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Satellite altimetry for meteorological and oceanographic applications

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सार – उपग्रह तुँगतामापी एक ऐसा सुदूर संवेदी सेंसर है जो स्थानिक और कालिक स्केलों पर वायुमंडल और महासागरों के समाकलित चित्र प्रदान कर रहा है। यद्यपि समुद्र सतह से तुँगतामापी की दूरी का पता लगाने का सिद्धांत सुगम है तथापि दोतरफा प्रगामी समय में काफी संशोधन किया जाना है। इस शोध पत्र में तुँगतामापी के मापों की त्रुटियों के विभिन्न स्रोतों और उसमें किए गए प्रयोगात्मक संशोधनों का विवेचन किया गया है। इसके अलावा मौसम विज्ञान और समुद्र विज्ञान के अध्ययन में तुँगतामापी के माप के संभावित अनुप्रयोगों का भी विवेचन किया गया है।

ABSTRACT. Satellite altimeter is a remote sensing sensor providing an integrated picture of the atmosphere and the oceans over large spatial and temporal scales. Though the principle of obtaining altimeter range from the sea surface is simple, quite a good number of corrections have to be applied to the two way travel time. The various sources of errors in the altimeter measurements and the corrections to be applied are described. The potential applications of altimeter measurements in meteorology and oceanography are also discussed.

Key words – Altimeter, Sea level, Ocean circulation, El-Nino, Cyclones, Remote sensing.

1. Introduction

The progress of any meteorological or oceanographic research/forecast heavily relies upon a number of *in situ* observations, particularly, over the data sparse oceanic regions. Satellite altimeter is a remote sensing sensor providing an integrated picture of the atmosphere and the oceans over large spatial and temporal extents. A satellite altimeter is a nadir pointing active microwave sensor designed to measure characteristics of the surface of the Earth. The return signals from oceanic regions provide information on significant wave height, surface wind speed and a range measurement from the satellite to the sea surface immediately below. A radar altimeter operates by timing the delay between emission of a short microwave pulse and the subsequent detection of the returned echo, recording the time and distortion of the returned signal.

The first requirement for any remote sensing instrument designed to observe the Earth's surface is that atmospheric attenuation of the electromagnetic signal be sufficiently small that detection of the return pulse is possible. Through most of the infra-red region, signal attenuation is large due to atmospheric water vapour and gases such as carbon dioxide and oxygen. In the microwave region between 100 MHz and 10000 MHz, however, signal attenuation is small; but certainly of considerable magnitude.

Emission of electromagnetic radiation by an aperture results in diffraction, the width of which is determined by the wavelength of the radiation and the size of the aperture. A uniformly and coherently illuminated circular aperture will produce a diffraction limited beam width defined by Fraunhoffer diffraction theory. At 13 GHz (wavelength ~2.3cm), Ku-band microwave signals emitted by a 1m antenna will have a beam width of 28 mrad or 1.6 degrees, which from an altitude of 800 km covers a disk of diameter 22 km. For higher frequencies or large antennas, this figure is correspondingly reduced (the latter being the basis for the resolution of Synthetic Aperture Radar techniques).

There is a second problem associated with the frequency of microwave radiation used: when a surface such as the ocean is illuminated by a coherent single frequency source, differences in optical path length cause constructive and destructive interference which can radically distort the signal received by the instrument. For a perfect single frequency transmitter, this produces an infinitely coherent source. In reality, all transmitters have a spectral width, and it is partly to avoid the problems of interference (known as fading) that radar signals are 'chirped', giving them a limited coherence length which is small enough to avoid fading for all but the flattest of reflectors. Bandwidth is defined as frequency spread of the emitted radiation. For ERS-1, the altimeter bandwidth is 330 MHz, resulting in a coherence length of around 90 cm.

A spot size of 20 km is too great for many applications of the data (for example high resolution geoid determination). There is therefore a need for a large antenna, a higher frequency or some other refinement to the emitted radiation. A large antenna on board the satellite is impractical while at higher frequencies, there is greater atmospheric attenuation of the returned signal; therefore the only alternative is the use of pulse limited altimetry. In this way, the leading edge of the return pulse provides sufficient information for an accurate estimate of the ocean height over a significantly smaller area. This is the second reason for chirping the emitted signal as this can simulate a short but sharply modulated pulse, the distortion of which is analysed on its return.

Besides these technical problems, the measurements from the altimeter have to be corrected for the instrumental, atmospheric and media errors which are discussed in the following sections.

2. Errors involved in altimeter measurements

The principle of obtaining the height of the altimeter above the sea surface is simple – it is computed as

$$D = Ct/2$$

where D is the distance between the satellite and the sea surface, C is velocity of light and t is the round-trip travel time taken by the microwave radar pulse to travel from the satellite to ocean surface and back. But obtaining the sea surface height (SSH) or the dynamic topography is complicated. In order to realize the full potential of satellite radar altimeter data, it is necessary to take into account a number of error sources and apply their associated corrections with an accuracy that is compatible with the proposed measurement precision. The two classes of altimeter errors playing significant roles in signal processing are:

(a) Errors that influence the measurement of the height of the ocean surface.

