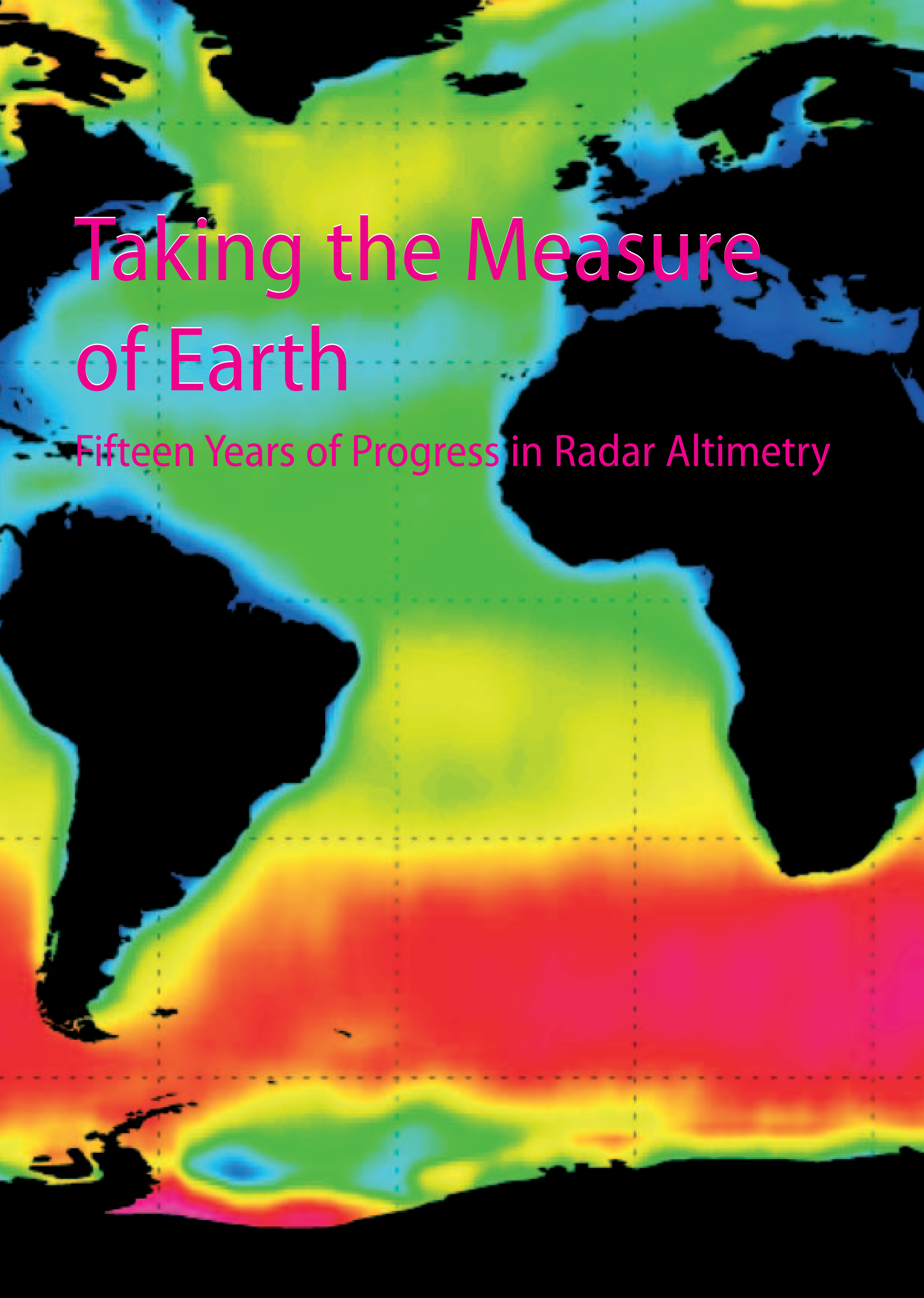
Taking the Measure of Earth

Fifteen Years of Progress in Radar Altimetry



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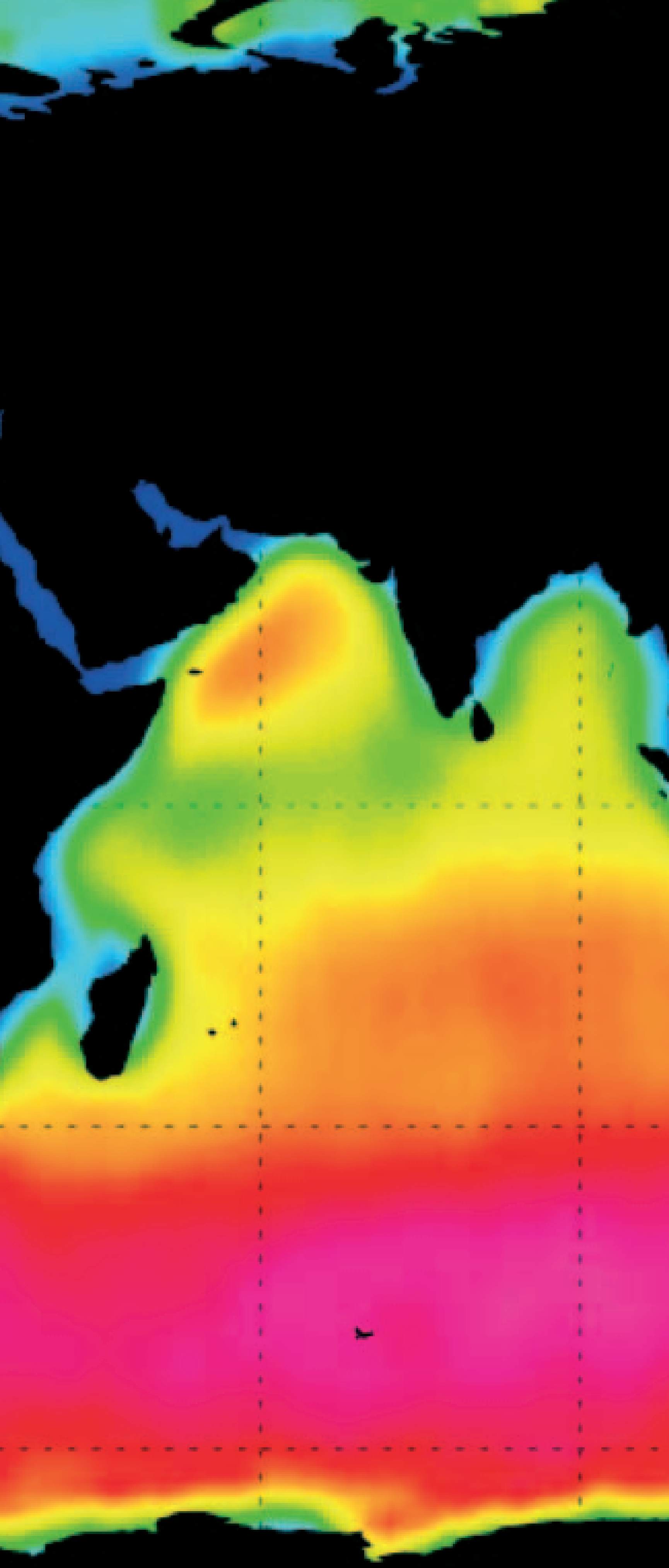
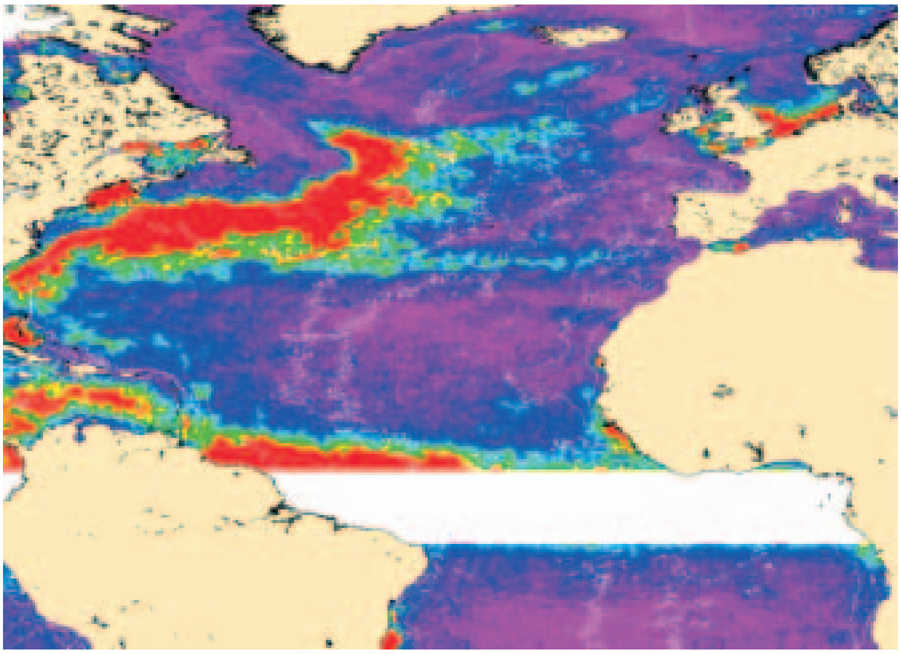


Wave heights measured by ERS-2 during the northern summer. Red/pink shows rougher seas during the southern winter

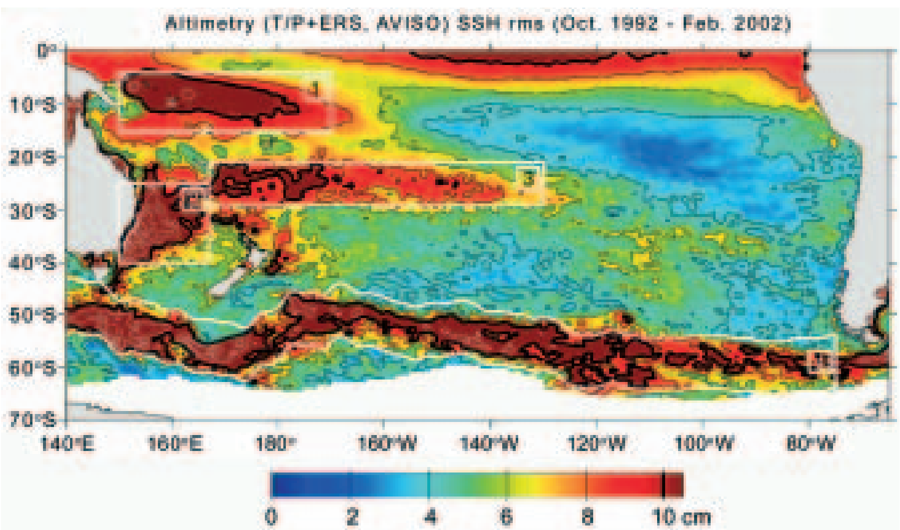
Radar altimetry is about to enter a new era. It is becoming an indispensable tool for oceanography as a new generation of radar altimeters providing higher resolution and precision is poised to begin service. Remarkable progress has been made since the launch of the pioneering ERS-1 in 1991.

Introduction

The ERS-1 European Remote Sensing satellite, launched in 1991, was ESA's first Earth-observation research satellite. Its comprehensive payload included an imaging synthetic-aperture radar, a radar altimeter and other powerful instruments to measure the sea-surface temperatures and wind characteristics. ERS-2 followed in 1995 and, remarkably, is still operating. At the time, the ERS twins were the most sophisticated Earth-observation satellites ever developed and launched by Europe. They have collected a wealth of valuable data on Earth's land surfaces, oceans and polar caps, and have been called upon to monitor natural disasters such as severe flooding or earthquakes in remote parts of the world.



