Project (TIGA-PP) was initiated. The primary product of the service will be time series of coordinates for analyzing vertical motions of TGBMs. Different Analysis Centers are providing weekly solutions for selected GPS stations near TGs on a continuous basis. Currently efforts are being made to establish a combination center at GFZ in order to provide a consistent data set of height time series for further analysis and combination with tide gauge records.

For up-to-date information about TIGA see the WEB page at <http://op.gfz-potsdam.de/tiga>.

Altimeter Calibration Campaigns at Ibiza Island and Cape of Begur (Spain)

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Topex Side-B altimeter experiences have been developed at the Cape of Begur area in 1999, 2000 and for Jason-1 in 2002 using wave rider GPS buoys. M-GDR products (in 1999 and 2000) and I-GDR products (in 2002) have been used for the comparison between the GPS derived sea surface (computed from the buoys) and the respective altimeter measurements. The kinematic solution (differential kinematic positioning) for the buoy placed underneath the satellite ground track (187) has used precise GPS orbits and the estimates of the wet zenith tropospheric delay computed at a fiducial GPS station placed in the coast. Results of the point calibrations are in agreement with the official values obtained in single point experiments with buoys, which range several centimeters. For the Topex Side-B single calibration, the range bias was estimated in +6.5 cm with 32.1 cm of rms and + 3.7 cm with 32.6 cm of rms in 1999 (Selective availability still on) and in +3.43 cm with 7.9 cm of rms in 2000, and for Jason-1 in +10.52 cm with 10.52 cm of rms in 2002.

L'Estartit float tide gauge has been used in all three campaigns. Description of the long-term time series of sea level records and of the actual activities related to the installation of a high-quality geodetic GPS and a new radar tide gauge at L'Estartit location to become a CGPS Reference Station will be presented.

A Spanish campaign, with French support, (including the IBIZA2003 Team) was conducted on June 10-16, 2003. The main objective has been to map with a new designed, builded and calibrated GPS catamaran, the local marine geoid gradient in three areas around Ibiza island under the ascending (187) and descending (248) Jason-1 ground tracks

in order to allow a better extrapolation of the open-ocean altimetric data to on-shore tide gauge locations.

Five GPS reference stations were deployed on Ibiza island and two tide gauges at Ibiza (ESEAS) and San Antonio harbours were used. The geodetic activities (e.g., GPS, levelling) have permitted to build a very accurate (few mm) local network linked to the European one, with a reference frame compatible with ITRF2000.

It is presented the first results on Jason-1 altimeter calibration using the marine geoid derived from the data collected during the Ibiza 2003 campaign. The Jason-1 altimeter bias was estimated to be 120 ± 5 mm. They agree relatively well with results obtained at Corsica, Harvest and Bass Strait calibration permanent sites. The main objective has been to test the value of Ibiza island as a permanent calibration site in the Mediterranean Sea complementary to the Corsica site. It is expected in the new campaigns to include ENVISAT ground tracks

These campaigns have been supported by the Spanish Government as Space Research R+D+I projects, CICYT ref: ESP97-1816-CO4-03 and ESP2001-4534-PE.

ESA's new range of radar altimeters for the extraction of geophysical parameters from land, sea ice and ocean surfaces

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Despite the loss of CryoSat, ESA's first Earth opportunity mission, during its launch sequence in Oct 2005, ESA have been fortunate enough to have acquired, processed to Level 1b and analysed a significant amount of campaign data from ESA's aircraft borne radar altimeter (ASIRAS) designed to have similar functionality to CryoSat's Synthetic Interferometric Radar Altimeter (SIRAL). This data acquisition took place for the original purpose of validating CryoSat retrievals.

Our initial analyses of the level 1b data have revealed some

very interesting results both over land and sea ice test sites from respective campaigns conducted in the Arctic during the land-ice spring/autumn campaigns of 2004 and for sea-ice in the Bay of Bothnia during March 2005. Since a further ASIRAS campaign in the Arctic is guaranteed for April/May 2006 we look at how this data can be exploited in view of future ESA Earth observation radar altimeter missions. Verification of the ASIRAS data with coincident laser altimeter and in-situ data collected at test sites is also presented.

One of the challenges of European Space Agency's new breed of radar altimeters is that they exploit echo phase in a far more complex manner than previous pulse-width limited counterparts (EnviSat RA-2 and ERS-1/2 RA, for example). We explain how the instrument level 0 data is processed to level 1b and we further describe the necessity to take a new approach to calibration requiring correction for a new range of instrument based phase errors alongside the usual range, gain and instrument filter corrections.

SSALTO/DUACS, 15 years of precise and consistent multi-mission altimetry data

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- Delayed Time Products: A consistent data set from built upon all altimeters:

DUACS is part of the CNES SSALTO multi-mission ground segment. It processes data from all altimeter missions: Jason-1, T/P, ENVISAT, GFO, ERS1/2 and GEOSAT. In 2005 the SSALTO/DUACS system has performed a complete re-analysis of all altimeter data with the state-of-the-art corrections, models and references recommended for the new generation of Jason/ENVISAT GDRs, as well as the best Cal/Val and intercalibration algorithms. It is the first time in altimetry history that a homogeneous and consistent merging of all missions is carried out.

This second generation of DUACS products is composed of global data sets of along track and gridded Sea Level Anomaly, Absolute Dynamic Topography (see Fig. 1), and geostrophic currents, but also of new regional-specific products. The system uses common processing facilities for global and regional applications. It ensures that upgrades are consistently applied on all products to better serve the altimetry user community.

- Near Real Time Activities:

Twice per week, DUACS provides GODAE and climate forecasting centers with directly useable, high quality Near Real Time (NRT) altimeter data. Regional products are delivered on a daily basis to operational projects such as MFSTEP or MERSEA.

NRT altimeter data from SSALTO/DUACS are distributed by AVISO on FTP, Web and through a Live Access Server. The DUACS system also provides a long term monitoring of NRT data it has used, to quickly detect anomalies, drifts and discontinuities in incoming altimeter data. Quality assessment reports are released twice per week.

- Upgrades in 2006:

The ongoing effort to improve the quality of DUACS combined data, and the robustness of the NRT system will be maintained with the analysis and the operational use of opportunistic Cryosat data on ocean, the computation of better global and regional mean profiles (fully compatible with the respective processing), and preliminary studies to take into account real time altimeter data (fast delivery ~ a few hours) into the NRT system.

Cryosat Level 1 Data Calibration with Transponder

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Two different softwares have been developed to calibrate CRYOSAT level 1A and level 1B data respectively with the use of a geolocated transponder. Level 1A data consist of bursts of complex, time domain echoes after internal calibration corrections while level 1B data consist of coherent multilooked echoes after slant range correction. The aim is to check several important level 1 parameters during the CRYOSAT commissioning phase, like range, datation, impulse response, interferometric phase difference, sigma0, etc. The softwares have been tested with simulations of CRYOSAT overflying a transponder in different geometrical and acquisition configurations.

CLIPPERTON campaign on altimetry side: Ocean observation site exploration

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CLIPPERTON campaign on altimeters side: Ocean observation site exploration
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Clipperton Island is a French uninhabited atoll located west of Mexico [10.2 °N; 109.3°W]. It is under wet tropical atmospheric conditions, on cyclones and tropical tempests tracks in Northeast Pacific Ocean. It's a perturbed area both in a meteorology and geophysics view (fault and volcano chain). Ocean circulation is under El Nino influence with Kelvin waves and hot water masses going from East to West. High sea surface level departures have been detected both by altimeters and tide gauges during the Clipperton mission (10 to 25 cm). Clipperton is over flight by 3 satellites -namely JASON, ENVISAT, GFO- that is fruitful in term of multi satellites comparisons. Using tools developed at CNES and LEGOS, we conduct an assessment of this potential new site: We have analysed the data collected in-situ by tide gauges and GPS buoys between 2005/01 and 2005/03 together with radar altimeter measurements in scope of the capability of the site for more consequent calibration campaign and oceanography research. Comparison between tide gauges and altimeters sea level anomalies is a validity test for both measurements. We show that the tide gauge is accurate enough to detect sea level anomalies linked to the local ocean dynamics. Their optimal cross use gives a good way to characterise strong events (ex El Nino, tropical tempest, and tectonic movements) Possibilities offered by this site have been screened keeping two objectives: altimeter calibration and ocean signal studies.

Impact of the geophysical corrections on studies of sea level variation

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Since the launch of ERS-1 in 1991 and Topex/Poseidon (T/P) in 1992, the progress achieved in sensor performance, satellite ephemeris accuracy and modelling of the major geophysical corrections rendered satellite altimeter data an invaluable tool for sea level studies. However, since sea level is a relatively weak signal, sea level variation determined from satellite altimetry is influenced by many factors. Amongst the most important are sensor characteristics and long term stability, the altimeter data processing, the mathematical techniques used to model sea level variation and the length of the altimeter time series.

This study addresses the impact of altimeter data processing on sea level studies, both at global and regional scales, with emphasis on the effects of the major geophysical corrections in the structure of the derived interannual signal and sea level trend.

The work focuses on the analysis of T/P data for a period of over twelve years. For this analysis corrected sea level anomalies with respect to a mean sea surface model have been computed from the MGDRs provided by AVISO using state-of-art models for the geophysical corrections. The effects of various models for the geophysical corrections on the interannual signal and sea level trend, with particular emphasis on the sea state bias (SSB), inverse barometer (IB) and radiometer wet tropospheric correction are analysed. The impact of each correction on the estimation of both global and regional sea level variation is discussed.

The advances in the modelling of the major corrections are reviewed and prospects of future improvements are discussed in view of their influence on sea level change. In spite of the advances in the modelling of these corrections, results show that the effect of applying different models can have an impact on the derived sea level trends of more than 1 mm/year.

The results strike the need for a continuous improvement of the various effects that influence the altimeter measurement and the importance of having follow-on altimeter missions which warrant the continuity of the present altimeter sea level records.

The use of data-quality information for optimal scientific application of altimetric data

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The objective of this paper is to show how the information related to the instrument status and the complex processing chain is fundamental to use in an optimal way the altimetric data. Instruments are designed as a compromise between scientific requirements and technical feasibility. Data processors are designed as a compromise between extraction of maximal information from the instrument and the constraints in processing and dissemination resources. This latter compromise should drive the data quality expected from an instrument. In practice, data quality is variable due to several sources of quality degradation. Optimal application of these data to scientific studies requires knowledge of the data quality. This paper explains important transient error sources that frequently affect data quality. These are related to instrument anomalies and degradations, near-real-time calibration quality variations, and data processor issues. The paper outlines the various sources of information that have been set up to provide the data user with quality information, in particular many dedicated records in the products themselves, and several documentation resources available on line. It also describes methods of applying this information, for example by filtering using specific data fields. For some parameters, error information in product files is not yet adequate, and improved information is available in separate documents. Finally the off-line consolidation of products allows corrections to near-real-time orbital data and the usage of more up-to-date auxiliary informations, and have therefore a significant quality advantage over near-real-time data. This paper addresses the most important differences between the two.

ENVISAT Ra-2 Sigma-0 Absolute Calibration, Methods and Results

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The nadir backscattering coefficient, sigma-0, measured by radar altimeters is being used for wind-speed retrieval over ocean using empirical methods. For this reason only relative calibration has been traditionally performed between the different missions. In the last few years the need aroused to perform an absolute calibration to be used within physically based models.

Two methods have been used to pursue the goal: an active approach implemented by using a transponder has been followed by ESA as part of the Cal/Val activity and instrument long term monitoring (Roca et al., 2002, Féménias et al., 2004). In parallel, during the Commissioning phase, a passive approach has been tested for the first time, which was implemented by setting the RA-2 instrument in a noise listen mode (Pierdicca et al., 2004).

This paper describes the rationale behind the two methods and the results obtained.

Precise orbits of altimetry satellites ERS-1, ERS-2 and TOPEX/Poseidon

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Studies of sea level changes can profit by using orbits of altimetry satellites derived in the same, well defined reference frame for all satellites and using the same, most precise models for satellite perturbations. Precise orbits of altimetry satellites ERS-1, ERS-2 and TOPEX/Poseidon

have been derived in the ITRF2000 reference frame using recent EIGEN-GRACE geopotential, ocean tide and other models. The orbits are based on the use of SLR, PRARE, DORIS and altimetry crossover data for the respective satellites and cover the entire time period from 1991 till 2005. The quality of the orbits is illustrated using the results of single crossover analysis. In particular, the paper shows improvements in the quality of the satellite orbits derived using the recently developed EIGEN-GRACE geopotential models compared to previous orbit determinations.

Review of the use of satellite crossover altimetry

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The majority of older as well as recent gravity field models did not use satellite crossover altimetry (SCA) which does not contain the strong signals of surface gravity. Therefore SCA can be used in principle to test the accuracy of the low degree and order portions of these models provided the SCA data is precise and accurate enough. If these conditions are met a calibration of these models is possible with SCA if their formal covariance matrices are also available. The method was developed and used to test many such models since 1992. We outline the results of such testing, including the identification of model deficiencies, with a focus on those with CHAMP data. We find that current SCA is accurate enough to test all models up to those with CHAMP data. To calibrate GRACE models will require an improvement in the accuracy of the long-term averaged SCA (with better models of media effects) including a recalculation of the altimetric satellite orbits using GRACE geopotentials.

ERS-1 / ERS-2: a long story of altimeter data and improvements

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Since the launch of ERS-1, CLS has been much involved in calibration/validation and cross-calibration activities, including several altimetry data such as ERS-1/2, TOPEX/POSEIDON, and recently Jason-1 and Envisat, all this in the frame of CNES, ESA and IFREMER projects.

The routine work consists in validating the Ocean Products data delivered to users and in monitoring the relevant parameters. This includes cross-calibration analysis of ERS-2 with ERS-1, ERS-1/2 with TOPEX/POSEIDON but also ERS-2 with Envisat. Besides these routine activities, many studies have been performed at CLS to continuously enhance data with new algorithms and corrections. Moreover, improvements proposed by other laboratories were also assessed. From precise cross-calibration studies, a method was developed to enhance the ERS orbit by using simultaneous data from other precise orbit missions. This allowed homogenizing the ERS data with other missions for the objective of building a combined multi-mission altimeter dataset. Other studies consisted in evaluating and validating the impact of retracking on ERS-1 Ocean Products, already undertaken since phases C and G have already been produced and disseminated, and still on-going with other phases of ERS-1 (D,E,F).

With the new generation of altimeters, new instrumental and geophysical corrections have been proposed. Thus it is important to assess the improvement of these new techniques. Among several items, we can note the progress provided by the non parametric Sea State Bias estimation, the neural algorithm used to compute the wet troposphere correction, the combined high frequency atmospheric correction from MOG2D model, the GIM ionosphere correction, the FES2004 and GOT00 tidal models, the CLS01 MSS, and the new generation of Delft orbits. All these improvements contribute to precise and consistent Sea Surface Height measurements along the whole period from ERS-1/2 to Envisat.

Further work is still needed on ERS-1/2 data to provide oceanographers with a long time series as precise as possible, focusing on the homogenization and merging with other missions. Furthermore, significant improvements can also be expected in coastal areas by refining ERS altimeter data processing and enhancement in these areas. This will lead to more precise coastal altimeter mean profiles that are essential for applications and studies using past and present altimeter data.

Envisat ocean altimetry performance assessment: continuity and improvement of the ERS series

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With more than three years of altimetric measurements over ocean Envisat not only ensures the continuity of the observations provided by ERS-1 and ERS-2, but significantly improves the data quality. The quality assessment of these data is routinely performed at the CLS Space Oceanography Division in the frame of the CNES Segment Sol Altimétrie et Orbitographie (SSALTO) and ESA French Processing and Archiving Center (F-PAC) activities. This poster presents the main results in terms of Envisat data quality and performances: verification of data availability and validity, monitoring of the most relevant altimeter (ocean1 retracking) and radiometer parameters, assessment of the Envisat altimeter system performances. Envisat carries a new generation of dual frequency radar altimeter (RA-2) which allows correction of ionosphere effects and a Microwave Radiometer (MWR) for wet troposphere path delay retrieval. From statistical and spectral analysis, it appears that a low amount of ocean data is discarded by conventional editing procedures compared to other missions and that a low level of noise is found on 1Hz data. In addition, the presence of a Doris receiver allows high precision orbit determination, highly improved compared to ERS. Thus the Envisat altimeter mission reaches the high level of accuracy of other precise missions such as T/P and Jason-1. From cross-calibration analysis, also included in this work, the Envisat precise altimeter measurements can be merged with data from other missions in a multi-mission altimeter dataset.

Synthesis of the main Features and Evolutions of ESA and CNES/NASA Radar Altimeters, Ocean Ground Processing and Products

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A global and unbroken coverage of the globe is insured for 15 years by radar altimeters, thanks to a series of ESA and CNES/NASA missions (ERS-1 / 1991, TOPEX-Poseidon / 1992, ERS-2 / 1995, Jason-1 / 2001 and ENVISAT / 2002).

On behalf of ESA, CNES or IFREMER, CLS has been in charge of the definition, the specification and the development of the ground processing of the corresponding ESA and CNES altimeters data (ERS-1/2 altimeters, Poseidon-1/2 and RA2) from level 0/1 up to level 2 products. CLS is also in charge of the maintenance of the operational ground processing of ERS-2 altimeter data (IFREMER/CERSAT-2), of RA2 data (ESA/IPF for the NRT ocean processing, CNES/SSALTO-CMA for the off-line processing), of Poseidon-1 data (CNES/RADALT) and of Poseidon-2 data (CNES/SSALTO-CMA).

Thanks to our experiment in altimetry for 20 years, we propose to present a synthesis of the main features and evolutions of ESA and CNES/NASA radar altimeters, ocean ground processing and products. Instrumental features and on-board processing will be compared (e.g. emitted frequencies, operation modes, tracking method). The main functions of the ground ocean processing will be identified and their major evolutions from a mission to another but also within each mission will be presented and discussed (e.g. ocean retracking algorithm, geophysical corrections, environmental parameters, auxiliary data used). Finally, the various kinds of ocean products will be presented and characterised (e.g. type of product, impact of the processing evolutions on their accuracy).

High standard tide gauge network for scientific studies

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We propose to make a point on our OSTST Jason proposal on the implementation of a "high standard tide gauge network for scientific studies". This proposal aimed to bring together a certain number of tide gauges distributed on different part of the global ocean in order to build a coherent sea level network. From a technical point of view the aim was to build a network of reference for scientific studies. This network exist, it is at the moment constituted of a set of tide gauges located on Islands in Atlantic, Indian, Pacific, Austral ocean and Mediterranean sea. All these sites are administrated by different persons for different scientific purposes. We have proposed to upgrade these sites in order to fulfil our scientific objectives and to maintain this network on a long term base. This poster summarizes the main technical and scientific advances of the OSTST proposal.

The effects of seasonal and atmospherically induced sea level variability in satellite altimeter calibration. Results from the GAVDOS Cal/Val experiment.

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Shallow water processes, bathymetry, topography and sea-surface slopes give rise to differences in sea-surface heights as measured by satellite altimeters in open water and by tide gauges on the coast. These differences may bias the estimation of satellite altimeter errors if one compares directly altimetric and tide-gauge records.

In this work we attempt to reduce such differences by taking into account the seasonal cycle in shallow waters prior to satellite calibration. By subtracting estimated signals in both records at the altimeter and tide-gauge locations, data variability decreases and both measurements are closer to an equipotential surface.

Within the GAVDOS calibration experiment, the Jason-1 absolute altimeter bias has been estimated to be 144.7 ± 15 mm over the cycles 70 to 90. The seasonal differences of sea-surface heights between the GAVDOS tide-gauge site and the area extending a few tens of kilometers South of Gavdos are of the order of 1 cm. These values have been established by hydrodynamic modeling during October 2003-September 2004. In this work, we have found that the absolute bias of Jason-1 and its associated standard error is decreased by about 1 cm when the seasonal cycle is subtracted from both measuring system records.

As the seasonal cycle in the Mediterranean Sea is associated with changes in the steric sea level, we also search for differences that may emerge from atmospheric forcing. This is done by employing a surge model that accounts for the atmospherically driven sea level variability.

Along-track Topex/Poseidon data collected North of Souda Bay in Greece have been compared with the Souda Bay tide-gauge readings before and after reducing the seasonal cycle and the surge. After removing the seasonal cycle from the Souda tide gauge records, the surge model accounts for about 60% of the remaining data variability. The surge model can be applied till 2001, thus the analysis has been restricted to the first ten years of Topex/Poseidon mission.

Absolute calibration of Jason, Topex-Poseidon, GFO and Envisat using GPS buoys on Issykkul lake and Caspian Sea

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The Topex /Poseidon satellite launched in 1992 and the following altimetry mission (Jason, Envisat), has been designed to study the ocean variability. Since few years this technic is also widely used in continental area: lakes, rivers and wetland. Due to the high precision of the current altimeters, and thanks to progress in orbitography, altimetry became a fundamental tool to study ocean and continental water bodies. It however highlighted the need of knowledge of the instrumental bias. Numerous calibration site in the ocean field (Harvest offshore platform in California,

Corsica, Bass strait in Australia) has been used for this purpose. Recently a calibration site on Lake Erie (USA) has also been used to evaluate altimeter bias of Topex Poseidon and Jason over continental area. 2 new sites of calibration are presented. One in the region of Baku in Azerbaidjan (Caspian Sea), the second one over the lake Issykkul in Kirgistan. These sites have been chosen because they present some interesting characteristics: the dynamic variability is low, those lakes are fully covered by all current altimetry satellites (Jason, Topex Poseidon, GFO and Envisat), in-situ water level are available in the vicinity of the calibration site, they allow to densify in continental area the pool of existing calibration site. 2 campaign with GPS receivers have been conducted on Issykkul lake (2004 and 2005), with receivers installed on a boat, and receivers on the shore. One campaign was conducted in 2005 on Caspian Sea. Cruise with GPS data along the ground track of each satellite were conducted. They allow to estimate absolute bias of each altimeter, and relative bias between them. Cruise also allowed to map the profil of the mean lake surface which is very steep in the case of ther Issykkul lake.

Comparison between sea height GPS measurements and satellite altimetry data in the New Hebrides Subduction Zone.

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We conducted an experiment of sea surface elevation measurement in the New Hebrides subduction zone using on-board kinematic GPS recordings and Topex/Poseidon and Jason satellite altimetry data. This area is of particular interest because of strong crustal and mantle heterogeneities due to intense tectonic activity that create huge local geoid variations. Several sea surface surveys were conducted around Santo Island, on the West (Sabine and Wusi banks), South (Malo to Mallicolo islands) and East (Sarami Bay) of the main island in 2003 and 2004, using onboard GPS (R/V Alis) and an on purpose designed GPS buoy. These high rate data were processed in kinematic mode using a scientific GPS software and related to sea surface height using

calibration sessions to estimate the antenna height. Instantaneous sea surface height map was thus obtained with a few centimetres precision. Tide gauges data from Sabine and Wusi Bank as well as ocean tide models for the East Santo coast provide us tide corrections. We therefore get a local map of the sea surface height, which can be compared to satellite altimetry mean surface. To investigate more specifically the elevation difference that we observe between 2003 and 2004 experiment, we compare the GPS data collected along Topex/Poseidon and Jason tracks during both campaigns. Sea surface elevation derived from GPS can give access to shorter wavelength components of the geoid and thus could help in the geodynamical understanding of the area.

ocean bathymetry merged together, giving a unity and a complete, dense and homogeneous coverage of the world, with an unprecedented accuracy. This new global model at 5-arcminutes resolution will replace the previous model used in ENVISAT data processing and the model at 30-arcsecond resolution will be also used for MERIS and ASAR application projects.

Global Land Topography and Ocean Bathymetry from Radar Altimetry

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The main objective of this work was to generate a new Digital Elevation Model for ENVISAT with a 5- arcminutes per 5- arcminutes grid spacing. This Global Model was achieved by integrating a Bathymetry model built by Walter Smith from NOAA Geosciences Lab and David Sandwell from Scripps Institution of Oceanography, USA with the Altimetry Corrected Elevations (ACE) produced by Philippa Berry of De Montfort University, UK. Both models were used because they present the advantage of associating satellite global altimetry grid with field datasets (depth sounding for the bathymetry and local DEM for the altimetry). To take full advantage of the resolution of both input datasets, two other DEM were also produced with a respective grid spacing of 2 arcminutes and 30 arcseconds. To obtain a final model with a full, dense and homogeneous coverage, that includes all the information from the initial models and preserves their accuracy, a merge of the data sets was performed carefully respecting the boundary between land and ocean because both original grids had different resolutions. Then, the entire dataset was divided in small geographical tiles that were separately triangulated and interpolated. Edge effects were avoided by taking in consideration an overlap boundary zone. Finally, three grids were obtained at different resolutions, 30 arcseconds, 2 arcminutes and 5 arcminutes (respectively, 1, 4 and 10 km approximately) to be used for applications requiring different scales. All the processing composed by merging of both input datasets and the re-gridding at different resolutions was performed using IDL (Interactive Data Language) to benefit of its map visualization and processing capabilities. These global grids are the first models including essentially satellite radar altimeter measurements of land elevation and

Session 5.2:

Building the 15-Year Altimetric Record - Other/Retracking

OSCAR : looking at continental surfaces with radar altimetry.

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The OSCAR project (observing continental surfaces with radar altimetry) intends to develop applications of the radar altimetry outside the ocean. It is based mainly on TOPEX, ERS and ENVISAT data. We processed the whole ERS2 mission dataset from WAP to retracked level using an equivalent of the ICE2 retracking procedure used on ENVISAT ground segment. In addition to the ice caps, we show here applications to continental surfaces, snow depth survey, sea ice, inundated surfaces, lakes, rivers and ocean coastal zones.

The National Oceanography Centre, Southampton Retracking Scheme: Measuring Global Ocean Tracker Bias

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The National Oceanography Centre, Southampton retracking algorithm has been optimized to retrieve geophysical information from Envisat RA-2 18-Hz ocean averaged waveforms in an operational way. The retracking algorithm is based on Maximum Likelihood Estimation. In its linear form, it retrieves the significant wave height and the time origin. Extra information can be retrieved from its non-linear form, regarding the non-linearity of the ocean waves, introducing a non-linear parameter: wave-skewness. The on-ground retracking of Envisat RA-2 18-Hz ocean averaged waveforms is developed under the assumption of linearity of the ocean waves. Thus, this approximation may introduce a bias in the estimation of the range. We made the first estimations of this tracker bias using Envisat RA-2 ocean waveforms. From the results obtained we estimated a mean tracker bias for the global ocean of 0.13 ± 0.07 SWH showing that temporal and regional dependent errors are introduced when using a linear retracker processing approach.

A comparative analysis of waveform data from seven altimeters

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Altimeter waveform data are used for an increasing variety of applications. Their analysis over oceans is being pushed to new levels as investigators study the skewness of sea surface height, and also the structure of storm systems, as revealed by the attenuation caused by rain. Improved tracking algorithms are also being developed for ice and land applications. However, the use of inconsistent datasets could lead to spurious trends within the 15-year series. This poster will examine the waveform data from the ESA satellites, ERS-1, ERS-2 and Envisat, from NASA/CNES's Topex, Poseidon and Jason-1 and from the US Navy's GFO. The shape of the mean waveform, with attendant ripples and spikes, indicates possible power leakages and the quality of the corrections for filter response. The variability about this mean indicates the number of degrees of freedom in each waveform bin, which needs to be known for some waveform-fitting algorithms. Thirdly, the correlation between anomalies in neighbouring bins indicates smoothing or signal leakage within the waveform.

Estimation of the Sea State Bias Effect on the Altimetric Measurements Using a Parametric Model

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The sea state bias (SSB) which affect the altimetric measurements on the sea surface is estimated using empirical parametric model (BM4), calibrated by the analysis of the altimeter data. This model is a simple linear function that links the SSB with the significant wave height (SWH), the wind speed (U) and the backscatter coefficient (σ_0). The knowledge of the backscatter coefficient determined by altimetric signal processing allows to determine the significant wave height and the wind speed. The use of Topex and Jason-1 altimetric data to calculate the sea state bias with the BM4 model and the comparison of the results obtained with the SSB value transmitted in the message of each satellite allowed us the validation of the

methodological approach developed. The proximity of the results obtained with Topex data is sufficient for the most altimetric applications as the determination of the mean sea level which was calculated on the western Mediterranean Sea during a 72 cycles period. Concerning Jason-1, the difference of the results in the determination of the SSB can be explained by the nature of the instruments on board and also the type of model used.

Keywords – Estimation, Parametric model, Empirical, Sea State Bias, Topex/Poseidon, Jason-1.

Improvements in geophysical corrections for coastal altimetry using retracked data

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While the primary reason for under-utilisation of satellite radar altimeter data in coastal regions over the past 15 years is the lack of available data due to the influence of the land within the altimeter footprint, the availability and accuracy of geophysical corrections in the coastal zone poses a significant challenge. New retracked multi-mission altimeter data sets have been generated by the Earth and Planetary Remote Sensing (EAPRS) lab. using an expert system to select an appropriate retracking algorithm based on altimeter waveform shape. These data sets are merged with 1 Hz GDR data sets and state-of-art geophysical corrections at the Faculty of Science, University of Porto.

This paper presents an investigation of the performance of various geophysical corrections in the coastal zone. Particular attention is given to the wet tropospheric correction and the sea state bias; improved techniques for modelling these corrections are presented. The current status of altimetry data use in coastal applications and the focus for future work in this field are discussed.

ENVISAT RA-2 S-band Anomaly: Detection and Waveforms Reconstruction

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As widely known the ENVISAT RA-2 data are affected by the so-called “S-Band anomaly” discovered in the early days of the Commissioning Phase. It consists in the accumulation of the S-Band echo waveforms that starts, apparently randomly, after an instrument Acquisition phase.

Investigation is on going to try and find the instrumental cause of this behaviour but in the meantime the data affected by this anomaly are completely unusable. For this reason the need has arisen for the users to be able to detect the anomalous data and eventually reconstruct a usable signal from them.

This paper describes the algorithm developed for the L1b processor that allows to set a flag identifying the data affected by the “S-Band anomaly” and reconstruct normal echo waveforms to be then ingested in the nominal re-tracking procedure at L2. It presents also the results obtained after the implementation in the L1b reference processor.

of sub-optimal, but fast, retrackers which often had to trade-off height biases against noise. With the advent of faster computers, it is possible to attempt a truly optimal retracking algorithm. To this end, we introduce a Maximum a Posteriori (MAP) retracking algorithm which significantly improves the covariance of the retrieved parameters. We will present the theoretical basis of this algorithm and compare against other algorithms currently in use.

We have performed waveform retracking of TOPEX and Jason-1 data during their colinear phase in 2002 using the MAP retracker in order to understand and remove instrumental effects that may affect the cross calibration. Because the satellites were on the same track only about 70 seconds apart, environmental effects are identical, so one can more directly compare the instrumental response. By using the same algorithms on the two altimeters we also eliminate this source of difference in the comparison. We will present findings on variations in the instruments in a variety of conditions, e.g., wave heights, to produce geographically consistent results. These results will allow the cross calibration of TOPEX and Jason-1 to the one centimeter level which is needed for continuing global sea level studies.

Centimeter-Level Cross Calibration of TOPEX and Jason Using Retracking

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The use of altimetry data for new challenging applications, such as determining sea level rise or more accurate sea surface slopes for bathymetry determination, has made improving the accuracy of altimetry heights of paramount importance. As an outstanding example, we note that the TOPEX and Jason altimeters suffer from relative sea state biases which may be related to the different processing of the waveform data.

In the past, the use of altimeter waveform retracking has been limited by computer resources. This has led to the use

Session 5.3:

The 15-Year Altimetric Record/Long time series

Generation of Climate Data Records from Ocean Radar Altimetry

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Satellite radar altimetry mapping of the ocean surface has achieved remarkable success in recent years, yet is one of the most complex forms of remote sensing. These systems produce measures of the sea surface height within a dynamically evolving reference frame, along with a measure of the sea state. A consistent geodetic reference system and set of correction algorithms for all altimetric missions are essential so that a time change in a series built from two or more altimetric missions can be interpreted as a change in sea level, and not in the measuring system. However, in concert with this challenge for consistency is the realization that state of the art entails a constant state of change, including data coming from new missions which must be brought into a common frame with existing data, improved estimates of instrument drift, and a continuous upgrade of algorithms as a result of access to better data (e.g. GRACE) over time. Thusly, value can continuously be added to existing data holdings and these holdings significantly expand over time. With a goal of using these data to measure unambiguously sub-mm changes in global sea level and producing a valuable Climate Data Record database, altimeter science retains an evolutionary character despite its current “operational” status and perception. Here we present the impact of recent improvements to both the current level of TOPEX/Poseidon (T/P) orbit accuracy (from the current 2-cm level to better than 1.5-cm) through reduced dynamic methods based on the latest GRACE derived gravity field within a consistent well defined terrestrial reference frame, as well as improved GPS based orbits for Jason-1. The anticipated success of this effort will provide a seamless transfer from T/P to Jason-1, directly improve correction algorithms empirically derived from sea surface height

measurements (i.e. revised GOT ocean tide model, sea state bias, and ionosphere corrections) thus improving the ability to isolate subtle yet highly significant long period signals, and provide an improved coincident reference frame for ENVISAT and GFO.

North-East Atlantic current systems from 10 years of multi-mission satellite altimetry

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Satellite altimetry data provide a quasi-synoptically description of the sea level anomaly (SLA) field, which can be the base to ocean circulation variability studies. Although continuous single mission analysis can now be performed for a series of 13-years of Topex/Poseidon (T/P) data it has been recognised that merged multi-mission data sets allow the observation of the ocean at better spatial and temporal resolutions, leading to an improved understanding of the ocean circulation at higher scales, in particular the mesoscale, and its seasonal and interannual variability.

ERS-2 and Topex/Poseidon (T/P) data continuity was provided by the launch of Envisat and Jason 1 missions, in 2002 and 2001, respectively. From these missions a ten year continuous and homogenous data set of merged data from the NASA/CNES 10-day missions T/P and Jason-1 and the ESA 35-day missions ERS-2 and Envisat can be derived.

At the Faculty of Science, University of Porto (FCUP) data from several altimeter missions are regularly reprocessed using state-of-art geophysical corrections and merged data sets are derived. In this study a 10 year series (from June 1995 to June 2005) of merged data of T/P/Jason-1 with ERS-2/Envisat has been used to characterise the SLA field in the NE Atlantic (3° – 50°N, 50° – 5°W). From early-2003 onwards, Envisat, T/P and Jason-1 SLA data sets have also

been merged and analysed.

This paper presents the analysis of the surface current systems for two main sub-regions: the eastern tropical Atlantic and the region of the Azores-Portugal current systems. The seasonal and interannual variability of the oceanic processes present in each region have been analysed from monthly maps of various computed oceanographic variables: SLA, ADT, geostrophic currents and eddy kinetic energy. The advances in the determination of oceanographic variables from the merged two-mission data set are discussed and compared with the information derived by the unique combination presently provided by T/P, Jason-1 and Envisat.

Inter-Annual Long Equatorial Waves in the Tropical Atlantic (1981-2000)

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The purpose of this study is to determine to which extent linear theory can explain the inter-annual variability observed in the Tropical Atlantic and interpret the TOPEX/Poseidon data in terms of long equatorial waves. Due to the relative scarcity of observed data in the subsurface, we first investigate the vertical structure variability in the Tropical Atlantic based on the CLIPPER project high-resolution Ocean General Circulation Model (OGCM) simulation for the 1981-2000 period.

The results reveal that the 6 first baroclinic modes are necessary to accurately represent the surface zonal current and sea level inter-annual variability. The second baroclinic mode is the most energetic, with a variability peak in the central basin. The first and the third modes contribute with comparable amplitude but with different spatial distribution in the equatorial wave guide. The first mode exhibits a variability peak in the western part of the basin, where the largest variability in zonal wind stress is observed, whereas the energy of the third baroclinic mode is confined in the eastern region, where the thermocline rises. The summed-up contribution of the high-order baroclinic modes variability (4 to 6) is as energetic as the gravest modes and is the largest in the east.