(b) Errors that influence the interpretation of the measurements.

The origin of these discrepancies and their corresponding rectifications can be separated into the following five categories:

(*i*) Instrument Errors

(*ii*) Propagation Medium Corrections

(*iii*) Geoid Modelling Errors

(*iv*) Effects of Temporal Variations in Ocean Surface (Tides, Barometric Pressure)

(*v*) Space Craft Orbit Determination Errors

2.1. *Instrument error*

The instrument errors consist of a random part and a systematic long wave part. The random component refers to the precision of the instrument. This precision for the first altimeter flown on Skylab in 1973 was 60 cm which could hardly deduce the sea surface slope across the Gulf stream. This was gradually improved and the present precision for the Topex/Poisodon and Jason-1 is 2-3 cm which is sufficient to detect even small amplitude eddies. The different instrument errors that have to be accounted for are:

2.1.1. *Tracker bias*

This correction arises from the calibration bias in the discrete samples of the return waveform used in the onboard tracking algorithm which is designed to accommodate linear changes in the height (constant velocity) of the altimeter. When there is a rapid acceleration in height, for example when the altimeter passes over a narrow ocean trench, there is a corresponding induced height error which must be compensated for.

2.1.2. *Waveform sampler gain calibration bias*

This correction occurs due to the fact that the amplitude of the received signal varies with the cross section of the monitored surface. An automatic gain controller is used for this signal attenuation adjustment, but rapid changes in echo strength mislead the circuit that tracks the position of the leading edge of the pulse, thereby producing a calibration error.

2.1.3. *Pointing errors*

Actually a combined effect of the satellite antenna gain pattern in relation to the antenna off-nadir pointing error on the shape of the return waveform correction occurs when the sub-satellite point is near the edge of the area illuminated by the altimeter. The resulting radar echo distortion produces an unwanted error bias.

2.1.4. *Average pulse shape uncertainty and time tag bias*

The error in return pulse shape stems from the uncertainty due to random variability of the pulses used to calculate the mean echo. The residuals associated with averaging, say, 1,000 pulses, therefore contribute noise to the measurement. Also, the aging of microwave parts and long term clock drifts can induce height errors. Clock drifts can be accounted for by comparing the altimeter clock with some reference. Drifts in the height measurement induced by aging can be partially compensated for with the altimeter's internal calibration mode.

2.2. *Propagation medium corrections*

Two types of errors are included in this category: (a) Total sea state bias of the onboard tracker estimate of mean sea level and (b) Resultant decrease in the local speed of light due to index of refraction changes as the altimeter's signal travels through earth's atmosphere.

2.2.1. *Sea state bias*

Two effects contribute to the discrepancy between the electromagnetic (EM) sea level estimated by the onboard tracking algorithm from averaged return waveforms and that of true mean sea level:

(a) *Electromagnetic bias*

This correction arises because of the height difference between mean sea level and the mean scattering surface. The way this occurs is through the differential backscattering of power per unit surface area between wave troughs and that of wave crests. This deviation results from the fact that the power backscattered from a small wave facet is proportional to the local radius of curvature of the long-wavelength portion of the wave spectrum. In general, ocean troughs have a large radius of curvature than wave crests; thereby creating a bias in backscattered power towards wave troughs. A greater prominence of small scale "wavelets" super-imposed on wave crests creates an increased roughness which further scatters the altimeter pulse in directions away from the incident radiation; effectively enhancing the bias. The backscattered power measured by the altimeter is therefore greater from wave troughs than from wave crests, thus inducing an EM sea level bias towards wave troughs. A direct correlation between significant wave height (SWH) growth and EM bias increase allows researchers to estimate the required correction.

(b) *Skewness bias*

This error occurs because of the height difference between the mean height of specular scatterers and the median scattering surface that is actually measured by the onboard tracker. This is a direct result of the non-gaussian distribution of the sea surface height which shifts the median from the mean sea level toward wave troughs; which in turn also contributes to the EM bias towards wave troughs.

2.2.2. *The atmospheric effects*

The atmospheric errors are introduced into the altimeter measurements because the speed of electromagnetic propagation in the real atmosphere differs from that in vacuum basing on which the altimeter range is estimated. The two major sources of errors are from ionosphere and the troposphere.

(a) *Ionospheric correction*

This correction takes into account the variation in the number of free electrons present in the sub-satellite ionosphere location. Typically, the electron content varies from day to night (very few free electrons at night), from summer to winter (fewer during the summer), and as a function of the solar cycle (fewer during the solar minimum). The signal delay encountered is inversely proportional to the altimeter monitoring frequency squared. Topex/Poisodon is the first satellite which carried a dual frequency altimeter to obtain an accurate estimate of the ionospheric effect basing on this property.

