Towards More Efficient Use of Radar-Altimeter Data

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Introduction

Twenty years ago, experimental altimeters on NASA's Skylab and Geos-3 were already demonstrating the potential of such instrumentation. This led in turn to the development and launch by NASA in July 1978 of the Seasat oceanographic satellite mission. Both Geos-3 and Seasat were very successful in their pioneering missions, but were limited somewhat by poor coverage in the case of Geos-3 and an abnormally short mission duration in Seasat's case.

The Committee on Earth Observation Satellites (CEOS) has been striving to standardise product formats since 1984, in particular through its Working Group on Data, which is also addressing networks, archiving, storage media, data management, etc. There is currently no clear consensus on how to build geophysical data sets so that users will never be caught off-guard by changes in product format.

In the case of radar altimetry, the ever-growing scientific community is still relatively small and traditionally 'digests' all available global data sets. Altimetry is thus an appropriate domain in which it should not be too ambitious to think about product harmonisation already at the geophysical data level.

Table 1. Radar-altimeter missions

Past missions	
Skylab	NASA, 1973
Geos-3	NASA, 1975 – 1978
Seasat	NASA, July to October 1978
Geosat	US Navy, data processed by NOAA, March 1985 to November 1989
Current missions	
ERS-1	ESA, July 1991 – ...
Topex-Poseidon	NASA/CNES, August 1992 – ...
Future missions	
ERS-2	ESA, 1995
Envisat	ESA, 1999
Topex-Poseidon follow-on (NASA/CNES)	
Geosat follow-on (US Navy)	

Nevertheless, the results that the international scientific community was able produce from the two missions were sufficiently promising for ESA and NASA/CNES to start developing the altimetric missions that are flying today, namely ERS-1 and Topex–Poseidon.

Geosat, initially a purely military geodetic mission which subsequently became a declassified oceanographic mission, bridged the gap during the second half of the eighties, furnishing the first long-term global-coverage altimetric data set.

The earlier pioneering missions and today's steady flow of data from ERS-1 and Topex-Poseidon have demonstrated beyond doubt that radar altimetry is a powerful, if complex, instrument concept that contributes to a better understanding of our planet's global climatic system and the effects of mankind's activities upon it. The following are just a few examples of what is being achieved by the international scientific community through the use of radar-altimeter data.

Sea level and the marine geoid

The spaceborne altimetric system – i.e. the radar altimeter itself and its ancillaries, such as the microwave sounder and tracking system – measures the range between the spacecraft and the surface below. Over the oceans this measurement is transformed into elevation of the sea surface (Figs. 1–3). This surface has a dynamic range of some 200 m and roughly represents the gravitational geopotential surface, called 'the geoid'.

The geoid represents the shape produced by the gravitational attraction of water at rest. The sea surface also contains small vertical displacements, of the order of 1 m, about the geoid, known as 'the dynamic topography', which is related to the ocean circulation (Fig. 4). In order to analyse the ocean dynamics, the geoid is subtracted from the measured sea surface.