Kelvin and meridional Rossby components are then derived for each of the gravest baroclinic mode contributions by

projecting onto the associated meridional structures. The effect of longitudinal boundaries close to the equator is taken into consideration. Equatorial Kelvin and Rossby waves propagations, with phase speed values close to the theoretical ones, are identified for the first three baroclinic modes. Comparisons with a multi-mode linear simulation (OLM) and TOPEX/Poseidon derived sea level and currents indicate that long equatorial wave in the Atlantic explain a large part of the inter-annual variability and that they should be identified from altimetry. However, the peculiarity of the equatorial Atlantic thermocline, with regards to the baroclinic mode energy distribution, renders this exercise difficult without the information provided by subsurface observations or model outputs. Nevertheless, OLM forced simulations allow for the interpretation of the observed altimetric signal, in particular during the boreal spring 1996, when the equatorial Atlantic went through anomalous warm conditions.

Altimetric Mean Sea Surfaces - and inter-annual ocean variability (DNSC05-MSS)

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The central quantity bridging the geoid and the ocean circulation is the mean dynamic topography (MDT), which is the difference between the mean sea surface and the geoid. In a comparison between hydrodynamic derived MDT and synthetic derived MDT derived from the difference between the Mean sea surface and the geoid, the result depends of the quality of the different surfaces but also on the inter-annual ocean variability. In principle the mean sea surface used to derive the synthetic MDT should be the same period as used to average the hydrodynamic derived MDT.

Different global mean sea surfaces (CSR98, GSFC00, CLS-SHOM98, CLS01, KMS01) are based on different time-epoch for the T/P altimetry used in their derivation. Consequently, inter-annual ocean variability (like the major El-Nino event in 1997-1998) will be visible to a larger or smaller extend in these different MSS. (the MSS are actually quasi-stationary MSS).

We have investigated a method to model the effect of inter-annual ocean variability on the derived Mean Sea Surface. This way the derived mean sea surface can be made to include the inter-annual variability for a specific period (creating a quasi-stationary MSS over the selected period). From the 12 years of T/P altimetry the inter-annual ocean anomalies have been modeled using the averaged sea level

height relative to the MSS and the long-term trend.

Evaluation of the available mean sea surfaces will be carried out in GOCINA study region in the Northern Atlantic region. An extended comparison will also be presented in the Arctic Ocean to demonstrate the impact of improved geoid and mean sea surface modeling to derived reliable synthetic Mean Dynamic topography.

Mediterranean Sea Level Analysis from 1992 to 2005

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The Mediterranean Sea is a suitable test site for remote sensing techniques, specially for altimetry due to its semi-enclosed nature. Because of its limited extension, this Sea is also particularly sensitive to the climatic change. Broadly speaking, Sea Level Variations (SLV_{total}) in the Mediterranean Sea have a double origin $SLV = SLV_{steric} + SLV_{mass}$, where steric (volumetric) changes in sea water can be monitorized using time series of salinity and temperature. These parameters can be obtained from numerical models, such as ECCO. Altimetric measurements from different satellites/instruments (ERS-1/2, GFO, Envisat, Jason 1 and Topex/Poseidon) are considered through the use of the merged products from AVISO Altimetry and can be used to estimate SLV_{total} in the former equation. The combination of these two measurements allows for an indirect estimation of SLV_{mass} variations in the Mediterranean Sea as it is shown by means of the GRACE mission. Sea Surface Temperature in the Mediterranean Sea is also considered as indicator of the climatic change and hence analyzed. These observations are compared with NAO index in order to obtain relationships between regional processes which occurs in the Mediterranean Sea with others taking place at larger spatial scale. Regular data processing tools as Principal component analysis and trend analysis are used.

Use of global ocean reanalyses for reconstructing sea level variability patterns over the last 40 years: methods, results and limitations

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A 40-year reanalysis (1962-2001) of the ocean circulation, carried out in the framework of the European ENACT project, has been used to investigate how sea level variability can be reconstructed. This reanalysis has been obtained by the assimilation of historical in situ temperature measurements into a global low-resolution version of the OPA ocean GCM. The observational data set is the quality controlled in situ data gathered for the ENACT project by the Metoffice (Ingleby and Huddleston, 2005). The assimilation scheme is the 3D-Variational scheme described e.g. in Ricci et al. (2005), with a full multivariate background error covariance term, which enables the correction of all model variables at each 10-day analysis window.

The model's hypothesis of a local free surface, but assuming a constant total volume of the ocean, does not allow to investigate global mean sea level variations over the period, but only regional patterns of variability. It furthermore imposes rigorous constraints for any comparison to observations such as altimetry or tide gauges, and, theoretically, for the computation of innovations in the context of data assimilation. Therefore, the protocol for a rigorous comparison is exposed in the poster, and results using historical tide gauges and precise Topex/Poseidon-Jason altimetry are shown. This validation shows that, though the best agreement is in the tropical regions, low frequency signals at the midlatitudes in sufficient agreement to be analysed over long periods.

Over such a long period, the assimilation system causes long term drifts which have regional signatures, mostly due to the fact that salinity variations are not sufficiently constrained by the assimilation scheme. Fortunately, the more-than-a-decade record of altimetry helps identifying them using a statistical method. An application is shown in the North Atlantic region, where the drift is a 15-year regular change of the east-west sea level gradient. Finally, corrected sea level anomalies are analysed in this region through Empirical Orthogonal Functions. The dominant mode is close to the tripole observed in winter SST anomalies. Link with winter North Atlantic Oscillation forcing is evidenced.

Mediterranean Sea Surface Variability during the last 15 years from altimetry

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The objective of this paper is to give a review of the main learning obtained from altimetry data on the Mediterranean surface variability. First, a brief history of the altimeter Mediterranean data analysis will be proposed. It starts with the first analysis done by Larnicol et al. (1995) where the two years of Topex/Poseidon measurements (1993-1995) have firstly monitored the seasonal cycle and the mean sea level variations. Then, among other authors, Ayoub et al. (1998) has shown that the merging of several altimeters (T/P, ERS-1) is needed to correctly sample the mesoscale activity. This corresponds to the discovering period where the ability of altimetry to monitor the Mediterranean surface variability was demonstrated. Since the 2000 year, altimetry is enough mature to precisely analyse the different components of the Mediterranean variability as steric effect, mean sea level variation, mesoscale, seasonal and interannual signals. An overview of the main results obtained will be proposed starting with the analysis of the impact of the different satellite configurations (Pascual et al. 2005), and the advent of the mean dynamic topography for the Mediterranean sea that allows us to analyse the absolute altimetric signal. The identification of the main components of the circulation will be also analysed in term of their sporadic, recurrent or permanent state as well as the analysis of the main seasonal, interannual and decadal signals (Pujol and Larnicol, 2005). All these results will be confronted with the state of the art of the knowledge given through modelling and data analysis from other kind of data as sea surface temperature and in-situ measurements

Session 5.4:

The 15-Year Altimetric Record/Mean sea level

Regional Long-term sea level and sea surface trends from satellite.

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TOPEX/POSEIDON and JASON-1 sea level observations and Reynolds AVHRR sea surface temperature observations over the most recent 12 years have qualitatively been used to study global and regional correlations between long-term changes in sea level and sea surface temperature and to deduce the steric contribution to sea level change over this period. Consistent increases in both sea level and sea surface temperatures are found in most parts of the Atlantic Ocean over this period. In the Indian Ocean and particularly the Pacific Ocean, the trends in both sea level and temperature are still dominated by the large changes associated with the large El Niño Southern Oscillation in 1997-1998 (ENSO). Considerable effort have been put into the correction of the TOPEX and JASON-1 to account for possible offset between the missions. A mission offset of 154 mm have been applied along with adjustments to the TMR and JMR corrections.

Mean Sea Level trend estimation from multi-mission altimetry and tide gauges

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The Mean Sea Level (MSL) trend estimation has become an essential objective of satellite altimetry, as it is related to global climate change. However, great precision, high

stability and long term series are required. So maintaining altimeter systems and data at the level of accuracy of 1 mm/year at global scale still remains a challenge.

With a 15 year time series, altimetric measurements are now widely used for MSL trend estimation. As an expert in altimetry, CLS is involved in the calibration and validation of TOPEX/Poseidon, ERS-1/2, Geosat Follow-On, Jason-1 and ENVISAT. To insure reliable Mean Sea Level estimations, precise cross-comparison between altimetry missions is necessary. Estimates from the different missions are compared and analysed according to the specificities of each altimeter system in terms of performance of instruments, orbit or geophysical corrections.

Moreover, comparisons to an independent data set are also of great interest to detect drifts and biases. The usefulness of tide gauge data networks for calibrating satellite altimetry systems was demonstrated by several authors (Mitchum [1994, 2000], Chambers et al. [1998], Cazenave et al. [1999]...). We took over the works of the above authors and improved them to compare altimeter measurements with a specific tide gauge database (Badomar) processed at CLS. Selecting tide gauge stations where the differences between altimetry heights and tide gauge sea levels are small, is essential to get good variance estimates. The methodology of the comparisons of altimeter data against tide gauge measurements is now operational and produces results routinely for all altimetry missions.

Modeling the global and regional sea level variability in the last decades

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The study analyses the sea level variability from tide gauge and multi-mission satellite altimetry and its reconstruction in the last decades using the dominant patterns and the climatic indices.

The method involves performing a decomposition of the

variability of each field and of their coupled variability by Principal Component Analysis and by Canonical Correlation Analysis and constructing the sea level using spatial patterns from altimetry and temporal patterns from tide gauge stations. The first dominant modes are chosen to be correlated with the climatic indices, the others are determined to best fit the observations.

We expect the corresponding spatial patterns to be persistent and constant in time, as linked to a physical phenomena. The stability and persistency of the spatial temporal patterns are investigated using sea surface temperature and thermo-steric sea level heights that, differently from the sea level data, are available globally over several decades. In this case the correlation of the dominant modes with the climatic indices is lower than when sea level heights are used.

Globally, in 1993-2005 the empirical model reproduce the interannual variability observed by altimetry in 1993-2005 with a root mean square error of about 2 centimeters and corresponds to about 50% of the interannual variability.

For the European region a regional empirical model is estimated using multi-mission altimeter data. Comparing steric interannual variability and observations in the Mediterranean Sea over the last 15-years a better agreement is found with altimetry than with some of the tide gauges. The selection of the tide-gauge stations used is of relevance for the model construction.

Validation of T/P data in the South Indian Ocean

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The TOPEX / POSEIDON sea surface height data were compared with the in situ data of the ROSAME tide gauge network. This network is constituted by four real time coastal stations: 3 are located in the South Indian ocean at Kerguelen, Crozet and Saint-Paul Islands and 1 is located in Antarctica at Dumont d'Urville. Moreover two moorings are maintained nearby the Islands of Amsterdam and Crozet. The TOPEX/POSEIDON altimetric data have been derived from GDRs using a new processing strategy developed for coastal zones applications. A particular attention was given to the tide and inverse barometer corrections using a high-resolution 2D finite element gravity waves model (MOG2D). The estimation of the altimetric sea level trend over the period 1992-2005 will be analysed and compared to the recent works made on historical trend observed at the Kerguelen tide gauge.

Comparing Global Sea Level Rise Estimates from Satellite Altimetry and a Global Ocean Reanalysis: 1993-2001

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Satellite altimeter observations show that global mean sea level has been rising over the past decade at a rate of about 3 mm/yr, well above the centennial rate of 1.8 mm/yr. This has been occurring despite the presence of large geographical variations, including broad areas of falling sea level. Here we investigate the global and regional nature of this signal by comparing satellite altimeter measurements of sea level change between 1993 and 2001 with estimates of the steric component of sea level change for the same period based on the SODA 1.2 reanalysis of global temperature and salinity (Carton et al., 2005).

A map comparison of the two trend data sets shows broad geographical similarities, including high positive rates (>10 mm/yr) throughout much of the western Pacific and eastern Indian Oceans, negatives in the eastern tropical Pacific, and positives in the North Atlantic. Surprisingly, the reanalysis rates tend to have higher absolute values than the altimeter rates, particularly in the tropical Pacific. Analyzing the data sets in three zonal bands (66N to 30N, 30N to 30S, 30S to 66S) reveals distinct latitudinal differences. The northern and equatorial bands exhibit roughly similar average altimeter rates of sea level rise, at 2.5 and 2.3 mm/yr, respectively, and similar levels of correlation (~0.7) between altimeter trends and reanalysis trends on a local (grid point) basis. The southern band shows the highest average altimeter rate, at 3.9 mm/yr, suggesting that much of the increase between the centennial global rate determined from tide gauges and the 1993-2001 global altimeter-derived rate is due to rapid changes in the Southern Ocean. However, a local comparison shows that the reanalysis trends are poorly correlated with the altimeter trends in this band, making it difficult to distinguish between steric and eustatic contributions in the band of greatest sea level rise. The poor correlation between the two data sets is probably due the lack of in-situ hydrographic observations in the Southern Ocean, a situation which no longer exists because of the advent of the Argo program, coincidentally in 2001.

Session 6.1:

The Integrated Approach/Systems

The Global Observed Ocean Products of the French Mercator project

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In the frame of the French Operational Oceanography Mercator project, satellite and in-situ measurements representing the two major complementary key components of the Global Ocean Observing System (GOOS) are combined in order to provide gGlobal oObserved oOcean pProducts at high temporal and spatial resolution. Two kinds of products are generated that both allow to monitor the ocean variability and to validate the MERCATOR Mercator simulations.

First, accurate but sparse in-situ T/S profiles data are merged with high resolution altimeter and SST data in order to reconstruct global instantaneous thermohaline fields from the surface down to 1500 m depth. The merging approach uses first, a multiple linear regression method to derive synthetic T and S profiles from the satellite measurements. These synthetic profiles are then combined with the in-situ T and S profiles using an optimal interpolation method that takes into account analyzed error on the different observations. Twelve years (1993-2004) of 3-D thermohaline fields have been produced with this method and have been first validated and compared with independent in-situ data sets in order to provide an estimation of the performances of the system over the whole ocean. Moreover, the impact of the different observing systems (Argo, SST) has been analysed. The quality of the estimated fields additionally allows us to study the interannual variability of the global ocean heat content as well as of the global mean sea level.

Second, global instantaneous surface currents are derived from a combination of altimeter geostrophic currents, Ekman currents derived from wind-fields and in-situ surface currents derived from drifting buoys. First, a two-parameter model, $U = b e^{i\alpha} \sqrt{\tau}$, is used to compute the wind-driven circulation (Ekman component). b and α are estimated with a least square minimization method using drifting buoys and wind stress fields. Then, the geostrophic component of the circulation is obtained by combining altimeter currents with

the drifting buoys through a multivariate optimal interpolation method. Finally, the Ekman and geostrophic components are added to produce global surface currents products. Five years (1999-2004) of global $1/3^\circ$ daily surface currents have been produced using QuickSCAT winds, altimeter data (Jason/ENVISAT), and drifting buoys coming from the AOML center. Impact of Ekman component, Mean Dynamic Topography (MDT), and drifting buoys are successively analysed.

Finally, the Global Observed Ocean Products (3D-thermohaline and surface currents fields) have been used as referenced fields for validation studies. Indeed, the comparison between MERCATOR simulations with these observed fields allows us to characterise the differences between observed products and simulations and to quantify the information provided by the model and its dynamic.

The U.S. Navy's Real Time Altimetry Data Processing in Ocean Monitoring and Forecasting

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The U.S. Navy has a long history with satellite altimetry going back to virtually its nascence. Over this time it has incorporated data from almost every mission: GEOSAT, ERS-1/2, TOPEX/Poseidon, GFO, Jason-1, and Envisat. The data produced has been invaluable to the understanding of the ocean environment, both through its direct measurements and assimilation into other systems. Due to the Navy's operational nature, the largest emphasis has been on real time and forecasting applications. The benefits to the Navy and commercial interests has been multifold and ever expanding as new applications and technologies are discovered. Two staple Navy altimeter data assimilating systems, the Navy Layered Ocean Model (NLOM) and Modular Ocean Data Assimilation System (MODAS), are presented in the light of their ability to accurately monitor and forecast the ocean environment. These systems and many others have benefited or been made possible by the

advent of high precision altimeters like TOPEX/Poseidon and Jason-1. The improvements in processing techniques, sea state bias determination, and environmental corrections, along with improved tide models and more precise orbits have all combined to aid in the greatest understanding of the global ocean ever. An overview of the processing techniques utilized by the Navy in creating real time altimeter products is presented. Special focus is given to techniques unique to the Navy's processing. These include the mean sea surface employed in determining sea surface height anomalies and an orbit correction technique. Refinements and development of improved altimetry data processing techniques continue as altimetry remains the backbone of numerous Navy systems.

Session 6.2:

The Integrated Approach/Demonstrations

Dispersal Model of Condensate from Malamapaya Deep Water Gas Production

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Environmental concerns about the possible accidental discharge of oil and condensate from the operations of the Malamapaya Deep Water Gas-to-Power project and its potential effect on natural resources of Northwest Palawan has been recognized. A dispersal model was developed to predict the transport of condensate from the Shallow Water Platform (SWP) to identify potential impact areas and assess vulnerability of environmentally critical areas along the Northwestern Palawan shelf.

Oceanographic features off Northwest Palawan were examined to characterize the variability of wind and sea level variations and to relate it to local seasonal characteristics of the water column. The data used includes satellite measurements of windfields extracted from QuikSCAT Level 3 data set, the gridded MSLAs resulting from the merging of the T/P and ERS1/2 data, and historical temperature-salinity data from World Ocean Atlas 2001. The water column characteristics of the area were used in prescribing initial conditions of the hydrodynamic model, the velocity output of which was utilized as forcing for the dispersal model. The surface circulation of northwest Palawan was simulated using the Princeton Ocean Model (POM). A numerical experiment was conducted to estimate the relative importance of the physical factors to the dispersal patterns of condensate in the study area. The factors that account for these current variations are the coastal boundaries, the shallow water bathymetry over the continental shelf, the influence of remote forcing in the South China Sea, and atmospheric forcing.

A Lagrangian model used to simulate the mechanical transport of condensate estimates the distribution of oil (mass and concentrations) on the water surface and along the coastlines that consequently, determines potential impact areas in Northwest Palawan.

Recent Progresses in Modelling the Global Ocean/Sea-Ice Circulation at Eddy Permitting Resolution

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Solutions of numerical models of the ocean general circulation always showed a significant dependency upon numerical schemes and physical parameterizations that are used. Series of sensitivity tests have been performed with a z-coordinate, global eddy permitting (1/4°) ocean/sea-ice model (the ORCA-R025 model configuration developed for the DRAKKAR project), to carefully evaluate the impact of recent state of the art numerical schemes on model solutions. The combination of an energy-entropy conserving scheme for momentum advection with a partial step representation of the bottom topography yields significant improvements in the mean circulation. Well known biases in the representation of western boundary currents, such as in the Atlantic the detachment of the Gulf Stream, the path of the North Atlantic Current, the location of the Confluence and the strength of the Zapiola Eddy in the south Atlantic, are partly corrected. Similar improvements are found in the Pacific, Indian and Southern Oceans, and characteristics of the mean flow are generally much closer to observations. Comparison with other state of the art models show that the ORCA-R025 configuration generally performs better at similar resolution. In addition, the model solution is often comparable to solutions obtained at 1/6° or 1/10° resolution on some aspects concerning mean flow patterns and distribution of eddy kinetic energy. We conclude that significant corrections of the mean biases presently seen in general circulation model solutions at eddy permitting resolution can still be expected from the development of numerical methods which represent an alternative to increasing resolution.

Variability in Southern Hemisphere Interocean Exchanges Part I: The Agulhas Current

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The heat, salt, and momentum fluxes carried by major ocean currents and embedded in interocean leakages constitute important benchmarks of ocean climate. In oceanography few time-series exist of sufficient duration and resolution to study this component of climate, in particular its variability, on seasonal to interannual time scales. While occurring over large spatial scales, these fluxes demonstrate significant variability at the mesoscale, presenting difficulties for in situ sampling programs. Moreover, fluxes at a variety of density horizons are important to the global heat and salt balances. Satellite altimetry (in particular the Jason-TOPEX/Poseidon missions) provides one of the most promising sources of observations for monitoring oceanic variability and long-term change in the ocean. This is particularly the case in undersampled regions such as the southern hemisphere.

In this paper we investigate interocean thermohaline fluxes into the South Atlantic Ocean via the Agulhas Retroflexion region (the "warm water" route) and evaluate our ability to measure them using satellite altimetry. Our study synthesizes information from the Jason and T/P altimeter missions, information derived from the stand-alone 0.1° global Parallel Ocean Program (POP) model, and in situ profile and mooring data.

From the POP model output we evaluate length scales in the Agulhas Retroflexion as well as the fully-resolved eddy fluxes along appropriate altimeter groundtracks, thereby gaining measures of their intrinsic variability in this location. We also use the model output to calculate fully-resolved model heat, salt and momentum fluxes in the region, both baroclinic and barotropic contributions. We subsample the model at altimeter overflight times and locations to determine the likely nature and extent of aliasing in the altimetric sea surface height anomaly (SHA) and in the fluxes calculated from them. For the quantities of interest, aliasing in the signal is less than might be expected.

We synthesize historic profile data into a streamfunction climatology, allowing heat, salt, and mass fluxes to be estimated from steric height (a major component of SHA) in our study region. When the climatology is used with altimeter data, the barotropic signal contained in SHA, another significant component, will introduce error in this method. Therefore we assess the relative magnitude and importance of the baroclinic and barotropic contributions to SHA using a variety of techniques, including in situ bottom

pressure gauges and historic profile data. A variety of methods for removing the barotropic contribution to SHA are considered. Finally, the altimeter-derived thermohaline fluxes from the Agulhas Retroflexion are compared to those from a recent field project, the Agulhas-South Atlantic Thermohaline Transport Experiment (ASTTEX, 2003-2005).

Understanding of the East (Japan) Sea Circulation by using Altimeter, Argo and SST

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The East (Japan) Sea has been drawing keen attentions to its surface circulation feature as well as to vertical ventilation processes. Since mid 90's, the East Sea was recognized as 'Miniature Ocean' suitable for studying global warming problems in relatively smaller time and space scales compared to open ocean water.

In this study, various datasets such as satellite altimeter and AVHRR image data (SSH and SST) at the sea surface and Argo Float Profiles (AFP) in the subsurface layer are utilized in understanding the circulation patterns and other dynamic processes such as meso-scale warm eddy generation and subpolar frontal meandering. Any single dataset alone can not provide enough information for the complicated circulation features in the East Sea.

Hydrographic features captured by AFP such as meso-scale eddies, cold water sinking and major boundary currents will be illuminated and compared to historical and climatological dataset.

Thus we focus on the integrated approach using all the available datasets along with numerical modeling of the circulation in the East Sea based on POM_ES.

Global Surface Currents and Heat Transport : A new product for investigating ocean dynamics

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A global surface current and surface heat transport product is available at the Centre de Topographie des Océans et de l'Hydrosphère (CTOH). The surface current field is calculated from a combination of geostrophic current anomalies from altimetry, Ekman currents at 15 m depth from Quikscat scatterometry and the mean geostrophic circulation from a climatological mean sea surface product. The velocity field in the equatorial band is determined using the equatorial adjustment described by Lagerloef et al. (1999). The surface current field is validated using the global SVP lagrangian drifter data set, and at specific locations using ADCP data. Different applications will be presented showing how this surface current product can be used for tracking water parcels, eddies, or marine life. These surface currents can also be combined with concurrent sea surface temperature (SST) data from the combined global microwave TMI/AMSR-E $\frac{1}{4}^\circ$ SST product available from the RSS group from 2002. A preliminary analysis shows how the combined product can be used to calculate heat transports and heat budgets, and investigate the relative roles of eddy heat transport, mean geostrophic heat transport and Ekman heat transport.

Control of a free-surface barotropic model of the Bay of Biscay by assimilation of sea-level data in presence of atmospheric forcing errors

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A data assimilation method is set up in the barotropic, free-surface, finite element MOG2D model, implemented in the Bay of Biscay and nested in a North East Atlantic domain. The model is forced by the ARPEGE meteorological model.

In a first step, we explore the model error subspace in presence of coherent atmospheric forcing errors. This is done via an ensemble modelling approach in which the atmospheric fields are perturbed in a multivariate and coherent way : by generating an a priori ensemble of perturbed atmospheric forcing fields, and calculating the corresponding a posteriori ensemble of model simulations, one can approximate the forecast errors of the model by ensemble spread statistics, such as background error Ensemble EOFs.

These approximated model error covariances, in form of 6D-EOFs (Sea Level Anomaly, barotropic velocities, atmospheric pressure and wind-stress), are shown to be neither homogeneous over the domain, nor stationary, since they are very dependent on the meteorological forcing.

Such statistics are then used in a Reduced-Order Optimal Interpolation sequential scheme (SEQUOIA, developed at LEGOS/POC) to constrain the model forecast via sea level data assimilation. Twin experiments are conducted in the last quarter of 1999. Results show that the use of time-independent error statistics allows to control the model but that time-dependent statistics often lead to better results, advocating for a more advanced scheme in a future step.

Finally, several Observing System Experiments (OSEs) and Observing-System Simulation Experiments (OSSEs), are carried out in order to test the sensitivity of the results to the altimetric configuration, with or without tide gauges acting in a complementary manner. The impact of velocity measurements near the coast (HF radars) is also illustrated.

15 Years of Oceanography in the Azores; from oceanographic cruises to an integrated approach.

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Physical oceanographic research in the Azores has only started 15 years ago. Nevertheless, it has been possible to evolve from the typical "research cruise approach" to a more versatile and more integrated approach, that has proofed to be more rewarding and adequate for the size and resources of the group.

The Azores Oceanographers have participated or conducted several research cruises since 1990, but anticipating the importance of correlating in situ data with satellite data has lead us to plan the last of these so that there was a coincidence of transects, moorings and satellite ground

tracks (Alves et al. 2002)

On the other hand, the group has invested in data processing and merging hydrological historical data with the results from the above oceanographic cruises, creating a hydrological database for the whole Atlantic Ocean (Alves et al. 1994, Juliano 2003). Also, through the application of a novel methodology and approach, has contributed to a new vision of the currents systems in the South Atlantic Ocean, namely with the newly found St. Helena Current, the congener of the Azores Current (Juliano 2003, Juliano and Alves 2005).

Ultimately, as a result of this continued shift in methodology, the group is now using an integrated approach where field data, model output and processed altimeter data are fused to produce operational oceanography products, such as sea state charts and daily oceanic current charts.

Preliminary estimates of the time-variant heat budget in the Tropical Atlantic

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A better understanding of the mixed layer heat budget in the tropical Atlantic is important for climate research and prediction. Of particular interest are regions where the heat balance is not dominated by the surface heat fluxes. Such regions include, for example, the equatorial cold tongue and the coastal upwelling regions off Africa. The approach is based on the analysis of a wide range of insitu and satellite observations covering the years 1997-2005. Hydrographic profiles are used to derive the a time series of the monthly heat storage rate. Where the temporal resolution is poor these observations are augmented by sea surface temperatures and sea surface height anomalies from satellites. The oceanic heat transports are derived from drifter observations in conjunction with geostrophic velocities from altimetric fields and Ekman currents from scatterometer winds. Preliminary results from this analysis show that good estimates of the heat budget can be derived with this approach. For example, in the tropical South Atlantic (10-3S, 15-0W) the difference between the heat storage rate and the net surface heat flux is on the order of 40 W/m² in boreal summer, and the peak of the heat storage rate lags behind the peak of the surface flux by about a month. When taking the advection of heat into account the phase shift is gone in most years and the difference in the boreal summer peaks is reduced to less then 10 W/m² in most years.

Session 6.3:

The Integrated Approach/Diagnostics

Assimilating altimeter sea surface height data in an operational ocean forecasting system - an historical overview

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The Forecasting Ocean Assimilation Model (FOAM) system produces operational short-range forecasts of the deep ocean every day. It was first implemented in the operational suite at the Met Office in 1997 as a global model at 1 degree horizontal resolution which assimilated in situ and satellite sea surface temperature data and in situ temperature profile data. In April 2001, a 1/3 degree resolution model of the North Atlantic and Arctic started running operationally which took its boundary conditions from the global model. This eddy permitting model was the first configuration to assimilate along-track altimeter sea surface height (SSH) data as well as the other data. More recently, various other configurations of FOAM have been run at higher resolution, including a 1/9 degree model of the North Atlantic. These configurations assimilate all the temperature and salinity profile data available over the GTS as well as the satellite altimeter data.

The along-track altimeter SSH data is assimilated in FOAM by first performing a two-dimensional analysis using the Analysis Correction scheme (an iterative approximation to Optimal Interpolation), giving SSH increments at every model grid point. For each model grid point, the water column is lifted/lowered to produce the given SSH increment such that there is no change in bottom pressure using the Cooper and Haines scheme. This paper gives an overview of the way in which altimeter data has been assimilated in the FOAM system, together with a description of the various improvements which have been made to the scheme.

Controlling the large-scale ocean circulation using a multivariate 3D-Var approach: the complementary role of altimetry and in situ measurements.

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The Mercator-Ocean operational systems routinely assimilate in situ and altimetry measurements using an optimal interpolation scheme to estimate initial conditions for two-week ocean state predictions. More advanced assimilation methods are under development in collaboration with external research groups: one of them is the variational approach. In this presentation we explore the ability of a 3D-Var version of OPAVAR, developed at CERFACS, to constrain the global large-scale ocean circulation by assimilating in situ and remote-sensing observations. The experimental design is based on the framework defined in the European ENACT project. Reanalysis experiments for the period 1993-2001 will be described. The experiments are performed with a 2-degree global ocean model, the ORCA2 configuration of OPA. The first one assimilates only in situ temperature and salinity data from the ENACT quality-controlled data-set; the second experiment assimilates only sea-level anomalies from the CLS data-base; and the third experiment assimilates both data-sets. Those simulations are analysed and compared with a free-model run. The relative impact of the different types of observations to constrain the model dynamics and water masses will be investigated. Particular attention will be paid to the large-scale surface and subsurface circulation, its mean and variability on seasonal-to-interannual time-scales. The problem of the MSSH will also be addressed.

Assessment and validation of the new multivariate Mercator high resolution forecasting system.

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The Mercator Ocean Monitoring and Forecasting System is routinely operated in real-time in Toulouse by the Mercator Project since early 2001, and has been regularly upgraded through three prototypes of increasing complexity (PSY1, PSY2 and soon PSY3), expanding the geographical coverage from regional to global, improving models and assimilation schemes. In this contribution, we focus on the North Atlantic and Mediterranean High Resolution Prototype PSY2. The ocean model is based on OPA-8.1, a general circulation model developed at LODYC (IPSL Paris), and is designed to simulate the Atlantic and Mediterranean oceans with a very high horizontal resolution (5 to 7 km). The assimilation system is based on the Reduced-Order Optimal Interpolation algorithm and uses 1D vertical multivariate EOFs to extract statistically-coherent information from the observations. The multivariate PSY2 system assimilates conjointly altimeter data, SST and in situ observations (temperature and salinity profiles). After a brief presentation of the high resolution forecasting system, we will present some recent results obtained with the multivariate PSY2 prototype compared to the previous monovariate one. In particular, the assimilation of temperature and salinity vertical profiles allows to better represent water masses like mode waters and the Mediterranean Water Outflow. In the POMME area (16-22°W and 38-45°N), the mixed layer depth and its seasonal cycle are well represented. In the Gulf of Mexico, the new system is successful at representing realistic loop current eddy shedding.

Small-scale variability in sea surface heights and surface winds: Implications for errors in ocean models and observations

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Variability in nature exists on all spatial and temporal scales, including those smaller than the resolution of model and

observational data sets. Imperfect parameterization of the small-scale variability (SSV) in models and incomplete sampling of it by observational systems creates model and observational error on the resolved scales of variability. The SSV in sea surface height was found to play a major role in defining the error pattern of wind-forced ocean simulation and satellite altimetry assimilation products. The statistical modeling of the SSV in sea surface height suggests that in the tropical Pacific the major portion of this variability can be explained as a dynamical ocean model response to the SSV (and error) in the wind. Areas of high error which are not associated with local wind SSV are those of high shear and current instabilities in the ocean. Most GCMs underestimate the wind-driven sea surface height SSV even if driven by wind forcing with well-represented SSV (possibly because of dissipation schemes that overdamp small scales) and, as a result, underestimate variability on signal scales as well. Not only magnitude, but also decorrelation scales of the wind error are crucial for determining the error in the ocean response. Data assimilation procedures usually interpret observed data as if they could be expressed in terms of the averages over model grid box areas despite in reality the observations are either pointwise values (for in situ data) or averages over certain footprints (for remote sensing data). Therefore the difference between observations and model values ought to reflect the influence of the small-scale variability (SSV) of the observed physical field, because this variability is getting averaged differently by the model grid and by the observational system. Knowledge of the statistical details of the SSV, e.g. its standard deviations and temporal-to-spatial SSV ratios, helps to model data error better.

Extrapolating oceanic signals from surface data to deeper layers:

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Different approaches can be followed to extract as much information as possible from sea surface and vertically integrated measurements, potentially allowing to infer vertical profiles from sea surface level measured by satellite altimeters or acoustic round trip travel time measurements from inverted echo sounders, coupled to other remotely sensed data. Among these, data assimilation in numerical models is obviously crucial in order to obtain accurate analyses and forecasts, but its results are also strongly dependent on the models' assumptions and characteristics. On the other hand, the approach explored here, namely the

direct analysis of the sole observations and of their covariances, can help to identify what is the real information content of the data, how this can be extracted more efficiently, and also what measurements are needed operatively to optimize an observational network. Recently proposed Coupled Pattern Reconstruction (CPR) and multivariate Empirical Orthogonal Function Reconstruction (mEOF-R) directly couple steric height, temperature and/or salinity and chlorophyll concentration profiles (Buongiorno Nardelli and Santoleri, JTECH 2004; Buongiorno Nardelli and Santoleri, JTECH 2005; Buongiorno Nardelli et al., CIESM 2005). The two techniques have been first applied to time series of in situ measurements at fixed locations, and successively tested in an area of fundamental importance for the Mediterranean sea dynamics as the Sicily Channel. The more relevant results of these analyses will be summarized and presented.

Comparing Multiyear Altimetry, Drifter, and Satellite Image Derived Surface Currents in the California Current

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A 4-year time series, between 1994 and 1997, of sea-surface velocities for the California Current calculated from TOPEX/Poseidon and ERS-1/2 altimetry data, Lagrangian surface drifter data, and data extracted from thermal satellite imagery using the maximum cross-correlation (MCC) technique are compared. The relationship of the MCC velocities to other velocity estimates in the region gives a sense of the type of current MCC is measuring, problems with the MCC method, and insight into the current forcing mechanics in the region. MCC has an advantage over the other data sets of being temporal and spatially denser than altimetry and more widespread than drifting buoy deployments. 30-day spatial fields are created by compositing and optimally interpolating the individual data sets. Strong agreement was found between drifters and MCC in areas of high velocity currents away from the continental shelf. On or near the shelf thermal patterns can be distorted significantly in time, decreasing the accuracy of the MCC method. Velocity magnitudes measured by drifters and MCC were found to have no scale bias, in contrast to previous studies. Altimetry produced high correlations with MCC and drifters near satellite ground tracks, however consistently measured smaller velocities. The closer agreement between MCC and drifters, compared with MCC and altimetry, suggest a role of ageostrophic surface currents in this region, which is likely due in part to Ekman forcing.

Assimilation of altimeter data in the ECMWF ocean analysis system

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The operational ocean analysis system at ECMWF has been recently upgraded; among other changes it includes the ability to assimilate both salinity data and sea level anomalies derived from altimeter in addition to temperature.