The kinetic energy of eddies in the North Atlantic calculated from sea-level data along the Topex-Poseidon and ERS groundtracks. Red highlights the greatest energy. (Le Traon & Dibarboure)



The variability of sea-surface height from Topex-Poseidon and ERS data in the southern Pacific Ocean. Box 1 highlights the variability of the South Equatorial Counter Current. Box 3 shows the variability of the South Tropical Counter Current. (Qiu &Chen)

By 1992, the unique results from ERS and the CNES/NASA Topex-Poseidon had provided a strong foundation for the future of satellite altimetry and the missions then in development, such as Jason (CNES and NASA/Jet Propulsion Laboratory), Envisat and Geosat Follow-On (US Navy). Countries with different cultures, especially Europe and the USA, learned to work towards common goals, and the different geodesy, geophysics and oceanography scientific communities had to learn to work closely together. Cryosphere researchers benefited by adapting the technology and data-processing progress made by oceanographers, to monitor the ice caps and sea-ice.

Over several decades, new technologies with improved accuracy were developed. The accuracy of global geodetic measurements has increased from a few hundred metres at the beginning of the satellite era to a few centimetres now. Though a highly complex problem, it recently became possible to exploit radar altimetry to monitor inland water levels; the accuracy over these difficult terrains is improving rapidly.

After many years of development and data exploitation, radar altimetry is becoming operational in oceanographic applications. A new generation of high-resolution and high-precision instruments is entering service using techniques such as ‘delay-Doppler’ and interferometry. We now know much more about our Earth, ocean dynamics and the cryosphere than we would without altimetry, and we have laid the foundations for fully operational 3-D oceanography.

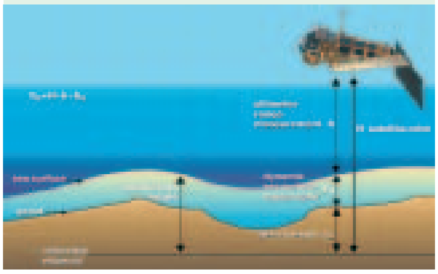
Understanding the Ocean

Radar altimetry has made an important contribution to oceanography by investigating the high-frequency variability in sea-surface height from global to basin scales, and its impact on the oceans’ general circulation. It highlights the importance of eddies in shaping and controlling the flows of major current systems such as the Antarctic circumpolar current and western boundary currents (Gulf Stream and Kuroshio), and the influence of eddies on the vertical mixing in the ocean. The results from 15 years of altimeter data on eddy variability in the oceans are outstanding and are certainly a major accomplishment. Altimetry has proved unique in dramatically improving our tide models, in observing internal tides and understanding the genesis of climatic events such as El Niño and the North Atlantic or North Pacific Oscillations. Now it is the interaction between phenomena such as planetary waves, eddies, tides and mean flow, and their impact on coastal regions, that must be investigated. These new studies will benefit greatly from the higher resolution sampling provided by the upcoming altimeter missions.

The Principle of Radar Altimetry

Radar altimetry measures the distance between a satellite and the surface below using radar echoes bounced back from the surface, whether ocean, ice cap, sea-ice, desert, lake or river. The characteristics of the echoes contain further information on the roughness of the surface, wave heights or wind speeds over the ocean.

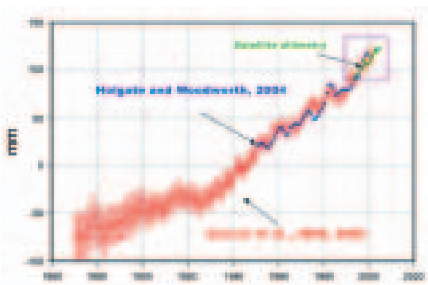
Altimetry measurements become scientifically more useful when the satellite's position is accurately known. Many satellites, including Envisat and CryoSat, carry the DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) radio receiver for precise orbit determination. DORIS calculates the orbit to an accuracy of a few centimetres by measuring the Doppler shift on signals broadcast from a network of more than 50 beacons spread around the world.



Sea levels

Altimeter observations from satellites show that the global mean sea level has risen over the past decade at a rate of about 3 mm each year, well above the rate of 1.8 mm per year over the previous 100 years. This is despite large geographical variations, including broad areas of falling sea level. Consistent increases in both sea level and sea-surface temperatures have been found in most parts of the Atlantic Ocean over the past 15 years.

The rise in sea level during the 20th century appears to be accelerating. Satellite measurements for the last 15 years are shown in green. (Cazenave et al.)



In the Indian and, particularly, Pacific oceans, the trends in both sea level and temperature are still dominated by the large changes associated with the large El Niño Southern Oscillation of 1997–1998. Fresh water brought by rain, snow, melting sea-ice, ice sheets and glaciers complicate our understanding of the rise in sea levels. It can be expected that the next decade of altimetry will provide fundamental new insights into these important features.

Tsunamis

The Sumatran tsunami of December 2004 was the first to be observed by altimeters in space, which has allowed scientists to improve our understanding of how tsunamis propagate. This is invaluable for helping to avoid disasters, in addition to being of great interest for science. One of the main components of building propagation models is the underwater equivalent to altimetry: bathymetry. This is the measurement of the depth contours of the soil, rock or sand at the bottom of a body of water such as an ocean or a lake. Deriving sea-floor topography from radar altimetry is improving the accuracy of these models because the nature of the floor influences how tsunamis move and build.