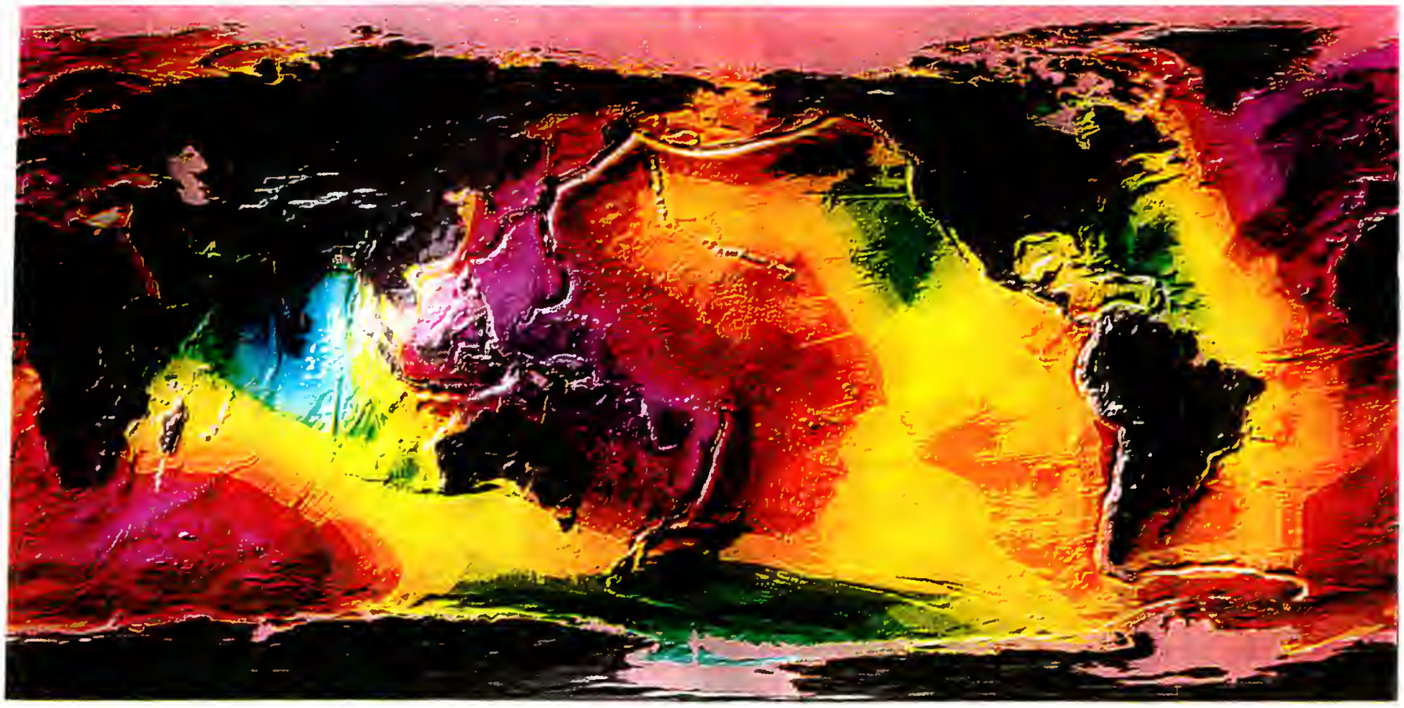


Figure 1. Global mean sea surface

Illuminated relief with coloured iso-contours of a sea-surface-height model. The latter is a digital data set consisting of a global set of sea-surface-height point values with respect to a reference ellipsoid. It was produced by the German Processing and Archiving Facility (D-PAF) from the Geophysical Data Records generated at the French PAF. Long- and short-term solutions are available. The long-term solution represents the mean sea surface over the longest time span available, updated every six months. The short-term solution is based on one 35-day or ten 3-day cycles.

(Courtesy of the German Processing and Archiving Facility)

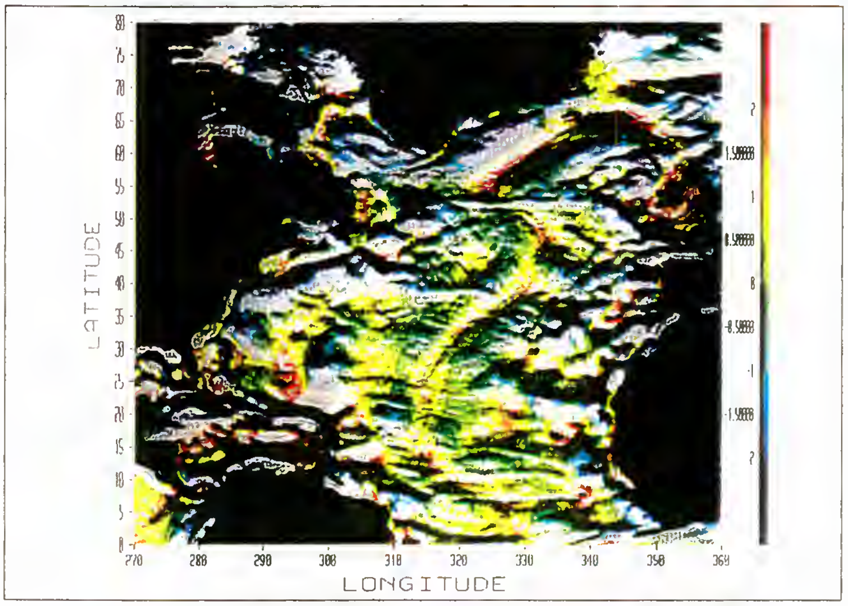


Figure 2. Mean sea surface of the North Atlantic

The heterogeneous shape of the mean sea surface, observed by Geosat, ERS-1 and Topex–Poseidon, is clearly visible in this map of the short-scale variations (variations with wavelength longer than 1500 km have been removed). The holes and bumps correspond to irregularities in the gravity field, which in turn reflect the heterogeneous distribution of mass in the Earth's interior and the presence of underwater relief.

The expected high resolution when ERS-1 is in its 176-day orbit cycle will lead to a major improvement in this map, and thus in our understanding of the Earth's interior.

(Courtesy of Groupe de Recherche en Geodesie Spatiale)

