Application of Satellite Altimetry to Ocean Circulation Studies: 1987-1994

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Abstract

Altimetric measurement of the height of the sea surface from space provides global observation of the circulation of the world's oceans. The last eight years have witnessed a rapid growth in the use of altimetry data for the study of the ocean circulation, thanks to the multiyear data from the Geosat Mission. Despite limitations caused by the errors in both orbit determination and altimeter measurement, significant advancement has been made from the Geosat studies in the knowledge of the western boundary currents, the tropical circulation, the mesoscale eddies, and the Antarctic Circumpolar Current. A great deal of progress has also been made in assimilating altimetry data into numerical ocean models. The advent of the TOPEX/POSEIDON Mission, an altimetric mission specially designed for studying the ocean circulation, has broken new ground for observing truly global phenomena. The altimeter aboard the ERS- 1 Mission has provided additional new data. The prospect of establishing a sustained global ocean observing system with altimetry as a key element is making the 90's the beginning of systematic, continuous monitoring of the ocean's role in climate change. A brief summary of the progress made in the last eight years and the future outlook is presented in the paper.

1. Introduction

The ocean plays a key role in determining the global climate and its time evolution. To understand this role and subsequently develop techniques for predicting future climate, one must understand the dynamics of the global ocean circulation - the movement of water that transports mass, heat, salt, and other biogeochemical properties of the ocean that are closely linked to the processes of climate change. The only viable approach to observing the global ocean circulation with sufficient resolution and consistent sampling is the use of a satellite radar altimeter to measure the height of the sea surface - the sea level (see Stewart (1983) for an introduction to the subject). After removing the effects of the tides and atmospheric pressure from the observation, the deviation of the sea surface from the geoid, called the ocean dynamic topography, is readily related to the velocity of the surface geostrophic flow - a component of the surface flow on which the surface pressure force is balanced by the Coriolis force due to the Earth's rotation. Moreover, the ocean dynamic topography provides a strong constraint for determining the ocean circulation through the entire water column via the dynamic equations governing the fluid motion. Precise measurement of the shape of the global sea surface thus provides a powerful tool for studying the dynamics of the ocean circulation.

Progress in the application of satellite altimetry for ocean circulation studies from 1987-1994 is reviewed in this paper. The reader is referred to Douglas et al. (1987), Brown and Cheney (1983), Fu (1983), and Wunsch and Goposchkin (1980) for early development in the subject. The last review of the subject was conducted eight years ago (Douglas et al., 1987). The past eight years have seen the greatest strides in the development of satellite altimetry as an observational tool in oceanography. The U.S. Navy launched Geosat in 1985 with a primary objective of mapping the marine gravity field for military applications. Most of the data collected during Geosat's first 18 month primary mission (the Geodetic Mission) are still classified However, the declassified portion of the data has led to significant advancement in marine geophysics (e.g., McAdoo and Marks, 1992). When its primary mission was achieved, Geosat was maneuvered into a 17-day repeat orbit, and an extended mission (the Exact Repeat Mission) for oceanographic applications started in October 1986 (Born et al., 1987; Douglas and Cheney, 1990). Although the mission was not designed specifically for oceanographic applications, the 2.5-year data set created the first opportunity for oceanographers to experiment with a multi-year global data set (see the March and October 1990 issues of the Journal of Geophysical Research devoted to Geosat.)

The most serious Geosat error source has been the uncertainty in the radial orbit height, but significant progress continues to be made in this area. The Geosat orbit error was on the order of 2 m in the initial data release, but was later reduced to about 30-50 cm in a later release largely through gravity model improvements (Cheney et al., 1991; Haines et al., 1994). However, the orbit accuracy rapidly degrades to the 1 m level after mid 1988 through the end of the mission due to inadequate modeling of the drag force cussed by the increased solar activities. By using the altimeter data as a constraint, Shum et al. (1990 a) achieved an orbit precision of about 20 cm. Finally, in 1993, the U.S. Navy released additional Geosat Doppler tracking data which have led to a further reduction in the orbit error to about 10 cm (S. Nerem and R. Williamson, private communication). Other important error sources include the altimeter signal delay caused by tropospheric water vapor and ionospheric free electrons (Emery et al., 1990; Musman et al, 1990). Based on the best orbit available, the present Geosat error budget is at the level of about 15 cm, an impressive accomplishment in view of the initial low expectations for the mission.