Marine meteorology

Radar altimeters are indispensable for observing the sea state in a variety of applications. Wave climatology, a well-established altimeter application, is continuously enriched by new data as they become available; the longer the record, the more consistent and reliable the results. Correlation of wave-height variations with climatological phenomena such as the North Atlantic Oscillation has been observed – and has opened a whole new area of science. Wave modelling, a traditional application, has greatly improved recently thanks to the assimilation of altimeter data in near-realtime, and is now generating accurate sea-state predictions, to the enormous benefit of the shipping industry. In addition, sea-surface topography measured by radar altimeters is also used in near-realtime jointly with sea-surface temperature and models to investigate how the upper-ocean thermal structure is involved in strengthening hurricanes.

Understanding the Cryosphere

Glaciologists had to wait until the advent of ERS-1 to see a polar altimeter flying over sea-ice and the ice sheets. The instrument proved to be a very powerful tool for glaciology, with three major scientific objectives: ice-sheet modelling and dynamics, ice-sheet mass balance and sea-ice thickness. There are also numerous secondary uses.

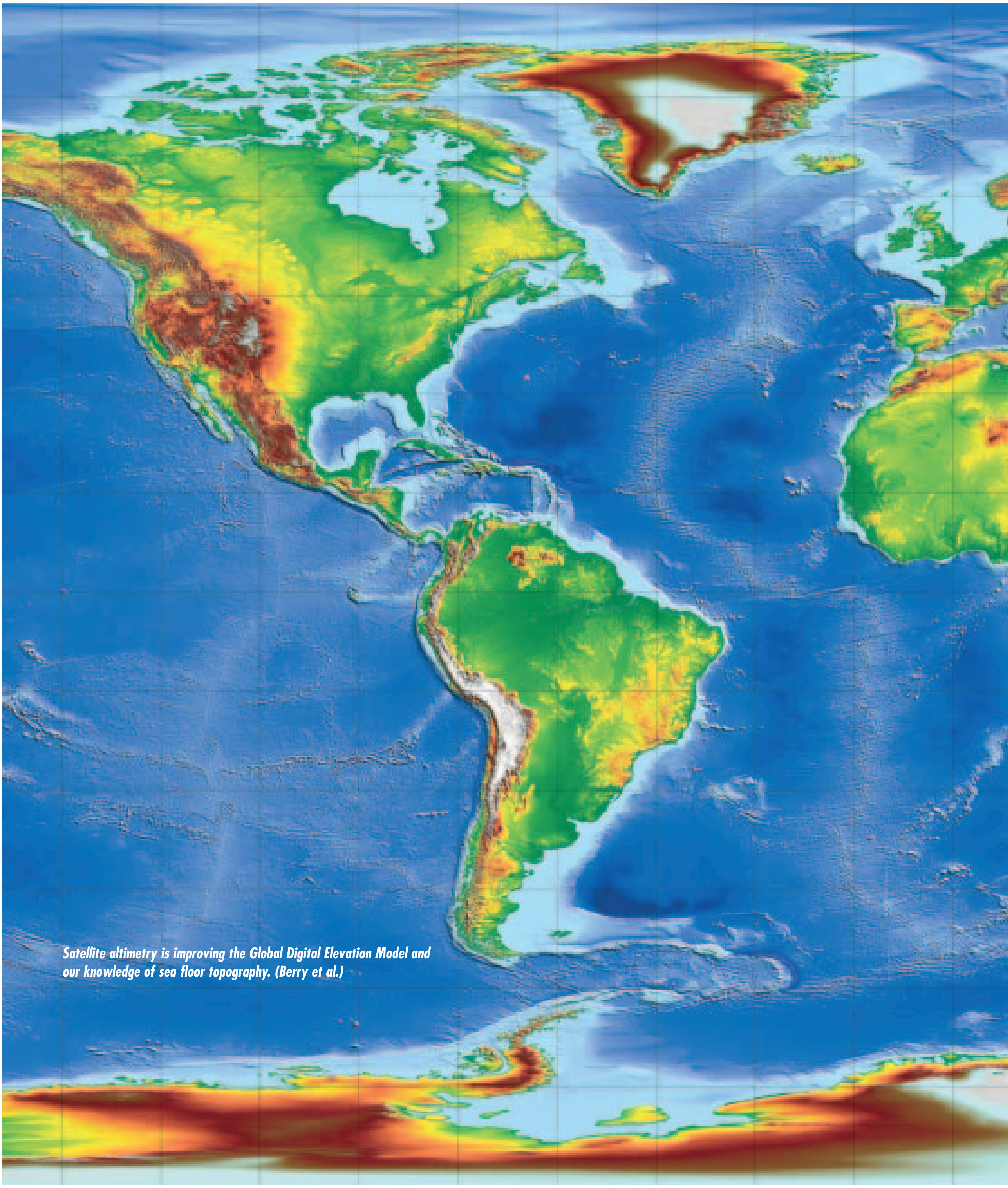
Ice sheets

The mass changes in ice sheets has been studied from space, ranging from the largest sheets in Antarctica and Greenland, to smaller ones such as the Austfonna (in Svalbard, the world's third largest icecap and the largest glacier in Europe). Overall, the Greenland and Antarctica sheets are found to be almost in equilibrium, losing as much ice as they gain, but local data suggest a loss that could accelerate in the near future.