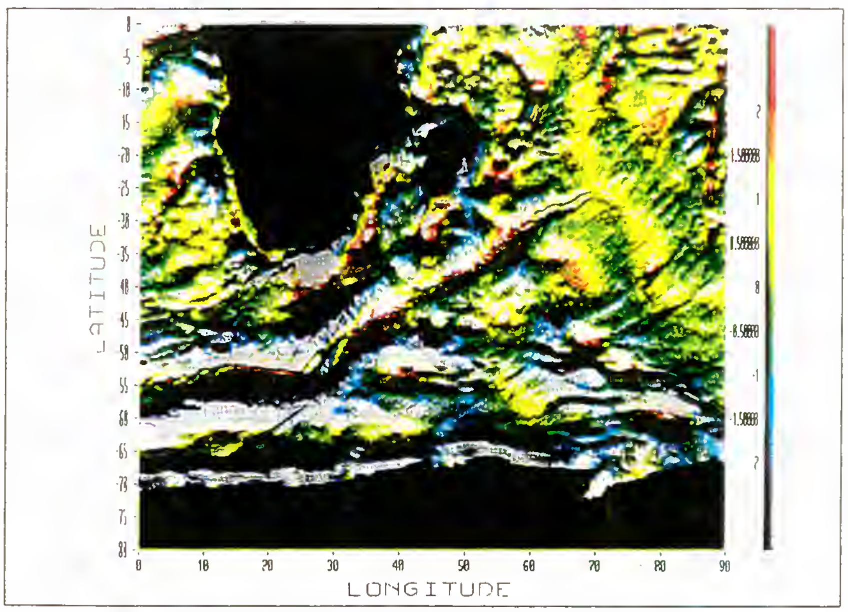


Figure 3. Same as Figure 2, but for the Southeast Indian Ocean

(Courtesy of Groupe de Recherche en Geodesie Spatiale)

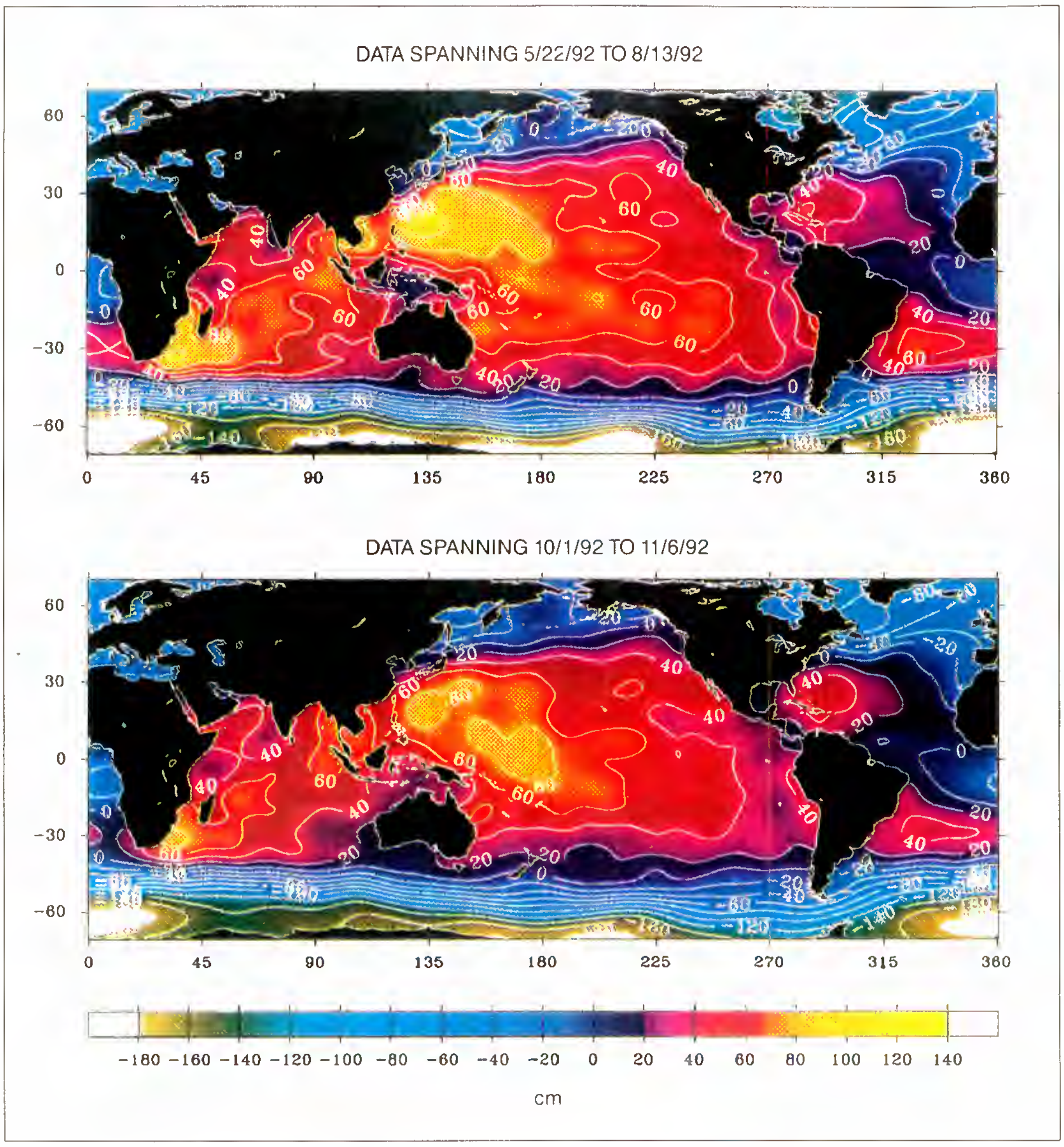


Figure 4. Dynamic ocean topography as observed by ERS-1 during Summer 1992

ERS-1 altimeter data were reduced to sea-surface heights using precise orbits computed at UT/CSR. The dynamic topography was filtered to keep only the large scale. The strong currents occur where the iso-contours are close together.