The altimeter data is used to correct temperature and salinity using the Cooper and Haines (1996) scheme. As part of the process of developing the new system, several ways of merging this information with the assimilation of subsurface data were explored and their respective merits compared. Additionally, attempts were made to use grace derived mean sea levels to reconstruct the total mean sea level. Although not used in the ECMWF operational system where only anomalies are assimilated, the relevance of this approach is discussed.

An ocean reanalysis was carried out from 1959 and has now reach real time. It assimilates subsurface data from 1959 and altimeter data from 1993. Results from this analysis are presented and compared with subsurface only assimilation runs.

Interest of combining satellite altimeter data with temperature and salinity data on the new assimilation MERCATOR System

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The French MERCATOR project is developing several operational ocean forecasting systems to take part in the Global Ocean Data Assimilation Experiment (GODAE). Prototype systems are designed to simulate (1) the Atlantic and Mediterranean Sea (from 1/3° to 1/15°), and (2) the global ocean circulation (from 2° to 1/4°). A new generation of fully multivariate assimilation system referred to as SAM2v1 is being developed from the SEEK (Singular Evolutive Extended Kalman) algorithm (developed at LEGI,

Grenoble). This scheme is a Reduced Order Kalman Filter using a 3D multivariate modal decomposition of the forecast error covariance as well as an adaptive scheme to specify parameters of the forecast error. The use of the SEEK filter and its 3D modal representation for the error statistic is intended to overcome some of the limitations of the previous OI scheme in highly inhomogeneous, anisotropic, and nonseparable regions of the world ocean such as shallow areas, as well as in the surface layer. Unlike the original SEEK filter, the variant of SAM2 which is considered here doesn't evolve the error statistics according to the model dynamics [Testut et al., 2003]. This would require prohibitive costs given the size of the operational systems. However, some form of evolutivity of the background error is taken into account by considering different error sub-spaces related to the analysis day. As the previous system, it allows to assimilate vertical profiles and SST in addition to altimetry (JASON, ERS-2 and GFO), but in larger quantity at a lower cost. To minimise the computational requirements, the analysis kernel in SAM2 has been massively parallelized and integrated in a generic platform hosting the SAM1 and SAM2 kernel families [Tranchant et al., 2005]. This platform is driven by the PALM software [Lagarde et al., 2001; Piacentini et al., 2003] which makes the coupling between the model codes and the assimilation schemes more effective. Several Observing System Experiments have been performed with SAM2 for various prototypes (North Atlantic to Global configurations) and results will be presented and discussed.

Exploration of model errors in terms of Sea Surface Height and Temperature in a $\frac{1}{4}^\circ$ model of the North Atlantic

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The knowledge of model errors is a fundamental issue as it is needed to evaluate the quality of a GCM simulation and to formulate data assimilation problems. Understanding the errors covariance structure is also critical for the interpretation of surface data, such as altimetry or satellite temperature observations, in terms of subsurface signal on both the tracers and dynamical fields. Despite the considerable development in data assimilation techniques stemming from the availability of altimetric data since the ERS1 and TOPEX/POSEIDON missions, and in spite of the increasing realism of numerical models, the estimation and formulation of model errors remain a vexing methodological issue as well as a major drawback to forecasting systems. This study aims to contribute to the exploration of model

errors in the surface layers within a realistic modelling framework of the North Atlantic circulation. The focus is on errors induced by uncertainties in the atmospheric forcing fields. The approach is based on an ensemble method. Our objective is to understand the sensitivity of the superficial heat content to the forcing and the relationships between errors on surface fields and on subsurface variables that are not directly observed. The emphasis is on sea surface height and temperature (SSH and SST) data since satellite observations provide very complete datasets and are thus part of most data assimilation systems. Furthermore, correlation between errors in SSH and SST are expected to be significant since both fields contain the signature of heat content and dynamical processes. We are interested in seasonal scales. Since the sensitivities are expected to depend on the ocean state, separate analyses are done for winter and summer conditions. The ocean model is OPA9 in a $\frac{1}{4}$ deg. configuration over the North Atlantic, stemming from the DRAKKAR project. The model uses bulk formulae for the air/sea exchanges. ERA40 reanalysis fields are used for the atmospheric forcing for the years 1984-2000. Our work consists of generating an ensemble of atmospheric forcing perturbations. This is followed by an analysis of the ensemble of integrations. The objectives are threefold: - 1/ to estimate error covariances in SSH, SST and sea surface salinity (SSS), - 2/ to characterise the impact on the mixed layer properties and heat budget, - 3/ to identify the space-time structure of the impact of local SST and SSH perturbations on other model variables. The results presented are for a 6-month run in 1993.

On an Adaptive Filter Based on Forecast Errors Modelling for SSH Data Assimilation and its Comparison with Optimal Interpolation Method

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Defining the gain is a key problem in application of filtering technique for data assimilation in meteorology and oceanography. Due to insurmountable difficulties related to very high dimensions of the system state and uncertainties in modelling model error, simple sequential algorithms like OI schemes are widely used in comparison with other advanced methods (Kalman filter ...) because of its less time consuming and less computer memory. The performance of the OI scheme depends essentially on specification of the forecast error covariance matrix (ECM)(or background

covariance matrix). Usually the ECM is chosen a-priori as a constant matrix. The question on how to specify the ECM is of first importance since it determines a performance of the filter. This question will be addressed in this talk in the context of SSH data assimilation for oceanic models. The approach used here is based on modelling the forecast errors. It will be shown that the procedure of modelling forecast error is quite similar to that done in the construction of breeding modes. The filter gain can be derived : (i) either by using only the forecast perturbations derived from integration of the numerical model alone (without using the observations). The filter with the gain obtained in this way (it is in some sense an OI algorithm) will be applied after to assimilate the observations; (ii) or by integrating the model from a set of analysed and perturbed states and evolving the gain during the assimilation process. The forecast errors will be used to estimate some parameters of the parametrized ECM and thus, to initialize the gain structure. It will be shown that the proposed filter performs much better than the standard Cooper-Haines filter. A considerable improvement of the filter performance can be achieved also by employing the adaptive technique based on parametrization of the gain derived from the modelled forecast errors.

Recent advances in data assimilation in the MERSEA project

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The MERSEA European project aims at developing a European system for operational monitoring and forecasting on global and regional scales of the ocean physics, biogeochemistry and ecosystems. The purpose of this paper is to review the recent advances of data assimilation in the MERSEA project. Fundamental studies are lead with the Ensemble Kalman Filter (EnKF) and the Sequential Importance Resampling (SIR) filter to deal with biases and non-linearities of the ocean model, while more applied studies are lead with the Singular Evolutive Extended Kalman (SEK) filter to control the mixed layer, and to explore the impact of the control on an ecosystem model.

First of all, the EnKF developments are aimed at conditions where bias and non-linearities are not negligible. The approach is to modify statistical estimators based on geostatistical methods (Gaussian anamorphosis, bias estimation) with applications to coupled ice-ocean systems

and ecosystems.

Another fundamental study similar to work with the EnKF filter is carried out with the SIR filter. In contrast with the EnKF, the SIR filter updates probabilities of the ensemble members and not the ensemble states themselves. This difference makes the SIR filter a truly variance minimizing scheme, which can be easily applied to strongly non-Gaussian ecosystem models that MERSEA needs to investigate. Several tests on such a nonlinear model have been performed, estimating model state, model parameters and even model noise strength. We found that by making the strength of the model noise variable in time the model parameters became much less time dependent, which leads to a much more realistic ecosystem model.

The SEEK filter development consists of two parts. The first one is to explore the problem of estimation of turbulent momentum, heat and fresh water fluxes, one of the main sources of ocean model errors that strongly penalize the operational capacity to provide realistic forecasts of the thermohaline characteristics of the mixed layer and of the surface ocean currents. The idea is to augment the control space of the filter to include, in addition to the state variables, information about the air-sea fluxes. For this purpose the turbulent coefficients CE and CH of latent and sensible heat flux were chosen among parameters which contribute mainly to the errors of heat and fresh water fluxes. The possibility to control errors from atmospheric forcing by assimilation is shown.

Another part of SEEK filter development work is to quantitatively improve the representation and space-time variability of marine ecosystems in ocean basins, by coupling with multi-data assimilative eddy-resolving circulation models, focusing on key coupling mechanisms (mixed layer dynamics, diapycnal mixing, eddy activity, and vertical advection). To serve this purpose, a prototype of a coupled physical-biological assimilation system is developed. The data assimilation system mainly uses satellite derived products such as Sea Surface Temperature and Sea Surface Height. The impact of the assimilation of multivariate data sets on the coupling and ecosystem response is studied.

A synthesis of the results obtained during the first phase of the MERSEA project will be presented at the Symposium.

How altimetry can complement in situ observations in the estimation of the upper ocean heat storage

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The main objective of this study is to improve the estimates of the upper ocean heat storage, which is key to achieve a better understanding of the heat balance in the world oceans. These estimates are necessary to improve climate forecast capabilities of coupled general circulation models. The data we use cover the years 1992 through 2005. Temperature profiles, approximately 500,000, are obtained from XBTs and profiling floats. The altimeter data consist of the gridded AVISO sea height anomaly fields. The correlation between the sea height anomaly and the depth of the mixed layer and of selected isotherms is investigated in the upper 800m. The sea height anomaly fields are used to monitor the upper ocean heat storage within a two layer reduced gravity approximation where these correlations are good. We present here global maps of altimeter-derived upper ocean heat storage and the errors associated with these estimates obtained from the XBT and profiling float observations. The final goal of this work will be to fill with altimetry estimates the spatial gaps created where profiling float coverage is not adequate. Moreover, this work will also provide information on where more in-situ observations are needed because altimetry cannot be used as a proxy to estimate the mixed layer depth or the upper ocean heat storage.

On the role of GRACE for the joint assimilation of altimetry and in-situ data

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The measured altimetric signal, i.e. the Sea Surface Height (SSH) can only be used in oceanography in its “residual” component, i.e. the Sea Surface Anomaly (SLA). Because of geoid uncertainties, altimetric applications have indeed concentrated on ocean variability using SLA. The lack of an adequate mean dynamic topography (MDT) is a recurrent issue on physical oceanography and especially on altimetric data assimilation. The recent advances of our knowledge of the geoid brought by the satellite gravity mission such as

CHAMP launched in 2000 and the GRACE experiment launched in 2002 provides a more accurate geoid reference and therefore the possibility to exploit the absolute sea surface height measurements in physical oceanography studies.

In this study, we investigate the impact of the absolute altimetric signal in numerical model via data assimilation method. Assimilation experiments are performed with the OPA 8.2 general circulation model in its ORCA configuration (free surface global 2° low resolution with a meridional grid spacing refinement down to 0.5° in tropical region to improve the equatorial dynamics). The assimilation scheme is a reduced-order sequential Kalman filter (SEEK filter). To avoid the shocks that are induced into the model by intermittent analysis, an Incremental Analysis Update (IAU) scheme is added to the regular SEEK filter procedure.

The contribution brought by the use of an observed absolute MDT is illustrated by multi-annual experiments jointly assimilating altimetric SSH (from TOPEX/POSEIDON and ERS1&2) referenced to the GRACE geoid and the in situ TAO temperature profiles. The focus is made on the tropical Pacific region, which is the region where data assimilation is performed within the global model. The objective of the study is to assess how the assimilation of the GRACE geoid into a realistic model can improve the modelling of the Tropical Pacific dynamics and what impact it may have on the multiple data assimilation process. The solution is evaluated with regards to our present knowledge of the Pacific tropical dynamics as given by various data bases. In particular, independent XBT profiles coming from the CORIOLIS project data base are used in order to validate the thermal structure of the assimilated run.

The first results are promising, especially in term of compatibility between in situ and satellite data observations. It is clear that by providing an observed absolute reference for altimeter data, GRACE data make possible the assimilation of multiple data sets such as SSH and in situ temperature profiles. The use of an absolute dynamic topography opens the ways for the development of efficient assimilation systems based on multiple data sets using altimetry and in situ data.

Operational multivariate assimilation of satellite and in situ observations in the Mediterranean Forecasting System

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The Mediterranean Forecasting System (MFS) is an integrated operational activity in the Mediterranean which combines observations, data assimilation and forecasting. Since September 2004 the MFS has deployed 23 ARGO floats in the Mediterranean. In the same period it started to use a new oceanographic model set-up based the 1/16th degree and 71 vertical layers ocean general circulation model combined with a multivariate optimal interpolation scheme. The system produces daily analysis of oceanographic parameters by assimilating satellite observations of sea surface temperature and sea level anomalies, and in situ observations of vertical profiles of temperature and salinity made by XBT and ARGO floats. The presentation will describe the MFS assimilation system and demonstrate the impact of the multivariate assimilation of satellite and in situ observations on the quality of MFS analyses and forecasts.

Session 7.1:

Data Services

Online altimetry service for hydrology: The CASH project

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CASH « Contribution of spatial altimetry to hydrology » is a project funded by the French Ministry of Research and Technology (Réseau Terre et Espace). The coordinator of the project is IRD (Institut Français de Recherche pour le Développement) and the industrial partners are CLS (data supply from satellite-based systems for studying and monitoring the environment) and BRLi (consultant in water and the environment). The scientific teams involved are LEGOS (altimetric and geodesic data processing and interpretation), LMTG (hydrology and geodynamic of the great river basins, in particular the Amazon basin), and ESPACE (remote sensing, reception station network and decision support systems). The first goal of the project was to determine the ability of radar altimetry to measure the elevation of continental water bodies. It was then to define the scientific and technological environment necessary to complement the existing in-situ gauges network, or even to substitute spatial measurements to some distant gauges, delivering in several months unprecise or irregular data, or to gauges that have switched off. The target was therefore the definition of a global, standard, fast and long term access to a set of hydrological data concerning the greatest river basins in the world.

Specific aims are then: - Create an elevation database for the water bodies of eight great basins (Amazon, Congo, Ganges, Yangtse, Parana, Lena, Mekong, and Danube) from T/P GDR (Topex/Poseidon Geophysical Data Records) - Improve T/P and Jason data by using retracking algorithms and geophysical/environmental corrections designed specifically for continental waters - Define and develop an online demonstrator of a decision support system for the test site of the Amazon basin able to get from distant database and mix models and processes, spatial data and in-situ data. The demonstration will apply to some decisional environment implying key hydrological knowledge such as flow modeling for a given reach, calculation of the volume of water potentially stored in the inundation plains, elevation/discharge conversion at a given “virtual” gauge (or intersection between radar satellite track and river), retrieving of water height value at any point of the hydrological network by spatial interpolation between satellite tracks including for gauge levelling, spatial

interpolation conversion of elevation at virtual gauge measured each ten days (for T/P) in daily water height, design of an optimum in-situ gauge network for a given uncertainty at the virtual gauges.

Hydrological data base from satellite altimetry

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In the recent years satellite altimetry has been used to obtain water level time series over inland seas, lakes, rivers, floodplains and wetlands. We have developed a global data base of water level time series over lakes, rivers, man-made reservoirs and floodplains based on satellite altimetry data from several missions : Topex/Poseidon (1992-), ERS-2 (1995-), GFO (2000-), Jason-1 (2001-) and ENVISAT (2002-). Most of the water level time series of the data base are constructed using the Topex/Poseidon GDRs data, but a number of lakes water levels are also based on ERS, GFO, Jason-1 and ENVISAT data. At the time of writing, about 100 lakes, 200 virtual stations on rivers, 50 reservoirs and a few tens of floodplains sites worldwide are available on the data base, accessible via internet. The numerical water level data can also be downloaded. Several examples of hydrological applications in different river basins worldwide are presented. In addition to water level time series, discharge time series over several large rivers as well as time-variations of surface water volumes over floodplains are also presented.

Aviso Altimetry Products: select your choice!

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Since the launch of Topex/Poseidon, more than 13 years ago, satellite altimetry has evolved in parallel with the user community and oceanography. As a result of this evolution, we now have:

- A bigger choice of products, more and more easy-to-use, spanning complete GDRs to pre-computed sea level anomalies and gridded datasets

- a mature approach, combining altimetric data from various satellites and merging data acquired using different observation techniques, including altimetry, to give us a global view of the ocean;

- data available in real or near-real time for operational use.

Aviso have been distributing Topex/Poseidon and ERS altimetric data worldwide since 1992, and Jason-1 and Envisat since 2002. Soon Cryosat data will join the crew... Integration of all those missions is one of the keys to global modeling of the ocean for assimilation in Godae. An overview of available products, describing their applications and features, will be presented.

Basic Radar Altimetry Toolbox and Radar Altimetry Tutorial: a new set of tools for all altimetry users

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Whether you're a newcomer or an old-timer in altimetry,

Whether you're working on ocean, atmosphere, ice, or on the more solid land,

Whether you need your data fresh from the satellite, or lovingly matured through the ground segment processing,

Whether you ingest data like a horse or like a bird,

Whether you like flashy color maps or prefer serious black and white curves,

BRAT & RAT are made for you!

The field of satellite altimetry has matured to a point where it is now time to encourage a multimission approach (between various altimetry systems) and conceive an "all-altimeter" toolbox and tutorial. Such an integrated approach and view is vital not only for assessing the current status of what offers altimeter products but also to show the system sustainability (Cryosat, Jason-2, Sentinel missions, NPOESS missions) and consistency with the past. Thus ESA and CNES join their forces to produce:

- A general Radar Altimetry Tutorial (RAT) taking into account 15 years of effort in education and public outreach on satellite altimetry, including web site, brochures, tutorials, lectures, etc.

- An "Open Source" Basic Radar Altimetry Toolbox (BRAT) able of handling several altimetry missions' data products, of performing advanced data processing, and of visualizing the data. The toolbox will be complete, with all the needed documentation and advanced processors needed for satellite altimetry scientific applications in any of the following research domains: cryospheric science, oceanography, marine meteorology, land process studies including hydrology and geodesy.

The main beneficiaries of these toolbox and tutorial will be the altimetry users, experienced as well as beginners, and particularly the users of the upcoming CryoSat mission.

The toolbox overall objective will be to facilitate the use of satellite altimetry products for altimetry users and answer to particular needs of specific applications. This objective drives a few others like:

1. to form the young scientists and professionals (young in term of experience) that will be the principal movers and users of altimetry outputs (cf. tutorial + application issues),

2. to facilitate the visibility / understanding / exchange of the altimetry data (standardised discovery metadata giving special attention on the users' need, disseminating products in a shared and distributed way),

3. to facilitate the acquisition, editing & selection of altimeter products and auxiliary data (with care for choice of environmental corrections and reference fields, data removal according to validation criteria),

4. to cover special data issues like combining altimetry measurements together in order to provide long term data series or high-resolution merged products.

5. to facilitate the using, viewing and post-processing of level 2 altimeter data products for an optimal use by oceanographers at higher levels and the handling of necessary auxiliary data.

Just-In-Time Altimetry: International Collaboration in Provision of Altimetry Datasets

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In order to carry out environmental research, researchers require access to quality controlled, calibrated data. The rapid and repeated release of updated corrections, calibrations and algorithms for satellite altimetry data, results in the most readily available data, i.e. those from standard products, being out of date relative to the best products that could be produced by specialists. Satellite altimeter data are used in a range of environmental research, primarily oceanography but also for studies of ice and land surfaces. These data need to have corrections and calibrations applied from a variety of sources, including tidal models, atmospheric measurements and other instruments such as meteorological buoys. These corrections are available from a number of sites globally and often there are several different options for which correction to use. Users who are not altimeter specialists may not have access to the latest corrections and may be unaware of the latest updates or most appropriate corrections to use for their application. As alternative altimeter data sources are developed to try and overcome some of these problems, it becomes ever more confusing to compare products and select the most appropriate one. We will present a GRID based methodology to give all users access to the best possible altimeter data product, tailor made for their specific application, using the 'best' corrections available at the time the product is requested. A data portal system would be based on a "Network of Trust" consisting of the data providers and a certificating authority. Requested data products could be produced within this network using the most efficient process, at the time of the request. In addition to authorised data providers, the system would include certified 'experts', authorised to provide recommended correction sets and sources for particular product types: e.g. a calibrated wind speed product or a sea surface height anomaly product suitable to determining large scale ocean circulation. A web 'front-end' to the portal service would allow the user's full interaction with the portal to select products, formats and delivery method. This system would build on the experiences gained in combining two existing

Altimeter Data services (GAPS and RADS), both with significant numbers of users, to produce a coherent data service with alternative web interfaces and configurable users access.

Mersea ocean Portal, Proof of an Integrated System

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Because of its high degree of maturity as well as the current operational status reached, satellite altimetry is currently one of the most important data sets to serve operational oceanography. But on the road to operational oceanography, the issue is just not a matter of satellite altimetry and covers also any ocean observation from space being remote sensing data or collected in situ data.

To allow the various systems to converge, the Europe through its GMES programme (Global Monitoring for Environment and Security) launched an important project called Mersea Integrated Project ('Marine Environment and Security for the European Area') to develop its ocean component over the period 2004-2008. This project should lead to the setting up of a European Center for Ocean Monitoring and Forecasting (ECOMF) that will provide an integrated service for monitoring and forecasting the global and regional ocean.

Mersea project gathers about fifty European partners and the principal operational oceanography actors in Europe. Mersea system is envisioned as an operational network that covered three main areas: o In situ and satellite observing systems and provision of data directly useable by models (that is: quality controlled, low and high resolution data sets, real-time and delayed mode delivery + historical data base of key sea surface parameter estimates - sea surface height, sea surface temperature, ocean colour and sea ice -) o Monitoring and forecast systems coordinated to cover the global ocean and the oceans and seas surrounding Europe (North East Atlantic ocean, Mediterranean Sea, Baltic/north Sea, Arctic Ocean). o Products, applications and services demonstrations

To serve and communicate with such different thematic communities, the challenge for Mersea is, besides reaching the operational and reliable status, to set up a coherent strategy that will integrate marine data streams across disciplines, institutions, time scales, and geographic regions. It is essential to enable interoperability and allow a multi-disciplinary and integrated use. This strategy end up with what we called a data management, communication and distribution plan.

Mersea Ocean portal (<http://www.mersea.eu.org>) demonstrate the plan application and usefulness that is showing 1- how the Mersea Integrated System and its common operational unified framework is being set up, step by step, and 2 – the ending with operational activities including the visibility, understanding and exchange of reliable ocean data.

This plan is applicable to any system and the strategy is already well acknowledged and pushed forward in a lot of national, european and international programmes and projects (cf. Roadmap, Seadatanet, Godae, IOOS – DMAC, etc.). Not following such requirements, the various service systems will not be constrained enough to provide reliable and interoperable products and operational oceanography will end as a failure.

CTOH – 17 years of altimetric service

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The Centre de Topography des Océans et de l'Hydrosphère (CTOH) is a French National Observational Service dedicated to satellite altimetry studies, first established in 1989 to investigate ocean dynamics from Geosat data. The main objective of the CTOH is to maintain up-to-date, homogeneous altimetric data bases for studying long-term changes in the ocean sea level, or continental surfaces, with an emphasis on precise monitoring for climate studies. Our data bases provide support for scientists working on open-ocean processes, but also for the emerging fields of coastal satellite altimetry, satellite hydrography (over lakes and rivers), and the cryosphere. For these new altimetry applications, the standard altimetry products (which are tuned for open ocean conditions) are either absent or the data are not accurate enough.

Over the last 17 years, numerous altimetric corrections and algorithms have been developed by the research groups at LEGOS and validated and distributed as part of the CTOH/LEGOS activities. These include the retracking algorithms for the ERS/ENVISAT altimeters (ICE2 algorithm) (Rémy, Legresy); the tidal models and corrections of the FES1999, FES2002, FES2004 series (Le Provost, Lyard), the high-frequency barotropic correction of MOG2D (Lyard, Carrère), various improved corrections for maintaining maximum precision for global sea level studies (Cazenave, Minster, Le Provost), and specific algorithms for improving altimetric data quality and coverage in the coastal

domain (ALBICOCCA project, Lyard, Roblou) and over lakes and rivers (Cazenave, Crétaux, Gennero). The CTOH maintains these up-to-date corrections from LEGOS and other research groups for all of the available altimetric missions, aiming for a rapid upgrade and distribution of its data products.

At CTOH, we currently maintain two types of altimetric data bases. For ocean and coastal sea level studies, and continental and cryosphere surface levels, we maintain GDR data products with up-to-date corrections from the Topex-Poséidon, Jason, GFO and ENVISAT missions (1992 – 2006+). For the emerging applications in the coastal domain, over continental surfaces, lakes and river and over the cryosphere, we have a ERS/ENVISAT waveform data base retracked with the ICE2 algorithm for the entire ERS-ENVISAT period (1991 – 2006+).

Various data products are available, including alongtrack GDR data with the most recent corrections (MOD2D, FES2004, etc), global gridded surface currents from altimetry and scatterometry data (see poster Sudre and Morrow), retracked topography and surface roughness over the continental and coastal domains (see poster Legresy et al.). We are currently developing specific high-resolution products for the coastal zone (see posters Lyard et al.; Birol et al.). The CTOH also has an outreach mission in providing easy access to altimetric data products for internal and external scientific users, and also in providing training on the use of altimetric data, and the physical interpretation of the different altimetric components, for students, visiting scientists, and external users.

For more information see our new web site :
<http://www.legos.obs-mip.fr/en/observations/ctoh>

Near Real Time Altimetric Monitoring of Lakes and Reservoirs

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Satellite radar altimetry has the ability to monitor variations in surface water height (or stage) for large lakes and reservoirs. A clear advantage is the provision of data where traditional gauges are lacking or where there is restricted access to ground-based measurements. A joint USDA/NASA funded program is performing near-real time altimetric monitoring of the largest lakes and reservoirs

around the world. Data ingestion and manipulation follows the path of the NASA Ocean Altimeter Pathfinder program although extra provisions have been made regarding these smaller targets. Initially near-real time stage measurements for about 80 lakes were derived from the incoming Jason-1 mission (post 2002, IGDR data set, <10cm orbit accuracy, delivery time <4days after satellite overpass) and the archived measurements were taken from the TOPEX/POSEIDON mission (1992-2002). Phase 3 of the project will bring additional lakes on-line via the inclusion of data from the GFO, ERS, ENVISAT and Topex-Tandem missions. The stage products, with accuracies ranging from a few centimetres to tens of centimetres depending on the target size and mission, are placed on the Production Estimates and Crop Assessment Division's (PECAD) web site http://pecad.fas.usda.gov/cropeexplorer/global_reservoir. A database containing simple graphic and text products allows access via a clickable map interface. This system enables free public viewing as well as the delivery of information to the USDA for their irrigation potential estimates and general observation of potential drought or high-water conditions. Current emphasis is on the quality and quantity of the new stage measurements with special focus on the merger of all mission data. The advantages of such a multi-mission system is apparent with the continued delivery of new information for agricultural and water management applications.

Mercator Ocean forecasting products: fitting into the users needs

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Mercator Ocean is a French public initiative aimed to develop ocean forecast operational systems based on ocean physical models assimilating routinely remote sensing (altimetry from Envisat, Jason-1, GFO and Topex/Poseidon), sea surface temperature, and in the years to come SMOS sea surface salinities) and in situ data. The other essential and subsequent mission is to allow operational oceanography downstream applications. For that purpose, Mercator Ocean makes its products available through two different ways:

1. Images on the web targeting the general public Every week, more than 2000 maps are updated describing 3D modelled ocean: nowcast, forecast for up to 14 days and hindcast, temperature, salinity, surface current and other ocean parameters, 5 depths from surface to bottom. These images are freely available on the web, except the zonal maps younger than 30 days. For these, the user is expected to fill an on-line form, asking his/her motivations and the use he/she intends to do with these maps. This controlled

access allows us to draw the profile of this audience: on an amount of 180 users (end of September 2005), about 30% are researchers, 23% are sailors, using the surface current maps to optimize or better know their oceanic environment, 20% are ordinary on-lookers and interested people. Other uses come from the world of education (14%) -students, teachers-, 8% are public institutions in charge of State missions such as oil drift prevention, environment monitoring. The last 8% are professionals coming from maritime fret, offshore industry, recreative/professional fishing. The analysis by country shows a great audience in France (76%) but a breakthrough into Europe (Spain, Portugal, Italy), Canada and USA.

2. Numerical files targeting professional uses The use of numerical files containing the Mercator outputs 3D fields is the most important criteria to evaluate the impact of the usefulness of our products. Mercator has created 'showcase products', summarizing Mercator outputs on regular grids and in NetCDF format. We offer several ways to access these products : a server from which the user can make requests and get the products file by file, an Opendap server allowing him/her to extract area, ocean parameters, and enabling continuous time aggregations outputs in one file, and a service à la carte where he/she can make request to a dedicated Mercator team what exactly he/she wants when showcase products are not fitting his needs. The number of our numerical products users reaches about 60 teams, divided into 2 groups. The first half concerns the members of the Mercator Ocean Public Interest Group (CNES, CNRS, IRD, Ifremer, SHOM, Météo-France). Most of them are for research interest. Three applications are for operational issues : the French Navy for operational knowledge of the oceanic environment, and the French Meteorological Office for both seasonal forecasting and pollutant drift modeling. Among the second half of our numerical products users, 21 projects deal with research, not only physical oceanography, but also biology and biogeochemistry. Only two projects are involved in a commercial activity in the field of information service for fishing industry and offshore industry.

NOAA/AOML Altimetric Products

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NOAA/AOML distributes on its web server several products derived from altimetric sea height anomaly fields, for weather and climate studies. These products are validated using data from a variety of platforms, such as XBTs, drifters, moorings, and profiling floats:

1. Near-real time global geostrophic currents 2. Near-real time Tropical Cyclone Heat Potential (TCHP) 3. Surface currents 4. Upper ocean heat storage

The global near real-time surface currents, a project of the NOAA CoastWatch Caribbean Node that is housed at NOAA/AOML, are produced daily using altimeter-blended data obtained from NRL. A Java-powered web interface allows users to dynamically specify the output settings. The geostrophic current estimates involve two components: a mean topography, which can be selected from a menu offering several choices; and an anomaly component, obtained from the altimeter sea height anomaly fields. In addition to the current velocity vectors, which are overlaid on the image, concurrent drifter paths can also be displayed superimposed to the current field. This feature serves as a way to visually compare and evaluate modeled and observed currents. Results can yield important information on the dynamics and structure of the upper ocean circulation. This implementation is a showcase of how altimetry can serve this purpose.

The fields of TCHP, a parameter proportional to the integrated vertical temperature from the sea surface to the depth of the 26C isotherm, are produced for each of the seven basins where tropical cyclones occur with a two-day delay. These fields are estimated within a two-layer reduced gravity scheme using near-real time sea surface temperature and climatological fields of vertical temperature. The TCHP fields have shown to be a critical tool to investigate the role that the ocean has in tropical cyclone intensification. Typical examples where the ocean has been closely linked to hurricane intensification are hurricanes Opal (1995), Brett (1999) and Katrina (2005). The validation of these fields are done in near-real using temperature profiles available through the GTS.

The spatial and temporal variability of several surface currents, which are key components of the Meridional Overturning Circulation (MOC) are also being monitored on this web site. One of the goals of this monitoring is to identify cycles in the variability of these currents that could be linked to climate signals. Some of the currents monitored through this project are the Agulhas and North Brazil Currents, and their associated rings, the Yucatan Straits and Florida currents.

The role of RADS in building the 15-year altimetric record

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To serve interdisciplinary research programs, applications and operational tasks on an international scale, operational observing systems like satellite altimetry call for International Services. DEOS anticipated this by launching the Radar Altimeter Database System (RADS) project in 2001. Since then RADS has been embedded in the Netherlands Earth Observation NETwork (NEONET) and as such has been supported by the Dutch government. In this project we set up and explored a facility to easily manage and access calibrated and validated altimeter data that are in many respects consistent throughout the data base. For this purpose we collected the altimeter and ancillary data from all available altimeter missions and combined them with the latest (correction) models and orbits, arriving at an internationally appreciated altimeter data set, comprising over 15 years worth of valuable sea level, wave height and wind data. To date, whenever new data (including the latest GFO, Jason-1 and Envisat data), models or knowledge arrive, the database is updated. This, however, is not RADS' only asset. Much effort has been put in the building of a data organization incorporating common data and meta file formats and ultra-flexible file data augmentation, in the development of a web-interface (rads.tudelft.nl), not only providing access to (almost) raw, processed and value-added data, but also access to other altimeter related information, and in the development of RADS data utilities like data extractors and converters, a collinear track analyzer and a multi-satellite crossover generator. The RADS system has successfully been deployed at NOAA, SOC, KMS, and at three universities in SE-Asia. At TUDelft it is used both for research and education.

ADS – A Data and Processing System for Altimetry

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Several groups on the national and international level are recently active in building up radar altimetry data services to

facilitate the access to upgraded and harmonized data to a broader community, especially the access to higher level products. GFZ Potsdam is currently developing the modular German Earth Science and Information System (GESIS). In the frame of GESIS the Altimeter Database System (ADS) has been already developed, implemented, and is being further improved.

The ADS module provides high quality altimeter data for a variety of different altimeter missions and, moreover, processing capabilities for radar altimetry data to a wide range of users. The ADS is an attempt to offer easy access to the daily growing satellite altimetry database and numerous geophysical correction models and orbits. Due to the effectiveness of the underlying data structure and software system, new missions and models can be added to the system at any time. The system has undergone several tests by users successfully and has been proven to be very useful. Especially to users not having convenient access to a satellite altimetry data processing system and a database, ADS offers new possibilities for research.

ADS can be accessed worldwide via the internet based user-interface "ADS Central" with a standard browser at <http://gesis.gfz-potsdam.de/ads>. After a supervised registration process the system offers higher level standard products, calculated routinely from the harmonized and inter-calibrated satellite database. Additionally, ADS allows generating individual user specific products. The user is able to perform several processing and analyzing steps, e.g. to generate mean sea surface height grids, to extract altimetry data time series around a given location, to analyze parameter variability, or to perform a crossover analysis.

The user can specify general parameters like the time interval or regional subsets and may select different correction models (e.g. tidal models). It is further possible to enter several quality parameters to optimize the data selection for individual applications. These user defined products are automatically processed by ADS at GFZ Potsdam and are subsequently distributed to the user by anonymous FTP.

Currently the use of ADS is offered to selected research groups only. However, the system will easily allow providing a service function capability for future altimetry services.

Steps towards an Operational Service using Near Real-Time Altimetry Data

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The measurements of the radar altimeter play a significant role in an ESA programme referred to as CAMMEO (for Co-ordinated Approach to Markets for Marine Earth Observation). The programme involves research centres and value-added companies working together with the Norwegian Meteorological Service to provide near real-time satellite information on sea-state alongside regular forecasts. Users of the service include shipping, search and rescue operations and other specialist marine operations.

The principal sensors providing data are the radar altimeters carried by JASON, Envisat and ERS-2, and the wind scatterometer on QuikSCAT.

The type of information that can now be made available to ships and other marine users with regular updates throughout the day following a satellite overpass, will be demonstrated.

An International Altimetry Service – focussing altimetry for global Earth observing systems

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Satellite altimetry has evolved into an operational observational technique and has demonstrated interdisciplinary application across oceanography, geodesy, hydrology, and glaciology, and geophysics qualifies itself as an essential component of global Earth observing systems (GOOS, GCOS, GGOS), coordinated by the international

program, the Global Earth Observing System of Systems, GEOSS. There is a generally accepted need for long, accurate time series of multi-mission altimeter data, which requires standards on formats, geophysical corrections and reference frames, as well as the knowledge of the long-term stability of altimeter and its ancillary sensors. The latter implies cross-calibration between past, present, and future altimeter missions as well as between different altimeter technologies (pulse limited, laser, lidar, wide swath, Delay Doppler, etc). All these requirements are best fulfilled by an International Altimeter Service (IAS), acting in a mission and agency independent capacity, with the purpose to advocate scientific and world-community use of satellite altimetry, and to promote further innovative applications of the sensor. International Services have been established after a comprehensive study commissioned by scientific organisations, including IOC/GLOSS, ESA, IAG. At present, it is proposed to be operating under the umbrella of the Federation of Astronomical and Geophysical Services (still under ICSU). They are in most cases based on voluntary contribution of processing and data centres working anyway with data and products. The most prominent example is IGS, the International GNSS Service, today recognised as an inalienable frame for the precise geolocation of sensors and satellites. This model can be adapted to the envisaged IAS which would be founded on voluntary contribution of existing national and international organisations and legal entities. The present paper reviews the feasibility and scope of an independent International Altimeter Service and discusses details on the current organisation plan and the proposed terms of Calls for Participation.