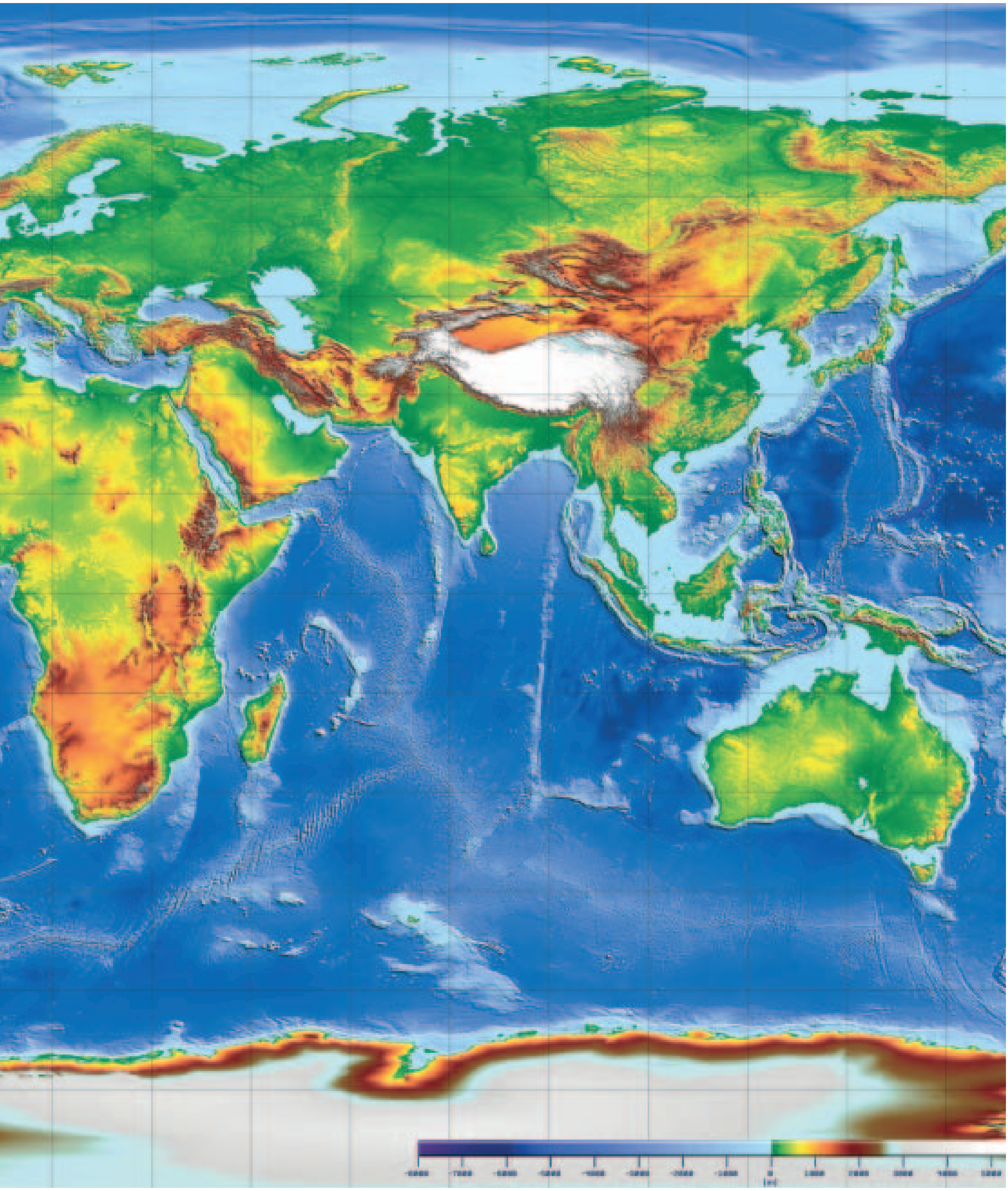
Radar altimeters are not only able to map the global trend but can also catch local imbalances. However, discrepancies between some studies may be explained by the behaviour of radar waves interacting with packed snow. This is why Envisat's dual-frequency altimeter is helping to improve our knowledge of how radar waves penetrate the snow.

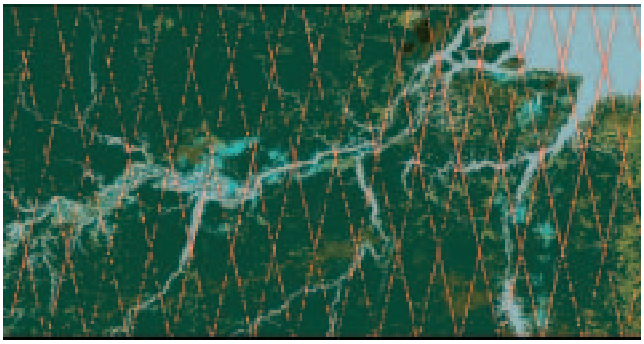
Altimetry over Land and Inland Water

The potential of satellite radar altimeter data for applications over land and inland water is now well known, as data from Topex-Poseidon, Jason, ERS-1, ERS-2 and Envisat have extensively shown. Initially developed to make precise measurements of sea surfaces, radar altimeters rapidly proved able to provide information over the continents. Their development to monitor continental water surfaces provides a powerful tool for studying regional hydrological systems.

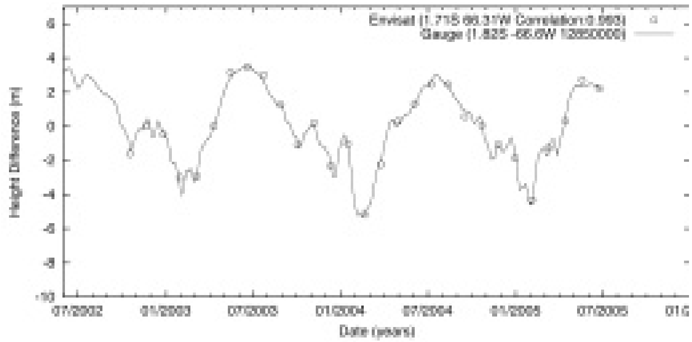


Satellite altimetry is improving the Global Digital Elevation Model and our knowledge of sea floor topography. (Berry et al.)