In 1991, two years after the end of the Geosat mission, the European Space Agency launched the ERS- 1 (European Remote Sensing Satellite - 1) altimeter. An identical satellite, ERS-2, will take its place in 1995. These two missions provide the type of continuous, long-term coverage needed for studies of interannual ocean variability and also provide altimeter data to operational users in near-real time (Cheney and Lillibridge, 1992). Because the ERS series of satellites carry a suite of sensors, a number of different ground track patterns have been followed, including 3-day and 35-day repeats. During most of its final year of operation, the ERS-1 satellite will be flown in an orbit that will yield a dense global network of altimeter profiles spaced 15 km apart at the equator for geodetic studies. As was the case for Geosat, orbit error is the primary obstacle to be overcome for ERS-1 altimeter applications. The problem was compounded by early failure of one of the two onboard tracking systems. However, laser tracking together with advanced gravity models have now resulted in orbits with an accuracy of about 15 cm (Lillibridge et al., 1993).

To be useful for studying the ocean circulation, especially at the basin scales, the accuracy of altimetry measurement must be less than 15 cm (TOPEX Science Working Group, 1981). To achieve this goal, a satellite mission with specially designed instrumentation and orbit configuration, and much improved knowledge in the earth's gravity field for orbit determination was required. The TOPEX/POSEIDON Mission was the result of this conviction by scientists and engineers in both the U.S. and France (Fu et al., 1991 a; The TOPEX/POSEIDON Science Working Team, 1991). TOPEX is an acronym standing for Ocean Topography Experiment, the name originally used by the U. S.; POSEIDON is the original French name for the mission. This joint U.S./France mission was launched in August, 1992 with an expected lifetime of 3-5 years. The performance of the mission has exceeded its specification. Orbit and altimeter accuracies are estimated to be 3.5 cm and 3.2 cm, respectively, resulting in an absolute accuracy of 4.7 cm for the determination of geocentric sea level (Fu et al., 1994). For the first time, oceanographers have a global observing system that is providing data of sufficient accuracy and sampling for the study of the global ocean circulation. Preliminary results from TOPEX/POSEIDON are just appearing (see the December 1994 issue of the Journal of Geophysical Research), and significant advancement in the dynamics of the large-scale ocean circulation is expected in the near future.

A brief summary of the accomplishments made in the past eight years is given below in categories based on oceanographic phenomenology. Only those papers addressing direct applications to the ocean circulation are reviewed. A large body of literature on techniques for altimetry correction and data analysis has thus been left out (see Chelton, 1988 for an overview). Of great importance to the utility of altimeter data is the correction for the tidal effects on the sea level observation. The reader is referred to Cartwright and Ray (1990) for estimating tides from altimeter data.

2. The Western Boundary Currents

The western boundary currents can be easily resolved even by the relatively crude Geos-3 radar altimeter because of the large sea level variation across the currents (e.g., Fu et al., 1987). A host of studies of the various western boundary currents of the worlds oceans have been conducted using the much improved Geosat data. Among the numerous accomplishments is a powerful technique developed by Ken y and Gille (1990) for estimating the absolute dynamic ocean topography across strong currents from their temporal variabilities. An analytical model is used to describe the dynamic topography of an isolated jet with its kinematic parameters (i.e., location, width, and amplitude) determined from the observed temporal sea level changes as an inverse problem (also see Tai, 1990). Comparison of the altimetry-derived velocities with simultaneous in-situ velocity measurements demonstrated the validity of the technique (Joyce et al., 1990), The technique was applied to the Gulf Stream and the Kuroshio for studying their spatial and temporal characteristics with results consistent with in-situ data (Ken y, 1991; Qiu et al., 1991). Tai and White (1 990) extended this approach to addressing the eddy-mean flow interaction of the Kuroshio Extension. Other studies based on the technique have been conducted on the recirculation flanking the main current of the Kuroshio (Qiu, 1992) and the Gulf Stream (Qiu, 1994), By combining the altimetric estimate of the surface dynamic topography with historical hydrographic data, Qiu (1994) estimated the deep circulation of the Gulf Stream region with results comparing well to in-situ data. Kelly and Watts (1994) applied the technique to both altimetry data and inverted echo sounder data and obtained excellent agreement. Qiu and Kelly (1993) and Kelly and Qiu (1994) used altimetrically derived surface current velocities in conjunction with atmospheric wind and thermal forcing to study the heat budget of the upper ocean in the Gulf Stream and the Kuroshio regions.