(Courtesy of Univ. Texas Center for Space Research)

Today, the geoid is not known to sufficient accuracy at wavelengths below 3000 km. In order to increase our understanding of ocean behaviour, dynamic topography must be distinguishable from the geoid at mesoscale wavelengths, say of order 100 km. Moreover, knowledge of the geoid per se is an important step towards understanding the dynamics of the Earth's interior. A radar altimeter can also be thought of as a tracking device onboard an orbiting platform integrating the Earth's gravity field. Altimetric missions therefore contribute to improving our knowledge of the gravity field (Fig. 5).

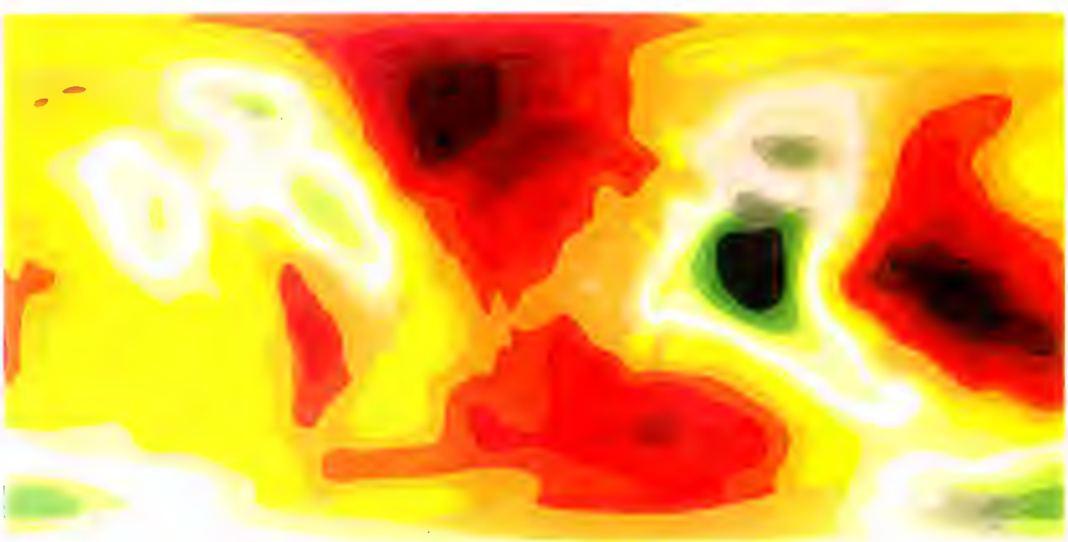


Figure 5. The improved Earth gravity-field model used for ERS-1

The gravitational geopotential produces the principal acceleration on Earth. A precise orbit restitution applying dynamic methods therefore requires a precise model of the geopotential with a resolution requirement depending on the satellite's altitude. The Earth does not have a uniform gravity field; it is weaker south of India than in Indonesia.

(Courtesy of German Processing and Archiving Facility)

If the absolute sea level is still difficult to assess, methods have been developed for observing the variations in ocean circulation. They are based on the analysis of the differences between two sets of measurements. The steady gravitational contribution to sea level contained in the two sets of measurements is removed and the varying part can then be analysed. This is achieved by observing differences between successive overflights of the same ground track, or by observing differences from points where ascending tracks cross descending tracks, called 'cross-overs', or by differencing the altimeter measurements along the track to derive the 'slope' of the sea level. The idea is that the inadequately known geoid is removed during the differencing process and thus local variations can be mapped.

Figure 6 shows the mesoscale variability computed as the standard deviation of the sea-level slope between April 1992 and June 1993, extracted from ERS-1 radar-altimeter data. The main current systems playing a key role in heat exchange can be detected and their variability quantified.

Sea-level variations involve a broad range of space and time scales. Mapping of temporal variations in currents at intermediate scales (300–3000 km) and basin-wide circulation requires an orbit determination precise to the sub-decimetric level. Precise orbit computation is dependent on a permanent flow of good-quality tracking data and a state-of-the-art gravity model. The quality of the altimetric measurements is directly dependent on the quality of the orbit computation.