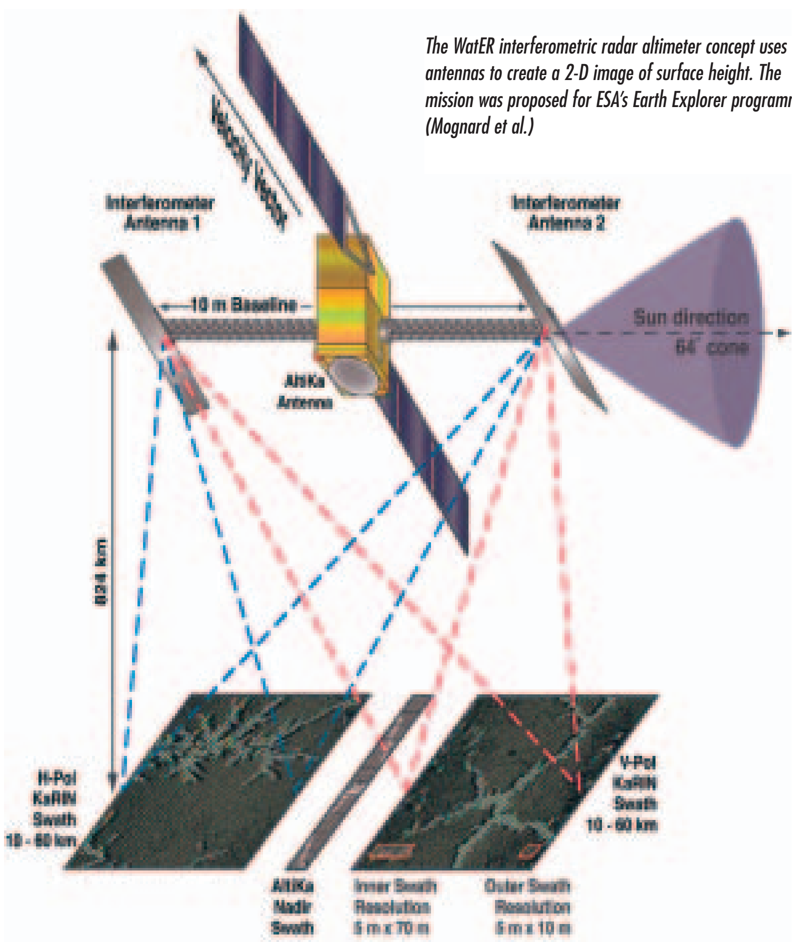
The ground track of Envisat's radar altimeter over the Amazon basin, using a 35-day repeat cycle. The height readings over the rivers were used to produce the accompanying graph of river levels since 2002 (Berry et al.)



Envisat altimeter measurements (circles) of the river levels in the Amazon Basin compare well with in situ readings from gauges (line). (Berry et al.)

Although monitoring inland waters is rapidly developing, the potential of multi-mission altimetry is only now being realised. One such mission is WatER, proposed both to ESA in 2005 as a response to the second call for Earth Explorer core missions and to NASA as a possible partnership mission with ESA. There are different scientific and technical challenges to be overcome in such missions. One is the need to map river basins in two dimensions, inferring the slopes as well as the levels of rivers.

While WatER would need several years to be developed, if selected, scientists are meanwhile focusing on exploiting today's missions (ERS-2, Envisat, Jason-1, Geosat Follow-On) and on the future CryoSat, Jason-2 and Sentinel-3 missions for studying inland waters.



The WatER interferometric radar altimeter concept uses two antennas to create a 2-D image of surface height. The mission was proposed for ESA's Earth Explorer programme (Mognard et al.)

Gravity and Marine Geoid Modelling

Geodesy

After years of slow progress, two missions – CHAMP (2000) and GRACE (2002) – are providing exciting results in global geodesy, and GOCE (2007) will soon join them. Geodesy primarily concerns positioning and the gravity field and geometrical aspects of their variations, and it can include the study of Earth's magnetic field. Gravity anomalies reflect mass variations inside the Earth, offering a rare window on the interior. The geoid is the shape of an ideal global ocean at rest, and it is used as the reference surface for mapping all topographic features, whether they are on land, ice or ocean. The geoid's shape depends solely on Earth's gravity field, so its accuracy benefits from improved gravity mapping. Measuring sea-level changes, ocean circulation and ice movements, for example, need an accurate geoid as a starting point. Heat and mass transport by oceans are important elements of climate change, but they are still poorly known and await measurement of ocean surface circulation.

The new EIGEN04 gravity model derived from these missions and terrestrial gravity data eliminates much of the 'meridional striping' seen in gravity models. Subtraction of this new model from an altimeter-derived sea surface reveals the dynamic ocean topography, at a resolution nearly sufficient to resolve the western boundary currents.

These models are an improvement over the EGM96 combined model and thus will provide an improved reference for higher-resolution marine gravity models derived from altimetry. The new global-scale geoid models also serve as a global vertical reference system. Scientists are preparing for the GOCE mission, which will provide improved spatial resolution (about 100 km), sufficient to resolve western boundary currents such as the Gulf Stream fully.

Marine gravity

Although no new non-repeating orbit radar altimeter data have been available since the ERS-1 geodetic phase in 1994–1995, reprocessing the raw altimeter waveforms has produced a near-40% improvement in the accuracy of the gravity field. Comparisons with shipborne gravity measurements over the deep ocean show the accuracy is now 3–5 mGal and the shortest half-wavelength resolved is approaching the altimeter track spacing of 8 km from ERS-1.

The Cryosat launch failure was a major setback for the marine gravity and geophysics communities because that mission would have provided a new global altimeter dataset with dense track spacing and, more importantly, it would have demonstrated the technology for the next generation of marine gravity measurements by altimetry. Scientists are delighted that ESA is rebuilding the satellite.

