

ALTIMETER DATA FOR OPERATIONAL USE IN THE MARINE ENVIRONMENT

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ABSTRACT

TOPEX/Poseidon has been collecting altimeter data continuously since October 1992. Altimeter data have been used to produce maps of sea surface height, geostrophic velocity, significant wave height, and wind speed. This information is of proven use to mariners as well as to the scientific community. Uses of the data include commercial and recreational vessel routing, ocean acoustics, input to geographic information systems developed for the fishing industry, identification of marine mammal habitats, fisheries management, and monitoring ocean debris. As with sea surface temperature data from the Advanced Very High Resolution Radiometer (AVHRR) in the late 1980s and early 1990s, altimeter data from TOPEX/Poseidon and ERS-1 and -2 are in the process of being introduced to the marine world for operational maritime use. It is anticipated that over the next few years companies that specialize in producing custom products for shipping agencies, fisheries and yacht race competitors will be incorporating altimeter data into their products. The data are also being incorporated into weather and climate forecasts by operational agencies both in the US and Europe. This paper will discuss these products, their uses, operational demonstrations and means of accessing the data.

I. INTRODUCTION

Altimeter data products are in the process of making the transition from scientific to operational use. Altimeter data from TOPEX/Poseidon, which is

an Earth orbiting satellite, have been used extensively by the science community to better understand ocean circulation and the role of the oceans in climate and weather. As derived products have been made available, use of the data for operational purposes has increased, as it has become evident that the data complements other information at the mariners disposal. It has also become apparent that incorporation of altimeter data into weather and climate forecasts increases the accuracy of these products.

II. PRODUCT TYPES

Product types include maps of sea surface height, geostrophic velocity, significant wave height, and wind speed. Products of most use to mariners are likely to be sea surface anomaly maps with superimposed geostrophic velocity vectors.

A. Sea Surface Height

Sea surface height is defined as the distance of the sea surface above a known reference surface, such as the earth's ellipsoid or the marine geoid. The sea surface height is computed from altimeter range and satellite altitude above the reference ellipsoid. (The "reference ellipsoid" is the first-order definition of the non-spherical shape of the Earth as an ellipsoid of revolution with equatorial radius of 6378.1363 kilometers and a flattening coefficient of $1/298.257$.) An alternate reference surface to the earth's ellipsoid is the marine geoid, which is defined as the shape the ocean would take if it were at rest. When altimeter data are referenced to an ellipsoid

the dominant pattern seen is the order 100 meter amplitude signal of the marine geoid corresponding to changes in sea surface height associated with changes in the mass distribution of the earth. These changes in height reflect changes in the gravity field and are useful for marine geology and offshore oil and gas exploration. Of more interest to mariners is the sea surface height relative to the geoid, which shows the order one meter sea surface height changes associated with the mean and time varying ocean circulation. Unfortunately, errors in current estimates of the marine geoid are large enough to prevent the accurate mapping of the mean circulation at the smaller scales (<10 degrees) of interest to mariners. Fortunately, the time varying component can be measured accurately using an altimeter. For this reason sea surface height is often shown as a sea surface height anomaly or deviation, the difference between the sea surface height at the time of measurement and the average sea surface height for that region. Producers of these data use various averages; some averages include all available data and some averages are specific to seasons. To recover the total sea surface height associated with the ocean circulation, a "synthetic" observation is constructed by adding the mean dynamic height determined from shipboard hydrographic measurements taken over the years to the anomaly. Maps derived by adding the sea surface height anomaly to an estimated mean surface from hydrography realistically depict the total sea surface height associated with regions of persistent current such as the Gulf Stream in the North Atlantic and the Loop Current in the Gulf of Mexico.

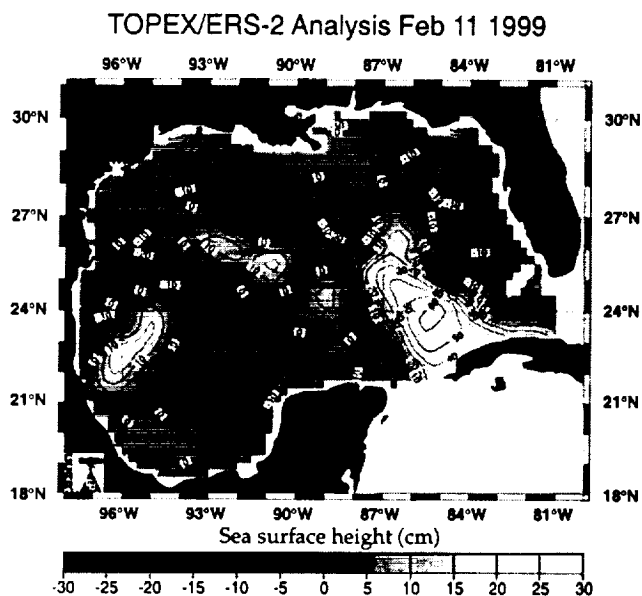


Fig. 1. Synthetic total sea surface height field for the Gulf of Mexico on February 11, 1999. This field was constructed by adding the mean sea surface height field from realistic numerical simulation of the Gulf to the interpolated altimeter measurements of TOPEX/Poseidon and ERS-2 with respect to a long-

term altimetric mean field. The streamlines (isolines of height) of the flow associated with the Loop Current enters the Gulf between Yucatan and Cuba, then loops and exits south of Florida through the Florida Straits. Circular streamlines depict the locations of energetic anticyclonic (sea surface highs shaded light gray) and cyclonic (sea surface lows shaded dark gray) eddies that commonly occur in the Gulf. The contour increment is 5 cm and every 10 cm are annotated. This type of product is available on a daily basis from the University of Colorado.