Session 7.2:

New Applications

Movement and accumulation of floating marine debris simulated by surface currents derived from satellite data

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Research results about movement and accumulation of floating marine debris drifting throughout the world's oceans were reviewed in this paper. A mechanism for the accumulation and the movement is strongly associated with surface currents consisting of Ekman drift and geostrophic current because all of floating marine debris is passive for surface currents. Geostrophic currents are derived from TOPEX/POSEIDON altimeter data, while Ekman drifts are derived from ERS/AMI data. We recognize the basic mechanism Kubota (1994) has shown for the North Pacific is common in the world ocean. After marine debris accumulates in the narrow Ekman convergence zone, these move to the east by geostrophic currents. Most important thing is that floating marine debris concentrates on some specific regions independent of the initial number of marine debris. It is demonstrated in this study that microwave altimeter data are quite useful for marine environmental problems.

Application of satellite altimetry for fisheries research

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Satellite altimetry data provide good possibility to reveal the zones of high dynamic activity, e.g. oceanic currents and fronts, mesoscale features, etc. The four oceanic region were

considered: Irminger Sea, Mid Atlantic Ridge (North Atlantic), Canary Upwelling Region (Eastern Central Atlantic), and Southeastern Pacific. Both satellite altimetry data (TOPEX/Poseidon, ERS -1, 2) and in situ measurements (oceanographic surveys) demonstrated good correlation between these two different types of data in revealing of dynamic features at the ocean surface. The main dynamic features in the regions are: Sub-Polar Front and North Atlantic Current (Irminger Sea and Mid Atlantic Ridge), Canary Current and coastal upwelling (Eastern Central Atlantic), Sub-Tropical Front and South Pacific Current (Southeastern Pacific). Analysis of distribution, abundance and biological state of various fish species revealed the links between organisms and their dynamic environmental conditions in the considered regions. Variability of the distribution and abundance of rock grenadier over Mid Atlantic Ridge is closely connected to variations of Sub-Polar Front location. Distribution of fishery grounds in the Irminger Sea coincides with dynamic heterogeneities at the sea surface elevation field. Distribution of small pelagic fish in Canary Upwelling Region is influenced by mesoscale features of Canary Current and coastal upwelling. Sub-Tropical Front meandering and eddies in Southeast Pacific influence significantly horse mackerel distribution. Thus the peculiarities of dynamic features of the ocean surface which can be derived by satellite altimetry might be a good opportunities for fisheries research.

New scientific applications for ocean, land and ice remote sensing with ENVISAT altimeter individual echoes.

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The Radar Altimeter on ENVISAT (RA-2) is the first space borne altimeter to provide average waveforms at two radar frequencies as well as bursts of up to 2000 individual echo samples at Ku band, in addition to standard altimeter geophysical products. This paper presents results of a recent study which investigates new scientific applications for ocean, land and ice remote sensing using ENVISAT RA-2 individual echoes. Examples of new applications include the possible use of RA-2 individual waveforms phase measurements to derive new ocean wave spectrum information and the development of improved re-tracking algorithms for rapidly varying land and ice surfaces. Analyses of bursts of individual echoes indicate much greater information content and that higher spatial resolution can be obtained over non-ocean surfaces than previously thought possible. Averaged waveform data at Ku and S band serve also to examine the change of response of ocean and land/ice surfaces with radar wavelength, with implications for a wide range of applications including vegetation and texture studies over land/ice, and rain cell and improved sea state measurements over the ocean and the coastal zone.

EnviSat Radar Altimeter Individual Echoes and S-band New Applications

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A unique feature of the EnviSat RA-2 is to provide bursts of individual, unaveraged Ku band echo sample data in phase (I) and quadrature (Q), at the full rate 1800 Hz. This data offers a unique possibility to assess the full capabilities of altimeter measurements.

Both technically and scientifically, much can be expected from these bursts of individual echoes, e.g., speckle characteristics over different altimeter scenes, ocean, ice, land, but also, potential blurring effects associated with range window changes during the 100 echoes on-board averaging. Moreover, for the first time in altimetry from space, investigations can be carried on the direct use of phase information from backscatter signals, opening a whole new line of applications.

EnviSat RA-2 also features a second frequency in S band. The combination between absolutely calibrated Ku and S band data can yield interesting improvement for wind speed, wave period, gas exchange estimates, etc.

ESA has run a study on this topic to seed the use of individual echoes by scientists. This study is completed and reconstructed echoes will be made available for the first time to the scientific community. Final results from the technical and scientific application of individual echoes and S band data will be presented.

Session 7.3:

Outreach

Introducing the Real Scientist: Using Outreach to Change Your Persona

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If on the Internet you do an image search for the word “scientist”, chances are that at the top of the hit list you’ll find images of a bespectacled old man in a white lab coat. You know and we know that this isn’t the real scientist at all. Unfortunately, this just might be the vision that enters the head of a pre-college student, a non-science teacher, or many people in the general public when they hear the word scientist. The profession itself may conjure up images of laboratories, Bunsen burners, and glass flasks, or worse yet; mad scientists producing strange creatures like those of Dr. Frankenstein.

How can you change this image? Your outreach team can help by suggesting ideas, products and venues. Community centers and civic organizations welcome science talks especially from someone actively engaged in the latest research. You’d be surprised at who is interested in what you do. To meet U.S. National Science Education Standards students receive some instruction in Earth sciences throughout the course of their pre-college education. It is not uncommon for teachers especially at the elementary level, to have little or no formal Earth science training of their own. In these cases your help is appropriate and appreciated and could be given in various ways from speaking in the classroom to providing input or feedback on written material. Career days are excellent programs that give you the opportunity to tell and show students that scientists are regular people who were once regular kids. Community colleges and universities often offer Earth science colloquia where invited speakers bring variety and the real-word perspective to the course.

The benefits of your participation in outreach are three-fold. Educators, students, and the general public learn first-hand about current Earth science research and technology; you fulfill the “greater good” requirement of your research activities; and, you help erase the myth of the nerdy scientist

by introducing yourself, the real scientist, to the public.

African Capacity Building in Satellite Altimetry with the UNESCO-Bilko Programme

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Capacity building in remote sensing is an important component of the first 5-year plan of GOOS-Africa, which began in 2004. Training future scientists and environmental managers in the use of satellite data is part of this strategy. With this in mind, the UNESCO-Bilko programme, supported by IOC and the European Space Agency, has begun developing teaching material for use in both distance learning and through workshops and courses across Africa and world-wide. In September 2004 a satellite altimetry workshop for environmental scientists and coastal managers from Kenya, Madagascar, Mauritius, Mozambique and Tanzania was held at the Luigi Broglio Space Centre in Malindi, Kenya. The workshop was based on material from remote sensing short courses run at the National Oceanography Centre, Southampton and used Bilko software and lessons to give participants hands-on experience in the use of satellite altimetry data. Two Bilko lessons were developed for the course, one using altimetry data with tide gauge sea-level data from the Western Indian Ocean, the other a study of eddies in the Somali current using SST and altimetry data.

The Bilko software is well suited for the African capacity building effort. Bilko is easy to use, demands only moderate computer resources, and supports a number of data formats commonly used in remote sensing, including NetCDF, HDF, USGS MapGen format and Envisat N1 format. It is specially written for educational use, supported by lessons that exemplify its power and which come complete with the images and other files needed. The lessons provide a step-by-step approach to data visualization and processing through hands-on activities supported by background information that makes them suitable for users working alone or in groups without direct access to remote sensing

expertise. All components are free to registered users.

The successful Malindi workshop was the first in a series of remote sensing training courses planned jointly by the Western Indian Ocean Marine Science Association (WIOMSA) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO, with support from the IOC Regional Programme for the Western Indian Ocean (IOCWIO), the Western Indian Ocean Satellite Applications Project (WIOSAP), the ODINAFRICA project (Ocean Data and Information and Information Network for Africa), and the Italian Space Agency. Other African training initiatives are also under development.

Outreach at CIOSS – The Cooperative Institute for Oceanographic Satellite Studies

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Outreach in the broadest sense is a prominent theme at the newest cooperative institute sponsored by NOAA/NESDIS: The Cooperative Institute for Oceanographic Satellite Studies. CIOSS has five Research Themes:

Theme 1: Satellite Sensors and Techniques: Development of satellite oceanography techniques and applications; evaluation of existing and proposed satellite sensors, algorithms, techniques and applications.

Theme 2: Ocean-Atmosphere Fields and Fluxes: Development, evaluation and analysis of improved fields of physical and biological parameters in the upper ocean, using combinations of remote sensing, in situ data and modeling.

Theme 3: Ocean-Atmosphere Models and Data Assimilation: Use of satellite-derived fields to force and evaluate numerical models of the oceanic and atmospheric circulation, including the assimilation of those fields using methods of inverse modeling.

Theme 4: Ocean-Atmosphere Analyses: Dynamical and statistical analyses of data sets derived from satellites, models and instruments, to increase our understanding of the physical, bio-chemical and societal processes that affect and are affected by the ocean.

Theme 5: Outreach: We include three broad Outreach areas, each to be related to CIOSS research and its results.

- Formal Education of students (K-12, undergraduate and

- graduate students), other scientists, resource managers and the general public in aspects of oceanography, surface meteorology and the use of remotely sensed data sets and numerical models.

- Informal Education of the same groups, but in contexts outside of the formal educational system, such as science museums, in short courses and workshops.

- Data Access includes activities that enhance the use of satellite-derived data sets by scientists, students, educators, resource managers and the general public.

Outreach to the scientific community is an integral part of Themes 1-4, as well as being central to Theme 5. For example, in Theme 1, CIOSS is helping NESDIS prepare for future satellites with research to develop algorithms for applications such as the detection of Harmful Algal Blooms by future multi-spectral sensors (HES-CW on GOES-R, etc.) and by evaluating the future passive microwave wind sensors. In Theme 2, it is helping the NESDIS CoastWatch program develop products to distribute, in support of the future Integrated Ocean Observation System (IOOS). In Theme 3, it is sponsoring workshops that will advance methods of data assimilation in coastal circulation and ecosystem models, another anticipated part of the IOOS system. Societal processes are also included in Theme 4. In this poster, we present some of the present and proposed activities within CIOSS.

Session 8.1:

The Future of Altimetry, part 1

Ka-band altimeter for future AltiKa oceanography missions

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In partnership with scientific laboratories and industry, and for several years, CNES has studied the feasibility of a high-resolution ocean topography mission named AltiKa, based upon a new class of wide-band Ka-band altimeter in preparation of the post-ENVISAT mission and in order to complement the OSTM/Jason-2 mission. The central objective is the retrieval of the ocean mesoscale circulation and data assimilation in global or regional ocean models. Moreover, other applications of the mission have been identified: coastal altimetry, continental water studies, ice sheet monitoring, low-rain systems characterization are the main “secondary” objectives identified so far. The proposed architecture for the Ka-band altimeter is based on the classical deramp technique for pulse compression and takes benefits of Alcatel and CNES experience from the realisations of Poseidon1, 2 & 3 and SIRAL (Cryosat mission). A bi-frequency radiometer is part of the compact Ka-band payload. Both altimeter and radiometer share the same antenna. Apart from the combined altimeter and radiometer, the AltiKa payload also consists of a DORIS plus LRA (Laser Retroreflector Array) orbitography system that will ensure a high level of accuracy in terms of orbitography. A preliminary definition study of a coupled altimeter-radiometer instrument has been performed in 2001-2003 with the support of Alcatel Space. At the present time, a delta phase B is being conducted, with an expected phase C/D at the beginning of 2006. Indeed, AltiKa payload could be embarked in the frame of a cooperation with ISRO (Indian Space Research Organisation) with an expected launch in 2009.

ITC and WatER: The Proposed Water Elevation Recovery satellite mission

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The water cycle and its associated hydrological processes are, as known and experienced by a majority of society, of a very dynamic nature both in space and time.

The core activities of the Water Resources (WRS) Department of ITC can be phrased as “develop and transfer knowledge in geo-information science and Earth Observation for water resources management and hydrology”, thereby combining water cycle science and water resource analysis and management with unbiased data acquisition from space and geo information technologies.

To this end, the WRS Department is engaged in scientific activities that require the Remote Sensing of surface hydrological processes and the WatER mission can compliment these activities by providing global centimetric accurate measurements of water surfaces at a high spatial and temporal scale.

For example, to determine flood effects on a regional scale at the confluence of the Megha and the Ganges rivers in Bangladesh, sequential multi-spectral satellite images and a band rationing technique to separate water and land was used. This approach reveals the spatial distribution of the inundated areas (flood stage mapping) and river dynamics (floodplain and channel alterations). When combined with measurements from a georeferenced active sounder, the changes of the river bottom can be mapped. Using water level measurements, flood volumes can be determined and predictions on possible future flooding can be made. The water levels are nowadays mostly recorded using staff gauges or (automatic) water level recorders and are of limited spatial coverage. The WatER mission could improve on flood predictions and flood damage assessments because it will help us better understand flood dynamics spatially and temporally.

WatER can also improve on hydrological and environmental studies. The WRS Department has been carrying out M.Sc. fieldwork in the Lake Naivasha area in Kenya for almost 10 years. Here, the water balance of the Lake Naivasha basin is

highly dynamic and natural fluctuations of the lake level during the last century have been as much as 8 meters. The lake level was used to calibrate hydrological models of the catchment by comparing simulated and measured lake levels. Once calibrated, future lake levels can be forecast using change scenarios that evaluate changes in e.g. population or climate, and lake management can be improved.

The intensive collaboration of ITC with the Institute of Tibetan Plateau Research of the Chinese Academy of Sciences has established the long-term monitoring of the water cycle and climate processes on the Tibetan Plateau, in particular the surface waters, e.g. the levels of the Namqu Lake as influenced by increased global warming. Having access to global lake water levels as provided by WatER makes it possible to not only study ungauged lakes, but also the dynamics between (gauged) lakes.

The expertise and global network that ITC obtained in its 55 years of existence, can also contribute to the WatER mission. Providing access to its network for mission validation purposes and sharing expertise on the use of Earth Observation technologies and GIS science for problem-solving water resources issues with users of the WatER mission data are a few examples.

Contribution of wide-swath altimetric cross-track measurements in the North Sea – Impact of the satellite roll errors

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The classical nadir-observing altimetric satellites, such as Topex Poseidon or Jason, provide the scientific community with sea level data from single measurement points under the path of the satellite. Though sufficient to efficiently capture the wide scale ocean dynamics, they are not well designed for coastal ocean applications. The interferometric technology such as the one which had been proposed for the Wide Swath Ocean Altimeter (WSOA), by measuring the sea level also in the cross-track direction, may be a good way to reach the space and time observation requirements to capture the coastal ocean dynamics. In this study, we develop a simple configuration of an observing system representing the WSOA contribution. It is composed of a 10 day orbit satellite measuring both the sea level and the oceanic slope at the nadir. The impact of this system is evaluated using a 2D barotropic model of the North Sea, and by assimilating the simulated observations by the EnKF

technique (Mourre et al., 2004). The slope measurement happens to have a wider influence zone than a single sea level measurement, and to significantly improve the reduction of the current velocity error variances. This system is also used to investigate the impact of the roll of the satellite. Indeed the interferometer is much more sensitive to the platform behavior, whose roll can lead to large measurement errors if not adequately processed. The EnKF is currently one of the best assimilation techniques for dealing with non linear errors, such as roll errors which exhibit correlation along the track of the satellite. As an overall result, these roll errors do not seem to significantly deteriorate the quality of a cross-track observation system based on a wide-swath instrument.

Relative performances of WSOA, altimeter constellations and tide gauges in controlling a model of North Sea barotropic dynamics

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The relative abilities of different possible future altimeter systems to control model error due to uncertainties in bathymetry in a barotropic model implemented on the North Sea shelf are estimated in this work. The focus is on the specific high-frequency response of the ocean to meteorological forcing, involving temporal scales from a few hours to a few days. Due to the specificities of the shelf dynamics, a special attention is paid to properly specify the shape and evolution of model error statistics, that are needed to assimilate sea level data into the model. Ensemble methods are used for this purpose, and model error due to uncertainties in bathymetry is more specifically studied. The finite-element barotropic model MOG2D is run over an ensemble of perturbed bathymetric solutions to approximate error covariances. An ensemble Kalman filter is then implemented to assimilate data in the model.

We performed multiple twin experiments to assess the capability of different observing scenarios to reduce model error (in the framework of so-called Observing-Systems Simulation Experiments). The diagnostic is based on the reduction of the ensemble spread thanks to the assimilation. The contributions of the Wide Swath Ocean Altimeter and different satellite constellations are first investigated. In the context of North Sea dynamics, a single WSOA has similar performances than 2 nadir satellites in terms of sea level correction, and is better than 3 satellites in terms of model

velocity correction. Due to the short temporal scales of the particular oceanic processes under consideration, the temporal resolution of observations is shown to be of major importance for controlling model error in these experiments. Such altimeter systems are precisely shown to lack temporal sampling to properly correct the main part of model error here. Tide gauges, that provide the required very fine temporal resolution, are then considered. In this particular context, they lead to very good global statistical performances. Looking into further detail, tide gauges and altimetry are demonstrated to exhibit some interesting complementarity, since high-resolution altimeter systems are more efficient on the inside of the shelf, whereas tide gauge networks make it possible to properly control model error in a ~ 100 km coastal band.

Session 1.4:

Oceanography: Tropics

Impacts of subtropical upper ocean variability on equatorial Indian Ocean

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The region between the core of the trade winds and the maximum westerlies which stretches around the globe between approximately 20° and 45° on either side of the Equator, is characterised by negative wind-stress curl in the atmosphere and by associated Ekman transport convergence in the ocean. The seasonal Indian and Asian monsoons affect the entire tropical Indian Ocean and western Pacific regions. Studies have shown that the interannual and interdecadal variability of air-sea interaction in the southern subtropical Indian Ocean are directly connected with the air-sea interactions of the tropical Indian Ocean. In the northern part of the zone the prevailing winds are light and variable, while in the southern area moderate to strong westerly winds prevail. Furthermore, studies of in situ measurements and a model-assimilated dataset reveals a strong influence of subsurface thermocline variability on sea surface temperature (SST) in this upwelling zone. In this study, we examine the sub-tropical upper ocean variability of temperature and salinity from ARGO, XBT and assimilated data sets. POP OGCM high resolution simulations are made to understand the zonal/meridional circulations and their contributions to the equatorial thermal structure. The weekly SSHA (TOPEX/JASON) datasets are used to measure the heat content variability in this above region. The results show that the sub-tropical variability significantly affects the tropical Indian Ocean. Moreover results indicate that the year to year off-equatorial sub-surface temperature variability may be due to remote forcing such as ENSO.

Investigating the Tropical Atlantic Ocean Variability from ARAMIS and Altimetry

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The ARAMIS program (Altimétrie sur un Rail Atlantique et Mesures In Situ) has been developed by the french IRD (Institut de Recherche pour le Développement) and CNES (Centre National d'Etudes Spatiales) organizations in order to get a long term survey of temperature, salinity and pCO₂ structures in the tropical Atlantic along a merchant ship line during at least 5 years. The line crosses the major equatorial currents, the InterTropical Convergence Zone and the Atlantic regions of Maximum Salinity Water around 20°S and 30°N. The line is also interesting as it is superimposed to one of the JASON tracks. Twice a year, in March then October, when the tropical Atlantic oceanic circulation reaches its minimum/maximum intensity, temperature and salinity profiles are obtained along the ship route between 20°S and 30°N every 30' of latitude, together with other on-route acquisitions. The first 2 ARAMIS cruises, in July 2002 then March 2003 were dedicated to JASON validation in the tropical Atlantic Ocean. During the more recent ARAMIS cruises, seawater samples have also been taken on board and ARGO floats launched. We will present the first results of the 2002-2005 campaigns together with the altimetric Jason series in terms of surface layers dynamic investigations in the tropical Atlantic ocean.

Comparison between 1997 and 2002 El Niño Events: Role of Initial State versus Forcing

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Within the past 15 years, a series of ocean and atmosphere remote sensing satellites (e. g., TOPEX/Poseidon and now Jason 1) have been launched that serve to supplement and enhance the coverage and latitudinal extent of the in situ observations being taken at the surface, and at depth, in the equatorial Pacific Ocean. The 1997 "El Niño Event of the Century" and the weaker 2002 event were the best monitored El Niños on record from the perspective of in situ and space-based observations. The 1997 El Niño was the first time a major El Niño event was observed from start to finish with a combination of remotely-sensed measurements of sea surface temperature, sea surface topography, sea surface winds, ocean color, and precipitation. This presentation will analyze the evolution of the 1997 and 2002 El Niño events from the perspective offered by several of these remotely sensed observations, data assimilation, modeling and coupled models. In particular we will isolate the differing roles of initial conditions and forcing that gave rise to the distinct nature of these two events.

Long time series of high quality ocean surface topography information allows a thorough comparison between two distinct El Niño events. The 1997 El Niño showed a strong ocean-atmosphere coupled system which propagated from west to east. The weaker 2002 event developed later in the calendar year and showed strongest anomalies near the dateline. In this study, observational data of sea level and sea surface temperature (SST) from satellite, and subsurface temperature and salinity (from all available sources including ARGO) are used along with data assimilation to improve the initial state of the ocean. Ocean model experiments are used to isolate differences between initial states of the system and forcing in the development of the two events. A statistical atmospheric model is utilized to highlight the atmospheric response to anomalous SST fields.

Different initial conditions (IC) for Nov 96, Nov 01 and Nov Climatology are used to initiate model experiments with climatological ECMWF forcing for the two El Niño periods (Nov 96-Dec 97, Nov 01-Dec 02). By differencing two experiments with the same forcing, but different ICs, the role of the ocean state at the start of the two events (Nov 96 versus Nov 01) can be examined. These results show that both initial conditions are predisposed to induce a subsequent El Niño. However for the first half of the 1997 event (Nov 96- Jun 97) the initial state of the ocean induces an eastward propagating wind field. For the 2002 event, the

initial state served to limit the eastward propagation of the wind field by inducing destructive interference near the dateline. For the second half of the event (Jul 97 - Dec 97) the initial state contributed little. However, the role of initial conditions contributed nearly half the total signal for the 2002 event.

In the same way that the role of the ICs can be isolated, the role of the different forcing fields can be identified. These results show that for both events forcing played a very weak role over the first half of the year. (In fact the statistical wind anomalies for these periods showed anomalous easterlies.) However, for the second half of the 1997 event the air/sea coupled forcing accounts for nearly all the wind anomaly. For the 2002 event, ICs and forcing contribute approximately equally to the wind anomaly field.

Session 1.2:

Oceanography: Coastal

A new approach to retracking ocean and coastal zone multi-mission altimetry

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The primary function of satellite radar altimeters has historically been the measurement and monitoring of the ocean surface. Most researchers utilise pre-processed altimeter products, optimised for precise range measurements to an ocean surface, using retracking algorithms which assume a Brown model waveform. However, a significant number of echoes returned from the ocean surface do not conform to this model. As the coast is approached, the percentage of Brown model echoes decreases rapidly, and the standard processing algorithms reject most of the data.

This paper presents results obtained by reprocessing ocean echoes using a rule-based expert system, which includes both Brown model algorithms and a range of algorithms configured to identify and retrack to ocean components within complex returns. This system also permits a much greater proportion of echoes from sea-ice to be successfully retracked. Using this system, ocean echoes from the Topex, Jason-1, ERS-1, ERS-2 and Envisat missions have been reprocessed globally, including the ERS-1 Geodetic Mission. Utilising this huge multi-mission dataset, a global comparison is made with results from standard altimeter products, and the enhancements in data quantity and quality which can be achieved using this approach is quantified.

Eddy-Mediated Transport Along Eastern Boundaries

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One of the advances in our understanding of the ocean that altimeters have demonstrated (in combination with other

satellite and in situ data) is the ubiquitous presence of mesoscale eddies along the eastern boundaries of the Pacific and Atlantic Oceans, at all latitudes. Several different processes create both cyclonic and anticyclonic eddies over or next to the continental shelves, which then propagate to the west. These eddies affect the offshore transport of water with coastal characteristics (including higher nutrients and plankton populations) in at least two ways. The first is the alternating onshore-offshore currents associated with the eddies. Combinations of altimeter data with satellite-derived pigment concentrations (from ocean color) and SST (from IR) demonstrate this at mid- and high-latitudes. The second mechanism involves the transport of water in the core of the eddies, as they propagate to the west. An unanticipated result is that both anticyclonic and cyclonic eddies can trap richer, coastal water and transport that water offshore within their centers, maintaining higher phytoplankton populations than the surrounding water. The normal expectation is that open ocean anticyclonic eddies depress the nutricline and suppress primary production.

At higher latitudes in the NE Pacific, anticyclonic eddies in the Gulf of Alaska have been examined in detail by a number of studies. These form along the eastern boundary and propagate westward in the open ocean and along the shelf-break of the northern boundary. They both pull shelf water offshore around them and maintain a core of richer water that continues to support phytoplankton populations for many months. At similar latitudes off southern Chile, anticyclonic eddies also form along the boundary and carry richer coastal water offshore, as shown by combinations of altimeter and ocean color data. An example is shown of a particularly strong and persistent eddy that formed during the 1997-98 El Niño and continued to have both SSH and color signals for over a year. Eddies off southern Chile have not yet been studied in detail.

At (higher) mid-latitudes, similar formations of anticyclonic eddies occur in winter, under downwelling conditions. Examples are presented in both hemispheres, using altimeter and ocean color fields. During persistent upwelling conditions, alternating cyclonic and anticyclonic eddies pull water off the shelf, often keeping the richer water inshore of a meandering jet. Field data off Chile show that cyclonic eddies that break off from the jet can also carry coastal water (with undercurrent characteristics) in their core. Subsurface (undercurrent) water is also seen in eddies at low latitudes in the SE Pacific. Eddies appear less long lived at mid-latitudes (weeks to several months) than at higher latitudes. At lower latitudes in the NE Pacific, a unique process forms eddies of both signs off Central America, due to wind jets through the mountain gaps. Anticyclonic eddies persist longer than

cyclonic eddie, also carrying water with characteristics of the eastern margin.

Session 5.3:

The 15-Year Altimetric Record/Long time series

Decadal Variability in the Large-Scale Sea Surface Height Field of the South Pacific Ocean: Observations and Causes

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Large-scale sea surface height (SSH) changes in the extratropical South Pacific Ocean are investigated using satellite altimetry data of the past 12 years. In the midlatitude region south of 30S, the decadal SSH signals are dominated by an increasing trend in both the western basin around New Zealand and the eastern basin centered around 45S and 105W, and a decreasing trend in the central South Pacific Ocean poleward of 50S. Spatially-varying, low-frequency SSH signals are also found in the tropical region of 10-25S where the decadal SSH trend is negative in the eastern basin, but positive in the western basin. To clarify the causes for these observed spatially-varying SSH signals, we adopted a 1.5-layer reduced-gravity model that includes the wind-driven baroclinic Rossby wave dynamics and the responses forced by SSH changes along the South American coast. The model hindcasts the spatially-varying decadal trends in the midlatitude and the eastern tropical regions well. Accumulation of the wind-forced SSH anomalies along Rossby wave characteristics is found to be important for both the long-term trends and their reversals in recent years. While it has little impact upon the midlatitude interior SSH signals, the boundary forcing associated with the time-varying SSH signals along the South American coast is crucial for the observed SSH signals of all timescales in the eastern tropical South Pacific basin.

Large-scale decadal changes of sea level in various parts of the worldrnocean

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The time covered by sea surface height (SSH) measurements derived from the TOPEX/Poseidon and JASON-1 altimeters allows a glimpse of decadal variability superimposed on longer-term changes. Many large-scale changes are found in various parts of the world ocean on these time scales. One conspicuous example is the rising SSH in the western tropical Pacific and southeastern Indian Ocean. This increase of SSH is observed for the period of 1992 to 2000. After 2000, the SSH in the region stabilizes and even begins to drop in recent years. A similar feature is seen from the SSH at mid-latitude southwestern Pacific (around New Zealand). These features suggest the influences by decadal oscillations such as the PDO that leaves a large footprint in the Indo-Pacific region. In the Atlantic Ocean, the SSH in the Gulf Stream extension and North Atlantic Current regions display a general decreasing trend while that at mid-latitude southwestern Atlantic rises consistently. The ECCO assimilation products capture many of these observed changes. These products are used along with model sensitivity experiments to diagnose the forcing mechanism of the decadal SSH changes (e.g., wind versus buoyancy forcing, local versus remote forcing) and the implications to ocean circulation (e.g., horizontal gyre and meridional overturning).

How much of the interannual-to-decadal fluctuations of the Indian Ocean Sea-Level is due to atmospheric forcing and to connections with the other oceans?

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oceanic boundaries play a significant role in feeding back onto inter-annual-to-decadal Indian atmosphere fluctuations, and also affect the intra-seasonal-to-seasonal variations of the Indian monsoons.

Sea-level variations relative to the 1980-1996 climatology are derived from XBT/TOPEX/Poseidon/Jason data for 25 years up to 2005 in the Indian and Pacific Oceans. The variations are averaged over the width of the ocean in latitudinal bands: [5°N-20°N] for the North Pacific, [5°S-20°S] for the South Pacific, and [30°S-5°S] for the Indian Ocean. When multiplied by their respective surface areas, the Indian-Ocean variations are as strong as for the Pacific, even though the Indian surface area is only one third that of the Pacific. To quantify the wind-induced sea-level variability, we apply the Sverdrup relationship to the FSU wind stress data. The observed and wind-determined variations are then integrated in time to focus on their cumulative effect at all frequencies. With opposite trends in the South and North, the Pacific Ocean is in balance with its wind until 1997/1998, while for the 25-year period the Indian Ocean sea-level variations are positively correlated to the North Pacific signal. The Indian Ocean and its winds reach balance in the early 90s, after 10 years of opposite trends. Note also that its sea-level accumulation drastically drops between 1998 and 2003.

We examine Indian Ocean sea-level, together with wind variations and internal ocean/atmosphere processes using a regional Indian Ocean model forced by FSU winds and GPCP rains since 1980. The model formulation allows for the decomposition the simulated sea level in terms of mass, heat and salt changes that are only due to the Indian atmospheric forcing or to the combination of surface and lateral forcings. In particular, we focus on the part played by the rain, heat flux and nonlinear advection on the basin sea-level variations. The southern boundary and Indonesian Throughflow transport variations are also addressed. In our control experiment, no flow from the Pacific is allowed, while the flow simulated across the 30°S boundary is controlled by a correction applied to conserve volume. Twin experiments are carried out, in which model conditions at the southern and eastern boundaries are modified by prescribing the 1980-2005 variations of inflow/outflow obtained from applying geostrophy to the XBT/TOPEX/Poseidon/Jason sea-level data along the boundaries. Then, using a tropical atmosphere model forced by the SSTs simulated by these different Indian Ocean experiments, we find evidence that the XBT/TOPEX/Poseidon/Jason prescribed at the lateral

Session 5.4:

The 15-Year Altimetric Record/Mean sea level

A 20th century acceleration in sea level rise and decadal impact on GMSL of volcanic eruptions

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Multi-century sea-level records and climate models indicate an acceleration of sea-level rise, but no 20th century acceleration has been detected. A reconstruction of global sea level using tide-gauge data from 1950 to 2000 indicates a larger rate of rise after 1993 and other periods of rapid sea-level rise but no significant acceleration over this period. We extend the reconstruction of global mean sea level back to 1870 and find a sea-level rise over the period January 1870 to December 2004 of 195 mm, a 20th century rate of sea-level rise of $1.7 \pm 0.3 \text{ mm yr}^{-1}$ and a significant acceleration of sea-level rise of $0.013 \pm 0.006 \text{ mm yr}^{-2}$. This acceleration is an important confirmation of climate change simulations which show an acceleration not previously observed. If this acceleration remained constant then the 1990 to 2100 rise would range from 280 to 340 mm, consistent with projections in the IPCC TAR.

From 1960 to 2000, volcanic eruptions contribute to the interannual variations in the rate of sea-level rise. Ocean observations and a set of climate simulations show that large volcanic eruptions result in rapid decreases in ocean heat content and global mean sea level (about $3 \times 10^{22} \text{ J}$ and 5 mm for the Mt Pinatubo eruption). The recovery of sea level following the Mt Pinatubo (1991) eruption contributes significantly to the difference between the 1950 to 2000 rate of sea-level rise (1.8 mm yr^{-1}) and the higher rate estimated for the modern satellite altimeter era (3.2 mm yr^{-1} for 1993-2000).

An Assessment of IPCC 20th Century Climate Simulations Using the 15-year Sea Level Record from Altimetry

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Recently, multiple ensemble climate simulations have been produced for the forthcoming 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Nearly two dozen coupled ocean-atmosphere models have contributed output for a variety of climate scenarios. One scenario, the climate of the 20th century experiment (20C3M), produces model output that can be compared to the long record of sea level provided by altimetry. Validation of the 20C3M experiment results is crucial to the goals of the IPCC. Generally, the output from these runs is used to initialize simulations of future climate scenarios. We present comparisons of global mean sea level, global mean thermosteric sea level change, and regional patterns of sea level change from these models to results from altimetry, in situ measurements, and reconstructions.

Session 4:

Hydrology and Land Processes

Lake level change in China from TOPEX/Poseidon altimetry: climate implications

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More than 10 years of TOPEX/Poseidon (T/P) altimeter data were used to compute time series of lake levels at six inland lakes in China. To verify our T/P data processing strategy, the T/P-derived lake levels at the Bosten Lake (west China) and at the Huron Lake (north America) are compared with lake gauge records, yielding good agreement between the T/P and the gauge results. Wavelet spectra indicate annual and interannual variations of these lake levels, which are also sensitive to climate variability. At the interannual time scale, the lake levels of Hulun (north China), Bosten (west China) and Ngangzi (east Tibet) are correlated with precipitation and ENSO, in particular they all respond to the 1997-1998 El Niño. The Bosten Lake level increased monotonically since 1993 due to increased temperature in Tianshan Mountain that feeds water into this lake. The lake levels of Hongze and Gaoyou (east China) show minor decreasing trends. The lake level of La'nga (west Tibet) decreased steadily from 1993 to 2001 with a total drop of 4 m. The lake level of Ngangzi decreased from 1/1993 to 12/1997, but after the peak of the 1997-1998 El Niño the slope was reversed and the lake level increased monotonically till present.