The laser altimeter aboard NASA's ICESat has provided new gravity information in those parts of the Arctic Ocean where permanent sea-ice closely conforms to the shape of the geoid. Further improvements in the accuracy and resolution of marine gravity would provide important contributions in both scientific and practical studies such as locating 50 000 uncharted seamounts in the deep oceans and exploring the offshore sedimentary basins for oil. Other applications include mapping the details of plate tectonics, planning shipboard surveys in remote areas and improved inertial navigation of aircraft and ships.

Bathymetry

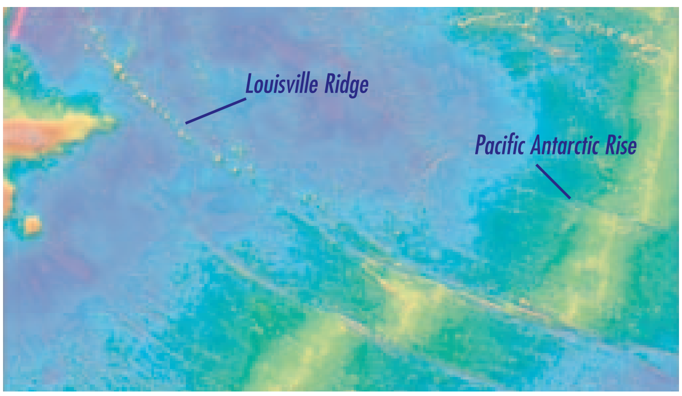
Ocean bathymetry is currently best measured by sonars aboard ships, but only a small fraction of the global ocean basins have been surveyed; it is estimated that it will take 125 ship-years to survey all of the deep oceans. The need for improved global bathymetry is critical because it forms the basic data for many fields, including tsunami propagation, hydrodynamic tide models/ tidal friction, ocean circulation, seafloor tectonics, identification of volcanic chains, defining the 2500 m isobath for the law of the sea, and fisheries management.

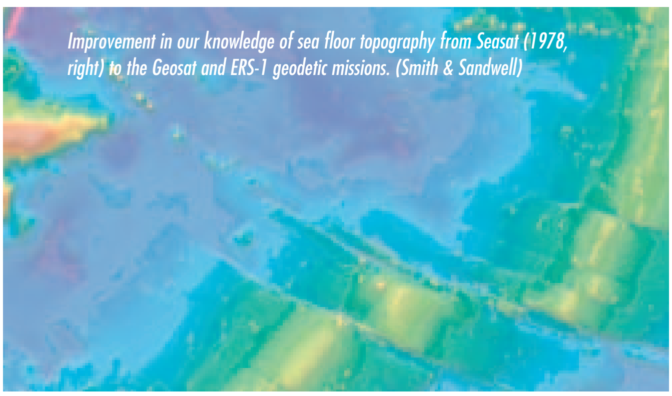
For example, the Pacific-Antarctic Rise and Louisville Ridge were unknown features 30 years ago. The Pacific-Antarctic Rise, covering an area about equal to North America, is a broad part of the ocean floor lifted up between two major tectonic plates. The Louisville Ridge lies to the west of this, and is a chain of large underwater volcanoes discovered in 1972 using depth soundings collected along random ship crossings of the South Pacific. Six years later, the full extent of this chain was revealed by a radar altimeter aboard NASA's Seasat. Recent data collected by Geosat and ERS-1 show the Pacific-Antarctic Rise and the Louisville Ridge in unprecedented detail.

Progress in Ocean Integrated Systems

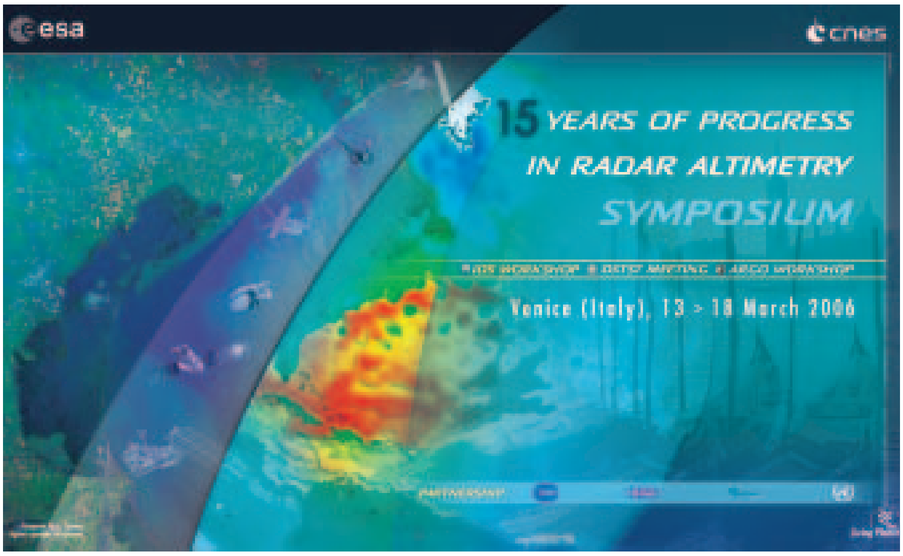
In 15 years there has been a wide range of activities: synergies between remote sensing and *in situ* data, development of operational oceanography systems, model validation and studies of the impact of the integrated approach on research and applications. The international Global Ocean Data Assimilation Experiment (GODAE) is a practical demonstration of near-realtime global ocean data assimilation that supports operational oceanography, seasonal-to-decadal climate forecasts and oceanographic research.

The main integrated systems developed as part of GODAE cover high-resolution (eddy-resolving) systems that focus on the forecasting of ocean mesoscale conditions, and lower resolution systems for climate applications. Such applications require a precise and dynamically consistent description of the ocean state. Use of advanced data assimilation techniques allows diagnostic studies such as heat balance. A major





Improvement in our knowledge of sea floor topography from Seasat (1978, right) to the Geosat and ERS-1 geodetic missions. (Smith & Sandwell)



issue for effective data assimilation is to estimate the model 'error covariance' and there has been a significant advance in accounting better for these errors.