B. Geostrophic Velocity Vectors

Geostrophic velocity vectors are also a widely used product and the vectors are most often provided superimposed on maps of sea surface height or sea surface height anomalies. The geostrophic current is a major component of oceanic surface currents. Ocean currents are a function of wind forcing, tidal forces, buoyancy, and the Earth's rotation and gravity. The earth's gravity acts to move water from areas of higher water levels (pressure) to lower water levels (pressure). When this component of the current caused by pressure is balanced with the component caused by the earth's rotations (Coriolis effect), the current is said to be geostrophic. In the deep ocean a large percentage of the ocean surface current is often in geostrophic balance and can be computed by knowing the changes in sea surface height and the latitude of the point of interest.

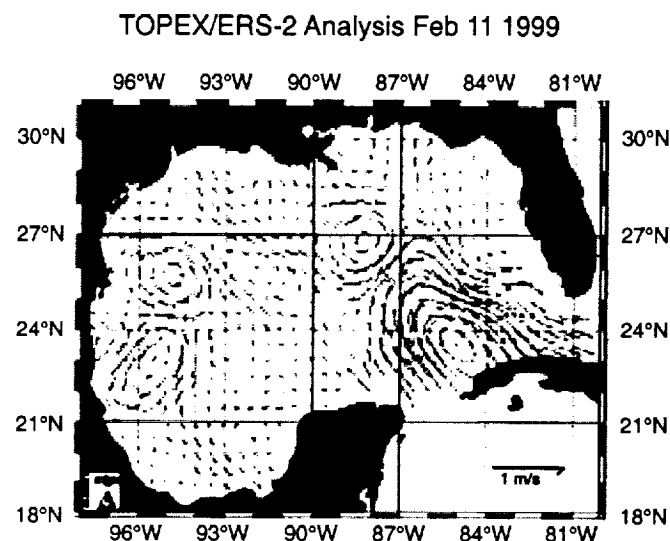


Fig. 2. Estimated geostrophic flow field associated with the total sea surface height field depicted in Fig. 1. The flow field is visualized using streamlines determined from a 2-day integration of simulated particles released at grid points of the geostrophic velocity field. The magnitude of the geostrophic velocity is proportional to the sea surface slope and is directed along isolines of constant height with higher surface height values to the right (left) when facing in the direction of flow for the northern (southern) hemisphere. Note the strong clockwise and

counterclockwise circulation associated with the anticyclonic and cyclonic eddies in the Gulf, respectively. This type of product is available on a daily basis from the University of Colorado.

C. Wind Speed

Wind speed as measured from an altimeter is an indirect measurement based on the small-scale roughness of the sea surface. Wind speed is measured from the strength of the returned signal. There is a reliable relationship between the energy scattered from near-nadir and the wind speed. The altimeter does not give wind direction. Satellite scatterometer wind observations can be used to determine both wind direction and magnitude and are of more use to the operational maritime community, however, wind speed from altimetry is useful for comparisons to these products. Altimetrically derived wind speeds are also valuable for generating wind climatologies because of the long time series available.

D. Significant Wave Height

Significant wave height is calculated from altimeter data based on the slope of the leading edge of the altimeter waveform, which is similar to a binned (time) histogram of the power returned by the radar pulse after it bounces off the sea surface. A calm sea with low waves returns a short, sharply defined pulse whereas a rough sea with high waves returns a stretched pulse because the energy begins to come back from the tops of the waves and continues until the pulse hits the valley of the wave. The significant wave height is the average height of the highest one-third of all waves in a particular time period. Wave direction is not provided by altimeter data. Maps of significant wave heights and wave height climatologies are useful for ship routing.

E. Combined Data Products

Combined data products are a final category of information products. Products generated by the University of Colorado and Stennis Space Center combine information from both TOPEX/Poseidon and ERS-2 altimeters to better map the mesoscale circulation associated with eddies and meandering currents. Private organizations have gone one step further in providing charts created by combining high resolution information from complementary data sets such as sea surface temperatures and geostrophic velocities. Examples of these companies are Scientific Fisheries Incorporated, Jenifer Clark's Gulfstream, and Roffer's Ocean Fishing Forecasting Service, Inc.