Caspian Sea water level fluctuation: comparison between ground measurements and altimetry

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The Caspian Sea is the largest inland water body of the world. The total basin catchment covers more than 3 billions of km², and the sea is fed by numerous rivers including the Volga, Ural, Terek, and Kura rivers. In the last 25 years the total surface area has varied from 360000 to 400000 km² due to high water level variations. These have shown oscillations between -26 and -29 meters (with respect to the zero ocean level) during the last hundreds years. The Caspian Sea is characterised by quasi - cyclic and high amplitude water level variations over historical time scales. For 2000 years the fluctuation were around 15 meters and for the last five centuries ~7 meters, noting extreme level oscillations of -23 m in the mid XVII century, and -29 in 1979. These are considerable sea level changes that merit an investigation of their causes and potential impacts. Coastal and delta areas are strongly affected by these events with subsequent damages on infrastructure and recurrent ecological disasters. Adaptation of human activities in the catchment area, efficient uses of water resources, sustainable development of the region, and ecosystem protection near and around the Caspian sea (human life, terrestrial and marine fauna and flora) fundamentally depend on the variations of the Caspian sea water level variations studies and analysis of the detailed water balance among other axes of research. The water balance of Caspian Sea is principally controlled by variations of Volga river and evaporation rate. The Volga river provide more than 80% of the total inflow, and dictates interannual variability of the Caspian sea. Other hydrological components (precipitation, evaporation, underground water, and river discharge to Kara Bogaz Göl) also influence seasonal and inter-annual variation of Caspian Sea. Investigations of water balance is based on more than a hundred years of in-situ data based on the network of hydrometeorological stations homogeneously scattered along the coast and Islands of the Caspian Sea. Since the

beginning of the nineties, however, altimetry measurements also provide precise measurements of Caspian Sea level variation. Comparison between ground measurements, hydrological in-situ data and altimetry allow to better understand the water balance of this water body. Spatial variability of the Caspian sea level variation is also studied through altimetry measurements. This showed the major impact of Volga river discharge.

Multi-Mission Radar Altimetry: Dynamics of the Amazon River

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Studies of river dynamics are important with relevance to the understanding of basin hydrology, engineering hydraulics analyses, and to sediment transport studies. The variation in river discharge and stage (elevation), river width and channel slope, and the inflowing volume and storage effects of tributaries and floodplains respectively, are all required parameters. The majority of such measurements are gained by ground-based methods, though they can be limited in quality and quantity for some regions. Satellite radar altimetry can provide measurements, accurate to tens of centimeters, for the largest rivers, and test-case studies have further demonstrated the ability to infer discharge and water-surface gradient, when combined with additional ground-based or remote sensing information.

The seasonal pattern of the water-surface gradient along a river is the combined effects of the hydrological inputs at each section and its conveyance capacity. The flow of the Amazon River receives significant and varying contributions from many major tributaries. With a low bed gradient, the passing through of the seasonal flood wave along the Amazon's main stem does alter its water-surface slope but tributary effects are unknown. Altimetric stage measurements from the Topex/Poseidon mission revealed the timing and amplitude of the peak flows of the Amazon and the spatial variation of the water-surface gradient between river reaches. The temporal variation of river gradient revealed hysteresis characteristics (between river gradient and discharge or stage) and gave a first insight into the nature of the seasonal peak-flow flood wave and the additional controlling effects of the major tributaries.

A new NASA-funded program will further these Amazon river studies via the use of current synergistic multi-sensor altimetric datasets. The increased spatial resolution will enhance the existing knowledge of the water surface

gradient along specific river reaches. The increased temporal resolution will allow observation of the variability of the deduced gradients in lieu of flood-wave and tributary influences. This presentation summarizes early gradient results based on the Topex/Jason tandem mission, and explores stage measurements from the ERS, ENVISAT and GFO missions. Emphasis is on the quality and quantity of the new measurements with special focus on the merger of the varying data sets. Target width limitations and the separation of floodplain effects from river channel variations will also be discussed.

Establishment of an Altimetric Reference Network over the Amazon Basin using Satellite Radar Altimetry (Topex Poseidon)

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Satellite radar altimetry (Topex/Poseidon T/P) was used to establish a consistent altimetric reference network over the Amazon basin.

A methodology was developed to quantify maximum annual water levels (referred to the geoid, using EGM96 geoid model) at intersections between the satellite ground tracks and the river network. Maximum annual water levels (referred to the geoid) at hydrometric stations were then derived using longitudinal interpolation. Comparison with maximum annual readings at gauges allowed the determination of local orthometric heights at these stations. Altimetric leveling from Topex/Poseidon measurements has been realized for 97 hydrometric stations along 27 740 km of the Amazon hydrographic network. Validation has been realized both by checking the overall hydraulic consistency of longitudinal river profiles at low and high river stages and by comparing, for 23 hydrometric stations, orthometric heights obtained from T/P measurements with values obtained from bi-frequency GPS positioning. Results show a good agreement between the two techniques (average root mean square error of 0.05 +/- 0.64m). This levelling method allowed the identification of discrepancies in direct geometric land leveling results from Brazilian and Peruvian networks.

These results are of major importance for the study of

Amazon river flow dynamics and sediment transport.

Using GRACE Gravimetry and Satellite Altimetry for water Storage studies in the Amazon Drainage Region

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We have jointly analysed GRACE and Satellite altimetry over the Amazon River Basin in order to resolve time-variable hydrological changes. The GRACE gravity changes are analysed using a local mascon approach derived by NASA/GSFC. In this approach it is possible to solve for mass change at 10-day intervals using 4 deg X 4 deg blocks from GRACE level 1B data. Satellite altimetry over the region from especially ENVISAT and JASON-1 has been processed using the EARRS Expert-retracker System. The system recovers substantially more accurate altimetry data over lakes than traditional altimetric data processing.

By combining the mass change estimated by GRACE with the observed lake level height we could both validate the two sets of observations. However, it is also possible to resolve the hydrological change in terrestrial water storage and changes in the observed lake volume.

Data from 2002 through 2004 have been studied to investigate hydrological changes on monthly to inter-annual time scales.

Session 1.5:

Oceanography: Tides

Toulouse Global and Regional Tidal Atlas : a review on progress and recent result in tidal science and products

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The Topex/Poseidon project has triggered one of the most important effort in the tidal science in the last 20 years. Both empirical and modelling approach have been widely developed and used in conjunction to improve our knowledge on the tidal dynamic over the global ocean. Not only the tides can now be predicted within a few centimeter accuracy all over the ocean, but also the understanding of the physic and energy budget of the tides has seen a striking move forward. In this field, the most impressive result of the Topex/Poseidon mission was to make us rediscover, and quantify, the importance of the barotropic tide dissipation through the energy conversion toward the internal waves. The state-of-the-art of the tidal science has taken advantage of these results, and the accuracy of purely hydrodynamic tidal solution is now up to three time better than it was in 1990. The improvement of the tidal atlas in shelf and coastal regions is now the new challenge of the tidal community, and the latest global (FES2004) and regional tidal atlas designed for altimetry de-aliasing are presented

Tide Simulation Using Regional Ocean Modeling System (ROMS)

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A three dimensional general circulation model (ROMS) is

used to simulate tides along the central western coast of US. The model is three-level nested with the finest resolution of 1.6 km in the Monterey Bay region. The motivation of the study is to test the capability of ROMS in simulating tides and to develop an operational forecasting system for the region. Forced by tidal signal along the open boundaries in west, north and south directions, ROMS can simulate tidal signal reasonably well in the region. The total error of the amplitudes of eight major constituents, measured by root of summed squares, is less than 4 cm in the open ocean compared with tide amplitudes estimated by satellite altimetry observation. Along the coastal region, the error of amplitudes is less than 6 cm which is about 10% of the amplitude of the most energetic M2 constituent. For these major tide constituents, the phase error is less than half hour. A comparison of hourly sea level for August of 2003 shows a RMS error of 8 cm, with slightly less error in the finest model domain. Comparing with barotropic tide models, the tide simulation from a general circulation model is not sensitive to model parameters such as bottom drag coefficient. The addition of tide signal in the ROMS model is a significant step toward an operational forecasting system of the Monterey Bay region.

Coastal Ocean Tide Modeling Using Multiple Satellite Altimetry

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Due primarily to the availability of TOPEX/POSEIDON (T/P) satellite altimetry, and advances in numerical modeling methodologies, semidiurnal and diurnal barotropic ocean tides are known in deep ocean (depth>1000m) to within 2 cm rms and with a spatial resolution longer than 50 km. Tides are much less well known in the coastal regions, over continental shelves and in polar oceans, due primarily to limited observations, inadequate spatial resolutions and

complicated spectra caused by non-linear hydrodynamics, including internal or baroclinic tides. Poor knowledge of coastal tides is also a primary limitation for nowcast or forecast coastal or shallow shelf circulations. We report our progress to use multiple satellite altimetry, including JASON-1, T/P, ERS-1, ERS-2, ENVISAT and GFO, to determine barotropic ocean tide models in the coastal regions, including Yellow Sea, East China Sea, Sea of Japan, Patagonia, Indonesian Sea, Atlantic Canadian Shelf and Hudson Bay. Both along track SSH anomaly data and SSH anomaly data at single or dual satellite crossover locations are generated from satellite altimetry stackfiles and used in empirical tide modeling, with the next step to use these point solutions for assimilated modeling. We compare the barotropic tide solutions and the Tokyo University internal tidal prediction with other solutions and with an assimilated solution which generates both barotropic and baroclinic tides in the NW US coastal ocean.

Non-linear tides in shallow water regions from multi-mission satellite altimetry (The Northwest European shelf)

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Accurate sea level measurements from the TOPEX/POSEIDON satellite have vastly improved our knowledge about global ocean tide since its launch in 1992. One of the outstanding problems in global tidal modelling is accuracy in shallow water regions, where complex tidal pattern, and non-linear tides degrade the global model. This calls for high resolution tidal modelling and inclusion of non-linear shallow water constituents. These constituents cause a considerable part of the tidal variability on the shelves. On the northwest European shelf the tides are dominated by semi-diurnal constituents and their shallow water constituents (M4, MS4, MNS2, MN4, and M6). One example is the M4 constituent, which exceeds 30 cm in the English Channel. New tidal models for the non-linear tides have been derived using coastal tide inversion, assimilating multi-mission altimetric observations into high resolution hydrodynamic models. Shallow water tides have shorter spatial wavelength, and the importance of high quality bathymetry and altimetry from both the T/P and the recent interlaced T/P Tandem Mission will be demonstrated

The Observation of SAR, Optical and Altimeter Data to Study the Generation of Internal Waves in Tsushima Strait

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The internal wave signatures have been detected in ERS1/2 and ASTER images data over the Tsushima Strait, Japan, during 1993-2004 period. The study area is located at northern side of East China Sea, well known as a region where energy for exciting internal tides should be large. Wavelet transform analysis and spectral reflectance analysis have been performed to delineate internal wave from sea surface wave and other oceanic features. Discreet Meyer wavelet transform analysis has been applied for internal wave detection in image, which succeeded in emphasizes the internal wave features 2-4.59 times, on horizontal and vertical detail coefficient of image transforms, compare to wind waves and sea surface features. Discreet Meyer wavelet is proposed for smoothness of feature, space save coding, and to avoid depashing in image.

The observation results show that the profile of a train of internal waves in ERS1/2 SAR and ASTER images data composes a formation of several taller waves, which the leading wave as the tallest one, and smaller depressed waves at one-third section. This shown that non-linier process was taking a part in transformation of internal tide into a train of independent solitary waves. The non-linier internal waves were occurred in north coast off Kitakyushu and NW/W/SW/E coast off Tsushima Island between June-September. The length and wavelength of the internal waves were detected between 6-28 km and 120 m-1.28 km, respectively.

The altimeter data products from Topex/Poseidon and Jason-1 data are used to analyze the ocean dynamic over the study area. In the Tsushima Strait, the geostrophic current generally flows from SW direction yearly around. During summer, the small-scale eddies appear at NE and SE coast off Tsushima Island, due the effect of current flows at south of the Japan Sea. The directions of internal waves were varied between NW-SW at eastern channel and N-SW at western channel of Tsushima Strait, parallel to the direction of the geostrophic currents. Meanwhile at NE coast off Tsushima Island, the internal wave packet propagates to S/SE direction. Internal wave is modeled using Combined of Korteweg de Vries equation. At eastern channel of Tsushima Strait, the internal wave induced current is calculated about 85 cm s⁻¹. The occurrences of internal waves were coincided to the area where the sea surface height anomaly increase steeply, e.g. between 2-6 cm. It is suggested that the internal waves were sourced from south coast off Tsushima Island and south coast off the Japan Sea. They were tidally

generated and formed due to bathymetric change.

evaluations, in particular, over sea ice and ice shelves.

Ocean Tide Modeling in the Polar Oceans

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Ocean tides play a significant role in climate due to its complex interactions between ocean, atmosphere, solid Earth and sea ice. Tides have strong effects on circulations near coastal regions or on continental shelves [Mofjeld et al. 1995; Han, 2000]. Tidal currents create turbulent mixing [Munk and Wunsch, 1998], tidal dissipation affects oceanic transport and thus climate [Wunsch, 2000; Egbert and Ray, 2000; Ray and Cartwright, 2001] and internal tidal mixing affects general circulation [Jayne and St. Laurent, 2001; St. Laurent and Garrett, 2002; Simmons et al., 2003]. Due primarily to the availability of TOPEX/POSEIDON (T/P) satellite altimetry [Chelton et al., 2001] and advances in numerical modeling methodologies [LeProvost et al., 1994; 1995; 1999], semidiurnal and diurnal barotropic ocean tides are known in the deep ocean (depth > 1000 m) to within 2 cm rms and with a spatial resolution of 50 km [Shum et al., 1997]. Tides are less well known in the coastal regions, over continental shelves, and in polar oceans [Yi et al., 2003] due primarily to limited observations with adequate spatial resolutions, data outage from T/P (and JASON-1) in seasonally or permanently sea ice covered polar oceans in which the complicated processes due to non-linear hydrodynamics including internal or baroclinic tides [Ray and Mitchum, 1996; Merrifield et al., 2001; Niwa and Hibiya, 2001] are poorly known. Most of the current global ocean tide models are primarily constrained by the FES94 hydrodynamics model [LeProvost et al., 1994] in the polar oceans. This paper provides a study of polar ocean (± 50 deg latitude, north and south poleward) barotropic tide modeling using high-latitude observing satellite radar altimetry including T/P, JASON-1, ERS-1/-2, GFO and ENVISAT. Dual-satellite crossovers are used for barotropic empirical tidal solutions with an objective to mitigate tidal aliasing [Yi et al., 2005], and techniques of data assimilations with hydrodynamic modeling [Matsumoto et al., 2000] are used to enable extrapolations into data outage regions. New high-latitude space geodetic sensors, GRACE [Han et al., 2005] and ICESat [Matsumoto et al., 2005], are explored for their contributions to polar tide modeling and accuracy

Session 5.4:

The 15-Year Altimetric Record/Mean sea level

Global and regional sea level change from multi-satellite altimeter data

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A record of fifteen years of precision altimeter data has been built up, including the data of ERS-1, TOPEX, ERS-2, GFO, Jason-1 and Envisat, each with their different strengths and weaknesses. Only by careful analysis and correction of drifts and biases in the altimeter and microwave radiometer data we can combine them efficiently to create an accurate record of sea level change both globally and regionally.

This presentation discusses some of the difficulties faced in the combination of such diverse altimeter records, including the importance of fixing long-term instrumental drifts, the existence of temporal and regional variations in sea level trend.

The combination of the data of all six altimeters is essential to the building of an accurate long-term record. Without comparison errors and drifts can remain unnoticed, and different observed regional trends stimulate and aid the analysis of the measurements and their numerous corrections. Some further emphasis is put on the trend in the Arctic region, measured by ERS and Envisat, but beyond the reach of TOPEX and Jason-1.

The altimeter data has also been compared to tide gauge data and estimates for sea level rise based on budgets for melting of ice shelves, increase runoff, thermal expansion, etc.

Satellite Measurements of Sea Level Change: Where Have We Been and Where Are We Going

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Over the last few decades, satellite geodetic measurements together with in situ measurements, have revolutionized our understanding of present-day sea level change. With measurements from satellite altimeter missions and satellite gravity missions, we are now able to start answering some important questions with regards to global sea level change and its regional variations. What have we learned from these measurements? Would we change any of the decisions we made in the past? What are the remaining questions to be answered? What suite of measurements are needed to answer these questions? The record of sea level change from satellite altimetry will be reviewed, its error sources and limitations discussed, and the results placed in context with other estimates of sea level change from tide gauges, in situ measurements, and global climate models. The much shorter, but just as important, record of ocean mass variations from satellite gravity measurements will be similarly reviewed. Finally, the need for continuing the satellite measurements of sea level change, and possibly developing new measurements, will be discussed in the context of future missions and the scientific gain that would result.

Why the sea is boiling hot: global warming and sea level rise

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In the first part of this study we use a global data assimilation reanalysis (SODA 1.4) to examine the relative contributions of steric and eustatic components of sea level rise. The work is motivated by recent altimeter observations indicating an increase in the rate of sea level rise during the past decade to 3.2mm/yr, well above the centennial estimate of 1.5-2mm/yr. Dynamic height calculated relative to 1000m from the SODA1.4 reanalysis, used as a proxy for the steric component of sea level, is compared with satellite-derived sea level for the years 1993-2004. The similarity of the rate of increase in the thermosteric contribution to sea level rise to the altimeter sea level record, as well as the similarity of its spatial structure suggests that the recent acceleration in sea level rise is explainable to within the error estimates by fluctuations in warming and thermal expansion of the oceans. Experiments with the data assimilation analysis explore these error bounds.

In the second part of this study we compare the rate of heating required to explain the trend in steric sea level with estimates of global heating as indicated by satellite radiances in order to investigate the sources of the implied thermal imbalance.

Understanding measured sea level rise by data assimilation

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Work at AWI that is related to altimetric measurements focusses on the estimation of the global oceans circulation, its sea level change and finally its mass budget. This presentation will shortly review the findings achieved so far.

Sea surface elevations as measured by the altimeter are together with hydrographic measurements are assimilated into a global OGCM that has a free surface, i.e. that conserves mass rather than volume. The combination of both types of measurements appeared to be necessary to get a reasonable estimate of the oceanic circulation. Furthermore referencing the altimeter data to the GRACE geoid improves the modelling of anomalies. Further improvement in estimating sea level change was achieved by including the steric effects (thermosteric AND halosteric) into the

modelled sea surface elevation, because local sea level trends vary substantial in space and time. They are closely associated to heat and salt anomalies in the ocean. This finally allowed to estimate the temporally varying oceanic mass budget from sea surface elevations.

Determination and Quantification of the 20th Century Sea Level Rise

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Satellite altimetry with a cluster of spaceborne instruments measuring sea surface height changes for over 15 years since the launch of ESA's ERS-1 mission, has been widely accepted to be a viable tool for monitoring contemporary and future global sea level changes. The observational data span extends to about two decades but with 3 year data gap, if one includes US Navy's GEOSAT satellite altimetry data. Sea level rise has been widely recognized as a measurable signal as one of the consequences of possible anthropogenic (human-induced) effect of global climate change. The small rate of sea level rise signal, at 1-2 mm/yr during the last century [IPCC, Church et al., 2001], at present could only be partially explained by a number of competing geophysical processes, each of which is a complex process within the Earth-atmosphere-ocean-cryosphere-hydrosphere system. These signals include the mass balance of the ice sheets [Thomas et al., 2004; Krabill et al., 2005], ice shelves, and glaciers [Dyurgerov and Carter, 2004]; retention of water in reservoirs [Sahagian, 2004], terrestrial hydrological balance [Milly et al., 2003; Ngo-Duc et al., 2005], thermosteric [Levitus et al., 2005] and halosteric effects [Boyer et al., 2005] and barotropic response [Ponte, 2005] of the ocean, and other effects. At present, these signals are unable to fully account for about 0.2-1.2 mm/yr of the tide gauge determination of 20th Century sea level rise rate of 1.8 mm/yr [Douglas, 2001, Church et al., 2004, Cazenave et al., 2004; Miller and Douglas, 2004]. Significant geographical variations in both the thermosteric and halosteric sea level [Levitus et al., 2003] and the "self-gravitational" sea level signal as result of present-day ice melt [Mitrovica et al., 2001; Plag and Juttner, 2001, Tamisiea et al., 2002], and the effect of glacial isostatic adjustment (GIA) since the last Ice Age causing vertical motions of tide gauge benchmarks [Peltier, 1995, Milne et al., 2001], along with sparseness of world tide gauge locations, all contribute to errors in tide gauge determination of the 20th century sea level rise. The use of multiple satellite altimetry (GEOSAT, ERS-1, TOPEX/POSEIDON, ERS-2, GFO, JASON and ENVISAT), which has near global coverage (up to ± 81.5 deg latitude), however, is limited in data span (1985-2005, ~ 20 years with 2 year gap) and requires knowledge of instrument drifts, making the determination of sea level

trend challenging. This paper provides an updated quantification of the 20th century sea level rise sources using data from multiple satellite altimetry missions spanning ~20 years and ~600 selected long-term tide gauges, accounting for relative biases between the altimeters, modeling effects of steric sea level, vertical motions affecting tide gauge measurements, self gravitations, barotropic ocean response and others. Finally the paper provides an assessment of the contribution of decadal altimetry to the problem of understanding past and future global sea level rise.

Session 4:

Hydrology and Land Processes

Characterizing the quality of river water level time series derived from satellite radar altimetry: efforts towards a standardized methodology

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Numerous works during the last fifteen years have shown the potential contribution of satellite radar altimetry for the monitoring of water levels of inland water bodies (inner seas, lakes, floodplains and large rivers). Currently a significant number of satellites provide radar altimetry information (Topex Poseidon, ERS, Envisat, Jason) and could ensure the continuity of operational monitoring of continental water levels. Recently, various groups have dedicated large efforts to build data bases of rivers and lakes water levels derived from satellite radar altimeters ("Global reservoir and lake monitor" Project, "River and Lake" Project, "CASH" Project).

However, as a general picture, hydrologists still do not use these data for operational applications such as water resource quantification, flood forecast or water resource management. Among the reasons accounting for the reluctance of hydrologists to use water level data derived from satellite radar altimetry is the lack of a standardized method to characterize the quality of these data (Birkett 1998). The presentation will focus on that subject and develop two complementary topics (1) the quantification of the accuracy of individual satellite measurements, (2) the characterization of the quality of water level time series reconstructed from sampled satellite measurements.

Quantification of the accuracy of satellite measurements

To quantify the accuracy of satellite measurements, for a given satellite and waveform processing algorithm, a few distinct parameters must be taken into account : * the density and dispersion (uncertainty) of satellite measurements at a given location and time (during one

satellite over flight), depending on one hand on the morphology and environment of the water body and on the other hand on the size of the targeted measurement window * the error distribution between satellite measurements and in situ measurement at a given location of a water body. The quantification of this error is generally biased by two factors : (1) the location of satellite ground tracks rarely coincides with hydrometric gauging stations, which implies the estimation of in situ measurement values based on information from distant gauging stations, (2) satellite measurements are given in a geodetic referential (ellipsoid) while in situ measurements are generally given in an orthometric referential (geoid) which implies the use of a geoid model to compare the two values, introducing an additional source of error.

Measurement density, dispersion and error distribution have been quantified for 200 observations areas on a large variety of continental water bodies (Amazon, Danube, Niger, Senegal, Rhône, ...). Results will be presented and discussed with a particular focus on their correlation with parameters and characteristics such as water body size and morphology, neighbouring topography, size of the targeted observation window. Possibility for a priori estimation of the accuracy (without confrontation to in situ measurement) will be discussed.

Characterization of the quality of water level time series reconstructed from sampled satellite measurements

While hydrologists generally require daily sampled time series of water levels for main rivers, satellite sampling periods range from 10 days (Topex Poseidon, Jason) to 30 days (ERS, Envisat). Reconstructing a daily time series from sampled satellite measurements, for instance through temporal interpolation, induces specific errors that must be estimated. The satellite sampling rate has an important coupling effect with the natural temporal signal. The Shannon theorem states that the sampling frequency must be greater than twice the maximum frequency of the signal to be sampled in order to avoid any loss of information. The spectral signature of a river water level signal –and its maximum frequency– can be determined using the Fourier spectral analysis. It depends on such parameters as the precipitation regime and hydrology of the upstream catchment, and local hydraulic conditions. Comparison between the spectral signature of a signal and the sampling frequency enables the determination of the information loss. Analysis of spectral signature of in situ water level time series will be presented for 200 hydrometric stations over a large variety of continental water bodies. The spectral signature will be parameterized and parameters will be

related to hydrological variables (precipitation regime, catchment size,...). Impact of satellite sampling on information loss will be presented, over-sampling techniques for daily signal reconstruction will be discussed and correlation between information loss and accuracy of the reconstructed water level time series will be developed.

Finally a synthetic method, quantifying both the accuracy of individual satellite measurements and the impact of satellite sampling rate on the accuracy of reconstructed time series, will be presented for complete characterization of the quality of water level time series derived from satellite radar altimetry. This method could both (1) allow hydrologists to use qualified water level time series, (2) allow the quantification of improvements generated by new waveform processing algorithms.

Uncertainties in water stages by altimetry assessed by field measurements

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Although no satellite altimetry mission has been dedicated yet to continental hydrology, radar altimetry from space has been successfully used to monitor temporal variations in lake and river stages. Compared with ocean studies, large uncertainties are reported. Several factors can be inferred to explain these large uncertainties, as -among others- the land-water mixture in the radar beam footprint, tracking-retracking algorithms, missing or inadequate geophysical corrections... But, for the present, uncertainties of altimetric radar measurements have been only assessed by comparison with in-situ gauge stations, sometimes located at tens of kilometres away from the satellite tracks. Thus, these uncertainties encompass the changes in hydrological regime between the station and the satellite track. Indeed, when a satellite track is running along a large river, as it is the case for the Tapajos River (Amazon Basin), measurement noise appears to be ~10cm, far less than the 20 to >100cm commonly reported.

We have conducted field campaigns in the Amazon basin, in order to assess radar altimetry uncertainties in river stage

estimates, for various morphological situations. We have realized altitude profiles for the Branco and upper Rio Negro rivers in GPS cinematic mode. These operations were conducted with GPS stations observing as fixed reference points every ~50 kilometres, and mobile GPS antennas set on top of a boat cruising down the rivers. ADCP (Acoustic Doppler Current Profiler) profiles were also performed under each crossing points between the T/P, JASON and ENVISAT tracks and the two rivers. These ADCP profiles provide cross-sections and flow velocity. Using the information from both GPS and ADCP, we run a 1D model to estimate the water stage at the crossing points. Comparison of modelled water stages and altimetric heights enables an evaluation of the uncertainties of radar measurements in different situations.

Assessment of multi-mission radar altimeter performance over the Amazon basin

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Satellite altimetry has been used for many years to monitor selected inland water targets. To assess the performance of past and current altimeters over inland water, a web based statistical tool has been developed which compares time series of heights over the Amazon basin from 2338 gauge stations with heights derived from satellite altimetry. The altimeter heights are derived using an expert system to extract echoes over the Amazon river network, and retrack each echo using one of 12 retracking algorithms to obtain a corrected range to surface. Using this tool, an assessment is presented of the performance of past and current altimeters over the complex targets of the Amazon river network, including Topex, Jason-1, ERS-1/2 and Envisat.

Use of satellite altimeter data for validating large scale hydraulic models

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Over large, remote basins very few ground observations of surface water elevation are available to validate the output of the distributed hydraulic models which are used to understand better the fluxes of water, sediment and nutrients in such basins. Those observations that are available are subject to considerable uncertainty as (a) elevation levels are frequently not tied in to any datum and (b) records are often incomplete due to instrument failures. Moreover, the number of ground observation stations is in serious decline, especially in the developing world. Given these constraints the data on river water surface elevation available from satellite radar altimeters may be useful source of model validation data. In this paper we examine the potential of such data to assist in the validation of a two-dimensional hydraulic model of a 280x200km reach of the Solimoes and Purus rivers, Amazonia, Brazil. This region includes the extensive confluence plain of these two rivers and provides a challenging problem in hydraulic modeling. Model simulations are conducted at a spatial resolution of 270m with ground topography parameterized from NASA SRTM data that have been corrected for vegetation effects on the basis of vegetation height surveys in the region conducted in June/July 2005. River bathymetry is parameterized from sonar data acquired during the same field campaign. The model is run for an annual flood cycle based on the average of 20 years of flow data and the predicted water surface elevations compared to observations of the same derived from TOPEX-POISIDON. The comparison allows us to better understand the strengths and weaknesses of the hydraulic model and leads to an improved understanding of the space and time scales of data required to validate such codes. The analysis shows that while point data of the type derived from existing altimeters is a contribution to model validation, they do not allow a complete validation of the distributed output of numerical models. Data of the type to be acquired in the proposed WatER mission will, potentially, allow this more complete analysis.

A Decade of Global River and Lake Heights from ESA Altimeter Missions

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The ESA altimeter missions ERS1, ERS2 and Envisat have gathered a unique dataset over the earth's land surfaces, including inland water. Key to this success is the mode switching capability, which has allowed the instruments to maintain lock on the surface over rapidly varying topography, and thus gather data over lakes and rivers even in mountainous terrain. To exploit this unique dataset, a processing scheme has been developed to extract inland water heights from lakes and rivers on a global scale. Key to the success of this scheme has been the development of new retracking algorithms, which allow the determination of inland water heights from a range of echo shapes. This now permits derivation of historical time series of river and lake heights from thousands of targets worldwide. These will be disseminated over the next 12 months. In an exciting new development, the near real time capability of the RA-2 is harnessed to generate measurements on a timescale of a few days over rivers and lakes on a global scale. These data are now made available online through a web based delivery service.

This paper presents an overview of the river and lake system, shows the global distribution of measurements available from both the near-real-time and historical time series, and demonstrates the unique capabilities of both the Envisat RA-2 and the processing scheme to measure heights of the earth's inland water surfaces.

Session 6.1:

The Integrated Approach/Systems

The ECCO Near Real-Time Ocean Data Assimilation System

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Products of the ECCO Sequential Ocean Data Assimilation System (<http://www.ecco-group.org/las>) consists of near-global ocean state estimates from 1993 to present. These results are being utilized in diverse studies of ocean circulation and in geodetic applications. This presentation will describe the estimation system, the skill of its estimates, its latest improvements, and future outlook.

The on-going near real-time estimation system is based on an approximate Kalman filter and Rauch-Tung-Striebel smoother (partitioned, reduced-state, time-asymptotic approximations), and assimilates altimetric sea level and in situ temperature profiles with uncertainty in time-variable wind forcing as model control. The model is based on the MIT general circulation model with a variable 0.3 to 1-deg spatial resolution in a near global domain (73S to 73N). Estimates are statistically self-consistent and are in closer agreement with independent observations than a non-constrained model simulation.

Various improvements to the operational system are being developed. These include expansions to the model control space, such as time-invariant errors (bias) and diabatic sources of model error. A higher resolution system is also being developed to explore estimation of meso-scale variability in an eddy-permitting global circulation model.

Synergy between ocean observations and numerical simulations : CLIPPER heritage and DRAKKAR perspectives

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Research on oceanic circulation, variability and underlying processes has been stimulated since the WOCE years by combined examinations of observations and model simulations. This synergy is achieved in data assimilation studies, but also whenever observations are used with unconstrained, high-resolution, multiyear simulations forced by atmospheric reanalyses. Between 1995 and 2003, the French CLIPPER project has developed and run Atlantic models based on the OPA8 code at 1°, 1/3° and 1/6° resolution to study various aspects of the ocean dynamics over the period 1980-2000+. Its successor DRAKKAR is a community modelling program that partly aims at improving model-observation synergies, in an extended context: European collaboration (France, Germany, Russia, Finland), wider domain (Atlantic-Nordic Seas to global), increased resolution (1/4° to 1/12°, with local grid refinement capabilities), longer period (1950-present), richer and improved physics (OPA9+LIM sea-ice, parameterizations).

The evaluation of numerical solutions against available observations is an example of model-data synergy. CLIPPER solutions were evaluated by several authors who extracted model counterparts of real data colocated in space (and possibly time) and treated both datasets identically. For example, lagrangian time/space eddy scales (Lumkin et al, 2002), deep subtropical zonal flows (Treguier et al, 2003a), Agulhas rings properties (Treguier et al, 2003b), interannual variations of water mass characteristics (CLIPPER Group, 2001) and of basin-scale eddy distribution (Penduff et al, 2004) were validated and studied by building and comparing colocated datasets (drifters, ADCP, BRAVO timeseries, and altimeter fields, respectively). More quantitative validation studies may involve model-data correlations as done by Illig et al (2004) for tropical sea level anomalies, or require the development of synthetic misfit (or model skill) estimates, as proposed by Penduff et al (2005) for current meter data. Within the OST/ST framework, the DRAKKAR group wishes to improve validation methods and make them more

quantitative, by generating synthetic datasets colocated with various observations (e.g. ARGO, T/P, Jason, etc) and defining appropriate skill estimates.

High-resolution satellite products should help improve the forcing of ocean models, in combination with atmospheric reanalyses. The CLIPPER group made use of satellite SSTs (Reynolds and Smith, 1994) for air-sea flux corrections, and observed that scatterometer winds may substantially improve the simulations at low latitudes. Reanalysed atmospheric variables are being used through bulk formulae to force the global and regional DRAKKAR models. The merging of recent satellite datasets (e.g. winds, radiative fluxes) with reanalyses is currently investigated, and their impact on oceanic simulations will be evaluated.

In turn, realistic simulations provide a dynamical context to interpret observations or design observing systems. Among other examples, CLIPPER-derived synthetic datasets proved useful for estimating the representativeness of hydrographic transects (Treguier et al, 2005), diagnosing the spatial and temporal scales of surface salinity for remote sensing applications (Molines et al, 2001), evaluate the design of the ARGO array (Guinehut et al, 2002) or its combination with satellite data for temperature analyses (Guinehut et al, 2004). One of DRAKKAR objectives is to pursue such collaborative investigations in order to characterize the representativeness of (possibly combined and/or future) observation systems, the observability of small-scale processes or climate indexes. To reach this goal, different kinds of synthetic datasets (satellite, in-situ, up to kilometric resolutions) will be designed, generated, distributed and analysed in collaboration with the OST/ST and observationalist communities.

Ocean Model Analysis and Prediction System (OceanMAPS): operational ocean forecasting based on near real-time satellite altimetry and Argo

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BLUElink is a joint Australian government initiative to develop Australia's first operational ocean forecasting system called OceanMAPS. The project has transitioned to

the implementation and trial phase using the infrastructure of the Bureau of Meteorology. OceanMAPS has a global grid with 1/10 by 1/10 resolution in the Australian region (90E-180E, 70S-16N) and uses the Modular Ocean Model version 4 optimised for the NEC SX6. The analysis uses an ensemble based multi-variate optimal interpolation scheme where model error covariances are derived from a 72-member ensemble of intra-seasonal anomalies based on a 12-year ocean only model integration. The scheme has been formulated to assimilate near real-time sea level height anomalies processed from Jason-1, ENVISAT, Geosat Follow-On and Topex/Poseidon and profile observations including Argo, XBT and the TAO array. The operational configuration including the data management of the near real-time observations is reviewed. An analysis of the impact of altimetry and Argo on both the analysis and forecast skill of OceanMAPS during the operational trials is presented.

HYCOM Ocean Prediction and Altimeter Data Assimilation

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A broad partnership of institutions is presently collaborating in developing and demonstrating the performance and application of eddy-resolving, real-time global and basin-scale ocean hindcast, nowcast, and prediction systems using the HYbrid Coordinate Ocean Model (HYCOM). The plan is to transition these systems for operational use by the U.S. Navy at the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, CA; and by NOAA at the National Centers for Environmental Prediction (NCEP), Washington, D.C. The partnership is also the eddy-resolving global ocean data assimilative system development effort that is sponsored by the U.S. component of the Global Ocean Data Assimilation Experiment (GODAE). The systems not only need to run efficiently on a variety of massively parallel computers, but they also need to include sophisticated, but relatively inexpensive, data assimilation techniques for assimilation of satellite altimeter and in-situ data. We will report on the performance of (1) a multi-variate optimum interpolation (MVOI) that use either the Cooper and Haines (1996) technique or synthetic T & S profiles for downward projection of SSH and SST, (2) the Singular Evolutive Extended Kalman (SEEK) filter, and (3) the Reduced Order Information Filter (ROIF). Both the SEEK filter and ROIF are especially well suited for large dimensional problems: In the SEEK filter, the dominant eigenvectors describing the model variability are used to specify the initial background error covariance matrix in decomposed form and this leads to fully three-dimensional, multivariate dynamically

consistent corrections. The ROIF method factors the covariance functions into horizontal and vertical components and represents the correction field implicitly, using techniques transplanted from statistical mechanics (Gaussian Markov Random Field). The reduced order aspect of ROIF refers to the fact that the information matrix is approximated as a banded matrix. The SEEK filter uses the non-linear model to propagate the error statistics forward in time while the ROIF assumes a tangent linear approximation to the system dynamics.