Using a straightforward technique to examine the cross stream sea level differences, Zlotnicki (1991) reported that both the Gulf Stream and the Kuroshio, after entering the open ocean, had similar seasonal cycles with peak surface currents occurring in the fall, consistent with the findings of the studies cited in the preceding paragraph. The discrepancy from the finding of Fu et al. (1987) that reported a peak Gulf Stream surface velocity in the spring during the Geos-3 mission could be due to interannual variability or large systematic errors in the Geos-3 data. A downstream decrease in the time scales of the Gulf Stream sea level variability was found by Vazquez et al. (1990). The spatial and temporal characteristics of the meandering of the Gulf Stream was investigated further by Vazquez (1993).

There have been numerous intercomparisons made between Geosat altimetry and in-situ data in the regions of the Gulf Stream and the Kuroshio (Hallock et al., 1989, 1993; Willebrand et al. 1990; Horton et al., 1992; Blaha and Lunde, 1992; Joyce et al., 1990), demonstrating the quality of the Geosat data for the study of the mesoscale structure of the western boundary currents. Carries et al. (1990) investigated the feasibility of estimating subsurface temperature fields from altimeter data in the Gulf Stream region with mixed results. Using a combination of the Geosat altimeter data with in-situ hydrographic data, a number of investigators constructed for the Gulf Stream region the so-called synthetic geoid (Mitchell et al., 1990; Porter et al., 1989, 1992; Glenn et al., 1991), which was useful for deriving approximate absolute Gulf Stream topography for research as well as operational applications. High-resolution geoids in the Gulf Stream region were also obtained by using geodetic techniques (Rapp and Wang, 1994) and by combining altimetry, hydrography, and direct current velocities (Kelly et al., 1991).

The Geosat data have also bee used to study the Loop Current and its eddies in the Gulf of Mexico. Johnson et al. (1992) tracked two Loop Current eddies whcih drifted southwestward across the Gulf. Jacobs and Leben (1990) reported a 10.5 month period for the shedding of eddies by the Loop Current. Leben et al. (1990) constructed maps of the mean sea surface and eddy variability of the Gulf.

Using the Geosat altimeter data with a numerical model,Matanoetal.(1993) studied the seasonal variability of the Brazil and the Malvinas Currents and found that the seasonal cycles of the two currents were opposite in phase (with the maximum of the Brazil Current during the austral summer). They interpreted the result in terms of the seasonal migration of the confluence zone of the two currents. Spatial and temporal characteristics of the variability of the Brazil-Malvinas Confluence region were analyzed by Provost and Le Traon (1993). They reported the dominance of semiannual fluctuations characterized by alternating positive and negative sea level anomalies with length scales of 400-500 km. The mesoscale variability was highly inhomogeneous and anisotropic. They also computed the Reynolds stress and discussed its relation to the dynamics of the mean flow.

The variability of the Agulhas Current was investigated using the Geosat data in a number of studies. Fu and Zlotnicki (1989) calculated the wavenumber-frequency spectrum which revealed the dominant wavelengths and periods as 300800 km and 50-200 days. Quartl y and Srokosz (1993) reported that the seasonal variation evidenced in the Geosat data was not reproduced by the Fine Resolution Antarctic Model (FRAM), suggesting possible directions for the improvement of the model (Quartly and Srokosz, 1993). Wakker et al. (1990) calculated the dynamic topography and the eddy variability statistics in the region.

3. The Tropical Oceans

Altimetric data are particularly useful for observing oceanographic phenomena in the tropical oceans because of their large zonal scales and relatively small meridional scales. Their detection by altimetry is thus not severely affected by the orbit errors whose effects are primarily on large meridional scales. However, careful treatment of the orbit errors still makes a difference when the errors are as large as in the early versions of the Geosat data (Cheney and Miller, 1990). There has been significant progress in all three tropical oceans.

3a, The Tropical Pacific Ocean

The 1986-87 El Nino was a major focus of the studies of the tropical Pacific using the **Geosat** data. **Cheney** and Miller (1988) and Miller et al. (1988) detected the Kelvin waves that initiated the El Nino as the ocean's response to a burst of anomalous westerly wind events (Kelvin wave is an edge wave involving the Earth's gravity and rotation). Using **4**-year long sea level time series constructed from both the **Geosat** Geodetic Mission and the **Exact** Repeat Mission, Miller and **Cheney** (1990) studied the budget of the upper ocean water mass. They identified a seasonal exchange of upper ocean water between the equatorial region (7° S -7° N) and the region just to the north (8° N -20" N). This exchange process was enhanced during the El Nine. The generation, propagation, and reflection of Kelvin waves and Rossby waves (a low-frequency wave caused by the vorticity of a rotating fluid) in the equatorial wave guide were studied in detail (White et **al.,** 1990 a; **Delcroix** et al., 1991; du **Penhoat** et al., 1992). Extensive comparisons were made between the **Geosat** observations and in-situ observations from tide gauges and expendable bathythermogmphs **(XBTs) (Tai** et **al.,** 1989; **Cheney** et al., 1989). The **Geosat** data were also **compared** to simulations of ocean general circulation models with some **success** **(Cheney** et al., 1989; Chao et al., 1993).