(b) *Tropospheric correction*

This correction is related to water vapor content and other gases present in the path of the signal. There is both a wet & dry tropospheric delay which must be accounted for. The dry correction can be modeled *via* surface pressure measurements. The wet portion is typically adjusted from measurements made by an onboard radiometer. It is significant to note that the dry term includes the weight of the water molecules while the wet term accounts for their additional influence on the index of refraction.

2.3. *Geoid modeling errors*

To obtain ocean dynamics information from sea surface height measurements a detailed knowledge of the geoid is required. This necessity arises from having to refer the acquired surface height and slope data to the ellipsoid/geoid reference frame (due to the non availability of exact geoid information) in order to yield sea surface topography. The deviations of the geoid from the reference ellipsoid range from -100 m (South of India) to +64 m (near New Guinea). The spatial variability can be large. For example, the geoid can vary by several meters over a few kilometers in areas where there are ocean trenches or ridges. This is in contrast to the variability of sea surface topography which is typically +/- 1.5 m. In order to determine the ocean surface topography accurately it is necessary to know the geoid shape to an accuracy that is required by a feature over length scales of the order of the ocean phenomenon being monitored. There are essentially three ways to measure the earth's geoid: (*i*) Satellite orbit tracking, (*ii*) Direct measurements of gravity and (*iii*) Satellite altimetry. Gravity fields deduced from satellite orbit tracking data include spherical harmonic expansion terms of rather low degree and order (typically less than 50). Discrepancies in the spherical harmonic coefficients and truncation of the spherical harmonic expansion produce errors in these models, the majority of which are due to inadequate global observation information at the short spatial scales referred previously.

2.4. *Effects of temporal variations in the ocean surface*

These include solid earth and ocean tides and the inverse barometric effects. The gravitational perturbations induced by the moon and sun are the primary factors controlling influence of earth's solid & ocean tides. Although third body effects from the other planets contribute, their magnitudes are negligible in comparison. Since the relative interaction/orientation of the earth-moon-sun system is known very accurately, its effect on the tide-generating potential at any point on earth can be determined rather precisely. This potential can be closely approximated by only the six constituents with the largest amplitude, all of which are diurnal (one cycle per day) or semi-diurnal (two cycles per day). The problem arises from the presence of continental boundaries and complex ocean floor topography and the effects of earth's rotation which introduce large errors in equilibrium predictions of these semi-diurnal and diurnal tides (not to mention the parameterization of friction in these models). Sophisticated models must take into account the time-varying motion of the solid earth, the time invariant latitudinally dependent portion of the deformation, and that portion due to ocean loading forces on the solid earth. However, since the tidal estimations are not very accurate closer to the coast, the altimeter SSH values are not generally considered wherever the ocean depth is less than about 100 m.

The inverse barometer correction is based on a direct proportionality of about 1 cm change in the sea surface height to a change of 1 hPa in the sea surface atmospheric pressure. That is, the ocean surface is depressed in response to the increased atmospheric pressure. Problems can arise in this relationship near storms or near shore where other effects such as wind setup are correlated with pressure. For example, the decrease in SSH due to the anticlockwise rotation of water under the influence of cyclonic winds dominates over the rise due to the pressure drop. Also, while the assumptions hold for weekly and longer periods, there is doubt as to short period ocean response to pressure changes having the same type of characterization.

2.5. *Spacecraft orbit determination errors*

The forces, in order of their significance, that contribute to perturbations in the satellite orbit error are parameterized as: (a) Gravity, (b) Radiation pressure, (c) Atmospheric pressure, (d) Geoid modelling, (e) Solid earth & ocean tides, (f) Troposphere and (g) Station location.

2.5.1. *Gravity*

The fact that the earth is not perfectly spherical in nature but rather shaped as an oblate spheroid creates an asymmetric potential in earth's gravitational field. The cyclical characterization of this perturbation requires rather a high level of degree and order in the spherical harmonic expansion representation in order to predict precise effects on the satellite orbit.

2.5.2. *Radiation pressure/Spacecraft radiation*

Solar radiation, albedo and infrared emissions are the three external radiative fluxes acting on a spacecraft. The two separate types of flux influencing a spacecraft's temperature are internal and external. Internally the equipment dissipates heat. Externally, the solar radiation, albedo, and infrared fluxes cause surface heating. These types of forces vary with spacecraft shape, orientation and reflectivity during the different phase events of orbit such as, (*i*) occultation effects, (*ii*) oblique illumination, and (*iii*) the spacecraft's thermal inertia changes.

2.5.3. *Atmospheric drag*

The effect of earth's atmosphere at orbit altitude creates a resistance. This is calculated using empirical relationships for air density, together with the known shape and orientation of the satellite which may be different from reality.