Altimetry and Military Oceanography : a Common Destiny

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Environmental support of naval operations strongly relies on the capability to properly describe the hydrological and dynamical state of the ocean. Since late 80's, the SHOM - Service Hydrographique et Océanographique de la Marine- is conducting research and development on oceanic forecasting systems to be used to elaborate operational products for French Navy ships.

SOAP -Système Opérationnel d'Analyse et de Prévision- is a defense program started in 1997. From the very beginning the SOAP system has been routinely assimilating the altimetric measurements of the successive missions from GEOSAT to JASON.

In this paper we propose to review the continuous progress in the environmental support of military operations and to illustrate how it is strongly related with the achievement of radar altimetry within the past 15 years.

In order to do so, the milestones of SOAP program will be introduced. For each SOAP version, altimetric data processing, modeling capabilities and corresponding operational products will be presented, and parallel improvements will be emphasized.

In conclusion, future requirements for naval operations in relation with growing coastal and amphibious issues will be listed. Expected contribution of futures satellite missions will be outlined.

The PSY3v1 GODAE/Mercator ocean forecasting system, a global eddy permitting (1/4°) ocean model assimilating altimetry data

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The Mercator-Ocean eddy permitting global ocean Prototype System (PSY3v1), assimilating satellite altimetry data, is the french contribution to the GODAE project for the global ocean, and the MERSEA project for operational systems, and is operated weekly since the end of 2005 to deliver oceanic forecasts of two weeks. The system has a 1/4° horizontal resolution and 46 levels on the vertical (ORCA025), and is forced with daily surface fluxes from ECMWF operational analyses, and constrained with JASON, ERS and GFO altimetry measurements from january 2005 up to real-time. Due to its fine resolution, the assimilation system provides an integrated description of the ocean with a realistic description of the meso scale features. Assimilation scores are presented, and independant in situ data of the Atlantic, Pacific and Antarctic ocean basins are contrasted with the simulation results in order to provide an estimation of the performances of the system. The results are also compared with the Levitus climatology, and with the 2003 ARMOR weekly products, which optimally combine satellite (SST, SLA) and in-situ (T/S profiles) near real time observations.

Session 1.6:

Oceanography: Marine Meteorology

Satellite altimetry: A revolution in understanding the wave climate

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Before the advent of radar altimeters our understanding of the world's climate was based on a few instruments moored off the coasts of Europe, Japan and North America and visual observations taken from merchant ships. This information was patchy and in many cases of poor quality. It was difficult to relate what was happening at one location with another. The advent of the radar altimeter has changed all that. We had a series of satellite instruments that made consistent measurements of significant wave height across the globe. Initial work concentrated on simply mapping the wave climate and investigating means and seasonal variation. However with longer records came the ability to look at inter-annual variability. It had been known since the late 70's that wave heights measured at a few sites around the North East Atlantic had shown a dramatic increase. It was only the combination of spatial and temporal sampling from the altimeter that allowed us to discover the extent of the changes and how they related to the North Atlantic oscillation index. Of course it is not only the mean wave conditions that are important, extreme waves are of vital interest to naval architects and the designers of off-shore structures. Being able to estimate extreme waves from altimeter data enables us for the first time to establish what extreme conditions might be in any part of the world. At present we do not exploit the spatial nature of the altimeter data in our estimation of the extremes but this is an active research area.

Research into further uses of altimeter data for looking at the wave climate continues apace. Algorithms for new parameters such as wave period are being developed. Real time applications are appearing. For such applications space-time sampling is an issue and people are coming up with innovative ideas using constellations of cheap altimeters. In this paper we review the progress made in the study of wave climate using the radar altimeter. In addition we look into current directions of new research and where we might be going next.

Progress in utilizing altimeter ocean backscatter measurements for sea surface roughness applications

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One of the cornerstone's of ocean remote sensing is the ability to detect changes in ocean surface waves related to different environmental conditions. The satellite altimeter continues to build a long-term global record of this ocean surface roughness variability from the unique vantage point of a radar whose angle of incidence is directly at nadir, a view that is most sensitive to the sea surface slope statistical distribution. Moreover, the TOPEX/Poseidon, Jason-1, and Envisat missions each carry dual-frequency radar altimeters that have added a new wave remote sensing perspective. This paper will provide a review of the progress made in interpretation and application of altimetry's ocean radar cross section measurements in the last decades. These applications include wind speed and stress estimation, air-sea carbon dioxide gas transfer, ocean slick detection, wave-current interaction measurements near strong boundary currents, direct impact on altimeter sea level estimates through the sea state bias correction, high resolution wind sampling within storms, and retrieval of surface wave properties spanning from cm to m scale wavelengths. Much of the recent progress has come from synergistic studies where collocated scatterometer, wind and wave model, and in situ data are blended to gain a more comprehensive definition of the role that sea surface waves play within the context of the applications above. Attention will be given to climate data record potential for the altimeter cross section measurements as well as the absolute and relative calibration of these data within and across satellite platforms.

Contribution of Satellite Altimetry to Wave Analysis and Forecasting

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During the last decade, the performance of wave models has significantly improved in term of wave analysis and forecasting, thanks to a better quality of the wind forcing fields, to the refinement of numerical wave model and to the assimilation of satellite altimeter data. Today, four satellite altimeters are in operation and the positive impact of altimeter data assimilation in numerical wave models at global scale has been proved and estimated by several authors .

Data assimilation at regional scale is presently an issue of interest and the knowledge of spatial correlation functions for prediction errors have to be derived for small basins where complicated structures are expected due to very high time and space variability of wind speed. Altimeter data are the only observation providing us with spatial distribution of wave properties that can be used to derive the required error correlation functions.

Because of their global coverage, altimeter data are also very valuable for assessing the impact of other satellite data for wave analysis and forecasting. In particular, the usefulness of Advanced Synthetic Aperture Radar (ASAR) for such purpose has been recently investigated by using altimeter data.

Buoys data are mainly located in the Northern hemisphere and in coastal areas while altimeter data are uniformly distributed over the ocean making them very useful to locate wave model errors in order to improve wave model parameterization of source terms and wave model numerical aspects.

A wind and wave atlas for the Mediterranean Sea

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Long term climatological data over the sea are much in demand for a number of reasons, ranging from pure scientific knowledge to the more important applications of, e.g., safety at sea and the design of sea structures. Till 15

years ago the only practical sources of the long term data required for a meaningful statistics was the collection of visual observations done from ships at sea. Starting from 1991 two new sources of data started to be available. The launch of ERS-1, and soon after of Topex-Poseidon, offered an unprecedented continuous flow of wind speed and wave height measurements. At the same time the improvements in computer power and numerical modelling led to a continuous synoptic description, typically at 6-hour interval, of the distribution of wind and wave characteristics at sea.

These two sources offered a wealth of data and today quite reliable statistics exist in the open oceans. However, the situation is less favourable in the inner seas. Here the global meteorological models exhibit a steady underestimate of the wind speeds, that in turn leads to an underestimate of the associated modelled wave heights. On the other hand the strong spatial gradients that characterise the basins with a complicated geometry, as in our case the Mediterranean Sea, imply that the spatial resolution of the altimeter ground tracks is not sufficient to provide the necessary details.

The solution lies in the complementary use of both the altimeter and the modelled data. The latter ones provide the background information, very dense in time and space, that is then calibrated using the information derived from the altimeters. This is done determining for each grid point, at 0.5 degree intervals, the series of co-located values, model and altimeter, for both wind speed and wave height. Provided the necessary reliability checks are satisfied, for each point and each parameter the best-fit slopes of the co-located data provide the correction coefficients of the model data. After some spatial averaging to avoid unrealistic local variability, long term time series of calibrated wind and wave fields have been obtained. These have been used to derive multiple long term statistics, both at synoptic and point levels. All these results have been made available in the MEDATLAS atlas of the Mediterranean Sea, available in both paper (A3) and interactive CD formats.

The results have also allowed a check of the correctness of the wind speed and wave height altimeter measurements. The direct relationship existing between these two quantities implies a consistency between their statistics. This is obviously present in the original data that are model derived, and it should be expected also in the calibrated data. On the contrary we have found that the calibrated wind speed values are lower than expected from the calibrated wave heights. As the latter ones have also been verified versus accurate buoy data, we suggest that the algorithm used to derive the altimeter wind speed provides values lower than the actual truth.

Altimeter wind and wave data and Ocean Wave Forecasting

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Over the past fifteen years there has been a continuous interplay between ocean wave forecasting and altimeter wind and wave observations. First, the prospect of the availability of global observations of wind and waves from the ERS-1/2 satellites provided a significant stimulus to the development of modern, third-generation wave prediction systems. And vice versa, the development of the altimeter wind and wave product was stimulated by the need to have reliable wave predictions.

Furthermore, wind and wave model products have been vital in the monitoring of the quality of the altimeter products, in particular in the first stages of the commissioning phase, while, on the other hand, the comparison between altimeter and wave model results has given clear guidelines for improvement of wave prediction systems. In 1993 the quality of the altimeter wave product was regarded so high that centres such as the Met Office and ECMWF decided to assimilate these data into the wave forecasting system, giving high quality analysed wave height fields. Although during the past 13 years we have seen considerable improvements in wind and wave modelling, it will be shown that the assimilation of altimeter wave height data is still of vital importance for the quality of the analysed wave height field.

Presently, the quality of the atmospheric and wave model analysis is so high that satellite retrieval algorithms have been developed on the basis of atmospheric analysis and forecast products. Examples are the scatterometer algorithms CMOD4 and CMOD5, the altimeter wind speed algorithms for Jason and ENVISAT and the total column water vapour algorithm for the MWR instrument on ENVISAT.

During the presentation, an overview of the above mentioned developments will be given, while we also discuss the accuracy of the altimeter and model wave height.

Application of multi-mission altimeter measurements to the analysis of wave height time and space variability over the Mediterranean Sea.

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The ability of satellite altimeters to measure the significant wave height (swh) has been demonstrated. Since 1991 six altimeters have been launched and, today, five altimeters are in operation. An effort for cross validation of swh measurements from the various missions has been performed and, now, intercalibrated altimeter swh data are available over almost a 15 year time period. This long term data set can be used to analyse the time and space variability of swh over the oceans. This paper presents such an application over the Mediterranean Sea. This study can be extended to any other regional or global analysis.

Firstly, the results of a global long term validation activity are summarized, allowing to correct swh measurements from the various missions, providing an homogeneous data set.

Secondly the 13 years (September 1992 to September 2005) of TOPEX and Jason swh measurements along the initial TOPEX orbit are analysed. Instead of collecting all the altimeter data available over a particular area to infer statistical description of swh, the data are collected along each ground track at a regular 0.05° sample in latitude. One advantage is to be able to detect short spatial scale variability. The main drawback is the poor time sampling, one pass every 10 days - this is illustrated using the data from the ERS-1 3-day repeat cycle phase A. Nevertheless it is shown that, over a long time period, seasonal spatial variability of swh can be estimated over the various basins of the Mediterranean Sea.

In a third part the swh time variability is estimated, by analysing the multi-mission (ERS-1&2, TOPEX Poseidon, GEOSAT FO, Jason-1 and ENVISAT) data set available over the various Mediterranean basins. The impact of the number of altimeters is analysed. Differences of swh time variability over the various basins is analysed and shown to be linked to the various specific regional short scale wind regimes over the Mediterranean Sea.

Session 3:

Marine Geodesy, Gravity, Bathymetry

High Resolution Global Bathymetry from Satellite Altimetry, with a detailed view of the Arctic Ocean

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Knowledge about the depth of the oceans is important to practically all marine activities. Satellite altimetry has earlier been recognized as a source of information that can provide valuable information about the bathymetry along with direct observations from ship using i.e. multibeam bathymetry. With its very dense geographical distribution, the altimeter data from the GEOSAT and ERS-1 Geodetic Missions has a high potential for recovering especially the shorter spatial wavelength. The global high-resolution altimetric marine gravity field (DNSC05) is used in an attempt to enhance the details of the ETOPO5 5' by 5' bathymetry model on 1/30 degree resolution.

A bathymetric model is created using ETOPO5 dataset for wavelengths longer than 200 km. For the shorter wavelength (10-100 km) a regression is made between the existing topographic information and the downward continued gravity field anomalies assuming a flat transfer function between the two quantities.

Intermediate wavelength (50-200) km was finally predicted using the integrated inversion method based on Parker's formula, for the relationship between gravity and bathymetry. A modified version of this approach was initially for global bathymetric prediction by Knudsen and Andersen (1996). The prediction of bathymetry is confined to depth greater than 250 meters, to avoid problems close to the coast where the accuracy of the gravity field modeling from satellite altimetry is known to degrade.

Altimetric marine gravity fields in polar regions: History, status and future prospects

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Altimetric contributions to mapping the global marine gravity field have, over the past 27 years, been substantial and of great importance to geophysicists. Beginning with SEASAT (1978), spaceborne radar altimeters including Geosat (1985-1989), ERS-1 (1991-2000), ERS-2 (1995-present) and Envisat (2002-present) have profiled sea surface topography with sufficient precision to permit computation of accurate marine gravity (to several mGals) therefrom over nearly all the world's oceans (e.g., Sandwell and Smith, 1997). Computation of marine gravity from altimetric sea surface profiles is possible because ocean topography closely conforms, in the mean, to a level surface, or geoid. However, because height trackers on board these satellite altimeters are optimized for open ocean - as opposed to ice-covered ocean - operation, the computation of polar marine gravity proved very difficult. These on-board trackers produce unacceptable height errors of order 10 m. In 1993, work (Laxon and McAdoo, 1994; McAdoo and Laxon, 1997) began on the reprocessing of ERS-1 return echoes and subsequent computation of detailed marine gravity in ice-covered polar seas. The resulting gravity fields revealed previously uncharted tectonic fabric, e.g., (1) a lineated low down the middle of the Arctic Ocean's Canada Basin locating the extinct spreading ridge which gave rise to the Basin's seafloor; (2) gravitational expression of fracture zones tracing early seafloor spreading associated with the separation of the New Zealand continent from West Antarctica.

Substantial improvements in altimetric polar gravity fields and associated maps of mean sea surface topography are now underway. Incorporation of acquired and future retracked Envisat RA-2 data will substantially improve polar gravity fields - particularly in Antarctic seas. CryoSat's SAR/Interferometric Radar Altimeter (SIRAL) data will enable a more precise separation of the sea ice "noise" from the gravitational "signal" possible heretofore from conventional, pulse-limited altimetry. Also, CryoSat data will nearly fill (to 88N) the polar "hole" (latitudes > 82N) or

coverage gap in existing Arctic marine altimetric gravity fields. Also future joint estimation of altimetric sea surface topography and polar geoids - which incorporate GRACE and GOCE gravity - should prove very valuable for the polar oceanographer.

On Combining Bathymetric and Ocean Circulation Altimeter Missions

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Spaceborne radar altimeters make high-precision measurements of ocean surface topography that are manifestations of both the geoid and ocean circulation. Sea surface height variations associated with the geoid are, in part, a reflection of the deep water bathymetry that distributes mass in a way that alters the gravity field at the ocean surface. Other sea surface height variations are a manifestation of ocean circulation. Ocean circulation and bathymetry are the two dominant applications for spaceborne altimeter sea surface topography measurements.

Missions optimized for either of these applications would be substantially different. A mission designed to measure bathymetry would have a long orbit repeat period to fill in a tight geographical grid. For an ocean circulation altimeter mission, such a TOPEX or Jason-1, one would prefer an orbit with a short repeat period, even though such an orbit would have sparser geographical coverage. The short repeat period allows for the averaging of many repeat passes to eliminate the geoid and mean ocean circulation signals. The variations of sea surface height differenced from a mean over many orbits is a measure of ocean circulation.

Altimeters designed for basin-scale circulation measurements use dual transmit frequencies and a radiometer to alleviate the effect of path delays caused by the ionosphere and atmospheric water vapor, respectively. Since bathymetric missions are looking for short horizontal spatial scale signals, they need not add the expense of dual frequencies and a radiometer

As a consequence of the many altimeter that have flown, we have a (1) a better model of the mean ocean surface, (2) better modeling of the ionosphere, and (3) better modeling of atmospheric water vapor. Here, we address the question: Given these improvements, to what extent can an altimeter designed for measuring bathymetry also be used to estimate mesoscale ocean circulation.

We make this assessment by comparing the sea surface anomaly fields computed during the same time period from TOPEX and ERS-1. TOPEX is a fully-capable ocean circulation altimeter. During its long-repeat period mission, ERS-1 mimicked the capability of a bathymetric mission altimeter. We found that the sea surface anomaly fields between the two agree to better than 10 cm. Such comparisons suggest that bathymetric altimeters could also be used to measure mesoscale circulation patterns.

From the altimetric sea level measurement to the ocean absolute dynamic topography: Mean Sea Surface, Geoid, Mean Dynamic Topography, a three-component challenge

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With the launch of the altimetric satellites ERS-1 and T/P in the 1990's it first became possible to measure with a precision of few centimetres the sea level above a reference ellipsoid. In order to extract from the altimetric measurement the absolute dynamic topography, (the sea level above the marine geoid, which is the signal of interest for oceanographers), the accurate knowledge of the marine geoid above the same ellipsoid is required. Huge improvements have been made in our knowledge of the geoid since the time when only the longest wavelengths could be retrieved applying the theory of perturbations to geodesic satellites (Starlet, Lageos, Etalon). Nowadays, with the succession of dedicated gravimetric missions (CHAMP, GRACE), the geoid can be estimated with centimetric accuracy at a 400 km resolution. However this resolution is still too coarse to fully resolve the entire spectra of oceanographic phenomena.

To compensate for the lack of an accurate geoid, the altimetric Mean Sea Surface is commonly subtracted from each single altimetric measurement to obtain an estimate of the variable part of the dynamic topography (or Sea Level Anomaly, SLA). Thanks to the global, continuous and repetitive set of altimetric observations allowed by the successive launches of ERS-2, Jason-1, Envisat, GFO, the ocean MSS is now calculated with a sub-centimetric precision for a spatial resolution lower than thirty km.

The reference field needed to reconstruct the ocean absolute dynamic topography from the SLA is the ocean Mean Dynamic Topography (MDT). It can be obtained subtracting the geoid from the MSS (the so-called direct method) but its accuracy and resolution is limited by the geoid accuracy. Other methods have thus been developed to estimate the shortest scales of the MDT, based on Ocean General Circulation models, inverse modelling, in-situ data, or a combination of different datasets.

The aim of this paper is to review the fundamental improvements realized since the launch of ERS-1 to precisely determine the MSS, the geoid and the MDT, all three key components of the altimetric measurement for oceanographic applications, as well as to investigate the contribution and limitation of upcoming altimetric (Altika, WSOA, Icesat) and gravimetric (GOCE) missions.

The benefit of EIGEN gravity field models for altimetry and vice versa

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Unique data from modern satellite gravity missions such as CHAMP and GRACE have revolutionized the determination of global gravity field models from space. In particular GRACE has propelled satellite-only global gravity models with respect to resolution and accuracy including the access to the variations of the Earth's gravity field at monthly time-scales.

The impact of such models on satellite altimetry is threefold. First, accurate gravity models are a prerequisite for precise orbit determination of altimeter satellites at or below the noise level of the altimeter instruments. Second, the novel models provide an independent, cm-precise geoid at unprecedented spatial resolutions to be used for the determination of sea surface topography from the altimeter data and consistent orbits. Third, time series of highly-accurate global gravity models together with altimetry are expected to give insight into the separation of mass and steric components of the oceans surface. On the other hand, gravity information derived from satellite altimetry is still an invaluable input for the generation of high-resolution gravity models based on the combination of satellite, terrestrial and altimeter-derived gravity data.

At GFZ Potsdam, CHAMP- and GRACE-based as well as combined static and time-variable global gravity models of

high resolution are routinely processed in the frame work of the EIGEN processing activities (EIGEN = European Improved Gravity model of the Earth by New techniques). This contribution presents latest results of a new gravity model product generation labeled EIGEN-04, which is mainly based on a recent reprocessing of CHAMP and GRACE data.

A New Global Continental Margin Gravity Model derived from Altimeter Data

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Since the mid 1990s, GETECH has developed new and more reliable techniques to repick (retrack) and derive the gravity field from altimeter data. These research studies resulted in 2002-2004 in an oil industry funded global study to generate a high resolution continental margin gravity model extending from 500 km offshore to within 2 to 5 km of the coastline for all open marine regions. The resulting model based on ERS1 and Geosat GM data, spatially images the geology of all the world's continental margins down to a resolution of 10 km full wavelength at ~3 mGals. This dataset is now playing a significant role within the oil industry in screening exploration opportunities in both the shallow and deep water areas of the continental margin.

This contribution will introduce delegates to the new techniques we have developed in the reprocessing of the altimeter data and will demonstrate the improved resolution of our gravity model with respect to existing data sets and to the more restricted higher resolution terrestrial marine data.

Session 6.2:

The Integrated Approach/Demonstrations

Interpreting low frequency sea level signals over the last decade

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Sea level variability on time scales from months to years can be associated with a variety of processes, from warming of the water column due to changes in surface heat flux to changes in the surface circulation driven by variable wind stress. Correctly interpreting the observed sea level signals can thus reveal important clues about the nature of ocean and climate variability. Here an attempt is made to unravel the processes behind sea level signals observed over the period 1992-2004, from the seasonal cycle to long term trends. The basic tool is the estimation procedure used by the ECCO-GODAE consortium that constrains an ocean general circulation model in a least-squares sense. Altimetric data, both time-dependent, and time-mean are a large part of the 410 million data constraints used, which also include CTDs, XBTs, ARGO float profiles, and meteorological variables. The constrained solution produces a good fit of the altimeter variability and compares well with a tide gauge dataset not used in the optimization. Variability in sea level is decomposed into bottom pressure, halosteric, and thermosteric terms, and each respective contribution is analyzed as a function of time scale and location. Both regional and global mean sea level signals are treated in terms of their relation to surface forcing, relevant dynamic and thermodynamic processes, along with discussion of shortcomings in model formulation and overall uncertainties in the constrained solution.

Mid-depth Circulation of the World's Oceans: A First Look at the Argo Array

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Satellite-based measurements of sea-surface height provide data that is highly complimentary to a wide variety of in situ data sets. One of the most robust such data sets is the Argo array of profiling floats. As of September, 2005, the Argo array has reached almost two-thirds of its target density and consists of more than 1900 floats, which now provide near-global coverage. In addition to producing a wealth of temperature and salinity profiles, Argo floats provide estimates of the mid-depth ocean circulation by drifting at a depth of 1000m over a period of 10 days. With roughly 3500 float-years of data now available, a preliminary estimate of the mid-depth circulation can now be produced for most of the oceans using Argo data. Estimates of the velocity field and dynamic height at 1000m depth will be presented. Altimeter-based estimates of sea-surface height anomaly also contain information about the geostrophic velocity field. In addition to the estimates of mid-depth circulation, the relationship between anomalous geostrophic velocity at the surface and 1000m float displacements was explored. Over much of the ocean, the altimeter data was found to be complimentary to the float displacement data and a technique was developed for combining these two datasets to create improved estimates of the time-averaged velocity field at 1000m. The altimeter data is first used to estimate anomalous geostrophic velocity at depth, which is then used to correct individual float displacements. Although improvements to individual float trajectories are not always discernable, the correction significantly reduces the variance of the displacement data and improves the signal to noise ratio by 50% in most regions, and more in regions of high eddy variability.

Altimetry, SST and ocean colour unveil the effects of planetary waves on phytoplankton

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Fifteen years of altimetry have dramatically increased our knowledge of planetary waves in the ocean, highlighting the ubiquity of the waves and reshaping the relevant theory. Prompted by this success, research has more recently widened into detecting the signature of the waves in other datasets. While their demonstrated presence in the SST record was somehow expected on the basis of dynamical considerations and in view of the long known correlation between temperature and height, the recent discovery of the almost ubiquitous signature of planetary waves in maps of phytoplankton chlorophyll from ocean colour satellites raises a number of intriguing questions. What is causing the westward propagating signals in the ocean colour records? Are there purely mechanical reasons for it, or is there a contribution due to biological processes? And if the latter is true, what is the importance of planetary waves for primary production and for the global carbon cycle?

The above questions can be addressed by contrasting the altimetric observations with those in other datasets. In this paper we will first review a number of studies that have highlighted the wave signature in SST and ocean colour; then we will discuss the different mechanisms that have been suggested to explain the formation of such a signature. These mechanisms range from purely physical, such as the horizontal advection of phytoplankton due to geostrophic velocities associated with the waves, to purely biological such as the increased growth due to upwelled nutrients. We will then show a comparative analysis of the wave signatures in altimetry and in the other datasets, based on cross-spectra, and we will demonstrate how this analysis, in combination with process modelling, is capable to shed some light on which mechanisms predominate in different regions of the world's ocean. We will conclude by discussing those questions that still remain open, and in particular the significance of planetary wave-induced production in the oceanic carbon pool.

Mean surface circulation of the global ocean inferred from satellite altimeter and drifter data

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A simplified form of horizontal momentum equation containing full acceleration, Coriolis force, pressure gradient and Ekman stress terms is used to combine data of the Aviso merged sea level anomaly, global array of near-surface drifters and NCEP reanalysis winds demonstrating good agreement with each other at high spatiotemporal resolution. Thus utilized drifter velocities provide the missing reference to satellite altimeter observations who in their turn correct the bias due to inhomogeneous distribution of Lagrangian drifters. Acceleration is shown to be an important part of cyclostrophic balance in the regions of high eddy energy.

Study of the relation between Ekman currents at the drifter drogue depth (15m) and local wind revealed significant variations both in latitude and longitude, strong seasonality and non-linearity to the wind speed. These variations are in a qualitative agreement with the theoretical effect of intensity of vertical mixing in the ocean mixed layer and stability of the atmospheric boundary layer and are used to improve the parameterizations of Ekman stress and velocity to NCEP reanalysis wind at 10 m level.

Local estimates of horizontal pressure gradient are combined with the data of the Gravity Recovery And Climate Experiment (GRACE) and integrated to produce the global grid of the 1992-2004 mean dynamic ocean topography (DOT) at mesoscale resolution. Mean geostrophic velocities derived from this DOT are used to revise the patterns of surface circulation in various regions. They reveal remarkable fine structure of major large-scale flows, such as the Gulf Stream, Kuroshio Extension and Antarctic Circumpolar Current. They also suggest corrections to the previous description of the South Atlantic Current with the change of its role from a branch of the Brazil Current to a southern analogue of the Azores Current and detect a system of relatively weak steady nearly zonal jets in the eastern North and South Pacific.

Combining Altimetric and All Other Data with a General Circulation Model

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The TOPEX/POSEIDON mission was formulated in conjunction with the World Ocean Circulation Experiment (WOCE). Although altimetric data are by far the largest ocean data set that emerged from that experiment, it was recognized from the outset that the best estimate of the ocean circulation and its variability would be made by combining all the data with a good general circulation model. The US ECCO-GODAE consortium has now produced useful estimates of the three-dimensional time evolving ocean circulation at 1 degree lateral resolution, 23 layers in the vertical, over the time period 1992-2004. At the present time, the solution represents a least-squares misfit to about 410million separate observational constraints. A huge variety of fields can be analyzed in the results, but the focus will be on the overturning circulation and its changes over this time period. The residual model/data misfits raise difficult questions about remaining errors in the altimetric/geoid fields.

Session 1.6:

Oceanography: Marine Meteorology

Surface Wave Field from Altimetry for Mixed Seas (sea and swell) under the Influence of Offshore Winds

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Analysis of the wave field is carried out from altimetry data from various sources (ERS-1, ERS-2, TOPEX-POSEIDON) for the region of the Gulf of Tehuantepec, México. The study area is characterized by the presence of strong and persistent offshore wind jet events (Tehuano Events) especially during the winter season. Arrival of swell practically over the whole year makes it a region with the unique opportunity to look in detail the wave field detected by the altimeters when locally generated wind sea propagates against the swell. Histograms of significant wave height (Hs) are analyzed for seasons under Tehuano events and compared to those for the rest of the year. During Tehuano events Hs histograms are wider in distribution resembling the presence of higher waves. A different approach for the analysis, based on Hs information for individual tracks, allows us to perform an evaluation of wave growth under opposing swell conditions. Individual track Hs measurements are compared to in situ observations carried out for a short period of time during the 2005 Tehuano season, when a couple of ADCP with wave measuring capabilities and an Air-Sea Interaction Spar (ASIS) buoy were deployed in the study area. While the ADCPs were mounted at the bottom in 20m water depth, providing us with directional spectrum estimates of the arriving swell, the ASIS buoy provided us with offshore wave information, at a region with 60m water depth. The potential influence of the wind stress on the determination of the significant wave height from the altimeter signal is to be addressed in this work, specifically from direct measurements of the momentum flux with ASIS buoy capability.

Analysis of extreme low pressure events like hurricanes and extra-tropical storms thanks to altimetry

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The relationship between atmospheric Sea Level Pressure (SLP) and the Sea Level Anomalie (SLA) measurements is investigated during storms and very low pressure conditions. Indeed the Inverse Barometer (IB) response has been extensively studied for normal meteorological conditions (Wunsh and Stammer 1997; Mathers 2000; Carrère 2003); but it remained uncertain that there exists a well SLP/SLA correlated signal during storms and hurricanes which are generally characterized by heavy rains, high sea states and strong winds.

The 2003-2004 period has been studied to benefit from the availability of 3 altimeter missions (ENVISAT, TP and Jason-1), an extensive observing network deployed by NOAA in the Atlantic ocean, high resolution ECMWF products (pressure and wind at 0.5°) and from the QuikScat scatterometer measurements.

Specific altimeter treatments have been applied because of too many missing measurements due to heavy rains and strong winds. The C- or S-band measurements are used because less impacted by rain, an expected Ku-band backscatter coefficient is defined for data impacted by rain, and continuous along-track wind speed profiles are computed thanks to the Young algorithm (Young 1993). Due to a non negligible error bar of 11 cm rms, these treatments were only applied on TCs observations, for which classical validated data are the less numerous. Along-track altimeter data were also filtered to remove ocean signal not related to atmospheric pressure : 600 km wavelength for TCs and 1500 km wavelength for extra-tropical storms which have significantly larger spatial scales.

The ability of altimetry to detect extreme low pressure events has been demonstrated during extra-tropical storms, with good correlation between SLP and SLA. It came out that one needs to use all storms cases at once to get a stable regression coefficient. The validation of the regression model showed interesting results (no bias and 6 cm standard deviation error if compared to ECMWF pressure, and 5 cm rms error if compared to colocalised altimeter-buoys

database); but a small residual error-SLA dependency still remains (error = SLPrestored-SLPecmwf).

For tropical cyclones, selected cases showed that altimetry could provide precise information about wind speed (Quilfen et al., submitted to JGR) compared to scatterometers for instance. However, the retrieval of surface pressure from altimetry during TCs was not possible due to the poor quality of the pressure datasets available during these events, to the more complex response of the ocean medium to such extreme forcing (maximum storm surge is due to wind during TCs), and to the heavy rains characterizing such extreme weather conditions.

Use of Altimeter and SAR Wave Data at the Met Office and Recent Comparison with Wave Model and Buoys

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Marine observations are relatively scarce in comparison with atmospheric ones due to limitation of observation tools and hindrance of the deep water. For centuries marine scientists have relied on sporadic cruise measurements and scattered buoys. The advent of remote sensing by aircrafts and satellites in late of the 20th century has greatly enlarged our ocean surface data set. UK Met Office has been involved closely with other international scientific organizations in the use of satellite wave observations. Altimeter data assimilation in ocean and wave models started in the 1980s with data from the SEASAT and Geosat satellites. Operational altimeter data assimilation began with the ERS-1 satellite launched in 1991. The most recent application of satellite data in the Met Office uses data from the ERS-2 and ENVISAT satellites. Radar altimeter wave data have enriched our knowledge of the global ocean waves and helped in improvement of our ocean wave models. On the other hand, ocean wave models have also contributed to the calibration and validation of satellite observations.

The operational wave spectral model suite run in the Met Office provides analyses and forecasts of sea state on grid spacing of approximately 60 km for the global model and 12 km for the nested regional models. As standard the models operate with a spectral resolution of 13 frequency and 16 directional bins, which represents waves with a range of periods between 3 and 25 seconds. The wave model is forced by hourly winds at 10m above mean sea-level generated in the Met Office Unified Model, which include observations from satellite, ship and data buoy networks in their 4-DVar assimilation schemes. The general performance of this wave model is comparable to other operational wave

models, such as the 3rd generation WAM model.

The modelled two-dimensional wave energy spectra have been compared with measured ocean wave energy spectra from 11 moored buoys and the Advanced Synthetic Aperture Radar (ASAR) aboard the Envisat satellite. Comparisons are also made with the ocean wave height observed by the radar altimeter (RA2) onboard the same satellite Envisat as the ASAR instrument over the two years 2004 and 2005. Measured ocean wave energy spectra from two moored buoys (ID 51028 near Christmas Island at 0.02° S 153.87° W and ID 42001 in the Gulf of Mexico at 25.86° N 89.67° W) are selected for illustration here. Altimeter and ASAR data close to these two buoys are also collected for buoy-model-satellite inter-comparisons. Apart from comparison of the total significant wave height (SWH), we also compare the SWH in 4 frequency sub-ranges. This spectral breakdown of ocean wave energy sheds some light on the spectral characteristics of the wave model and the observations.

Results indicate that the wave model SWHs are generally in agreement with all the 3 different observations (buoy, altimeter and ASAR). Model sub-range SWHs are more close to the buoy ones than to the ASAR ones, which have larger variations than the modelled ones in both ends of the wave spectra. Some improvement of the ASAR data since late 2004 is also showed.

The Indian Ocean Tsunami of December 26, 2004, Observed by Multi-satellite Altimetry.

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On December 26, 2004, at 0h59 p.m. UTC, an Indian Ocean earthquake with a magnitude of 9 generated a strong tsunami that produced huge waves at the coasts. They devastated the shores of all countries close to the Bengal Gulf with wave heights of up to 15 m. Until then, tsunami observations by satellite altimeters had not been significant. But due to its intensity and its large area, the Indian Ocean tsunami was the first one detectable by TOPEX, Jason-1, Envisat and GFO satellites together. The wave amplitude observed in deep-ocean by TOPEX and Jason-1 was close to 60 cm when both satellites overflew the tsunami 2 hours after the earthquake. Envisat crossed the tsunami wave 3h15 later and

measured a 30 cm wave. Finally, though GFO overflowed the tsunami 7h20 later, it observed a wave close to 20 cm. In order to better analyse the tsunami signal along satellite passes, we used a dedicated ocean variability mapping technique in order to decorrelate signals due to the tsunami and signals due to the ocean, such as mesoscale. First, altimeter observations and model outputs provided by CEA (Commissariat à l'Énergie Atomique) have been compared with good accuracy. Then, particular signals with wavelengths between 20 and 30 km could be evidenced along Jason-1 and Envisat profiles. They could be attributed to the tsunami according to the theory of wave propagation in dispersive medium.

These observations of tsunami waves in deep ocean highlight the essential role of satellite altimeter measurements for improving the modelisation of tsunami wave propagation.

velocity of the tectonic plane determine the spatial pattern of the tsunami. The use of OGCM accounts for ocean circulations and the sea floor forcing mechanism used allow quantification of the effects of both horizontal and vertical sea floor uplifts. We further use multiple satellite altimetry and world tide gauges to compare and diagnose the available tsunami models, including the OGCM tsunami model. The developed methodology offers an improved capability for tsunami modeling and potential more accurate predictions.