Evidence for equatorial waves in the strong shear region of the equatorial current system was reported in the Seasat data **(Malarde** et al., 1987; Musman, 1989, 1992). Characteristics of these waves **were** studied in detail based on the **Geosat** data by **Perigaud** (1990), who identified wave activities in two shear zones centered at 5° N (between the South Equatorial Current ant the North Equatorial Counter Current) and 12° N (between the North Equatorial Counter Current and the North Equatorial Current) with distinctively **different** periods and wavelengths. She also found correlations of the intensity of these waves to the seasonally varying strength of the shears. Using the **Geosat** data with various in-situ **data,** Hansen and Maul (199 1) and Maul et al. (1992) studied the formation and evolution of eddies in the eastern end of the North Equatorial Counter Current. These **eddies,** having strong nonlinear character, were formed during late fall when the current was strongest.

3b. The Tropical Indian Ocean

Using the SeaSat altimeter crossover **differences, Perigaud** and **Minster** (1988) investigated the movement of the "Great Whirl" formed in the Somali Current and found fair agreement between altimetry data and in-situ data. Variability of the Somali Current was studied by Perigaud and Delecluse (1989) using the Seasat altimeter data and scatterometer data and numerical models. They found that nonlinearity is crucial in explaining the observations. A large anticyclonic eddy formed in the eastern Arabian Sea during the northeast monsoon was studied by Bruce et al. (1994) using the Geosat data with a numerical model. Perigaud and Delecluse (1992) investigated the annual sea level variations using the Geosat altimeter data and a shallow-water model. Significant correlation was found between the first complex empirical orthogonal functions of both the observation and the model simulation. This annual signal was interpreted in terms of Rossby waves with the maximum amplitude located near 12° S and 90° E. Using 4 years's worth of the Geosat data, Perigaud and Delecluse (1993) investigated the interannual sea level variations and compared the observation to the simulation by a shallow-water model. Averaged over the basin studied (north of 20" S), the observation and the simulation were highly correlated (0.92). The signal was characterized by a sea level rise during the 1986-87 El Nino with the maximum amplitude (5 cm) occurring in the southern domain (10° S - 20° S). They also used the Geosat data to test the quality of the wind driving the model.

3c. The Tropical Atlantic Ocean

Combining the SeaSat data with the Geos-3 data into a monthly data base, Menard (1988) studied the seasonal cycle of the North Equatorial Counter Current and obtained encouraging comparisons of the altimetry analysis with in-situ data and model simulations. Carton (1989) studied the variation of the equatorial current systems using the first year of the Geosat data. He also estimated the zonal sea surface slopes associated with the current variabilities. A follow-up study was conducted to examine the seasonal variations of the North Equatorial Counter Current using two years's worth of the Geosat data (Carton and Katz, 1990), The current maximum was found at 38° W with peak transport of 40 Sv (1 Sv= 10^9 kg/see). Extensive intercomparisons were made between the Geosat data and various in-situ data (Carton and Katz, 1990, Arnault et al., 1990, 1992a). Arnault et al. (1992b) made extensive comparisons of the low-frequency variabilities between altimetry analysis and model simulations. Interannual variabilities in the Gulf of Guinea related to the 1986-87 El Nino were discussed. Arnault and Cheney (1994) conducted further investigation using 4,5 years' worth of improved Geosat data. They described 8090 of the sea level variance in terms of 3 empirical orthogonal functions and reported an increase of the volume of the equatorial upper ocean during 1987-89, indicative of the effect of the 1986-87 El Nine. Didden and Schott (1992) examined the variabilities of the North

Equatorial Counter Current and the North Brazil CM-rent using the Geosat data and the World Ocean Circulation Experiment (WOCE) Community Model and obtained good agreement between the two. Musman (1992) reported evidence for the equatorial instability waves at 4° N and 4° S with a period of 25 days and a wavelength of 970 km.