2.5.4. *Geoid model*

As indicated previously, current geoid models have relatively low orders of degree and order upon which their spherical harmonic expansions are based. These discrepancies combine to perturb the satellite's estimated orbit away from the true orbit.

2.5.5. *Solid earth & ocean tides*

As noted above, both oceanic and solid earth tides perturb the gravitational potential. Their influence on satellite orbits is calculated from a spherical harmonic expansion involving terms to a relatively low degree and order calculated from hydrodynamic models. It is meaningful to note that the largest amplitude M2 tide constituent is not the dominant contributor to satellite orbit anomalies. However, this same factor plays a significant role in tide frequency *vs*. altimeter signal aliasing and thus requires highly accurate tracking data in order to best define an adequate representation. Thus, the two most important tide modeling strategies are, (*i*) to improve the long wavelength tide terms which are in resonance with near-earth satellites and have distinctly large long period orbital effects and (*ii*) to produce as many as feasibly practical tidal coefficients which encompass many tide lines for inclusion in models thereby creating a whole category of short period perturbations.

2.5.6. *Troposphere*

As discussed in propagation medium corrections above, the signal delay caused by water vapour content and other gases present in the troposphere must be accounted for in satellite tracking theory and perturbation analysis. Typically, satellite laser ranging (SLR) techniques are involved which use frequencies in the visible portion of the electromagnetic spectrum and thus are not as susceptible as the radio frequency ranging methods to the delays listed.

2.5.7. *Station location*

Station position error, *i.e*., the inability to know the precise location of the tracking stations relative to the center of the earth, used to be the dominant problem in this category. However, with SLR, extremely accurate measurements are now possible. Station distribution is also a significant hindrance, with most SLRs concentrated in the northern hemisphere and on continents rather than being evenly dispersed around the globe. The advent of the DORIS tracking system considerably reduced this problem. Another, smaller in magnitude yet still present, discrepancy is that the coordinate system used to determine the station position is not precisely known because of polar motion and the variations in the length of the day.

3. Applications

3.1. *Sea level change*

Since a large segment of the population lives in a coastal zone, sea level change is of considerable importance in terms of the socio economic consequences. In addition, the rate of sea level rise is expected to increase in response to the green house warming. Thus the sea level changes obtained from altimeters can be used to validate the predictions from the climate models (Houghton *et a1*., 1996). Two fundamental problems are encountered in using tide gauge measurement for long term sea level changes. First, the crustal reference point over which the tide gauge measurements are referred, itself may move vertically at rates comparable to the sea level signals (Douglas 1995). Second, because of the limited availability of the tide gauges, they provide poor spatial sampling of the oceans.

Though the current satellite altimeter record is too short to arrive at any definite conclusion, altimeter data was used to study the long term sea level changes. Tapley *et al*. (1992) obtained a sea level change of 5 mm/year using 2 years of Geosat altimeter data. Sea level is the barometer for environmental change. Anthropogenic induced climate change, while likely to increase the global sea level, will actually cause sea level to decline at some locations and rise in others (Nerem & Mitchum 2001). The true power of satellite altimetry lies in its ability to map the geographic variation of sea level change. Leuliette and Wahr (1999) used the coupled pattern analysis technique and found that most of the long term sea level change signal observed by Topex is caused by changes in sea surface temperature related to ENSO phenomena.

3.2. *Ocean circulation*

Because of the ocean's vastness and inaccessibility and the limitations of the *in situ* measurements, understanding ocean circulation has been a slow process. With the limited data the results were interpreted in the climatological fashion with the assumption that the ocean did not change much with time and space. The capability of satellite altimetry to measure SSH above geoid, known as the dynamic height, gave an opportunity to study the variability of the oceanic processes not only at the surface but at depths as well. Water movements having spatial scales greater than about 30 km and time scales longer than about a day are in geostrophic balance to a first degree of approximation (Stewart *et al*., 1986), Hence over large temporal and spatial scales ocean circulation can be conveniently estimated from :

$$U = -\,g/f\ \partial\eta/\partial y$$

$$V = g/f\ \partial\eta/\partial x$$

Where, U and V are the zonal and meridional components of the current vector, g is the gravitational attraction of the earth, f is the Coriolis parameter and ∂y