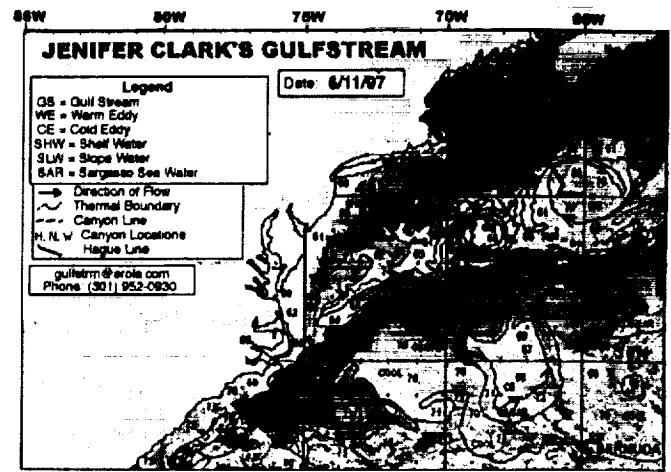


Fig. 3 Example of a chart provided to mariners by private industry.

III. APPLICATIONS OF SPACEBORNE ALTIMETRY DATA

A. Ship Routing

Maps of sea surface anomalies overlaid with velocity vectors have been used in commercial shipping and competitive sailing to optimize the route from one destination to another. The maps are used to locate ocean features such as currents and eddies which are associated with high currents. In cases where the rhumb line, the shortest distance between two points goes through strong currents a variety of tactics can be used. In the case where the rhumb line crosses orthogonal to a current, sailors are likely to cross at a point and at an angle such that the duration of the crossing is minimized.

Where the rhumb line crosses eddies, mariners use knowledge of the location of the eddies and velocity vectors to optimize their route. For instance, the current speed in warm eddies, rotating clockwise north of the Gulf Stream, averages 1-2 knots. Cold eddies circulate water in a counterclockwise direction, south of the Gulf Stream, and average 2-3 knots, and speeds of up to 7 knots have been encountered. A sail boat must be on the correct side of an eddy to take advantage of its current flow direction. Also important is for ships to avoid situations in which the current flow direction is opposite to the wind direction. In this case, dangerously high waves can form in locations such as the Gulf Stream north wall.

Commercial companies provide charts to mariners that incorporate spaceborne altimeter data in support of races including the Bermuda Race which is one of the world's premiere sailing events. Hundreds of sailors gather to race the 635 mile course, starting from either Rhode Island or Massachusetts, and crossing the Gulf Stream to Bermuda.

B. Ocean acoustics

Navy operations are critically dependent upon the ocean environment. Ocean acoustics determine the ability of ships to detect objects within the water, and the detection of objects such as submarines is vital to the safety of the fleet. Ocean acoustics in turn are determined by temperature and salinity properties within the ocean. Within the deep ocean, the dynamics affecting temperature and salinity may be measured through altimetry. Positive sea height anomalies (bulges) are usually associated with warm water and a depressed thermocline. Alternatively, sea level depressions are associated with cold water at a raised thermocline.

One of the main sources of variability within the ocean is the mesoscale field, which is composed of eddies and current meanders. The mesoscale field is non-deterministic since the eddies and meanders are the product of instabilities and turbulence. Thus, it is not possible to predict the mesoscale field far in advance. Altimeter measurements provide one means for observing the mesoscale field and providing the ocean acoustic environment.

One example of the effect of the mesoscale circulation on the ocean acoustic environment is given the Japan/East Sea just off the southeast coast of South Korea (Fig. 4). The acoustic signal excess provides an estimate of the acoustic signal of an object relative to the background noise level. If the acoustic signal excess is greater than zero then the reflected acoustic signal of an object is greater than the background noise, and the object is detected. Initially using a climatological density field based on the Generalized Digital Environmental Model (GDEM), the acoustic signal excess indicates a wide field of view. During this time, an intense AXBT survey provides the true synoptic environment. The true acoustic signal excess is significantly different from the field using the climatological environment and reveals a blind spot to the northeast of the acoustic receiver. The purpose of altimeter data is to provide a replacement for the large intensive AXBT survey.

The Navy Modular Ocean Data Assimilation System (MODAS) uses historical in situ data to derive statistical relations between surface observations (dynamic height and temperature) and subsurface quantities (temperature and salinity). Based on the derived surface to subsurface relations, given a measure of the surface height and surface temperature it is possible to reconstruct the subsurface temperature and salinity, (Fig. 5). The statistical correlations vary spatially and seasonally as the vertical relations depend on the local environment and dominant oceanographic processes.