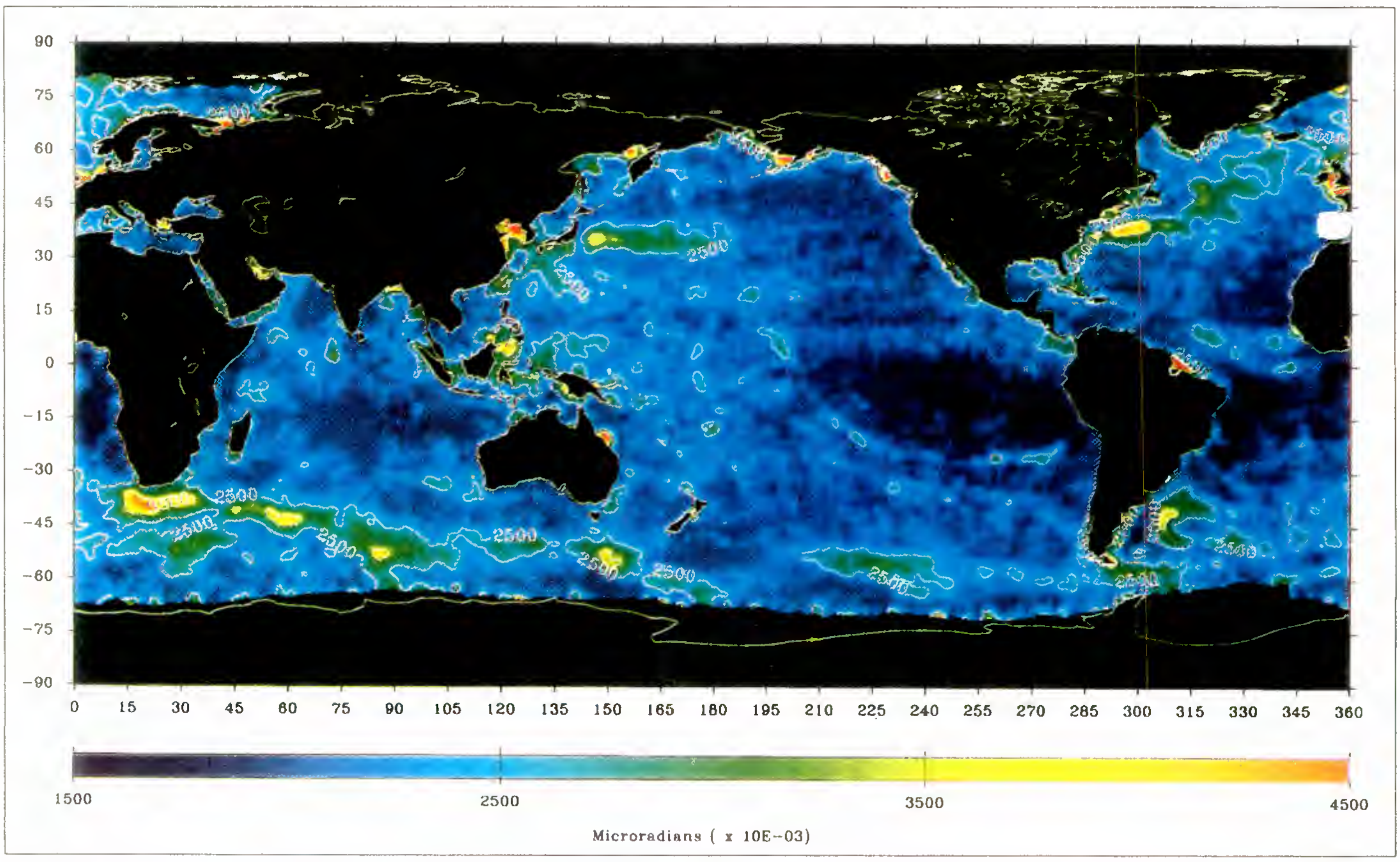
Outstanding progress has been achieved in the past five years by the international groups working on precise-orbit computation, by constantly exchanging data and actively working together. For example, the ERS-1 operational precise-orbit computation has been drastically upgraded and new orbital ephemerises are being re-computed for the whole mission.

The El Niño is another such large-scale phenomenon. In response to the weakening of the Trade Winds, the sea level in the eastern Pacific becomes higher than normal and the South American west-coast upwelling of cold and oxygen- and nutrient-rich water stops. One of the immediate local outcomes is that the anchovies migrate or die, resulting in a shortage of fish for human consumption and of the anchovy flour used to feed cattle. Ultimately, corn flour must replace fish flour during an El Niño year. The climatic impact of El Niño is not yet fully fully understood, but it is already clear that it is global, affecting all weather patterns (colder winters in the Northern Hemisphere, droughts in Australia).

Figure 6. Mesoscale variability

This figure indicates the global current system as seen by ERS-1 during the first year of its 35-day repeat cycle. The main currents stand out as regions of high variability due to the sea surface changing substantially more than in regions where there are no large currents present.

(Courtesy of Univ. Texas Center for Space Research)