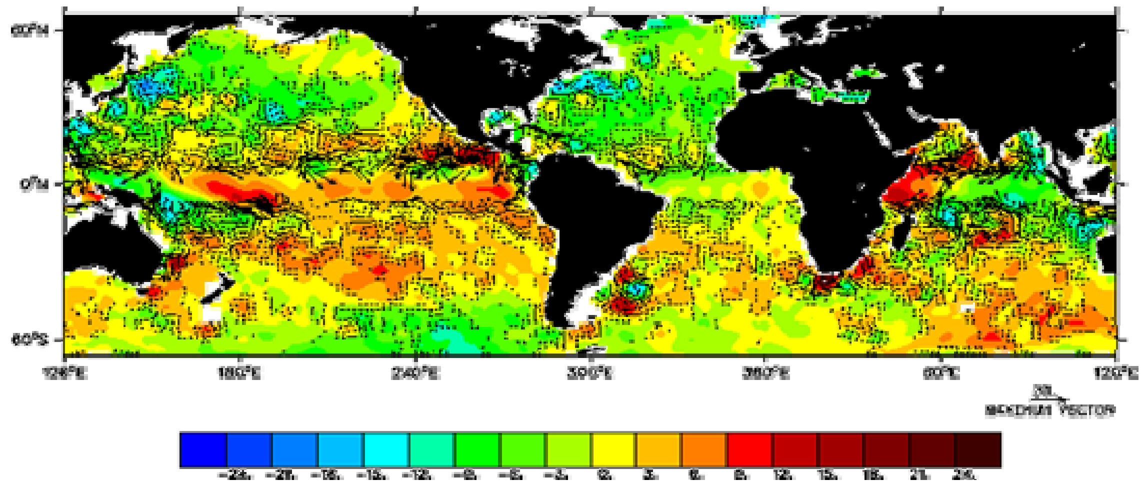


Fig. 1. Ocean current vectors from Topex altimeter

and ∂x are the distances in the zonal and meridional directions over which SSH, η, is estimated. However, ocean differs from geostrophic balance in a number of ways. For example, in the high core of the Gulf Stream, the downstream balance tends to be measurably non-geostrophic. Evaluation of the velocity fields with time, implying missing time dependent terms in momentum equations is another situation where actual flow deviates from geostrophy. Since absolute SSH cannot be estimated due to the lack of precise geoid information, only the current variability can be estimated. Even from the dynamic height estimations from the *in situ* measurements current variability alone can be estimated. However, satellite altimetry has an added advantage in the sense that if the SSH observations are referred with respect to a long time period average, the circulation estimated from the altimeter measurements can be regarded as the absolute ones with the assumption that the current vectors average out over longer time scale. This assumption is not, however, valid in regions like Somalia where the currents are towards northeast for about four months and in the opposite direction for the rest of the seasons. An example of the current vectors obtained from the Topex altimeter is shown in Fig 1. Obtaining the SSH to the required accuracy is a big challenge. Wunch and Stammer (1997) showed that for an ocean of 4000 m deep at 24 degree latitude, a one centimeter tilt in the ocean topography is associated with a mass transport of 7 Sv (1 Sv = 1 million tons per second, roughly the transport of all rivers combined), if the entire water column moves with the same velocity. The actual transport varies with latitude and the vertical distribution of the velocity. Measuring SSH from space with an accuracy of 1 cm is a tremendous effort. The present accuracy of 4 cm (rms value at 1/sec data rate) is achieved after two decades of untiring efforts. After spatial and temporal smoothing the accuracy is close to 2 cm on monthly time scales (Cheney *et al*., 1994).

3.3. *Ocean tides*

Ocean tides, the most fascinating natural events, is caused by the gravitational attraction of the sun and the moon. Tides have many impacts in geophysics and oceanography. Knowledge of total dissipation in tides is required in earth rotation studies, In geodesy, tidal loading of the lithosphere has to be considered. For all these studies a good tidal model, which is lacking till the advent of satellite altimetry, is required. Any *in situ* measurement approach to map ocean tides at global scales is not possible because of the complexity of the tides and the difficulties involved in the installation and maintenance of the instruments. In these two contexts the advent of satellite altimetry, offering to estimate tides all over the globe, has been totally revolutionary. Obtaining SSH observations from altimeter range measurements and correcting these SSH values for the tides obtained from the same range is complicated. Repeat passes or cross-over points are used to solve for the higher frequencies assuming oceanography as noise. Due to this estimated/ predicted tides over high energetic regions or coastal regions are relatively inaccurate.. Since tidal variations represent more than 80% of the SSH variations, tides must be removed from the altimeter observations to study the ocean circulation. Careful and accurate removal of the tidal information from the altimeter observations is very critical as different altimeter tracks observe different phases of the tides and if not properly removed the results from SSH variations can be interpreted as propagating signals.