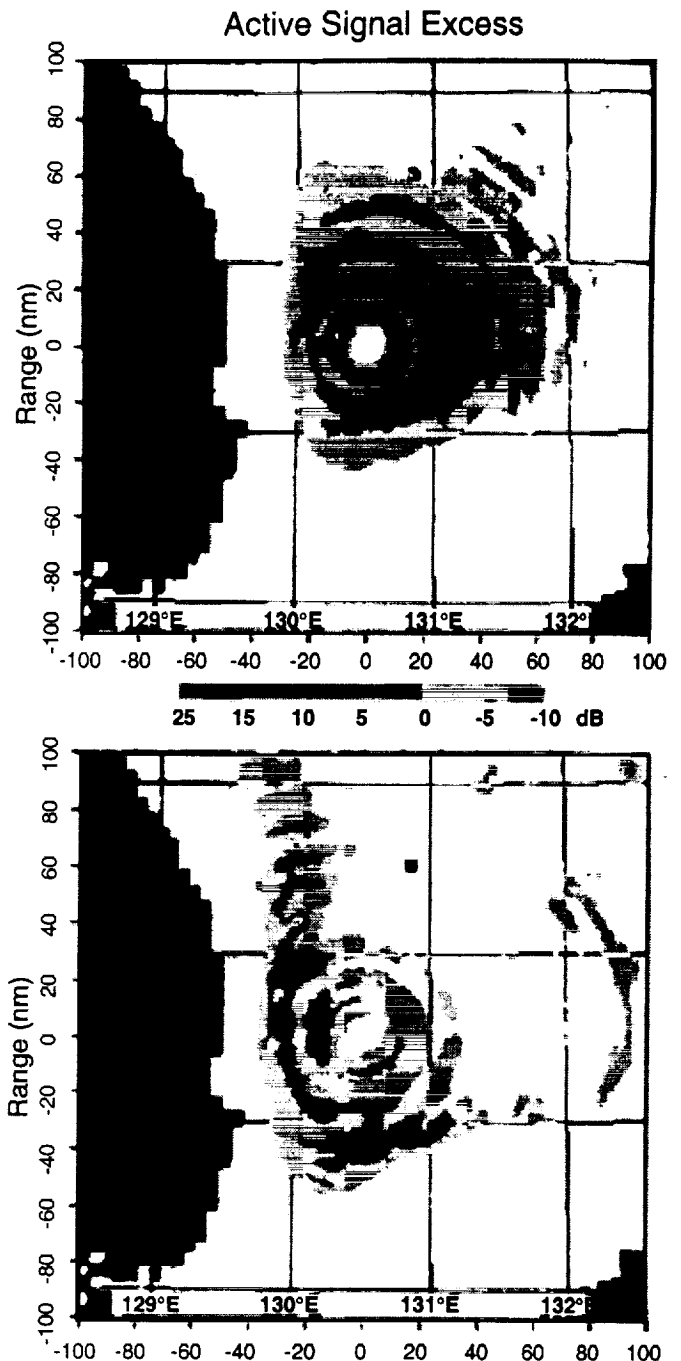


Fig. 4. The acoustic active signal excess calculated from climatological density field (top) and an in situ AXBT survey (bottom). The area is the Japan/East Sea off the east coast of Korea. Areas where the signal excess are greater than 0 indicate where underwater objects could be detected. The ocean density dramatically affects the sound propagation through the water, and the ocean mesoscale field impacts the density structure. The difference between the climatological result and the result with in-situ sampling is due to ocean eddies. The altimeter provides the ability to monitor the ocean eddies and reconstruct the ocean acoustic field.

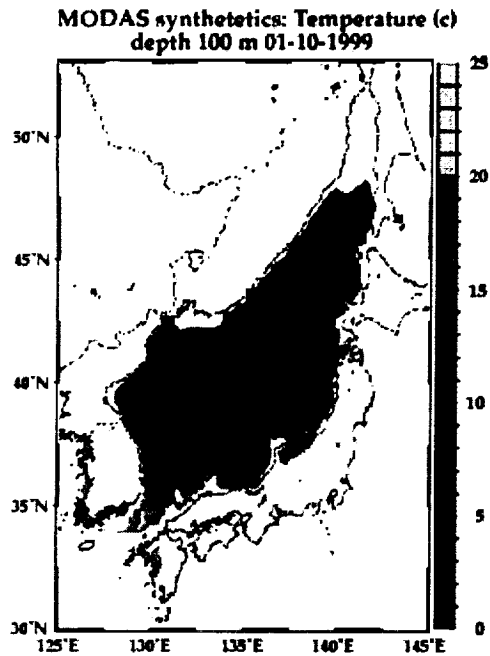


Fig. 5. The temperature at 100 m is derived from the sea surface height measured by altimeter satellites and the sea surface temperature. Warm core eddies occur at 130E and 134E with a cold core eddy between the two. The water temperature affects the density and the propagation of sound through the water. This is an example of a MODAS product available from the Naval Research Laboratory at Stennis.

C. Ocean Monitoring for Offshore Industries

Accurate estimates of the current and future state of the ocean are very useful to industries involved in offshore activities. Offshore operators that have used altimeter-derived monitoring tools include companies working on ocean cable and hydrocarbon exploration and production activities.

Telecommunications is an important area of growth in the global economy. With the explosion of world-wide communications, especially the Internet, the need for underwater communication cables has increased dramatically. Cable laying and repair requires accurate knowledge of the ocean circulation to minimize the impact of strong currents on the activities of the cable ship as it tends the cable and on underwater remotely operated vehicles working on the cable. The all-weather capability of altimeter data have been used to identify regions of strong currents along the edges of oceanic eddies near cable laying and repair operations, a monitoring capability that is especially important when thermal imagery is not available because of cloud cover.