A major contributing project to GODAE is Argo, an array of more than 2000 free-floating floats that provide temperatures and salinity measurements at various depths across the oceans. Argo results are scientifically valuable in their own right but can be combined with altimetry data for enhancing environmental and climate knowledge. Studies on the impact of altimetry and Argo on seasonal forecasts show they can significantly improve data-assimilation systems. Thanks to these studies, Argo and altimetry are now used in the operational seasonal forecasting systems of the European Centre for Medium range Weather Forecasting.

Physics and biology can be coupled through the joint analysis of altimetry, sea-surface temperature, ocean colour and model data. There are now studies into the different mechanisms that could explain the observation of planetary waves in altimeter, sea-surface temperature and ocean colour data. Horizontal advection is an important mechanism but vertical and biological effects cannot be ruled out. Other studies have shown the importance of ocean physics on the development of phytoplankton blooms in the wake of islands.

The main conclusion is that major advances over the past 5 years have helped to develop an 'integrated' approach to describe and forecast ocean conditions. Integrated descriptions of the ocean state are now available and are used to characterise and understand ocean climate variations better. This is crucial for the long-term sustainability of the global ocean observing system. The use of Argo and altimetry data is essential for developing an improved understanding of variations in the ocean climate. The strong synergies between Argo and altimetry will become more or more obvious as Argo is expanded.

A New Challenge: Coastal Monitoring

Altimetry may contribute in many ways to the study of coastal phenomena, especially tides, currents and sea state, that directly affect, for example, offshore oil exploration, fishing, marine aquaculture and coastal planning and development. Altimetry can supply direct measurements of sea level and sea state, and vital information about 'forcing' from areas just outside the coastal domain. These include the influence of offshore ocean circulation and the inflow of fresh water from land masses, closely tied to river and lake levels and to ice extent, all of which can be observed by altimetry satellites. However, coastal monitoring has very demanding requirements. The phenomena are often small-scale, rapidly changing and highly turbulent events calling for combined satellite and *in situ* data (such as from tide gauges and buoys) to ensure adequate resolution and coverage, as close as possible to the shore-line. Future altimetry systems will also have to meet these requirements, either by employing constellations of satellites or by developing new wide-swath radar concepts.

The Future of Altimetry

The European Commission-funded GAMBLE (Global Altimeter Measurements By Leading Europeans) project brought together European experts in 2002–2003 to consider future developments in satellite altimetry. The aim was to provide recommendations for research and future altimeter missions to support and build on current work in operational oceanography and to maintain ocean-monitoring programmes.

GAMBLE recommended in 2003 that coverage by a single satellite is not sufficient to meet both operational and scientific user needs. Rather, a constellation of at least three nadir-viewing altimeters is needed to provide the sampling required for many practical purposes. GAMBLE stressed the demonstration of new technology such as wide-swath altimeters and larger constellations of altimeters aboard microsatellites. The latter could prove to be very effective in the timely deliverance of sea-state information and in warning of natural hazards.

An important topic for the future of altimetry is the ongoing transition towards operational services. In Europe, a leading initiative is the Global Monitoring for Environment and Security (GMES) programme to develop a coordinated operational environmental information service, partly based on today's space infrastructures. The MERSEA ocean science component of GMES involves 50 European partners aiming to develop and sustain an integrated, operational system to provide analysis and forecasting over the global ocean and European seas.

For the GMES core marine services, the operational Sentinel-3 mission will deliver key information on sea-surface topography, sea-surface temperature and water quality, for example. The operational phase of Sentinel-3 is planned for around 2011–2015.

For the near future, the main operational mission will be Jason-2, developed by NASA and CNES to be operated by the US National Oceanic & Atmospheric Administration (NOAA) and Eumetsat. It extends the Topex-Poseidon and Jason-1 series and enhances the current altimetry services for climate monitoring and operational oceanography. In the longer term, Eumetsat is offering its capability as a leading European operational organisation to run some proposed future missions, such as GMES Sentinel-3 and, possibly, the Jason-2 follow-on.

Scientific developments have seen a recent tendency towards Ka-band altimetry. In particular, CNES is now proposing its AltiKa mission for a launch around mid-2009, aiming at filling the possible service gap after Envisat and complementing Jason-2 for the resolution of ocean mesoscale variability. It will increase accuracy and sampling capabilities in coastal regions and improve continental ice-sheet monitoring, though with the possible reduction of observing capability under exceptional rain and cloud conditions.

Considerable scientific progress is expected from wide-swath interferometric altimetry, not only by resolving smaller-scale ocean variability, but also by providing a truly 2-D sampling of hydrological systems. In August 2005, a consortium with over 150 participants from the wider hydrological community submitted the WatER mission proposal to ESA's Earth Explorer programme. To be flown after 2010, WatER would contribute to a fundamental understanding of the global water cycle by providing global measurements of terrestrial surface water storage changes and discharge. The main instrument is the KaRin wide-swath Ka-band interferometric altimeter, which could map rivers, lakes and wetlands at a spatial scale over 100 m with a height accuracy of 5–10 cm.

Finally, higher resolution is needed not only for progress in mapping ocean mesoscale and coastal variability and hydrological systems, but also to make the next advances in geodetic and bathymetric signals using space altimetry. Studies have shown that these advances could be realised in a highly cost-effective manner with a high-resolution radar altimeter (as carried by CryoSat) aboard a microsatellite.

Acknowledgements

This article is based on a report of the Symposium '15 Years of Progress in Radar Altimetry' held on 13–18 March 2006 in Venice (I). All abstracts, oral presentations and posters can be viewed at *http://earth.esa.int/venice06*. The papers are available in the proceedings SP-614 from ESA Publications Division at *http://www.esa.int*