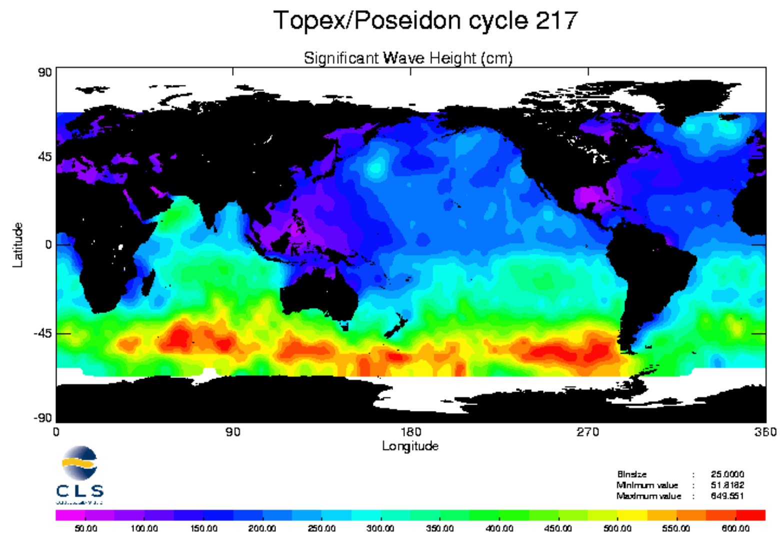


Fig. 2. An example of significant wave height from Topex

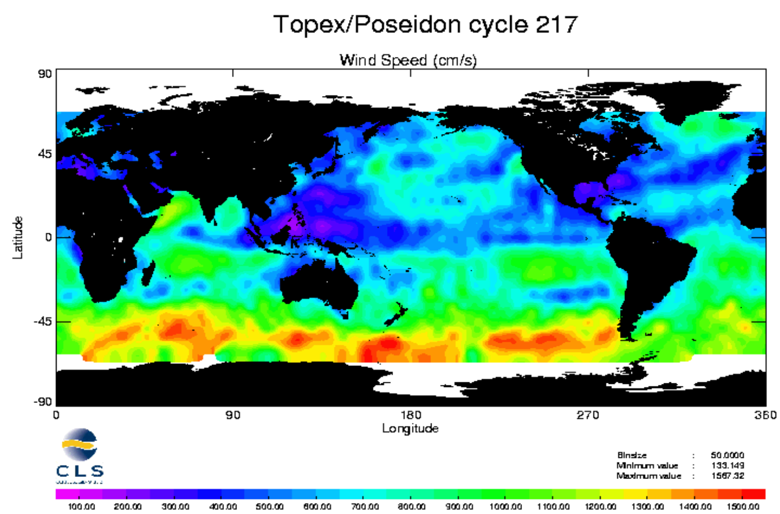


Fig. 3. An example of wind magnitudes from Topex

3.4. *Ocean surface wind wave studies*

Surface waves are the most important oceanic parameters as they provide the spectacular manifestation of the sea state. The slope of the altimeter return pulse is stretched in time because of the delay between reflections from the wave crests and troughs. This information is used to estimate the significant wave height which in turn is useful in correcting SSH observations for electromagnetic bias. The strength of the return pulse gives an estimate of the wind magnitude. These two parameters are closely related as evident from Figs. 2 and 3. Even though it is often difficult to have altimeter observations at the location of the hurricane at a time close to the passage, altimeter is the only instrument that can provide this information over the oceans. Thus altimeter allows the assessment of the meteorological forecast, based on independent data, enabling the corrections for the improvement of the models. The possibility of having real time sea state information from several altimeters in future will further enhance our ability to monitor and forecast waves generated by hurricanes and cyclones. Altimeter data is also useful for wave climate studies (Vethamany *et al*., 1999) which otherwise would be difficult from the conventional data collection platforms.

Wind speeds obtained from altimeters over oceans provide an useful information for many applications. Although it is difficult to estimate wind speed greater than 25 m/s with reliable accuracy, this data can provide information on the structure of the cyclones, the degree of symmetry and the spatial extent along the track.