The offshore hydrocarbon industry has also made extensive use of near real-time altimeter products and an operational nowcast/forecast system relying

on altimeter data assimilation (Kantha et al., 1999). In the Gulf of Mexico, from which nearly half of the US domestic oil is extracted, the strong currents (2 to 4 knots, 1-2 m/s) associated with the Loop Current and large Loop Current eddies impact hydrocarbon exploration and production activities along the Louisiana and Texas slope. An important aspect of the ocean monitoring and forecast system is the assimilation of near real-time altimeter data into a numerical ocean model of the Gulf of Mexico. For more than a year, near real-time nowcasts and forecasts have been made by the University of Colorado for potential use by the offshore oil and gas industry.

D. Debris Tracking:

Marine debris, floating and partially submerged material consisting of nets, timber, ship debris is increasing with human population and increasing contact with the sea. This material collects in locations based on wind and currents. Marine debris is capable of physically destroying coral, entangling marine mammals and can also be hazardous to small vessels. Russell E. Brainard, David G. Foley and R. Michael Laurs, of the NOAA/NESDIS CoastWatch program, Hawaii Regional Node and the National Marine Fisheries Service, Honolulu Laboratory are investigating the potential of TOPEX/Poseidon and other remotely sensed data in identifying likely locations of marine debris. Complimentary remotely sensed data sets are integrated to produce a tool that can be used to study the SubTropical Convergence Zone (STCZ). The STCZ area is one of the primary areas of responsibility for NMFS Honolulu Laboratory, and soon to be subject to much wider scrutiny due to it's role in the transport and subsequent anchoring of marine debris to the coral reefs of the Hawaiian Archipelago. By its nature a convergent zone has endemic cloud cover, complicating the use of sensors that require visible and infrared radiation signals from the ocean surface. Thus a group are working to develop new products using data from microwave and radio frequency sensors which can "see" through the clouds. Spaceborne altimeter data is one of these tools. These theories will soon be put to test in early 2000, when the Hawaii CoastWatch satellite imaging team will use the remotely sensed data sets to guide a Coast Guard vessel in the search for debris in the open ocean.

E. Fishing Industry:

Marine life is very often concentrated along oceanic frontal regions, which can be detected from altimeter-derived data. Operational tests of the utility of products that incorporate altimeter data are in progress. In cooperation with NASA, satellite altimetry is being provided to SciFish to incorporate into their Geographical Information System (GIS), FishTrek98. The product runs on a laptop PC integrated with a Global Positioning System (GPS)

receiver for real-time analysis and positioning. FishTrek98 is designed to provide ship captains with a variety of essential information such as bathymetry, snags, water temperature, historic catch figures, and by catch. In addition, vessel captains can log their catch, tide, current, marks, snags, temperature, sea conditions, weather, and lunar conditions in a personalized electronic log book that is fully integrated with all other available data sources. This product is currently in use by commercial fishermen, and has received several favorable reviews. In January 1999, SciFish formed a focus group composed of fishermen from the various Bering Sea fisheries to evaluate FishTrek98 with satellite altimeter, sea surface temperature, and sea ice real-time data. Feedback from FishTrek98 users during the 1999 fishing season will be used to access the utility of the data and improve the data products for future operational use.

F. Fisheries Management

Fisheries management personnel also use TOPEX/Poseidon data as one of a suite of tools to understand the close relationship between the marine environment and fishery dynamics. This type of knowledge is essential to the management of sustainable fisheries. Other specific applications currently in development at the NMFS Honolulu Laboratory include satellite-derived tools to address the mitigation of fisheries interaction with sea turtles, the recovery of endangered Monk Seals and monitoring and assessment of Coral reef ecosystems and essential fish habitats. Additionally, a recent study funded by NOAA/NESDIS has focused on the impact of geostrophic currents on the recruitment of spiny lobster larva. Spiny lobster larvae spend much of their time in the region of the thermocline where the current is largely geostrophically driven. Hence geostrophic velocity vectors derived from TOPEX/Poseidon sea surface height data provide a reasonable indication of the direction and speed that the larvae will travel in their planktonic state. The study, conducted for the Hawaiian Archipelago, shows that altimeter-derived geostrophic currents may be of use in predicting natural repopulation success. Repopulation is a topic of growing interest as over fishing occurs and efforts are made to replenish stock. This study by Jeffrey J. Polovina, Pierre Kleiber, and Don Kobayashi of the National Marine Fisheries Service Southwest Fisheries Science Center - Honolulu Laboratory (see Polovina et al., 1999, Fisheries Bulletin. 97:132-143).

G. Hurricane Forecasting

Altimeter data is one of the tools, along with other remote sensing and in-situ data, used to both predict the severity of a hurricane season and to forecast intensity changes of a given storm. The value of altimeter data is that heat content, which plays a role in the development and maintaining the formation of

hurricanes, can be estimated from sea surface topography. Research in both these areas is very active in an effort to improve the predictions.