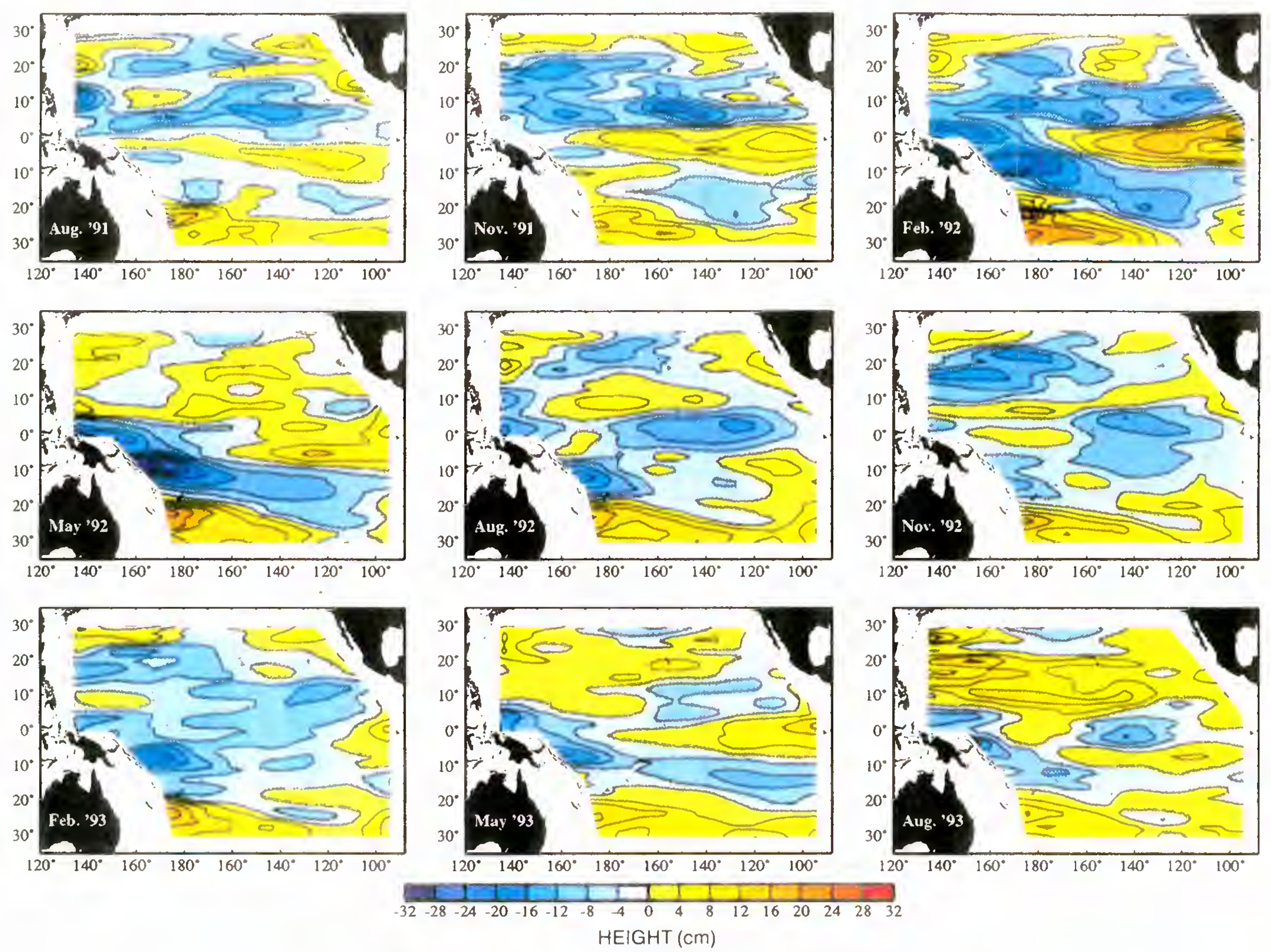


Figure 7. Maps of sea-level anomaly from ERS-1 altimeter data

In response to anomalous winds, an El Niño situation began in Winter 1991 and peaked in Spring 1992. The sea level returned to normal by Autumn 1992. This phenomenon has a period of three to seven years. The second, unexpected, warm event started early in 1993.

(Courtesy of J. Lillibridge & R. Cheney, NOAA)

The ERS-1 radar altimeter has been used to monitor two El Niño events so far (Fig. 7).

Ice-sheet altimetry

Almost 94% of all water on Earth resides in the oceans, whilst 1.5% is stored as snow and ice, most of which is to be found in Antarctica. The short-term drivers of sea-level change are the relatively small mountain glaciers whose typical variation time scales are of the order of 100 years, compared with 10 000 years for changes in Antarctica. The Greenland ice sheet's variability lies somewhere in between. Thus, mountain glaciers are believed to be sensitive indicators of climate change, but their impact on today's sea-level changes might be blurred by the Antarctica ice sheet still adjusting to past changes in climate.

Whatever the origin, the lag and the time scale, the volume of water frozen in the cryosphere (the ice and snow milieu) is ever-changing. Measuring the rate of that change is mandatory for sea-level change prediction. Very little is yet known about the actual mass balance of the cryosphere. Past glaciological research efforts have indicated that ground-based measurements cannot provide the requisite monitoring of the ice volume. ERS-1's polar orbit, taking it over the far north and far south of the globe, is allowing it to gather data of unprecedented value in terms of ice-sheet elevation monitoring.

In addition, ERS-1's radar-altimeter tracking system has a special agile mode that allows it to cope with steeper relief without losing track. Previous radar altimeters designed primarily for satisfactory tracking performance over the ocean tended to lose the signal from their tracking window when the topography became steep. In addition, the return power profiles, or 'waveforms', reflecting from sea ice or land masses do not have the same characteristics as ocean returns in that they are more spiky. The instruments' tracking algorithms did not perform properly on such land/ice waveforms, which had to be re-analysed on the ground to re-estimate the range – a process known as 're-tracking'.

Unfortunately, previous radar-altimeter missions could not cope either with extensive data downlinking, and so the raw data were

first compressed on board. Consequently, the ground 're-trackings' were not done using all of the original waveforms, but based on an average, from which it was not possible to calculate errors accurately. The ERS-1 radar altimeter downlinks waveforms at twice the rate of previous missions, thereby permitting more accurate re-tracking.