4. The Mesoscale Eddies

The spatial scales of most of the significant errors in altimeter data (the orbit, the tides, the signal delay in the transmission media, the sea-state bias) are generally longer than 1000 km, making the detection of mesoscale features, whose wavelengths are less than 1000 km, relatively less prone to the measurement errors. However, certain along-track smoothing is required to reduce the random measurement noise, limiting the wavelengths of the variability examined to greater than about 60 km (e.g., Le Traon et al., 1990). Moreover, a single altimeter mission has only limited capability for synoptic mapping of the details of mesoscale eddies in both space and time (Chelton and Schlax, 1994).

Maps of the statistics of the global mesoscale variability with much higher accuracy and resolution than the Seasat results have been produced from the Geosat data due to their large data volume and dense ground tracks (Zlotnicki et al., 1989; Sandwell and Zhang, 1989; Shum et al.,1990 b). Sandwell and Zhang (1989) computed the sea surface slope, which filtered out most of the large-scale errors, and converted it directl y to the kinetic energy of ocean currents. Seasonally-varying mesoscale energy was reported in the northeast Atlantic and the northeast Pacific by Zlotnicki et al. (1989). Energy level was found to be correlated with the strength of the wind stress curl. Shum et al. (1990 b) obtained similar results. Wavenumber spectra were estimated in a wide range of locations (Fu and Zlotnicki, 1989; Le Traon et al., 1990; Stammer and Boning, 1992). Different spectral slopes were found in the high-energy areas than the low-energy areas, but the interpretations were controversial (Le Traon, 1993; Stammer and Boning, 1993).

De Mey and Menard (1989) combined the Geos-3 data with the Seasat data in an objective analysis of the eddy field in the Polymode region (a 500- km square centered at 29° N and 70” W). The analyzed field was assimilated into an ocean model that yielded realistic subsurface fields. Bisagni (1991) created time series of sea level maps using the Geosat crossover data in a similar region, delineating westward propagating eddy fields that were consistent with previous in-situ data in the region. Tokmakian and Challenor (1993) applied the Geosat data to studying the eddy field in the Azores frontal region and the Canary basin of the North Atlantic. They reported slightly higher eddy energy in winter and discussed evidence for Rossby waves, although the effects of tidal aliasing was a concern for the detection of Rossby waves of the annual period (Schlax and Chelton, 1994). The Geosat data were also applied to the North Atlantic Current (De Mey, 1992) and the frontal zones east of Iceland (Robinson et al., 1989). Significant correlations between Geosat and in-situ observations were reported even in areas of extremely low eddy energy such as the Iberian Basin (Stammer et al., 199 1) and the Cape Verde Frontal Zone (Zlotnicki et al., 1993). A systematic study of the relationship between the time scale and the space scale of the eddy field in the North Atlantic was conducted by Le Traon (1991), who identified two regimes: higher energy areas where the space and time scales are proportional to each other, consistent with the quasigeostrophic turbulence theory; low energy areas where the space and time scales are inversely related, consistent with the linear Rossby wave dynamics.

The spatial and temporal characteristics of the eddy field in the South Atlantic were investigated by Le Traon andMinster(1993) and Forbes et al. (1993). Both reported evidence for westward propagating Rossby waves: the former emphasized the waves of the semiannual period at the subtropical latitudes west of the Walvis ridge; the latter identified the Agulhas Retroflection as a source for the waves with periods of 400-500 days. The variation of the characteristics of the eddy wavenumber spectrum in the region was extensively examined with results consistent with the findings of Fu and Zlotnicki (1989) and Le Traon et al. (1990).

The mesoscale variability of the Antarctic Circumpolar Current was investigated by Chelton et al. (1990), who reported that the eddy field was highly correlated to the mean flow and both were apparently steered by the bathymetry (also see Sandwell and Zhang, 1989). Eddy Reynolds stress was estimated at the crossover locations of Geosat (Morrow et al., 1992, 1994; Johnson et al., 1992). The resulting horizontal eddy momentum flux tends to generally accelerate the mean flow, but the zonally averaged eddy flux is an order of magnitude too small, and in the wrong direction to balance the eastward momentum input from the wind.

Jacobs et al. (1993) fit a Rossby wave model to the Geosat data in the entire Pacific Ocean. They found that less than 5 % of the variance could be accounted for by the model. However, most of the estimated wave amplitude was above the estimation error. Van Woert and Price (1993) reported evidence for Rossby waves north of the Hawaii Islands and found close agreement of the observed propagation characteristics and their latitudinal dependence with the theoretical dispersion relation. White et al. (1990 b) demonstrated that the annual fluctuations in the California Current region were consistent with Rossby waves propagating into the open ocean with wave fronts parallel to the bathymetry. These eddy activities were found to be consistent with the simulations of a primitive-equation model (Pares-Sierra et al., 1993), indicating that the eddies were forced by the wind adjacent to the coast. The annual-period Rossby waves were also detected in the Alaska Gyre (Matthews et al., 1992). Again the finding must be viewed with caution due to the aliasing effects of the tides (Schlax and Chelton , 1994). Evidence for topographic planetary waves in the Bering Slope Current was reported by Okkonen (1993).