Currently, the National Hurricane Center provides seasonal forecasts, consisting of the number of name tropical storms per season. This is done using a variety of information, including the El Niño-Southern Oscillation (ENSO) status in the Pacific Ocean which is provided by the National Centers for Environmental Prediction (NCEP) from data sources including the TOPEX/Poseidon altimeter and other remote sensing instruments. Once a hurricane is in progress, its development is in part affected by the amount of heat in the upper ocean. An example of this was documented on October 4th, 1995, when Hurricane Opal deepened from 965 hPa to 916 hPa in the Gulf of Mexico over a 14 hour period after it encountered a warm core ring shed by the Loop Current. As Hurricane Opal passed over one of the two warm rings existing at the moment in the Gulf of Mexico, the surface winds increased from 35 ms⁻¹ to more than 60 ms⁻¹, and the radius of maximum wind decreased from 40 km to 25 km (Shay et al, in press). Maps of upper ocean heat content are currently being produced in near-real time at NOAA/AOML (<http://www.aoml.noaa.gov/phod/cyclone/data/>). Further information on the relationship between sea height anomaly, upper layer thickness, sea surface temperature and hurricane heat potential in the western North Atlantic can be found on the web site listed above.

At the University of Colorado, the explosive growth of Hurricane Opal has been accurately simulated by a coupled atmosphere/ocean model by assimilating altimeter data to define the conditions in the ocean under the hurricane's path (Bao et al., in press). The success of such efforts highlight the future operational uses of near real-time altimeter data for the accurate prediction of hurricane development

As part of the United States Weather Research Program Hurricanes at Landfall, a joint NSF/NOAA experiment is being conducted over a warm core ring in the Gulf of Mexico in the summer of '99. The experiment will deploy Airborne eXpendable Current Profilers (AXCPs) and Airborne Xpendable Conductivity Temperature and Depth Profilers (AXCTDs). These profilers will provide 3-dimensional velocity and density data (temperature and salinity) to compare to the fields derived from TOPEX altimeter. This research is supported by the National Science Foundation and NOAA in support of the United States Weather Research Program on Hurricanes at Landfall. For more information see <http://storm.rsmas.miami.edu/~nick> and select wcr.html. Thus, by combining the early work of Leipper and Volgenau (1972) on hurricane heat content with the two-layer model developed by Goni et al. (1997) in combination with historical and in situ measurements (from aircraft), we will learn more

about the role of the upper ocean on hurricane intensity change. Michelle Huber, a NOAA Forecaster Specialist at the National Hurricane Center is working on transitioning the basic research to operational forecasting of hurricane intensity changes. During this summer, we will build a data base using both atmospheric and oceanic data in these systems.

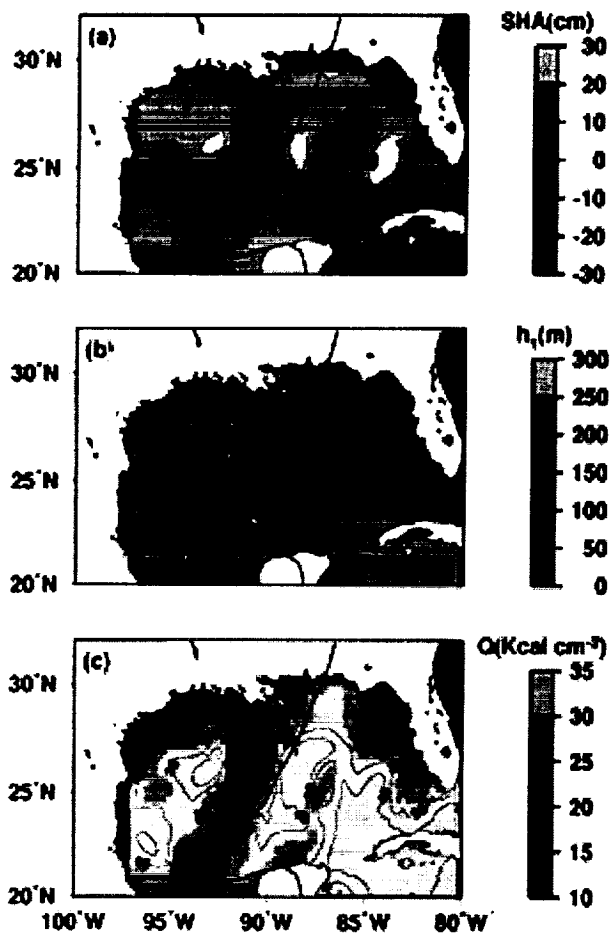


Fig. 6. Conditions in the Gulf of Mexico during the period September 18-28, 1995; before the passage of hurricane Opal.

a) TOPEX/Poseidon-derived sea surface height anomaly field.
 b) Depth of the 20C isotherm (upper layer thickness) derived using the T/P sea height anomaly field and a two-layer model.
 c) TOPEX/Poseidon-derived upper ocean integrated vertical temperature (heat content) between the surface and the depth of the 26C isotherm. The two warm rings in the Gulf of Mexico (WCR A and WCR B) are characterized by their high sea height anomalies, large upper layer thickness and heat content values. The track of Hurricane Opal is superimposed on each of the three panels. During October 4, 1995, hurricane Opal passed directly over WCR A, and increased its winds from 35 ms⁻¹ to 60 ms⁻¹.