ERS-1's radar-altimeter data over ice will provide the necessary information for many glaciological studies, such as delineating catchment basins, characterising flow lines, calculating ice-flow driving stresses, setting boundary conditions for numerical models, producing accurate digital elevation models, mass-balance studies, identification of the equilibrium lines between accretion (accumulation) and ablation (melting or iceberg carving)

Waves

As the power reflected from the troughs of ocean waves arrives later than the power from the crests, the significant wave height can be deduced from the return-power waveforms. The wave-height measurements from the radar altimeter are used for sea-state forecasts for such real-time applications as ship routing, offshore operations, coastal engineering, and the prediction of flooding

Figure 8 shows a monthly distribution of significant wave heights over the global oceans.

Wind

Wind speed over oceans is retrievable from radar-altimeter data because the wind stress on the sea surface affects its backscattering properties. Figure 9 shows a monthly distribution of wind speed over the global oceans.

In addition to its meteorological application, radar-altimeter wind modulus is also used to correct microwave-sounder measurements.

Modelling and assimilation

The above are just a few examples of the variables that a radar altimeter can monitor. In many instances, a variable determining the state of a system, say the ocean, is monitored by several independent measuring instruments. None of these instruments ever procure a complete description of the state of the observed system. The individual measurements themselves also often include small errors or suffer from sampling limitations.

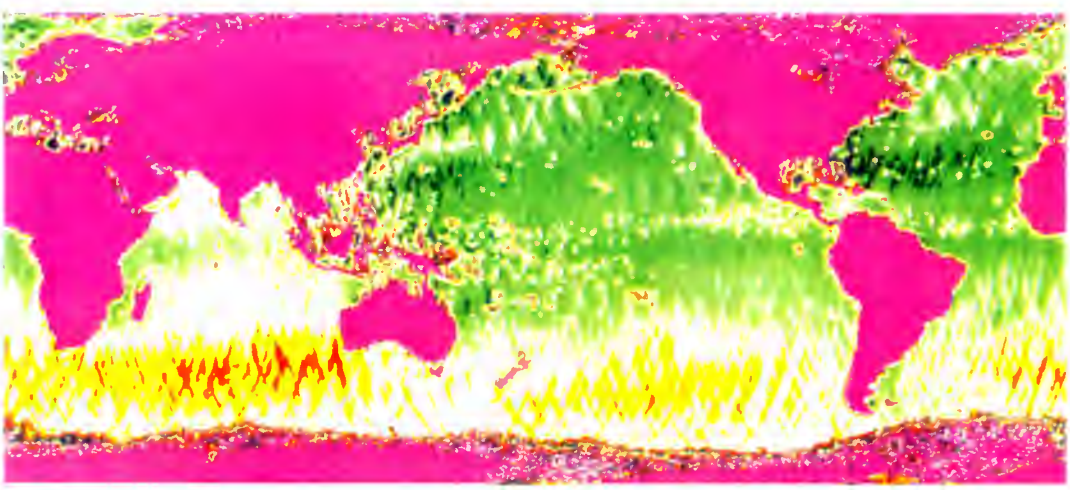


Figure 8. Significant wave height from radar altimetry

The significant wave height is derived from the analysis of the return echoes of the ERS-1 radar altimeter. This data is globally sampled and available within the quick-look sea-surface product which covers one full repeat cycle (35 days), generated every week. This sample is for 27 April to 1 June 1992.

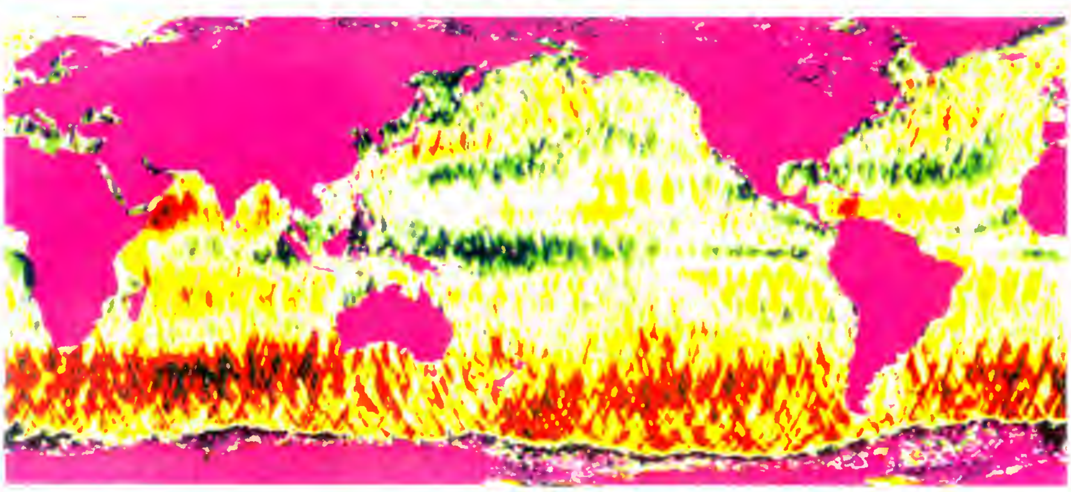


Figure 9. Wind speed from radar altimetry

The nadir wind speed is derived from analysis of the return power of the ERS-1 radar altimeter. This data is globally sampled and available within the quick-look sea-surface product which covers one full repeat cycle (35 days), generated every week. This sample is for 27 April to 1 June 1992.