3.5. *El Nino studies*

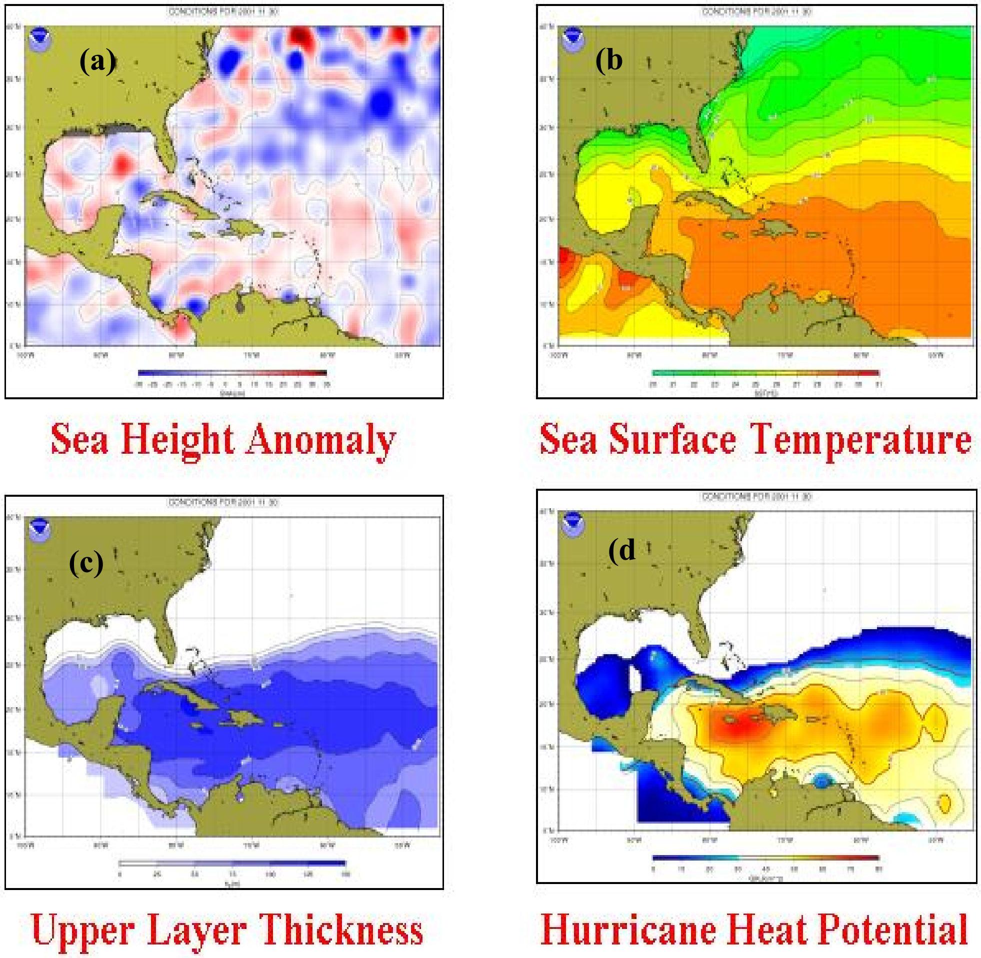
El Nino-related climate variations often have widespread and devastating impacts. Prior to El Nino surface water piles up at the eastern end of the equatorial Pacific Ocean. Satellite altimetry helps to monitor this phenomenon in all weather conditions, Besides, SSH observations offer a part of the solution to the problem of coupled ocean-atmosphere models which have attained significant forecast skill during the past decade, but they continue to be limited by an ocean observing system. In particular, an operational flow of altimeter data has long been desired by the modeling community as a means of estimating changes in upper ocean heat content to first order approximation. But even though altimeters have flown nearly continuously since 1985, two challenges have stood in the way of progress: (*i*) The altimeter data must be made available fast enough (within l-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; (*ii*) 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. A phenomena similar to the Pacific Ocean was also observed in the Indian Ocean by Ali and Sharma (1996) using Geosat SSH observations and SST patterns.

3.6. *Cyclone/hurricane studies*

The intensification of cyclones or hurricanes involves a combination of different favourable atmospheric conditions such as atmospheric trough interactions and vertical shear, which lead to good outflow conditions aloft. As a result of this, inflow conditions in the near-surface layer are enhanced. Clearly, as this process continues over the scale of the storm, the upper ocean provides the heat to the atmospheric boundary layer and to the deepening process. In this scenario, the upper ocean thermal structure has been thought to be a parameter that only played a marginal role in hurricane intensification. However, after a series of events where the sudden intensification of hurricanes occurred when their path passed over oceanic warm features, it is now being realised that it could be otherwise. While the investigation of the role of these rings and eddies is a topic of research in a very early stage, preliminary results have shown their importance in the intensification of hurricane Opal (Shay *et al*., 2000). Therefore, the monitoring of the upper ocean thermal structure has become a key element in the study of hurricane-ocean interaction with respect to the prediction of sudden hurricane intensification. These warm features, mainly anticyclonic rings and eddies shed by the Loop Current or developed due to the wind stress curl, are characterized by high SST at the elevated center, a deepening of several tens of meters of the isotherms towards their centers and with different temperature and salinity structure compared to the surrounding waters. Similarly, cyclonic features have low SST, depressed centre and shallow mixed layer. They can be easily located and identified from satellite altimeters, Ali *et al*., (1998) prepared an atlas of the North Indian Ocean eddies giving information of the eddies during 1993 to 1997 for every 10 day interval.

Oceanic features such as warm core rings (WCR), and the currents represent a source of enhanced air-sea fluxes to the atmospheric boundary layer that may cause strengthening of atmospheric disturbances. Warm layers exceeding 26° C extend to at least 100 m beneath the surface in these oceanic features, and represent high hurricane heat potential water. Satellite altimeter data from TOPEX is a useful tool to study oceanic mesoscale dynamic processes from of the sea surface height anomaly, and provides information on the vertical ocean structure when complemented by hydrographic data. Gopalan *et al*., (2001) have shown that cyclonic/ anticyclonic eddies can give an integrated picture of the subsurface thermal features in a broader sense.