H. Cetacean Habitat Monitoring

Altimeter data were used to locate eddies as part of the 1996-1997 GulfCet program. GulfCet was a field program run by Texas A&M oceanographers based in College Station, marine mammal biologists based in Galveston, with support from satellite oceanographers at the University of Colorado. The goal of the program was to survey the abundance for the Gulf of Mexico's 18 common cetaceans in continental margin areas of present oil and gas development. The survey also extended further offshore where oil and gas exploration will likely intensify in the near future. There is special interest in sperm whales because they are an endangered species.

Altimetric monitoring of the general circulation in the Gulf of Mexico served two purposes in GulfCet studies. Near-real-time altimeter data were used to map eddies, information which was used to plan research cruises to optimize the census process. Following the cruise historical altimeter data were used to map the fronts and eddies that occurred during the cruises. These historical data helped marine mammal biologists interpret when and where cetaceans were found during the cruises.

Scientists have learned that sperm whales are more abundant in cyclones and other habitats where nutrients and plankton are abundant near the surface. Where there were higher than average stocks of phytoplankton and squid, sperm whales gathered to feed. Locations of these cyclones can be tracked using altimeter data. Surveying these areas from ships enables scientists to gather information on numbers and behavior of cetaceans, (Ortega-Ortiz et al., 1999).

I. Forecasting of El Niño Related Climate Variations

El Niño-related climate variations often have widespread and devastating impacts. These include the frequency and severity of storms and the occurrence of droughts and floods. In the U.S. alone, business losses associated with 1986-87 El Niño amounted to \$10-15 billion. Although many of the consequences of El Niño cannot be prevented, skillful forecasts enable resource managers in climate-sensitive sectors to alter strategies and reduce economic vulnerability.' (Cheney et al., 1998). NOAA (National Oceanic and Atmospheric Administration) National Centers for Environmental Prediction (NCEP) has the mandate to provide forecasts to the nation to reduce loss of human life and minimize economic impacts.

Coupled ocean-atmosphere models have attained significant forecast skill during the past decade, but they continue to be limited by an ocean observing system which is extraordinarily modest. Satellites represent part of the solution. In particular, an

IV. DATA SOURCES:

operational flow of altimeter data has long been desired by the modeling community as a means of estimating changes in upper ocean heat (to first order, sea level is determined by the integrated temperature of the water column). But even though altimeters have flown nearly continuously since 1985, two challenges have stood in the way of progress: (1) The altimeter data must be made available fast enough (1-2 days) and with sufficient accuracy (a few cm) to track changes in the ocean within a tolerance that is useful for the ocean model; (2) The assimilation method must be capable of using a single parameter, sea level, to correct the model temperature as a function of depth.

Using TOPEX/Poseidon altimeter data, both of these problems have been solved through a collaboration among NOAA, the Naval Oceanographic Office (NAVOCEANO), and the Jet Propulsion Laboratory (JPL). The program became operational in March 1997, just in time to assist in the long-range forecasts associated with the 1997-1998 El Niño. The study by Cheney et al., showed that predictions of Pacific sea surface temperatures, a measure closely linked with El Niño/La Niña, that were made with Topex ocean initial conditions have higher skill than those made with XBT (eXpendable BathyThermographs) and the Tropical Atmosphere Ocean (TAO) data alone. Consequently, TOPEX data analyzed within 2 days of real time have been added to the operational assimilation scheme implemented at NOAA NCEP.

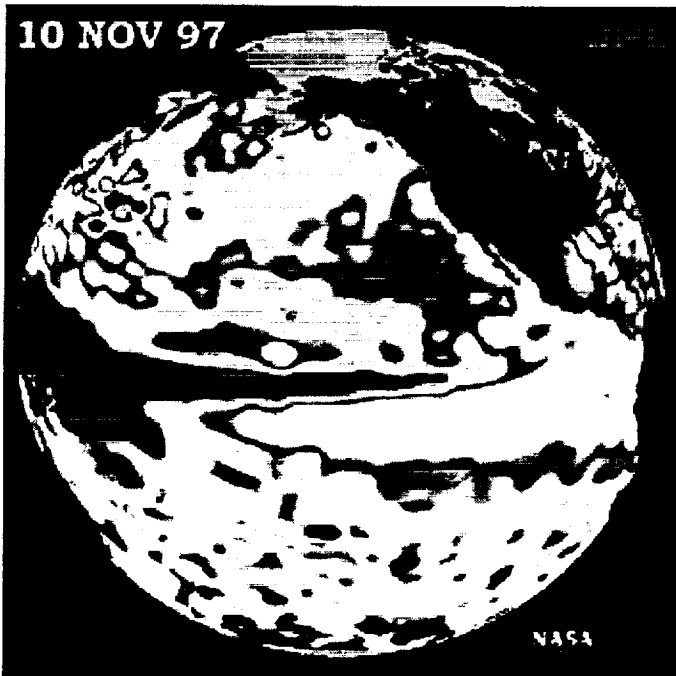


Fig. 7: The manifestation of the El Niño in sea surface height data is clearly visible in this image that was obtained at the peak of the '97 - '98 El Niño.