The formation, propagation, and mass transport of eddies were studied in detail by a number of investigators. Didden and Schott (1993) examined the eddies in the retroflection region of the North Brazil Current. Individual eddies were traced to the entrance of the Caribbean, Seasonal variation of the eddy energy was correlated to the seasonal cycle of the retroflection of the North Brazil Current into the North Equatorial Counter Current. The interhemispheric exchange of water mass was estimated to be 3 Sv. Gordon and Haxby (1990) were able to trace the eddies spun off from the retroflection of the Agulhas Current all the way to the western South Atlantic. They estimated as much as 15 Sv of the Indian Ocean water being transported to the South Atlantic by this process. Okkonen (1992) employed a novel eddy-tracking technique to follow and diagnose the shedding of an eddy from the Alaskan Stream. Ichikawa and Imawaki (1994) documented for the first time the complete life history of a cold-core eddy shed from the Kuroshio.

S. The Large-Scale Variability

The “large-scale” is used hereto refer to scales larger than 1000 km, a loosely defined upper limit for the mesoscale discussed in Section 4. In this range of scales, the signal-to-noise ratio is generally small for all the altimeters except for TOPEX/POSEIDON. As noted above, a variety of error sources such as the orbit, the tides, the signal transmission media, and the instrument systematic errors have dominant scales larger than 1000 km. Despite these obstacles, numerous attempts have been made to examine the large-scale ocean variabilities using the pre-TOPEX/POSEIDON altimeter data. The dominant orbit errors were reduced by a variety of methods, ranging from a dynamic approach utilizing gravity model adjustment (Koblinsky et al., 1992) to a purely geometric approach utilizing the spectral characteristics of the orbit error (Wunsch, 1991 a). The reader is referred to

Wagner and Tai (1994) for a discussion of the effects of the orbit error removal procedures on the detection of ocean signals.

Comparison of the low degree and order spherical harmonics of the Geosat sea level variations to a set of tide gauge data yielded arms difference of 5-10 cm (Wunsch, 1991a; Koblinsky et al., 1992). Similar results were obtained by Harangozo et al, (1993). Wunsch (1991 a) demonstrated a method of combining altimeter data with tide gauge data in enhancing the accuracy of the estimate of the global sea level variability. The results were used to investigate the large-scale response of the ocean to atmospheric forcing (Wunsch, 1991 b). Up to 50 % of the variance was accounted for by the forcing of wind and atmospheric pressure, Spatial pattern of the global annual and semiannual variabilities were examined in detail by Koblinsky et al. (1992) and Jacobs et al, (1992). Contamination of the annual cycle by ocean tides was removed by an empirical method in the latter study, The interannual change due to the 1986-87 El Nino were demonstrated (Wunsch, 199 1a; Koblinsky et al., 1992; Koblinsky, 1993),

There were also regional studies of the gyre- and basin-scale variabilities. The annual and interannual variabilities of the Alaska Gyre was investigated by Bhaskaran et al. (1993) based on a 4-year Geosat database. He found significant correlations of the sea level with atmospheric pressure and the Southern Oscillation Index (an indicator for the climatic condition of the tropical Pacific based on the sea level pressure difference between Darwin and Tahiti). Chelton et al, (1990) examined the large-scale structure of the temporal variability of the Antarctic Circumpolar Current (ACC) and reported that only a minor portion (33 percent) of the variance was zonally coherent, corresponding to the annual, semiannual, and interannual variabilities. The current has strong regional characteristics in each basin. Using the Seasat altimeter and scatterometer data, Mestas-Nunes et al. (1 992) analyzed the relation between the variability of the ACC and the wind forcing and reported that a quarter of the variance was accounted for by the linear response of the ocean to the forcing of the curl of the wind stress (the time-dependent Sverdrup relation). Gille (1994) used the technique of Kelly and Gille (1990) for estimating the mean dynamic topography of the entire ACC. She also reported that the model was able to account for 40-70% of the sea level variance along the axis of the ACC in terms of the meandering of the current.