Based on historical hydrographic measurements placed within the context of a two layer model, TOPEX derived upper layer thickness fields indicated the presence of two WCRs in the Gulf of Mexico during September and October 1995. Hurricane Opal passed directly over one of these WCRs where the wind field increased from 35 m/s to 65 m/s, and the radius of maximum wind decreased from 40 km to 25 km. Pre-Opal sea surface height anomaly in the WCR exceeded 30 cm where the estimated depth of the 20° C isotherm was located between 175 to 200 m, Thus on 4 October 1995, Hurricane Opal deepened from 965 hPa to 916 hPa in the Gulf of Mexico over a 14 hour period upon encountering a warm ocean ring during an upper level atmospheric trough interaction. Subsequent to Opal's passage, this depth decreased approximately to 50 m, which suggests upwelling underneath the storm track due to Ekman divergence. The maximum heat loss of approximately 24 $Kcal/cm^2$ relative to depth of the 26° C isotherm was a factor of six times the threshold to sustain a hurricane (Shay *et al*. 2000). Composite AVHRR derived SSTs indicated a 2 to 3° C cooling associated with vertical mixing in the along-track direction of Opal except over the WCR where AVHRR derived and buoy derived SSTs decreased only by about 1° C. Thus, the WCR's effect was to provide a regime of positive feedback to the atmosphere rather than negative feedback induced by cooler waters due to upwelling and vertical mixing as observed over the Bay of Campeche and north of the WCR.



Figs. 4(a-d). Processes involved in studying the oceanic role in hurricanes. (a) sea surface height anomaly, (b) sea surface temperature, (c) upper layer thickness and (d) hurricane heat potential.

Similarly, during August 1999, Hurricane Bret intensified twice in the western Gulf of Mexico over two regions associated with very high (values larger than 90 KJ/cm^2) hurricane heat potential. Thus it can be concluded that warm core eddies are the sources for the intensification of the cyclones. On the other hand, when the cyclone/hurricane passes over a cold core eddy where the temperatures are less and the mixed layer is shallow, it is likely to dissipate or suffer a reduced intensity.

The close relationship that exists between the dynamic height and the ocean mass field allows these two parameters to be used within a two-layer reduced gravity ocean model to monitor the upper layer thickness (Goni *et al.*, 1996), defined in this study to go from the sea surface to the depth of the 20° C isotherm. This isotherm was chosen because it lies within the center of the main thermocline and is often used as an indicator of the upper layer flow in the western tropical Atlantic and Gulf of Mexico waters. Although there are other factors controlling the SSH anomaly, it is assumed here that most of its variability is due to changes in the depth of the main thermocline and is of barotropic origin. The hurricane heat potential, Q, is defined here as a measure of the integrated vertical temperature from the sea surface to the depth of the 26° C isotherm. This parameter is computed from the altimeter derived vertical temperature profiles estimated in the upper ocean. The temperature profiles are estimated using ; (a) the sea surface temperature obtained from the Reynolds near real time weekly fields, (b) the altimeter estimates of the 20° C isotherm within a two layer reduced gravity scheme (Goni *et al*., 1996), (c) the depth of the 26° C isotherm from a climatological relationship between the depths of the 20° C and 26° C isotherm and (d) climatological estimates of the mixed layer depth. The hurricane heat potential, is a measure of the integrated vertical temperature between the sea surface and the estimate of the 26° C isotherm (Shay *et al*., 2000). The SSH anomaly, SST, upper layer thickness and the final hurricane heat potential over the Atlantic Ocean are shown in Fig 4.

3.7. *Rainfall studies*

As mentioned earlier when the altimeter signal passes through a rain cell it is considered as noise to the SSH measurements and such points are discarded for oceanographic studies. On the other hand it is a signal for the estimation of rainfall. Besides, dual frequency radar altimeter observations are useful in estimating the rain rate. Topex and Jason have altimeters operating at C-band along with the nominal Ku-band. The primary objective of the C-band altimeter is to provide collocated ranging measurements to correct for atmospheric path delay in the Ku range estimates. This dual frequency altimeters have two more capabilities: to study the oceanic rainfall and to correct the surface wind speeds. Ku and C band signals are differentially attenuated by the atmospheric precipitation. Bhandari and Varma (1996) used this property to identify rain events associated with the southwest monsoon. Quartly *et al*. (1999) studied the seasonal changes of rain rate using Topex dual frequency altimeter data.

4. Conclusions

Satellite altimeter has a potential of providing information which is useful both for oceanographic and atmospheric studies. The potential of altimeter measurements for studying the phenomenon of El-Nino, rain rate and cyclones is revolutionary. Use of sea surface height measurements in estimating the cyclonic heat potential in studying the intensification of hurricanes is still in its initial stage. Besides other meteorological parameters, the cyclonic heat potential obtained from altimeter could be one of the most important parameters controlling cyclogenesis and cyclone intensification/movement. This capability of the altimeter is yet to explored, particularly, in the Indian Ocean where cyclone track prediction is one of the challenging tasks.

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