A. Near Real Time

Near real-time products from altimeter data are made available by several organizations. The products vary in format, parameter, time interval averaged and in time elapsed from data collection. Products for marine operators are available from the Colorado Center for Astrodynamic Research, University of Colorado, (<http://www-ccar.colorado.edu/~leben/research.html>), the Naval Research Laboratory, Stennis Space Flight Center (<http://www7300.nrlssc.navy.mil/altimetry/>), and the Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Active Archive Center, (PO.DAAC) (<http://podaac.jpl.nasa.gov/topex>). The National Oceanic and Atmospheric Administration (NOAA) Laboratory for Satellite Altimetry also produces an operational near-real time sea level product (http://ibis.grdl.noaa.gov/SAT/near_rt/topex_2day.html), that is assimilated into the operational NOAA ENSO forecast models. In Europe, Developing Use of Altimetry for Climate Studies (DUACS) also provides near-real time products (<http://www.cls.fr/duacs>).

The MODAS system, at Stennis Space Flight Center presently uses real time altimeter data from TOPEX/POSEIDON and ERS-2 to produce global sea surface dynamic height on a 1/8 degree grid. Sea surface temperature is also generated on a 1/8 degree grid based on real-time AVHRR data. The gridding of both the surface height and temperature is carried out in a manner to retain the local mesoscale variability and not to only produce the large-scale global dynamic height. The operations are performed globally to allow access to every region across the world. Using the gridded surface height and temperature, MODAS uses the statistical relations of surface to subsurface properties to generate the subsurface temperature and salinity.

The Quick Look Intermediate Geophysical Data Records (IGDRs) available from PO.DAAC is an 8 hour product automatically generated about an hour after downlink from the NASA Altimeter using the operational science software and a medium precision Global Positioning System (GPS) orbit. The products contain only the best quality data and data are provided in a simple ASCII format for ease of use. Parameters include sea surface height, sigma-0 and significant wave height. Derived parameters include wind speed, water vapor content and total electron content. Data are not available during Poseidon cycles.

As mentioned in section II there are also a number of private agencies producing ocean maps from data taken from a variety of sources. Many of these agencies also provide customized analysis for specific regions and support specific events.

B. Climatologies

Climatologies consist of averaged data usually over as many years as are available. Climatologies are valuable to the operations community for planning, where a knowledge of what conditions to expect is valuable. Many sites that provide near-real time data also provide archives and climatologies of these data. In addition, climatologies and historical altimeter data are available, at a higher precision than the near-real time data products, from the JPL PO.DAAC (http://podaac.jpl.nasa.gov/TOPEX_P.html) and from AVISO in France (<http://www-aviso.cls.cnes.fr/>)

V. FUTURE DATA PRODUCTS AND DATA STREAMS

To be truly operational, the stream of data must be assured. This is being accomplished with the planned launch of Jason-1 in May 2000, a follow-on mission to TOPEX/Poseidon. In addition the ERS (European Remote Sensing) satellites also provide altimeter data. Altimeter data from these satellites are envisioned to contribute to the existing types of information products over the next decade. In addition it is anticipated that with growing familiarity of the benefits of altimeter data, that they will be used as a complement to other remotely sensed and in-situ data. It is anticipated that much of the generation of information products from remotely sensed data will occur in the private sector.

REFERENCES

Bao, J.-W., J.M. Wilczak, J.-K Choi, and L. H. Kantha, "Numerical Simulations of air-sea interactions under

high wind conditions using a coupled model: A study of hurricane development", *Monthly Weather Review*, 1999 (in press).

Cheney, R.E., L. Miller, C.K. Tai, J. Lillibridge, J. Kuhn, M. Ji, and D. Behringer, "Operational Altimeter data processing and assimilation for El Niño Forecasts", *AVISO Altimetry Newsletter*, No. 6., April 1998, p 36,37.

Goni, G.J, S.L.Garzoli, A.J.Roubicek, D.B.Olson and O.B.Brown "Agulhas Ring Dynamics from TOPEX/POSEIDON Satellite Altimeter Data", *J.Mar.Res.*, 55, 861-883, 1997.

Kantha, L.K., J.-K. Choi, R. R. Leben, C. Cooper, M. Vogel and J. Feeney, "Hindcasts and Real-time Nowcast/Forecasts of Currents in the Gulf of Mexico", *Proceedings of the Offshore Technology Conference*, Houston, TX, May 3-6, 1999.

Leipper, D., and D. Volgenau, "Hurricane heat potential of the Gulf of Mexico", *J. Phys. Oceanogr.*, 2, 218-224, 1972

Ortega-Ortiz, J. G., R. W. Davis, C. A. Ribic, D. C. Biggs, K. D. Mullin, R. R. Leben, W. E. Evans and B. Wursig, "Cetacean habitat associations in the northern Gulf of Mexico", abstract, to be presented at the *Society of Marine Mammalogy 13th Biennial Conference*, Maui, HW, Nov. 28 to Dec. 3, 1999.

Shay, L.K, G.J. Goni, and P.G. Black, " Effects of a Warm Oceanic Feature on Hurricane Opal", *Monthly Weather Review*, 1999 (in press).