Assessment of Tsunami Modeling Using Satellite Altimetry and Tide Gauges

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The 26 December 2004 Indian Ocean tsunami is triggered by the largest earthquake in 40 years, the Mw=9.3 Sumatra-Andaman undersea earthquake. The resulting earthquake tsunami of this magnitude is the first to occur since the advent of both digital seismometry and multiple satellite radar altimetry. Both have independently recorded the event, but from different physical aspects. The strong tsunami is also detected by world-wide tide gauges significantly away from the source. The seismic data have been used to estimate the earthquake fault parameters and the satellite observed tsunami waves are used to determine the initial sea-surface-displacement as well as the effects of 1300 km seafloor ruptures with a duration of ~40 minutes triggered by the great Sumatra-Andaman earthquake. Here we show that these two data sets provide consistent tsunami source, using independent methodologies of seismic-inversion and ocean general circulation modeling (OGCM), and provide an analysis of the OGCM tsunami model versus other tsunami models. Cross-examining the two independent results confirms that the earthquake-induced bottom-pressure-force is the most important condition that controls the tsunami strength, while the geometry and the rupture

Session 3:

Marine Geodesy, Gravity, Bathymetry

Combining Satellite Altimetry, Tide Gauge Observations and an Oceanographic Model to Derive the Baltic Sea Mean Sea Surface Topography

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In the Baltic Sea, the sea-level variability is dominated by meteorologically forced fluctuations with large seasonal and interannual variations. Besides the observations of satellite altimeters, a dense network of tide gauge measurements is available to determine these sea-level variations. Moreover, a high-resolution oceanographic model of the Baltic Sea provides sea-level heights that largely reflect the high-frequency sea-surface variations.

The different information can be combined in such a way that the variance of the altimetric sea-level heights can be substantially reduced. To achieve this reduction, the long-term variations as obtained from tide gauges and the short-term variations provided by the oceanographic model are applied to the altimeter data. The resulting smoothed altimeter time series form the basis for the estimation of mean sea-surface heights. The application of a geoid model then yields the mean sea-surface topography (MSSTop).

A high spatial resolution of the resulting MSSTop is achieved by the combination of several altimetric missions. For this purpose, observations of Jason-1, ERS-2, and Envisat are tied to the observations of TOPEX by minimizing the crossover point differences. This also provides information about the relative biases between the different altimeter missions.

The presentation will focus on how the sea-surface heights from the different sources and techniques can be combined, and the error budget of the resulting MSSTop will be discussed.

Tests of Geoid Height Skill Through Estimates of the Ocean Circulation

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New geoid height estimates are now available from the Gravity Recovery and Climate Experiment (GRACE) spacecraft. Such estimates are central to ongoing efforts to calculate the ocean circulation and its time variability, and it thus becomes important to understand the degree of skill in geoid knowledge. Here one of the GRACE estimates (GGM01s) is compared to that from a previous geoid estimate (EGM96) by examining the resulting estimates of the ocean circulation available from the ECCO and GECCO efforts now since several years and the residual misfit of the estimated sea surface height (SSH). Circulation estimates were obtained over the period 1992 - 2002 by combining most of the available ocean data sets with a global general circulation model on a 1 degree horizontal grid. When combined with altimetric data, as compared to EGM96, the new GRACE geoid produces fields that are more consistent with temperature and salinity climatologies, and thereby requires smaller adjustments to the initial model conditions. Because in both cases, the misfit of the the mean dynamic topography is small compared to other model-data misfits, differences in the time mean seasurface heights (SSH) from the two geoids are relatively modest. Therefore, an experiment was done in which the relative geoid error was artificially reduced, thus forcing the model circulation to be much closer to the absolute altimetric surface determined by GRACE. Adjustments occur in all aspects of the ocean circulation, including changes in the meridional overturning circulation and the corresponding meridional heat transport in the Atlantic of about 10% of their mean values. Overall this model state shows an improved skill in simulating in situ temperature and salinity profiles. Improved estimates of the dynamic sea surface height (altimetric surfaces - geoid) would be useful for quantitative improvements in estimates of the circulation and its climate impacts. As a by-product of this work, it appears that at the present time, the errors in the geoid height are comparable to uncorrected errors in the altimetric data sets.

Vertical seafloor deformation in a partially blocked subduction zone from tide gauge, altimetry and GPS data

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The Vanuatu archipelago is part of the Pacific « ring of fire », where plates are rapidly converging. In the area, movements are very rapid and the seismic activity is intense, which gives a good opportunity to study deformation and seismic cycle. To get an integrate picture of vertical deformation over one plate and between the two plates, one needs to be able to monitor vertical movements on both underwater and emerged areas. We conducted an experiment in the Vanuatu archipelago, South-West Pacific, to compare measurements from bottom pressure gauges and altimetry satellite data using constraints from kinematic GPS data. Two bottom pressure gauges are immersed since Nov. 1999 on Sabine bank (15.90°S, 166.14°E) and Wusi Bank (15.34°S, 166.55°E), West of Santo island, Vanuatu. Water height data provided by seafloor tide gauges is a combination of sea-level variations and ground motion. Both of these signals are of scientific interest, but they must be separated in order to be useful. One promising method to separate the two contributions and retrieve the ground motion signal we are looking for is to use satellite altimetry data which gives absolute water height. Satellite altimetry data must be calibrated using « ground truth » measurements, such as GPS. On board and buoy kinematic GPS data are also used to link pressure gauge and satellite altimetry data, because the pressure gauge is not located directly beneath the satellites tracks. Once different components of the signal are separated, bottom pressure gauges can be used to detect vertical movements of the seafloor such as co-seismic or slow inter-seismic motions. Our results are analyzed in comparison with vertical movements observed on-land at Wusi GPS station which is located a few kilometers East of the tide gauge.

How Radar Altimetry Discovered Marine Geodynamics

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Since the early altimeter experiments on GEOS-3 and SEASAT, radar altimetry data has been used to derive gravity and its variations over the world's oceans. Soon it became clear that altimetry is an excellent tool for mapping sea floor structures, including tectonics, sea mounts and rifts. The short wavelengths of the gravity field at the ocean surface mimics the uppermost structure of the oceanic crust, including the bathymetry, while long wavelengths reflect structures and processes in the Earth's mantle. This characteristic has been used to derive the bathymetry of the oceans, which revealed a vast amount of new geological information. However, besides the bathymetry, the derived marine gravity anomalies further allow closer insights into the structure of the lithosphere and crust, and the marine geoid. While the bathymetry - water density contrast is the most important to consider, there are remaining components in the gravity field that originate from internal crustal and lithospheric structures. Altimetry data has consequently been employed to better understand and interpret the present structure and the geological evolution of continental shelves, mid-ocean ridges and subduction zones. These data sets have been dramatically improved in terms of spatial resolution with the Geodetic Mission phases of GEOSAT and ERS-1. In addition, the higher inclination of ERS-1 opened the door to conduct geodynamic studies also in the polar regions. The paper outlines the contributions of radar altimetry to marine geodynamics and presents examples of geodynamic studies that include the opening history of the North Atlantic, boudinage and deformation structures in continental shelves, and lithospheric cooling signatures at the East Pacific ridge. Today, gravity anomalies derived from altimetry data is one of the fundamental data sets frequently used in the geoscience community.

Sea-level signature of bathymetric errors and their observability by satellite altimetry

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An experiment of bathymetry correction via the assimilation of sea level altimeter observations in a 2-dimensional numerical hydrodynamic model implemented on the North Sea shelf is presented here. Estimating sea level model error statistics due to uncertainties in bathymetry, and their relation to bathymetric errors, effectively makes it theoretically possible to update the bathymetric solution using both sea level observations and data assimilation techniques. In this work, this estimation is empirically performed making use of ensemble methods. A single experiment is carried out, as a by-product of a more general study aiming at estimating the ability of different altimeter configurations to control model error on the North Sea shelf. This is the reason why we do not aim at bringing here a complete answer to the question but rather propose a single illustration about the topic. We use the barotropic MOG2D model, and the focus is on the specific high-frequency response of the ocean to meteorological forcing (time scales from a few hours to a few days).

Sea level model error due to uncertainties in bathymetry is first carefully explored. An ensemble of bathymetric solutions is generated by randomly combining over the study domain elementary perturbations extracted from typical mismatches between different existing bathymetric databases. The model run over these perturbed solutions leads to an ensemble of simulations enabling to approximate model error statistics related to this particular source of error, and therefore to give an insight into the signature of bathymetric errors on model sea level. This signature appears to be neither homogeneous over the shelf, nor stationary, since it strongly depends on the meteorological regime and the associated oceanic processes at work.

Seafloor elevations are then included in the state vector together with model sea level, in order for them to be updated during the analysis. A space-time global inversion scheme taking into account all observed variables over a 20-day period is implemented. In the framework of twin experiments, we consider simulated high-resolution WSOA data (Wide Swath Ocean Altimeter) to correct a given perturbed bathymetric solution along the eastern British coast. Results are encouraging in the sense that the bathymetric update approximates to the control solution. However, a large part of the error remains uncorrected, meaning that bathymetric error signature on model sea level is not significant enough in this particular experiment to be

observed by the particular altimeter observations under consideration. A more thorough study would be needed to confirm these first findings.

Session 6.2:

The Integrated Approach/Demonstrations

Chlorophyll Bloom in the Western Equatorial Pacific During the 1998 El Niño / La Niña Transition: the Role of Kiribati Islands as Seen From Satellite, in-situ Data, and a High-Resolution Simulation

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During the 1998 El Niño / La Niña transition, ocean color observation from the recently launched SeaWiFS sensor showed a dramatic chlorophyll bloom that spread between 160°E and 175°E in the equatorial Pacific. Surface chlorophyll concentrations notably increased from March to June 1998, and reached more than 0.8 mg m⁻³ in May, in a region usually known as oligotrophic. Just prior to this event, the thermocline and the nutrient pool were shallow across the equatorial Pacific. In such environmental conditions, previous studies attributed this bloom to a wind-driven upwelling and to the shoaling of the Equatorial UnderCurrent, which brought both nitrate and iron to the surface waters. However, they do not explain its particular location, which coincided with the presence of the Kiribati Islands. These small coral atolls form an obstacle both for the surface westward flowing South Equatorial Current and the subsurface eastward flowing Equatorial UnderCurrent. In the context of a strongly uplifted nutrient pool on the equatorial basin scale, we investigated possible dynamical perturbations induced by the islands that could favor the phytoplankton growth. In addition to SeaWiFS chlorophyll data, we used satellite (Topex/Poseidon altimetry, TMI SST, ERS surface winds) and in situ data (TAO/TRITON mooring) to assess the physical context of the bloom. Variations of altimetric sea level anomalies (SLA) are mainly the result of the vertical motions of the thermocline. Therefore, altimetry is useful to gather information about the variations of the depth of the nutrient pool. Data from the equatorial TAO mooring at 165°E provided subsurface variations of temperature and currents. Then, we modeled the event with the Regional Oceanic Modeling System (ROMS) with 1/6° horizontal resolution and 30 vertical levels. The model reproduced the spatial patterns and

temporal evolution of SST and SLA, as well as the vertical structure of temperature and velocity. In an ongoing study, we use it to examine possible pathways of nitrate-rich and iron-rich waters, analyze why the chlorophyll bloom was confined west of the Kiribati islands and infer the role they played in the generation and development of the bloom.

Basin Scale Mass Variations in the Atlantic Ocean

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Variations in oceanic mass are on the one hand related to changes in ocean dynamics and on the other hand to changes in the global freshwater cycle. Until recently it has not been feasible to derive this quantity on large spatial scales from measurements. Nowadays it can be obtained by the reduction of steric from total sea level changes as well as by the analysis of temporal changes in the gravity field. In this study space-based altimeter (ERS-2, TOPEX and Jason-1) and in-situ Argo data (CORIOLIS project) are combined to derive monthly mass related sea level variations in the Atlantic Ocean for the period 2000 to 2005. From 2002 onward the global mass redistributions have been monitored by the GRACE satellites. An independent estimate of monthly mass variations in the Atlantic Ocean is generated from the latest time series of monthly GRACE-only gravity models in the Atlantic Ocean processed at GFZ Potsdam. After adequate spatial filtering the two data sets are compared and the advantages and disadvantages of the two approaches are identified. Typical temporal and spatial scales of these data and the relationship between steric and mass related sea level variations are further investigated for the Atlantic Ocean.

Results from the GOCINA project. Combining altimetric/gravimetric and ocean model mean dynamic topographies

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One of the major goals of the recently completed EU project GOCINA (Geoid and Ocean Circulation In the North Atlantic) is the determine the following three quantities; an accurate mean dynamic topography model, an accurate mean sea surface and an accurate geoid for the GOCINA region between Greenland and the UK and to use the common relationship between the three quantities for mutual improvement. The improved determination of the mean circulation will advance the understanding of the role of the ocean mass and heat transport in climate change. To calculate the best possible synthetic mean dynamic topographies a new mean sea surface (KMS04) has been derived from nine years of altimetric data (1993-2001). The regional geoid has furthermore being updated using GRACE and gravimetric data from a recent airborne survey. New synthetic mean dynamic topography models have been computed from the best available geoid models and the mean sea surface model KMS03. Subsequently, an integrated approach has been used to compute MDTs from joint inversions of data from the various sources. These models will be compared with state of the art hydrodynamic mean dynamic topography models in the North Atlantic GOCINA area. The results show that great improvements were obtained with the improved geoid information from the GRACE satellite mission. Further improvements in the local characteristics of the ocean transport were obtained with the enhance geoid. Compared with the Composite MDT the synthetic MDT derived from the mean sea surface and this NAT04 geoid showed very similar results.

The MERSEA Project : Development of a European system for operational monitoring and forecasting of the ocean on global and regional scales

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GMES (Global Monitoring for Environment and Security) is a joint initiative of the European Commission and the

European Space Agency, designed to establish a European capacity for the provision and use of operational information for Global Monitoring of Environment and Security. To support the development of the Ocean and Marine Applications component of GMES, the EC is funding the MERSEA integrated project. The system is based on the assimilation of remote sensing (altimetry, sea surface temperature, sea ice) and in situ observations (ARGO and XBT profiles) into high resolution ocean models. The project includes research and development activities on data products, ocean modelling, assimilation, nesting and downscaling, ecosystems, and seasonal forecasting. The project federates the European contribution to the GODAE. It intends to contribute to the development of integrated core ocean services in Europe. The system design includes a global, as well as four regional components (Nordic, Baltic / North sea, North East Atlantic, and Mediterranean seas) which provide ocean analyses and forecasts in real time through assimilation of in situ and satellite data. The essential variables are the temperature, salinity and velocity fields, but research efforts are underway to include biogeochemical and ecosystem variables. The input data and forcing fields are provided by dedicated Centres. The whole system is linked through an Information Management System. The overarching objective is to provide an integrated service of global and regional ocean monitoring and forecasting to intermediate users and policy makers in support of safe and efficient offshore activities, environmental management, security, and sustainable use of marine resources. Some forty agencies, laboratories and institutions participate in the research and development effort of this four year project, which started in 2004. The project is oriented towards applications, and the delivery of products and services in support of marine safety and offshore industry, marine meteorology, wave forecasts and ship routing, oil drift fate prediction, seasonal forecasting, research, and reporting to public bodies. The system is also intended to deliver boundary conditions and data to coastal operational systems. Since Octobre 2005, the system has been upgraded to its version V1, and an intensive pre-operational test period will be run for six months. We will present an overview of the system design and preliminary results from this Target Operational Period, from the point of view of validation and assessment of the quality of the outputs.

Sea surface salinity from a simplified ocean mixed layer model using global altimeter data

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A vertically integrated 2D model of the ocean mixed layer is

used to estimate the anomalies of Sea Surface Salinity (SSS) caused by atmospheric heat fluxes, evaporation-precipitation budget, wind friction and geostrophic circulation. The input parameters are the Sea Surface Temperature and air/sea fluxes derived from ECMWF meteorological model and the geostrophic currents from SSALTO-DUACS altimetry analysis. The model is first tested with a high-frequency climatological forcing dataset, in terms of variability and space distribution of SSS response. It is shown that variations in wind-induced transport is the first cause of salinity variability, but fresh water flux and geostrophic transport can dominate locally. Then the analysis is performed over several recent years, using an optimal combination of space-borne observations and model outputs. The results are validated using in situ measurements from buoy arrays in the tropical Pacific (TAO) and Atlantic (PIRATA), then using gridded fields from ARGO drifters over the North-Atlantic (Coriolis analysis). Finally, the interest of this method and its real-time application is examined in view of the future SMOS and Aquarius satellites, which will both be dedicated to SSS retrieval.

Session 8.1:

The Future of Altimetry, part 1

Requirements for Future Satellite Altimetry - Recommendations from the EC GAMBLE Project

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Measurements from satellite radar altimeters have revolutionised our knowledge of the ocean, through studies in sea level, ocean circulation and climate variability. Satellite altimetry is recognised as an essential component of global ocean observing systems under programmes such as GODAE, CLIVAR and GOOS, and through its ability to provide stable and accurate long term monitoring of sea-level change.

Altimeter data products are an essential input to European operational oceanography systems such as MERCATOR, MERSEA, FOAM, TOPAZ, and MFSTEP. Altimeter data are also routinely assimilated into wave forecast models, providing support to offshore operations around the world.

The EC Framework 5 GAMBLE Thematic Network brought together European experts in ocean altimetry in a series of workshops to make recommendations for future activity. Specific objectives were:

- To establish error budgets and measurement requirements necessary to resolve key features in sea surface height and sea state.
- To make recommendations for future research, and for future altimeter missions necessary to support recent developments in operational oceanography and to maintain ocean monitoring programmes.

In this poster we present the key recommendations of the GAMBLE community – as they relate to meeting priority requirements for sea surface height and sea state data

In particular the team identified that under present plans the existing satellite altimeter monitoring capabilities are expected to degrade significantly in the medium term. This will have severe implications for the capability of the

integrated operational oceanography systems being developed. In addition, a failure of the one altimeter mission currently planned for the period 2008-2011 would break the continuous chain of precise altimeter global sea level measurements seen as an essential component of the international climate change monitoring programmes. Early action is required to avoid this potentially disastrous situation.

Such a situation is incompatible with high priority issues related to global ocean monitoring, coastal area survey and water resources management, as indicated in the European GMES programme, nor is it sufficient to support operational ocean monitoring programmes like MERSEA and MFS in Europe, or Mercator and FOAM at the national level, which are part of the International GODAE initiative.

AltiKa: a Ka-band altimetry system for operational altimetry during the GMES period

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In partnership with scientific laboratories and industry, CNES has studied the feasibility of a high-resolution ocean topography mission based upon a new class of wide-band Ka-band altimeter in preparation for the post-ENVISAT mission and in order to complement the OSTM/Jason-2 mission. Altimetry is considered as one of the major elements of the ocean observing system to be made sustainable through the GEOSS (Global Earth Observation System of Systems) and GMES (Global Monitoring of the Environment and Security) programs. The central objective is the retrieval of the ocean mesoscale circulation in global or regional ocean models data assimilation. Moreover, other applications of the mission have been identified: coastal altimetry, continental water studies, ice sheet monitoring, low-rain systems characterization are the main ‘secondary’ objectives identified so far. The proposed architecture for the Ka-band altimeter is based on the classical deramp technique for pulse compression and takes benefits of Alcatel Space and CNES experience in the development of Poseidon-1, -2 and -3 and SIRAL (European Space Agency Cryosat mission). A bi-frequency radiometer is part of the

compact Ka-band payload. Both altimeter and radiometer share the same antenna. Apart from the combined altimeter and radiometer, this payload also consists of a DORIS plus LRA (Laser Retroreflector Array) orbitography system that will ensure a high level of accuracy in terms of orbitography. The technical feasibility of a coupled altimeter / radiometer AltiKa payload has been demonstrated. The altimeter shall provide sea-surface measurements with a very high accuracy. Improved performances over other types of surface shall also be reached, first thanks to the reduced size of the radar footprint compared to a Ku-band instrument, and second thanks to the implementation of new tracking algorithms. Because an opportunity to embark the AltiKa payload on the OCEANSAT-3 platform has appeared in the frame of a cooperation between CNES and ISRO (Indian Space Research Organization), a delta phase B has started at the beginning of July 2005, with an expected start of the phase C/D during the first half of 2006. The launch of OCEANSAT-3 is presently planned in 2009-2010. This mission would thus be a demonstration of Ka-band altimetry as a complement to the Jason-2 mission. The AltiKa payload on OCEANSAT-3 should then be considered as the post-ENVISAT altimetry gap filler.

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ESA's Sentinel-3: An Operational Oceanography Mission for GMES

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The European Space Agency (ESA) recently initiated an industrial definition phase study activity for a satellite mission that shall provide operational continuity to specific ocean surface observations in the post Envisat era (2010 onwards). This mission, known as GMES Sentinel-3 forms part of the Earthwatch line of missions within ESA's Living Planet Programme, and addresses the sustained observational requirements of the ESA/EU Global Monitoring for Environment and Security (GMES) programme.

GMES Sentinel-3, is one of the first EarthWatch mission concepts to be thoroughly studied to address global operational oceanography monitoring issues requiring long-term, systematic, and robust data collection and processing.

The required measurements to be supported by this operational satellite mission are sea-surface topography (SSH), sea-surface temperature (SST), and ocean colour (OC) characteristics. Some of these data streams form the kernel of products used in the latest generation of ocean forecasting models being developed under the data assimilation schemes of the FP6 MERSEA large-integrated projects, as well as operational Numerical Weather Prediction models. Other examples that will directly use Sentinel-3 data are the ESA MEDSPIRATION study and the GODAE GHRSSST Project who are developing near real time merged SST products, as well as projects such as HABILE which is using operational ocean colour data in the study of harmful algal bloom impact on the Marine ecosystem. Sentinel-3 required ocean variables form the basis for a large number of existing product services in ESA's GMES Service Element as well as the EC's Marine and Coastal Service.

Initial design studies have investigated a variety of competing altimeter technological solutions, along with visible and infrared spectrometer sensor packages (with AATSR-quality SST; and MERIS quality ocean colour and vegetation products) that allow global acquisition of radiometrically accurate 250m data over a broad swath. Advances in wide-swath spectrometry may also allow the development of smaller instrument packages for use on operational satellites, and provide the basis for monitoring of primary productivity, harmful algal blooms, climate quality SST data, and routine monitoring of biogeophysical processes that determine the unknown ocean contribution to the global CO₂ budget.

The status of the Sentinel-3 definition study will be reported primarily in the context of its altimetry.

Retrieving High Precision River Stages and Slopes from Space

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Conventional radar altimetry has been successful in retrieving water level measurements at altimeter crossings with an accuracy of 10cm to 20cm. Although promising, this measurement accuracy is insufficient to provide global monitoring of fresh water bodies, as has been proposed by the WatER mission, for instance. In this paper we examine in detail the error sources that a near-nadir synthetic aperture radar interferometer, such as the KaRIN instrument proposed to meet the WatER requirements, will be subject to and demonstrate that with appropriate calibration techniques, measurements of river stage with an accuracy of approximately 5 cm and river slope with an accuracy of 1

cm/1km can be obtained. In the first part, we examine the main error contributors to the height measurements and quantify the expected magnitude of the errors. The errors sources examined include tropospheric effects, spacecraft orbit and attitude stability, the effect of vegetation, and the effect of topographic lay-over. These sources of error are examined analytically and also with the help of an instrument simulation which includes all error sources to generate simulated measurements. Simulated performance results will be presented for the Ohio river basin and for the Amazon basin at the Solimoes/Puros confluence. In the second part, we examine calibration techniques to mitigate the errors mentioned above and demonstrate the feasibility of achieving the height and slope performance given in the first paragraph. Simulated calibration results will be presented for both Ohio and Amazon basins. Finally, we propose a method for processing the interferometer data to optimally filter random measurement noise and provide high precision estimates of river stage and slope which can be assimilated simply into hydrologic models or used in conjunction with ancillary data or physical assumptions to provide estimates of river discharge.

state-of-the-art- products of e.g. sea surface temperature, surface heat fluxes, sea surface winds and sea ice. In this presentation, the status and developments of EUMETSAT contribution to the Jason-2 program will be presented including an explanation of the products and their dissemination. In addition, an outline of the current and future OSI-SAF services will be shown together with EUMETSAT's view of its role in operational oceanography.

EUMETSAT and Operational Oceanography

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Currently, a major enterprise of the operational oceanography community is to develop an operational integrative service, providing real time and prognostic information on the state of the global ocean. This service will help its users to perform their duties in understanding and monitoring the world's marine environment and controlling a safe, unpollutive and sustainable human exploitation of this environment. Core elements of the service infrastructure are global and regional numerical ocean models, advanced data assimilation systems and timely streams of observational data. Since vast parts of the global ocean are very remote to human life, operational satellite systems are indispensable for the latter and hence the success of the service. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is one of Europe's leading centers in Earth Observation. It has the capacity to guarantee a timely provision of high-quality observational data originating from operational satellite systems and its involvement in operational oceanography is growing. For the Ocean Surface Topography Mission (OSTM), the Jason-2 program, EUMETSAT will be one of the operational centers, delivering the Near Real Time altimeter products for the global ocean. Secondly, being part of EUMETSAT's distributed ground system network, the Ocean and Sea Ice Satellite Application Facility (OSI-SAF) is disseminating

Session 7.2:

New Applications

The distribution of bigeye tuna, *Thunnus obesus*, and three-dimensional thermal structure estimated from satellite altimeter

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Images of sea surface height (hereafter SSH) derived by satellite altimeter have been used in Japanese tuna fishery. Fishermen empirically know that most of favorable fishing grounds locate at boundaries between high and low SSH area. Although good fishing ground appears near the boundary of different water masses, the dynamics and the mechanism of fish concentration are not well understood. In order to improve the accuracy of fish distribution, one needs to know oceanographic conditions where fish concentrate. In this contribution, we propose an empirical approach to estimate three-dimensional thermal structure in real time using satellite altimeter data. Making use of a two layer system model (Goni et al, 1996), an empirical regression model for three-dimensional thermal structure is derived combining absolute dynamic topography (ADT) by AVISO, in-situ data of temperature and salinity measured by Argo data, and monthly mean objective analysis data of temperature and salinity. We have applied the proposed technique to estimate three-dimensional thermal structure of mid-Pacific ocean. We show a good agreement between the model result and observed temperature profiles taken from XBT. We also demonstrate that the location of bigeye tuna (*Thunnus obesus*) fishing ground appears near the boundary of different water masses.

Altimetry helps understand the behavior of marine animals

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Understanding how marine animals utilize, and are constrained by, their oceanic environment is critically

needed to devise sound management strategies for marine ecosystems threatened by climate changes and direct anthropogenic pressure. To this aim, a large number of marine animals are now electronically tracked and their trajectories are scrutinized by marine biologist attempting to understand their behavior.

But trajectories record the combined effects of the animal's own motion and the motion of the surrounding fluid (drift). Without altimetry providing synoptic current estimates, the two motion components could not be separated.

In this paper we review recent findings obtained by using altimeter-derived ocean currents to process marine animal tracking data. They show that currents can substantially distort the observed trajectories and affect very important results deduced from track analyses such as inferences on the animal's orientation skills, energy budget, distribution of travelling and foraging periods, etc.

Altimetry is thus becoming an indispensable tool in marine ecology !

Paper submitted in the session

"15-year altimetric record: challenges and achievements"
Sub-theme : interesting/unexpected results !

Oceanography and yacht racing: a handful of competitors, millions of spectators

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The Sydney to Hobart yacht race focusses much of the Australian public's attention on the Tasman Sea for a few days of their Christmas holiday period. For many years, CSIRO have used this event to publicise the abilities of the global ocean observing system. The eddies of the East Australian Current can be the deciding factor of the race. The fact that we can map the ocean conditions four days ago with much more confidence than 4 days ahead only adds to

the excitement. With time, our web site has become more highly automated, with national, year-round coverage that is accessed by many types of marine operators, scientists, students, journalists, and others.
<http://www.cmar.csiro.au/remotesensing/oceancurrents/>

A Role for Altimeter Radars in Gas Exchange Studies

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Accurate estimates of air-sea transfer rates of radiatively active gases are needed for studies of regional and global gas cycling and for climate change studies. However, estimates using traditional wind speed – gas transfer velocity parameterizations vary by a factor of 2-3, contributing significantly to error budgets in global modeling of gas exchange and the carbon cycle. A decade of research has shown the utility of sea surface roughness, represented by the mean square slope (mss) due to gravity-capillary scale waves, as a proxy for gas exchange. Normalized backscatter of altimeter radars can be used in scattering models to estimate mss by combining coordinated ship-based measurements of mss with satellite overflights. These coordinated field experiments over the last decade have begun to provide the data necessary to calibrate mss estimates from altimeter radars. Now we have developed this technique into an alternative approach for assessing global gas transfer velocity fields remotely. Our presentation will trace the evolution of this concept from key laboratory and in situ observations to remote sensing observations and construction of a decade-long time series from the TOPEX and Jason-1 data streams.

Development in rain altimetry from Seasat to Envisat and Jason

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The return signal received by an altimeter is the product of the radar's interaction with the Earth's surface, and its propagation through the atmosphere. Of the latter's effects, the most spatially variable is the attenuation by raindrops. Anomalies in altimetry data, affecting estimates of sea surface height, wave height and wind speed, were noted for

Seasat. These were studied in much greater detail for ERS-1, using the waveform data to explain the effect upon the various parameters. The arrival of Topex, the first dual-frequency altimeter, enabled much more reliable detection of rain, allowing the development of a high-resolution altimeter rain flag from and the first quantitative estimates of rainfall from an altimeter. Jason and Envisat also have this dual-frequency capability, providing quantitative estimates of rainfall. Now, the latest challenges are in combining their high-resolution rain records with data from other sensors to give a wider picture of rain events.

Session 6.3:

The Integrated Approach/Diagnostics

Impact of ARGO temperature and salinity measurements in the new ECMWF ocean analysis system, with focus on the interaction with altimeter data

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The impact of temperature data from ARGO floats in the ECMWF ocean analysis system was addressed in a previous study (Vidard et al 2005). No evaluation was made of the salinity information, since by the time of the study the ECMWF system did not have the capability of assimilating salinity. Besides the time period for the impact of ARGO in this study was restricted to 2002-2003.

Recently, the operational ocean analysis system at ECMWF has been substantially upgraded, and both salinity data and sea level anomalies from altimeter are now assimilated together with subsurface temperature data. The new system is used to assess the impact of both temperature and salinity measurements from ARGO by conducting observing system experiments (OSEs) during the period 2000-2005. The potential synergy between ARGO and altimeter information is specifically addressed in the experimental design.

Using altimeter measurements for quantitative assessment of high resolution ocean models

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Satellite altimeter missions since the 1990s have provided an important benchmark for the evaluation of the fidelity of ocean models. Eddy kinetic energy and sea surface height variability have been used extensively as a comparison point for models of northern hemisphere western boundary

currents and their extensions. As longer time series of altimetry observations have become available, they can be used, along with other observations, to evaluate the model's ability to reproduce longer term variability. Quantitative comparisons then become possible. During the 1990s, ocean models have improved immensely, benefiting from improved forcing fields, as well as from an amazing increase in computational power. These developments have resulted in increased model complexity as well as an increase in resolution and length of model runs. The realism of western boundary current extensions in these models in particular has improved. The increase in resolution to better than 10 km has allowed the western boundary current to separate from the coast at about the correct latitude, making possible more detailed comparisons with altimeter observations and observationally derived budgets.

Comparisons that are possible with the long time series of altimetric observations include an evaluation of the mean path strength of the current and now, because of the long time series of altimeter data, path variability. In addition, the upper ocean heat budget can be examined using as observational estimates diagnostic model results that rely on the altimeter observations (Vivier et al, 2002; Dong and Kelly, 2004). Hindcast model runs over some of the same time period can be evaluated against these metrics. Two very high resolution model runs are evaluated critically against the altimeter observations, one in the North Atlantic, and one in the North Pacific. These two model runs are from different ocean models and use two different model representations of the vertical coordinate, but each, at least qualitatively, has a western boundary current that has a good separation latitude, penetration into the interior and strength.

However, with a more quantitative analysis, model biases can be used to infer deficiencies in model physics. In the North Pacific, the 11 year run at 1/12 degree resolution using the HYCOM (Hybrid Coordinate Ocean Model) show good qualitative performance; however, in a quantitative assessment, the western boundary current path has systematic errors that lead to errors in both the SST and the regional heat budget. In addition, the interannual variability of the strength of the Kuroshio and its path is weaker than observed, with the western boundary current extension being less stable than is observed. The errors have potentially many sources, including errors in the forcing fields; however advection errors in the model ocean explain at least some of the model biases. A similar analysis is done for a North Atlantic simulation that is run using POP (Parallel Ocean Program).

With the advent of increased computational power, coupled

climate models will begin to be run at eddy resolving resolution in the ocean. It is important that the model performance is understood in an uncoupled framework and without data assimilation so that model biases are known and can potentially be corrected. The forced ocean model simulation evaluations described here are a first step in determining the validity of high resolution coupled simulations of future climate.

Importance of TOPEX/Poseidon/Jason data to improve the coupled ocean-atmosphere modeling of El Nino

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More than a decade of research where altimetric data have been used in ocean models that are either FORCED or COUPLED with the atmosphere have led to the following conclusions: 1) The events simulated in COUPLED experiments are sensitive to 1 cm sea level accuracy whereas they are not in FORCED. 2) It is not necessarily because of model errors that COUPLED experiments are sensitive, it can be because of physical reasons that matter in reality. We choose two examples to demonstrate these important conclusions.

The sensitivity of the simulated Nino3 SST index to off-equatorial sea level changes is always smaller than 1 Degree C in FORCED and reaches 4C in COUPLED. In FORCED experiments, the observed atmosphere which controls the model experiment has equatorial trade winds that relax/strengthen and make the ocean simulate warm/cold events regardless of what happens beyond the equator. But in reality, the off-equator plays a role in the recharge/discharge of the equatorial oceanic heat content for a (warm event/relaxed trade winds) to develop. Indeed, TP-Jason data show that the equatorial recharge by the off-equator is not symmetric as previously thought: a warm event charges the equatorial Pacific, it does discharge the South off-equator as known, but it recharges the North, making the sea level rise in the North because of the ITCZ equatorward migration. TP-Jason data are then used in the model outside the equator as the only source of data controlling the COUPLED behavior, and simulations from this “almost-data-free” experiment successfully reproduce the warm/cold events that have been observed since 1992.

Similarly, experiments are sensitive to the eastern boundary conditions of the model by more than 4C in COUPLED and less than 1C in FORCED. So TP-Jason data are then used in

the COUPLED model to control the variations of the eastern boundary conditions only. This “almost-data-free” coupled experiment allows to reproduce the series of warm/cold events that have been observed since 1992 too. Experiments similarly controlled by altimetry at the western boundary are also performed, allowing the Indo-Pacific connection. The first experiment we performed was as successful as above when we used the one baroclinic version of the coupled model. But the experiment is not successful when performed with the model version which has two baroclinic modes and a vertical diffusion term added among other improvements. We need to improve our use of TP-Jason data to control the boundary conditions in case of 2 baroclinic modes, and also to refine the parameterization of the vertical mixing term which plays a key role on ENSO behavior. Absent in most common intermediate coupled models, this term deserves more attention. All these experiments demonstrate that we need altimetry with 1cm accuracy to make progress in understanding how ENSO is actually sensitive to COUPLED physical processes that have been neglected so far because they cannot be detected in FORCED ocean simulations.