The solution is to make optimal use of each data set, separating and rejecting the errors and extracting the real signals from the measurements. To do so, it is important to have a good statistical description of the likely errors in the various measurements. The limitations of each instrument can then be taken into account in the data-combination process by assigning weighting factors to the various data sources based on their likely error content.

To illustrate the concept of combining data from different instruments in this way, one can consider that sea level can also be measured by shore tide gauges, by bottom pressure gauges, by inverted echo sounders, by measuring temperature and salinity profiles, etc. Satellite altimetry benefits directly from such in-situ measurements during the calibration and validation phases of each mission, but there are tremendous gains to be realised when all such data measuring the same variable, but obtained with very different approaches, are optimally combined.

This is usually best organised around a numerical model and an assimilation scheme to absorb the different data sets and extrapolate the information in space and time. Such a numerical-model approach is the key to extrapolating the large amounts of sea-surface information collected by radar altimetry to the interiors of the World's oceans. Even in a context not relying on a numerical model, the improvement that can be expected from combining data from two or more altimetric missions is not one-sided for the less-accurate data sets; in addition to the obvious accuracy improvement, merging data from two or more radar-altimeter missions immediately improves both the temporal and spatial resolutions.

Combining ERS-1 and Topex–Poseidon altimeter data, for example, means that the shorter-scale (both temporal and spatial) signals can be resolved and detected for the first time, rather than being aliased into larger-scale signals.

Preparing the user data products

Before any data can be combined with other data or assimilated into numerical models, or even used directly, they have to be processed from 'instrument level' into meaningful geophysical units. The former levels can include anything from raw electrical signals downlinked to the receiving stations, to their computer-processed counterparts. The data sets at the latter level are the so-called 'Geophysical Data Records' (GDRs). The meteorologist interested in wind speed expects his anemometer to read in metres per second, not volts created by the dynamo. The users of space-acquired data expect no less from the satellite system.

The ground segment must therefore be designed not only to gather the radar-altimeter data, but also to prepare it for the users. Beyond generating the GDRs per se, this complex task includes flagging the slightest inconsistency in the instrument output, such as a perturbation of the micro-wave measurement over the ocean due to the presence of a small island. The data produced must also be verified to guarantee their quality, and efforts invested to refine or develop processing algorithms. To best channel these efforts and to optimise the generation and use of the data, the producing agencies and the users must maintain close contact.

Today, ERS-1 and Topex–Poseidon are providing complementary altimetric data. ERS-2, Envisat, a Topex–Poseidon follow-on mission, and a Geosat follow-on mission are planned. Each of these missions is dedicated to monitoring different geophysical signals, with different sampling strategies. As explained above, no observing system is completely self-sufficient. The simultaneous operation of these new altimetric missions will greatly enlarge the scope for cooperation in radar-altimeter and microwave-sounder (ATSR/M on ERS) sensor evaluation and product validation, in addition to the prime geophysical goals.

Given this new multi-mission environment, such issues as sensor cross-calibration, inter-consistency of processing algorithms, product specifications, and external data sources must be defined, solved and verified in a consistent manner. Only by doing so will we be able to guarantee that users will be in a position to straightforwardly and confidently exploit data from these missions. The goal must be to harmonise the altimetric Geophysical Data Records from the various missions and their quality assessment, and thereby further optimise their quality.

At the beginning of an era in which climatic and economic circumstances dictate that we should monitor our planet closely, the pace of data acquisition can be expected to increase dramatically. This makes it even more crucial that we put every effort into simplifying the data usage, or in other words into making the measuring chain more efficient.

ESRIN is intending to unify and augment the tools necessary to generate fast-delivery products from the ESA instrument data, to control and evaluate them, as well as be able to cross-calibrate and cross-evaluate between ESA's missions. ESRIN is therefore developing a precision processor for ESA's altimetric mission instruments – radar altimeter and microwave sounder – uniquely dedicated to sensor, algorithm and product evaluation, external to the routine operations environment and capable of dealing with data products from multiple missions.
This tool will be used in future definition, implementation, testing and upgrading of fast-delivery altimetric user products and systems.

A lesson that has clearly emerged from all previous radar-altimeter missions is that there is a need for an intensive algorithm-validation and engineering-assessment effort early in each mission, in addition to the regular development phases. Success can only be achieved with the appropriate tools.

Conclusion
The two ERS missions and the future Envisat mission (extensively described in this Bulletin) cannot be considered in isolation. They are inevitable stepping stones for the success of the World Research Climate Programme. Further missions are also being planned, as continuity of altimeter measurements is essential in order to study long-term changes in ice and sea-surface topography, for climate studies and climate change prediction.

The advanced data users will always seek the optimal solution by exploiting as many different data sources as possible. In addition to standardising storage media and product formats, therefore, standardisation of the 'Geophysical Data Records' emanating from the various radar-altimeter missions, as well as of the method of quality and error-budget estimation for each remotely sensed variable, is an essential ingredient for the optimal use of future earth-observation data.