By comparing the global sea level derived from Seasat to that from Geosat, Haines et rd. (1992) examined the difference between the summer of 1978 to that of 1987 and found good agreement with in-situ observations. This result demonstrated the potential of combining observations from different altimetry missions to monitor long-term changes in the ocean, The success of Haines et al. (1992) was largely due to their recomputing the Seasat orbit using the same gravity model as the one used for Geosat, thus eliminating the large difference in the geographically-correlated orbit errors that could be aliased to temporal changes (Cheney and Douglas, 1988).

Change in the global mean sea level has both scientific and practical implications. The dense, global sampling of a satellite altimeter makes it one of the most viable approaches to monitoring the change in the global mean sea level. Born et al. (1986) first demonstrated the idea using the Seasat data. Due to the large orbit error, the result showed more than 10 cm fluctuations in 24 days. Tapley et al. (1992) showed that therms variability of the global mean sea level calculated from 2 years' worth of the Geosat data was about 2 cm. The rate of change was estimated +/- 0.5 cm/year. Similar results were obtained by Visser et al. (1993). The various errors affecting the global mean sea level estimate were discussed in detail by Wagner and Cheney (1992). Based on the first year of the TOPEX/POSEIDON data, Nerem et al. (1994) reported that therms variability of the global mean sea level was reduced to a level of 0.5 cm. Although significant progress has been made, there is still a long way before altimeter can detect the 1 mm per year global mean sea level change.

6. The General Circulation

Determining the absolute surface geostrophic circulation of the worlds oceans has been a tantalizing prospect of satellite altimetry since the advent of the technique. The difficulties arise from the errors in both the orbit and the geoid. The orbit errors of concern are the systematic (or geographically correlated) component that cannot be reduced by averaging in time. This error must be reduced by improved gravity models or by continuously precision satellite-tracking using the Global Positioning System (Bertiger et al., 1994). As part of the TOPEX/POSEIDON Mission, a gravity model improvement effort was initiated in both the U.S. and France in the 1980s. This effort has progressively produced improved gravity models (e.g., Marsh et al., 1988, 1990 a), which in turn have also led to improved long-wavelength components of the geoid. For instance, Tai (1988) reported improved estimate of the ocean dynamic topography using the gravity model of Marsh et al. (1988)

The ocean dynamic topography is usually solved as an inverse problem involving simultaneous adjustment of the orbit, the gravity model, and the dynamic topography.

Using this approach, a number of groups have estimated the global ocean dynamic topography up to spherical harmonics degree and order 6-10 (Tapley et al., 1988; Marsh et al., 1990 b; Denker and Rapp, 1990; Nerem et al., 1990; Visser et al., 1993), For shorter scales, the geoid errors overwhelm the oceanographic signals. Using an inverse model of the North Atlantic circulation involving a large amount of oceanographic data, Martel and Wunsch (1993) evaluated the Geosat altimetric dynamic topography of Nerem et al. (1990) and concluded that the Geosat result was inconsistent with the conventional oceanographic data and that the error in the Geosat result was at least a factor of two too large to improve the existing knowledge of the circulation. Preliminary examination of the data from the TOPEX/POSEIDON Mission have shown promise for using the data to improve estimate of the ocean general circulation (Stammer and Wunsch, 1994).

7. Data Assimilation

It has long been recognized that one needs to combine observations with dynamic models to achieve an optimal description of a turbulent global fluid system such as the ocean. This model/data combination is referred to as “data assimilation” following the terminology in metrology. The development of data assimilation into numerical ocean models has been hampered by the lack of well-sampled data. For a review of the status of the subject the reader is referred to Ghil and Malanotte-Rizzoli (1991) and Bennett (1992). The availability of satellite altimetry data has spurred significant progress in ocean data assimilation over the past several years.

One approach to data assimilation is direct data insertion, or reinitialization. Berry and Marshall (1989) inserted data only to the surface layer and let the information be dynamically transferred to the lower layers. De Mey and Robinson (1987), De Mey and Menard (1989), and Hurlburt et al. (1990) projected the surface information to the deep layers using statistical methods such as empirical orthogonal functions. Altimetry data along with the subsurface projection were then directly inserted into a model, resulting in a more efficient vertical information transfer. Robinson and Walstad (1987) used a feature model for the Gulf Stream and its eddies to initialize the 3-dimensional field for data insertion. Haines (1991) demonstrated a novel approach in which the data insertion was applied to the surface stream function while the potential vorticity of the lower layers were kept unchanged so as to create an effective adjustment of the lower layers to the data insertion at the top layer.