Ocean Surface Current Monitoring from Space: Methodology and Progress

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Monitoring the ocean surface currents is a primary application of the highly successful satellite altimetry missions that started 15 years ago. This symposium coincides with the implementation of a significant achievement of the NOAA Ocean Surface Current Analyses Real-time project (OSCAR, <http://www.oscar.noaa.gov>), namely the extension of satellite-derived surface current processing, and its associated datacenter, to the global ocean. We present a synthesis of the efforts resulting in the estimation of surface currents from satellite and their subsequent application to some climate studies, within the framework of OSCAR. In the first part, we summarize the methodology associated with OSCAR, particularly emphasizing the respective contributions of satellite

altimeter data (TOPEX/Poseidon and Jason-1) and scatterometer data (QuikScat) to the diagnostic calculations of surface currents. Additionally, we show how the methodology has been extended from the tropics, where it was initially developed, to the mid and high latitudes. An overview of the comparison between the OSCAR currents and in situ data for each ocean basin and with respect to latitude is presented. Notably, we discuss the accuracy of the calculated velocities when applied to seasonal-to-interannual surface current variations, at present a major application of the OSCAR currents. In the second part, we review the most prevalent types of low-frequency and large-scale variability of the surface currents that are identified in the 13-year OSCAR database. We especially focus on the most important short-term climate disruptions that occurred throughout this time period and that involved large-scale surface current changes. In this regard, the 1997-98 El Nino in the tropical Indo-Pacific, the “El Nino of the 20th century”, remains the most dominant event of this longer-than-a-decade period. We briefly recount the co-evolution of the surface currents (SC) and the sea surface temperature (SST) up to the present, and show how the principal SC mode leads the SST mode by about 3 months on interannual timescales. Substantial surface current anomalies also appeared in the tropical Atlantic, associated with the tropical Atlantic variability (TAV). In the third part, we present an overview of climate events in ocean areas where the ocean surface currents have the largest impact on SST, a crucial variable for ocean-atmosphere interactions. In this regard too, the El Nino/La Nina events in the equatorial Pacific, which account for the 2nd highest mode of global climate variability after the seasonal cycle, are preponderant. The most intense large-scale, surface heat advection transport observed in the world ocean occurs at the frontal region between the warm-pool and cold tongue of the tropical Pacific. We show that surface currents also have a large influence on the SST in specific regions of the tropical Indian and Atlantic oceans. Finally, we underline the near real-time characteristic of these global climate analyses associated with the space-based monitoring of the ocean currents. This would not be possible without the continuous and on-going satellite coverage of the ocean surface height. Concomitant with the present and future altimetry missions, the OSCAR web site and data server will continue to be updated and will provide an account of any extreme surface current change occurring in the global ocean.

The Mercator 1992-2002 PSY1v2 ocean reanalysis for tropical and North Atlantic

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The objective was to provide an oceanic large scale reanalysis of the North Atlantic (70°N-20°S) for the years 1992-2002 that is :

- eddy permitting for mesoscale studies and embedding of area limited models -close enough to data to give a good context for specific cruise campaigns -homogeneous enough to allow the analysis of climate time series -continuous enough to use model outputs as bio-geochemical dynamic inputs -using ECMWF ERA-40 reanalysis

Outlines of the reanalysis will be exposed. The following performances will be detailed :

- SLA error < 5cm (analysis) - 8cm (forecast) - SST error < 0.7°C - Temperature error < 0.7°C (a) - 1.5°C (f) - Salinity error < 0.3psu

- good balance analysis/forecast - no shocks but some local transitories - good circulation, no bad region

Except some local biases up to 10cm/0.7°C, the coherence between the altimetry+MSSH, the in situ data and the model forced by ERA-40 is really good after assimilation. In particular, the interannual signal is reproduced in a fully coherent way.

The 1992-2002 decade was strongly impacted by the NAO change. In 1994, a warm anomaly accumulated in the South-East of the Gulf Stream entered in this current, and reached New-Ffoundland in 1995. This strong SST anomalies may have switched the NAO index from the very positive values of the late 1980s and early 1990s, to negative values. This shift onto a negative NAO regime enabled this warm anomaly to continue along the Subpolar Gyre. Meanwhile, thanks to winter deepening of the mixed layer, and lateral eddy diffusion, the anomaly was spread. Yet, the damped warm anomaly reached the Labrador Sea in 1998, and was probably an important factor in the extremely high SSTs of this year. Connexions with the subtropical gyre, the weakening of the Cape Verde upwelling, and the North Sea temperature are also evidenced. Overall, the strong North Atlantic rising of 3mm/y during Topex-Poseidon first decade was mostly an extreme NAO event, favored by a perfect timing of all patterns.

Fifteen Years of Altimetry and Satellite Data: Benefits for Mercator-ocean Operational Forecasting System

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Altimetry played a key role in the emergence of operational ocean forecasting centres such as Mercator-Ocean in France. The global synoptic data coverage and the very high measurement accuracy of Topex-Poseidon in the early nineties was one of the most important factors that pushed to set up the French operational oceanographic centre. Mercator has developed a series of assimilation techniques in order to optimally combine observations (SLA, SST, in situ T&S profiles) with ocean model simulations. Historically, the first method used (called SAM1) was intended to specifically assimilate sea level anomaly (SLA) data. It was based on an optimal interpolation (OI) analysis associated to the Cooper & Haines (1996) lifting / lowering of isopycnals. The second system to become operational was designed to take advantage from both in situ and remotely sensed (SLA, SST) data through fully multi variate assimilation (also based on an OI approach). Besides these operational systems, Mercator is developing the next generation of multivariate assimilation system, referred to as SAM2, based on Reduced Order Kalman Filters using 3D multivariate modal decomposition of the forecast error covariance. The use of 3D modal representation for the error statistics is intended to improve analyses in highly inhomogeneous and anisotropic regions of the ocean. Lastly, advanced data assimilation techniques such as 3D variational assimilation methods are investigated. We shall review how altimetric data is assimilated in Mercator analysis systems and how SLA impacts the ocean state estimation. In particular, we focus on the increasing capability of the systems to correctly analyse along track altimetry data. Results from Mercator operational systems as well as from global and regional reanalyses are presented.

Session 8.1:

The Future of Altimetry, part 1

WatER: The proposed Water Elevation Recovery satellite mission

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WatER Participants: over 150 people from more than 20 countries

http://www.legos.obs-mip.fr/en/recherches/missions/water/mis_partn.html

Surface fresh water is essential for life, yet we have surprisingly poor knowledge of the spatial and temporal dynamics of surface water storage and discharge globally. The core mission objective is to describe and understand the continental water cycle and the hydrological processes (e.g., floodplain hydraulics) at work in a river basin. The key question that will be answered by WatER is: "Where is water stored on Earth's land surfaces, and how does this storage vary in space and time?" WatER will facilitate societal needs by (1) improving our understanding of flood hazards; (2) freely providing water volume information to countries who critically rely on rivers that cross political borders; and (3) mapping the variations in water bodies that contribute to disease vectors (e.g., malaria).

Conventional altimeter profiles are incapable of supplying the measurements needed to address scientific and societal questions. WatER will repeatedly measure the spatially distributed water surface elevations (h) of wetlands, rivers, lakes, reservoirs, etc. Successive h measurements yield $\Delta h / \Delta t$, (t is time), hence a volumetric change in water stored or lost. Individual images of h yield $\Delta h / \Delta x$ (x is distance), hence surface water slope, which is necessary for estimating streamflow. WatER's main instrument is a Ka-band Radar Interferometer (KaRIN) which is the only technology capable of supplying the required imaging capability of h . KaRIN has a rich heritage based on (1) the many highly successful ocean observing radar altimeters, (2) the Shuttle Radar Topography Mission (SRTM), and (3) the development effort of the Wide Swath Ocean Altimeter (WSOA). The interferometric altimeter is a near-nadir viewing, 120 km wide swath instrument that uses

interferometric SAR processing of the returned pulses to yield single-look 5m azimuth and 10m to 70m range resolution, with an elevation accuracy of approximately 50 cm. Polynomial based averaging of heights along the water body increases the height accuracy to about 3 cm. The entire globe is covered twice every 16 days, and orbit subcycles allow the average visit to be about half this time at low to mid-latitudes, and almost daily at high latitudes. The WatER mission is an international effort with a large, supporting scientific community. It has been proposed as an ESA Earth Explorer Core mission and will also be jointly submitted to NASA's Earth System Science Pathfinder program. WatER is designed to meet high priority targets for all nations and will provide essential data for the EU Water Framework Directive and the European Flood Alert System. WatER will meet the United Nations call for a "greater focus on water related issues" responds to the hydroclimatological needs of the International Working Group on Earth Observations, and answers the U.S. federal government call to focus on our "ability to measure, monitor, and forecast U.S. and global supplies of fresh water".

ABYSS-Lite Science Requirements and Mission Concept

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We are delighted to participate in this meeting celebrating 15 years of progress in radar altimetry. For some time we have been suggesting a new altimeter mission concept that would address a mixture of bathymetric, geodetic, and oceanographic needs. We will present our views and also listen to the perspectives and interests of our colleagues.

Altimetry has enjoyed a variety of successes in applications as diverse as sea level rise, variability and change at planetary, basin, and meso- scales, geodesy and bathymetry. Some of these applications require absolute accuracy in the sea surface height measurement, and long term stability of that accuracy, while others require only relative accuracy

over defined spatial and temporal scales. In observing mesoscale eddies, for example, only sea surface height changes on spatial scales from tens to a few hundred km and time scales of weeks are needed. For geodetic and bathymetric applications it is the horizontal gradient of the time-averaged sea surface, and not the height itself, that is required.

The Ocean Surface Topography Mission is expected to continue the absolutely accurate sea surface height time series on the Topex and Jason 10-day repeat ground tracks. We would like to see a next-generation, higher-resolution altimeter to complement the OSTM, making mesoscale observations in the 300 km holes left by OSTM coverage while providing new data on the geodetic and bathymetric signals. We believe the ideal solution is one simple low-cost satellite hosting a single-frequency delay-Doppler altimeter (and perhaps a radiometer) in a non-repeating orbit tuned to have oceanographically optimal “near exact repeats”.

Data from the two geodetic missions to date have revolutionized our understanding of the marine gravity field and global bathymetry, confirming the plate tectonic theory, revealing many previously uncharted features, and raising new questions about the details of the seafloor spreading process and the volcanic and meteoritic history of the Earth. However, the resolution of these data is not yet adequate to support advanced inertial navigation systems, to characterize the seafloor roughness spectrum at scales that control ocean mixing, internal wave generation and tidal dissipation, or to determine the heights of seamounts accurately enough for navigation and habitat considerations. A new mission could meet these goals and reveal about 50 000 as yet unknown seamounts.

Requirements for such a mission are simple. Long-term sea-surface height accuracy is not needed; the fundamental measurement is the slope of the ocean surface to an accuracy of ~ 1 micro-radian (1 mm per km). The main mission requirements are: Improved range precision. A factor of two or more improvement in altimeter range precision with respect to current altimeters is needed to reduce the noise due to ocean waves. Improved along-track spatial resolution. The missing seamount and bathymetric data are in the 6-km to 25-km range. The shorter scales can be mapped only if the along-track resolved footprint of the altimeter is ~ 6 km or less. This requirement cannot be met by conventional radar altimeter data, especially in areas of large prevailing significant wave heights such as are typical of the southern oceans. Fine cross-track spacing and long mission duration. A ground track spacing of 6 km or less is required. A six-year mission would reduce the error by another factor of two. Moderate inclination. Existing satellite altimeters have relatively high orbital inclinations, thus their resolution of east-west components of ocean slope is poor at low latitudes. The new mission should have an orbital inclination close to 60° or 120° so as to resolve north-south and east-west components almost equally while still covering nearly all the world's ocean area. Near-shore tracking. For applications near coastlines, the ability of the instrument to track the ocean surface close to shore, and acquire the

surface soon after leaving land, is desirable.

A delay-Doppler altimeter [Raney, R. K., The delay Doppler radar altimeter, IEEE Transactions on Geoscience and Remote Sensing 36 (5), 1578-1588, 1998] meets the requirements for lower noise level, robustness of noise in the presence of large surface waves, fine-scale resolution, and better near-shore tracking. Abyss-Lite, comprised of a single-frequency Ku-band radar, on-board processor, and essential subsystems, is a relatively simple, low-cost, small-satellite design. This instrument and signal processing has proven heritage. Under NASA Instrument Incubator funding, the Johns Hopkins University Applied Physics Laboratory developed and proven through airborne trials an airborne prototype that emulates the innovative features central to the delay-Doppler concept. Thanks to signal processing techniques adapted from the field of synthetic aperture radar, the resulting delay-Doppler radar altimeter has significantly better measurement precision than is possible with any conventional radar altimeter [Jensen, J. R. and Raney, R. K., Delay Doppler radar altimeter: Better measurement precision, in Proceedings IEEE Geoscience and Remote Sensing Symposium IGARSS'98ed, IEEE, Seattle, WA, 1998, pp. 2011-2013]. Furthermore, its canonical post-processing footprint is ~ 250 meters along-track; several of these can be accumulated to generate ~ 5 km spatial resolution, a dimension that does not expand with increasing wave height. The precision and spatial resolution of this instrument are ideally suited to meet the demands of high resolution gravimetry and bathymetry. The altimeter in principle is similar to current conventional oceanographic instruments, and virtually identical to the SAR-mode of the SIRAL altimeter on CryoSat [Raney, R. K. and Jensen, J. R., An Airborne CryoSat Prototype: The D2P Radar Altimeter, in Proceedings of the International Geoscience and Remote Sensing Symposium IGARSS02, IEEE, Toronto, 2002, pp. 1765-1767]. However, unlike CryoSat, the Abyss-Lite altimeter payload includes a real-time processor, which has been true for all ocean-viewing radar altimeter satellites since Seasat. Consequently, the data storage and down-link rates are very small. (The inherent data rate from the instrument is less than 30 kHz.) Thus only one ground station is required to support the Abyss-Lite mission, with a factor of two reserve. Further, on-board processing sorts reflections by Doppler (along-track angle of the arrival), which is the basis for “smart” range-gate tracking to assure reliable near-shore operation.

This is a very low-cost mission, in comparison to other altimeters. The ROM cost of the spacecraft, two-string (redundant) altimeter, and water-vapor-radiometer (WVR) is \$75M, based on a Phase A/B start in FY 2006, and a launch in CY 2009. The spacecraft will fit the mass and size constraints of a Pegasus launch vehicle reaching the desired orbit. Thus, the ten-year cost, including implementation, launch, on-orbit operations, one ground station with embedded ground support, and science, is much less than \$200M. Cost estimates are based on the ABYSS ESSP proposal for the ISS instrument (peer-reviewed by NASA) and a NOAA-funded internal study at JHUAPL [Raney, R. K., Smith, W. H. F., and Sandwell, D. T., Abyss-Lite: A

high-resolution gravimetric and bathymetric mission (AIAA-2004-6006), in Proceedings, Space-2004, AIAA, San Diego, CA, 2004] that considered spacecraft trade-offs including those in the GSFC Rapid Spacecraft Development Office catalog.

We believe that this mission could provide mesoscale observations to fill the gaps left by OSTM, despite the fact that our scenario does not use a conventional exact-repeat orbit. For the geodetic application it is enough that the ground track pattern eventually becomes dense (order 6 km spacing between tracks) after sufficient time (order 15 months). However, the sequence in which those tracks are acquired is not important, so that the orbit may be designed to be rich in near-repeats, meaning that the orbit yields space and time sampling intervals that are small compared to the space and time scales of correlation of the mesoscale ocean signal. Since the mean sea surface is already well-known at mesoscale wavelengths, thanks to the existing geodetic missions, one may refer height profiles to the mean sea surface, rather than a history of exact repeats, to obtain the mesoscale anomaly signal. Two independent studies [Scharroo and Smith, unpublished; Monaldo and Porter, Oceans2005 conference] have already demonstrated this idea by recovering the eddy field from ERS-1 geodetic phases E and F and comparing that to the result obtained from Topex in the same time interval. Monaldo and Porter find that the rms difference between the non-repeat eddy height field and the Topex eddy height field is about 9 cm.

We regret the loss of CryoSat. We had hoped that CryoSat would give us the space demonstration of many of these ideas, allowing us to recover mesoscale signals from its non-repeat orbit, and offering a test of the delay-Doppler paradigm via its SAR mode.

Is there a future role for altimeters carried on micro platforms for the early warning of surface hazards?

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Satellite monitoring of the ocean surface could be revolutionized by the introduction of constellations of small, low-cost platforms carrying special-purpose altimeters to complement dedicated, high precision research missions. The latter have proved invaluable in revealing details of the ocean's surface currents and eddies that contribute to global climate. Their sampling remains inadequate, however, for providing rapid warning of impending dangers which can develop at sea within a matter of hours.

The EC GAMBLE study (to which over 40 European organizations contributed) demonstrated that even for the detection and tracking of relatively slow moving eddies, single altimeter missions with revisit times of many days could not keep up. It was shown that the introduction of microplatforms could potentially benefit both research and daily marine operations by capitalizing on the altimeter's ability to make contemporaneous measurements of sea surface height, wind speed and significant wave height.

The tsunami wave which engulfed coastlines around the Indian Ocean over a year ago was detected, quite fortuitously, by JASON passing over the area some 2 hours after the 'quake. It required the greatest marine disaster in living memory to focus world attention on the awesome power of the sea. But the severe storms across the globe that cause damage, delay and loss of life are almost a daily occurrence.

We discuss how greater sampling could be achieved at an affordable cost, how long-term ocean and climate research would benefit, and how an early warning system of approaching storms at sea could include a tsunami detection mode.

25 years of altimeter developments at Alcatel Alenia Space

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Alcatel Alenia Space is involved in altimeter design and manufacturing for more than 25 years since the early definition phase of the Poseidon altimeter for the reference Topex-Poseidon (T/P) mission. Alcatel Alenia Space is developing state of the art altimeters presented in this paper.

T/P is a joint NASA/CNES mission, launched in 1992 and still in orbit after 13 years of operation, which paved the way for high accuracy sea level measurements. The Ku-band Poseidon altimeter on T/P was embarked as an experimental payload to demonstrate in flight the new technology used. It has provided excellent measurements which were found to agree with the measurements delivered by the US operational altimeter of the mission.

The T/P mission has been pursued by the Jason 1 mission launched in 2001, embarking a dual frequency (Ku and C band) altimeter Poseidon 2, as the single operational

altimeter of the mission. The satellite and Poseidon 2 were manufactured by Alcatel Alenia Space under CNES contracts. Poseidon 2 is providing excellent measurements (see dedicated presentation in this conference). The range measurements are provided by the Ku band channel while the C band is used for correcting the excess path length due to the ionosphere. Poseidon 2 inherited from Poseidon-1 state of the art technology in order to have excellent performances (impulse response and calibration) while minimising as much as possible the demand towards the satellite in terms of mass, volume and power. For instance, Solid State Power Amplifiers technology has been used in Ku and C band for the Poseidon series.

In the mean time ESA launched the ERS-1 (1991), ERS-2 (1995), and ENVISAT (2002) multi-applications satellites on sun-synchronous ~800 km orbits. The Radar Altimeter (RA) on board ERS satellites is a single Ku-band altimeter with two bandwidth (330 MHz and 82 MHz) allowing operation over the ocean and over ice-surfaces. The repeat period of ERS 1-2 and Envisat orbits is 35-day allowing inter-track sampling of the T/P and Jason 10 day repeat period. The Radar Altimeter of Envisat (RA2) is a dual frequency altimeter (Ku and S bands), with bandwidth agility (320 MHz, 80 MHz and 20MHz) for measuring the ocean and the ice surfaces. The pulse width of RA and RA2 is 20 μ s (against 100 μ s for Poseidon) which requires a larger RF transmitted power (delivered by a Travelling Wave Tube). The RA and RA2 demand (mass, power) towards the satellite is therefore larger than for the Poseidon family, but the level of end product performances falls in the same category, i.e. around 2 cm for the Sea Surface Height measurements.

In 1997, Alcatel Alenia Space started a concept study with MSSL under ESA contract for a high resolution altimeter with the objective of monitoring the land-ice mass variations over Antarctica and Greenland and sea-ice thickness variations. This concept has matured to give birth to SIRAL (Sar Interferometric Radar Altimeter) embarked on the CryoSat satellite which had an unsuccessful launch in October 2005. SIRAL operates in the conventional pulse-limited altimeter mode over the flat areas, and in two advanced modes, the SAR mode over sea-ice and the SAR interferometric (SARIn) mode over the sloppy areas (ice sheet margins and glaciers). SIRAL will be the first SAR interferometric radar to fly on a satellite. The required interferometric phase accuracy of the instrument is less than 1.5 degree, a challenging value requiring extreme care in the design of the instrument and of the internal calibration, and for the stability of the instrument.

The Jason 2 mission will be a follow-on of Jason 1. The Jason2 satellite will embark the Poseidon-3 Ku/C band nadir altimeter. The performances of Poseidon-3 will be similar to those of Poseidon-2 in the operational mode over ocean surfaces. Improvements are implemented by Alcatel Alenia Space under CNES contract to improve the performances of non ocean surface tracking. They include new tracking algorithms (derived from SIRAL) and the possibility to directly control the altimeter altitude tracked using the

satellite position information derived from the real time on-board navigator of Doris (Diode) and the local elevation provided by an on-board DEM (Digital Elevation Map) file. This new feature will improve dramatically the tracking of inland water while preserving high resolution range measurement. Technologically, the Digital Processing Unit is derived from SIRAL in order to ensure a product line synergy and to cope with the obsolescence of electronics components. Phase C/D of Poseidon-3 started in spring 04.

The Alti-Ka concept proposed by CNES in 1998 is a single-frequency Ka band (35 GHz) pulse limited radar altimeter for ocean and ice surfaces. The main technological motivation for Alti-Ka is to have a compact instrument compatible with the resources available on micro-satellites (or as an opportunity passenger). Scientifically, thanks to the larger allocated bandwidth (500 MHz) and larger pulse repetition frequency the accuracy of the measurement of sea surface elevation is improved by a factor of ~2 compared with Ku/C bands altimeters, as in Ka band the radar vertical resolution is 30 cm. For a given antenna size the spatial resolution of the altimeter is also improved in Ka band compared to Ku band. The Alti-Ka altimeter has a built-in dual frequency microwave radiometer for wet path delay corrections. An high data rate mode (1 second of complex data) will be included, to analyse speckle and echo characteristics in coastal region. The open loop range tracking mode (Diode+DEM Mode) defined for Poseidon 3 will also be adapted and implemented in Alti-Ka. The altimeter has been studied by Alcatel Alenia Space under CNES contracts (Phases A and B) and technological developments have been performed on the chirp generation and on the SSPA. Alti-Ka phase C/D will start by the end of 2005, for a possible launch on the Indian OceanSat 3 ISRO satellite.

The paper will present the Alcatel Alenia Space altimeter product line with a status on current developments and also future studies for advanced interferometric oceanic altimeters.

Performances study of interferometric radar altimeters: from the instrument to the global mission definition

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The main limitations of standard nadir-looking radar altimeters have been known for long. They include the lack of coverage (intertrack distance of typically 150 km for the T/P and Jason tandem), and the spatial resolution (typically 2 km for T/P and Jason), expected to be a limiting factor first for both the determination of mesoscale phenomena in the deep ocean, and then for coastal and large basins hydrological applications. In this context, a new and revolutionnary altimetric measurement has been assessed for the past few years. Mixing altimetry and interferometry, it increases by almost a hundred times the observation swath and aims to keep a typical measurement error budget about a few centimetres to catch most of the ocean circulation. The Wide Swath Ocean Altimeter (WSOA) was primarily expected to be implemented onboard Jason-2 satellite. A global study of the performances of this instrument and its interactions with any external factors was driven by CNES (Centre National d'Etudes Spatiales) in cooperation with NASA/JPL since end of 2003. Every error domain has been checked and the outcomes have led to the definition of a dedicated mission to such an instrument.

Session 7.3:

Outreach

(Nearly) Fifteen years of Altimetry Outreach at CNES and NASA/JPL

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Since the 1992 launch of Topex/Poseidon, CNES and NASA/JPL have been involved in providing information about satellite altimetry techniques, applications, and ocean science to the world.

From the beginning, the TOPEX/Poseidon and Jason-1 Outreach Team has focused on reaching out to a wide range of people: from educators, students and the general public, to scientists and professionals who use the data. Our objective is to provide information and support appropriate to each audience. We have developed an extensive series of products on many relevant topics related to ocean science and altimetry, with levels ranging from easy-to-read to the expert point of view.

Through presentation of mission first results, the focus in the early years was on data quality and the varied data applications. Since 1997, El Niño forecasting was of major interest to the public, whereas the oceanographic community sought contributions to true operational oceanography.

With the launch of Jason-1, the focus is now on the need for a long-term data series and continuity in the missions. Educational activities related to ocean altimetry are continuing and expanding. Our aim in this realm is to help teachers and students across the world appreciate the ocean environment and the role satellites play in increasing our understanding of this crucial resource.

The evolution in our outreach activities is mirrored in the printed material distributed as hardcopy, and significantly in the regular updates to the web sites. As we approach nearly 15 years of continuous altimetry outreach our efforts are directed toward supporting the move toward operational oceanography (with GODAE and OSTM) and converging upon an integrated, multi-institutional outreach program.

Developing Ocean Awareness: The Argonautica Educational Project

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Everyone is familiar with weather and with the features that describe it, like cloudy with a chance of rain, sunny and hot, or windy and cool, and that weather conditions form in the atmosphere. Most people know the relationship between weather and climate, and practically everyone has heard about global warming and global climate change. But who knows that it is the interaction of the oceans and atmosphere that drives weather patterns and controls climate change? And who knows that since the first oceanographic satellite was launched, our knowledge of the oceans has vastly improved? Argonautica is an ongoing educational project whose objective is to show how satellites are helping to improve our knowledge of the oceans and protect the marine environment. The project involves students at the primary, middle and high school levels and includes lectures, communication, and hands-on activities. Students are able to use real time satellite data to track buoys drifting in the major ocean currents and to view and analyse the world's great animal migrations. The project also makes it possible for students to communicate with scientists and engineers through a worldwide network. The 2005-2006 Argonautica operation is organized in conjunction with the Jason-1 calibration/validation experiment in the Drake Passage. During the operation, two ships: the Polarstern, a research vessel; and a boat tracing the journey of the first Antarctic expedition will be relied upon for support. Student-built buoys will be released from the ships during their journeys. Both boats will sail beneath the Jason-1 satellite track and students will have the opportunity to process data from the buoys and correlate the information with Jason-1 data. Argonautica, initialized by CNES five years ago, is now part of the collaboration with NASA/JPL and is one of the activities being conducted in support of NASA/CNES ocean surface topography missions education and public outreach.

Keeping Ocean Altimetry in the Public Eye

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The 1997-98 El Nino, the largest on record, created a new media star – the ocean-observing Topex/Poseidon. Millions of people saw images created with ocean altimetry on the evening news and in newspapers and magazines as reporters tried to explain the climate phenomenon. Topex/Poseidon gave El Nino a face.

Today, more members of the public than ever have seen altimetry images in stories about El Nino, La Nina, hurricanes, ocean currents, and climate change. Along with this exposure is an increased public awareness of ocean altimetry and its importance. Scientists have an opportunity to build on this hard-won familiarity through the Internet.

The Internet gives scientists an opportunity to communicate regularly with the general public about their research. It also provides a challenge to describe projects in plain language and develop images that are easily understood.

Societal Benefits of Ocean Altimetry Data

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The NASA/CNES Jason-1 satellite, follow-on to the highly successful TOPEX/Poseidon mission, continues to provide oceanographers and marine operators across the globe with a continuous thirteen-year, high quality stream of sea surface height data. This unprecedented resource of valuable ocean data is being used to map sea surface height, geostrophic velocity, significant wave height, and wind speed over the global oceans. Altimeter data products are currently used by hundreds of researchers and operational users to monitor ocean circulation and improve our understanding of the role of the oceans in climate and weather. In addition to the scientific research applications, ocean altimeter data has many societal benefits and has proven invaluable in many practical applications including; • ocean forecasting systems, • climate forecasting, • ship routing, • oil production operations, • marine mammal habitat monitoring, and • hurricane forecasting and tracking.

The data has been cited in over 2,000 research and popular articles since the launch of TOPEX/Poseidon in 1992. In addition to the scientific and operational uses of the data, the educational community has seized the unique concepts highlighted by these altimeter missions as a resource for teaching ocean science to students from grade school through college. This presentation will highlight the wide variety of societal benefits of ocean altimetry data.

Satellite Altimetry Outreach During Hurricane Rita: Lessons Learned

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Two weeks after Hurricane Katrina made landfall, the Colorado Center for Astrodynamics Research (CCAR) released a media advisory through the Office of News Services at the University of Colorado, Boulder describing the oceanographic conditions, observed in near real-time using satellite altimetry hosted by the CCAR website, that contributed to the rapid and fierce intensification of Katrina over the Gulf of Mexico. There was no response to the advisory by the general public or any media outlet. One week later a similar advisory was released as another hurricane intensified over the Loop Current in the Gulf of Mexico, Hurricane Rita. This time the response was overwhelming. The great difference in the media's response is mainly attributable to the perception of the first news advisory as "old news" and the second as a news "scoop" central to the evolving news story on Hurricane Rita that was made all the more newsworthy in the aftermath of Katrina. While we as scientists would be equally interested in the two events purely from a scientific point of view, the public oceanographic and scientific outreach that we can affect through such newsworthy events makes it important for those of us involved in scientific outreach to understand how media interactions might evolve, so that we can get our message across and not become overwhelmed in the process. Often this means reacting quickly to an evolving news story with an approach that is acceptable to the media and easily understood by the general public. Unfortunately this is an acquired skill, one that most scientists are not well trained for nor comfortable doing. Thus, we often decline requests to do this important aspect of our research, which is to inform the public about the capabilities of ocean observing systems and the increasingly useful information these systems provide. This is all the more important as we better understand the critical role that oceans play in weather and climate. In this paper, we describe our outreach experiences during Hurricane Rita, the lessons we learned from our several days in the media spotlight, and the satellite

altimetry and oceanography outreach we affected through these activities.

Session 8.2:

The Future of Altimetry, part 2

Why a Hydrology Mission Needs Two-Dimensional Acquisitions of Water Surface Elevations

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A fundamental problem in our understanding of the global water cycle is the measurement and prediction of water flows across floodplains and wetlands. Fresh water bodies cover at least 4% of the earth's terrestrial surface whereas tropical wetlands, particularly in the Amazon Basin, occupy nearly 20% of their watershed. These vast water bodies are significant stores of freshwater that are often unaccounted in climate and water cycle models. Predictions of flooding discharge and related societal hazards are particularly difficult because the flows are spatially complex with both vast diffusive and locally confined hydraulics. This complexity leads to a rich variety of carbon, nutrient, and sediment dynamics within the wetland ecology. However, our ability to model and hence predict the hydrologic, ecologic, and societal consequences of floods is greatly limited by the complete lack of water height (h) measurements virtually anywhere on the globe during the passage of any given flood wave. Using spaceborne interferometric synthetic aperture radar (SAR) measurements, we show that changes in flood water heights (dh/dt) are far more complex than typically assumed. Typical modeling approaches assume that floodplain waters are horizontal and equivalent to those measured in the adjacent main channel yet such assumptions do not match our observed measurements. Instead, we find that during the passage of a flood wave geomorphic features such as small floodplain channels can act as not only as conduits of flow, but surprisingly as barriers. Both point-based stream gauge and profiling altimetric methods of measuring these water surface elevations and their changes are incapable of capturing the inherent dynamics. For example, using a profiling altimeter and a 16-day orbital repeat cycle, like that

of Terra, misses ~30% of the rivers and ~70% of the lakes in the global data bases. Restricting the study to the largest rivers and lakes provides better coverage, but significant water bodies are still missed. Furthermore, the rivers which are covered can have only a few visits per cycle, leading to problems with slope calculations. Instead, a high-resolution, image-based approach with broad, two-dimensional acquisitions of h, dh/dt, and dh/dx are required to answer important hydrologic questions. A 120 km wide swath instrument misses very few lakes or rivers: ~1% for 16-day repeat and ~7% for 10-day repeat. Therefore, an international team is proposing the Water Elevation Recovery mission (WatER). A key technology of the WatER mission is a Ka-band Radar Interferometer (KaRIN) which is capable of the required high-resolution 2D measurements.

Mapping Seafloor Tectonics from Satellite Altimetry: Requirements for a Future Mission

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Our current understanding of the topography and tectonics of the ocean basins is largely derived from dense satellite altimeter measurements of the marine gravity field combined with sparse geophysical measurements from research vessels. Data from ERS-1 and Geosat provided not only a spectacular confirmation of plate tectonics but also partly revealed smaller-scale structures including thousands of seamounts, propagating rifts, ridge jumps, and global-scale variations in seafloor roughness. In addition, the dense gravity information was combined with sparse ship soundings to construct global bathymetry maps at ~10 km resolution - a great improvement over hand-drawn maps but still far worse than our current maps of Mars, Venus, and the Moon. While these data filled a huge gap in our understanding of the ocean basins, they also triggered a thirst for more. Research efforts over the past few years have provided a 30-40% improvement in gravity field accuracy by retracking the raw altimeter waveforms using methods optimized for range precision. However, there are three broad areas of earth science that require an additional factor

of 5 improvement in gravity accuracy that can only be achieved with third generation altimeters: (1) resolving the fine-scale tectonic structure of the deep ocean floor (e.g., abyssal hills, microplates, propagating rifts, seamounts, meteorite impacts); (2) measuring the roughness spectra of the seafloor on a global basis to better constrain models of tidal dissipation, vertical mixing, and mesoscale circulation of the oceans; and (3) resolving the fine-scale gravity field for research, exploration and navigational needs.

The Cryosphere: A continuing challenge for radar altimetry

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Using space-borne altimetry to study the cryosphere raises challenges for science that are inherent in the very sensitivity of space-borne measurements, apt at revealing, better than any other type of technique, the dynamics of the cryosphere.

Altimetry and the integrated ocean observing system

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A central objective for future altimeter missions will be to provide data required by operational oceanography integrated systems (i.e. that use in-situ and satellite observations together with models and data assimilation to provide an integrated description of the ocean). We will review the development of global operational oceanography and the unique contribution of satellite altimetry. Requirements for future altimeter systems (e.g. continuity, accuracy, resolution, data availability) will then be analyzed and main issues will be discussed.

Towards Mapping the Ocean Surface Topography at 1 km Resolution

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Since Seasat we have realized the wealth of information in the details of the map of the surface topography of the ocean. The world was stunned by the first maps of the ocean current variability and the marine gravity anomalies. Despite the revolutionary impact of radar altimetry achieved over the past quarter century, its sampling capability has always been a compromise between the spatial and temporal requirements. As a result, high spatial resolution can only be achieved in the along-track direction, leading to asymmetry in the radar's mapping capability. For example, the zonal currents of the ocean tend to be better determined than the meridional currents, and the meridional gravity anomalies tend to be better determined than the zonal anomalies.

A new technology has been demonstrated by the Shuttle Radar Topography Mission for mapping the earth's land topography using the technique of radar interferometry. We propose to use the same technique with synthetic aperture radar to achieve spatially uniform high resolution for mapping the ocean surface topography. The intrinsic resolution is in the range of tens of meters. After spatial averaging, we can achieve centimetric precision at 1 km resolution, which is less than the smallest eddy scales in the ocean by an order of magnitude. For the first time, ocean eddies which account for 90 % of the kinetic energy of the ocean can be fully resolved from space. This new measurement will enable the calculation of ocean surface currents and marine gravity anomalies with much improved accuracies. It can also be applied to mapping the elevation of water surface on land as well as the free board of sea ice and elevation of land ice. The measurement principle and anticipated benefits as well as some of the design issues such as the selection of orbit parameters and radar frequency will be discussed.

The Future of Altimetry in Measuring Ocean Surface Waves from Space

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Altimetry's future role in measuring surface waves from space and its promise in forecasting, modelling, and monitoring the ocean surface.