A relatively simple and effective scheme for assimilating data continuously into a model is the so-called nudging technique (Holland and Malanotte-Rizzoli, 1989; Verron, 1990, 1992). The information of the altimetry data is ingested into the surface layer by placing in the model equations a term that is proportional to the difference between the model sea surface height and the observation, The information of the data is transferred to the deep layers by the model dynamics. This technique works quite well for quasi-geostrophic models (in which the flow is in near geostrophic balance) and has been applied to the Geosat data in the Agulhas Current (Holland et al., 1991) and the western North Atlantic (Verron et al., 1992). Smedstad and Fox (1994) demonstrated the use of the technique with a primitive equation model . However, the effects of observation error and model error are generally not taken into account in the nudging approach.

White et al. (1990 c) employed an optimal interpolation (01) technique to assimilate the Geosat data into a quasi-geostrophic model of the California Current, specifically taking into account the model and observation errors in the assimilation step. However, the information of the data was assimilated only to the surface layer, while the vertical transfer of information was via the model dynamics. Dombrowski and De Mey (1992) used the empirical orthogonal function technique to project the altimetry information to the lower layers of a quasi-geostrophic model and applied an 01 scheme to assimilating the Geosat data into all the vertical layers simultaneously. Using statistical correlation in the transfer of information from the sea surface height to subsurface fields, Mellor and Ezer (1991) and Ezer and Mellor (1994) demonstrated the use of an 01 scheme in assimilating altimetry data into a primitive equation model of the Gulf Stream region. The statistical correlation between the sea surface height and subsurface temperature was demonstrated by Ezer and Mellor (1993). The 01 approach is particularly effective in mapping the horizontal fields, but the vertical transfer of information to subsurface fields is somewhat problematic.

Variational methods have been applied to seeking model solutions that minimize a “cost function” related to the model-data misfit (Moore, 1991; Bourles et al., 1992; Schroter et al., 1993; Greiner and Perigaud, 1994). The solutions obtained are exact solutions to the model equations in the so-called strong constraint approach, Using a “weak-constraint” approach, Egbert et al. (1994) demonstrated the use of the variational method to obtain an optimal estimation of the global ocean tides by combining the TOPEX/POSEIDON data with the Laplace tidal equation. In addition to the optimal model solution, other parameters such as friction coefficient, wind forcing amplitude, and model initial conditions can also be estimated as part of the solutions. Although the approach is quite effective in testing the consistency between models and data, error estimates for the solutions were seldom discussed because of the required large computational burden.

The popular method of the "Kalman filter/smoother" in the engineering community is a sequential approach to optimal estimation by combining model prediction with observations in a way to minimize the estimation error. Miller (1989) demonstrated the use of the Kalman filter to assimilate the altimeter differences into linear ocean models. Gaspar and Wunsch (1989) applied the technique to extracting Rossby wave signals from the Geosat data in the western North Atlantic. They found that only about 6 % of the data variance was consistent with the Rossby wave dynamics. Fu et al. (1991 b, 1993) showed that a significant portion (68 %) of the Geosat data in the tropical Pacific was consistent with the dynamics of linear Kelvin waves and Rossby waves. Gourdeau et al. (1992) obtained similar results in the Tropical Atlantic. The computational burden of the Kalman filter/smoother is notoriously heavy, because the error covariance also needs to be carried forward in time by the model dynamics. Noting the rapid approach to a steady state of the error covariance in many Kalman filter applications, Fukumori et rd. (1993) developed a steady-state Kalman filter/smoother and demonstrated its use in assimilating the Geosat data into a simple, coarse-resolution general circulation model of the North Atlantic. The technique was also evaluated by Fu et al. (1993) by comparing it to an exact, time-varying Kalman filter calculation. To make the technique feasible to a full- scale ocean general circulation model, Fukumori and Malanotte-Rizzoli (1994) demonstrated a further approximation of the Kalman filter by assimilating only the large-scale content of the data. Such approach holds promise for assimilating data into truly global models.

8. Conclusions and Outlook

The last eight years have seen enormous progress in the application of the Geosat altimetry data to the study of oceanographic problems, albeit with a great deal of effort in treating the various errors in the data. Significant advancement has been made in the knowledge of the temporal variabilities of the western boundary currents, the mesoscale eddies, the tropical circulation, and the Antarctic Circumpolar Current. The multiyear, global data set has generated a great deal of progress in developing methods of data assimilation, setting the stage for using altimetry data as a fundamental constraint for global ocean modeling and description.

The launch of TOPEX/POSEIDON has provided scientists with the first truly global ocean observing system, producing a “snap shot” of the global ocean circulation with an unprecedented accuracy every 10 days. Coupling with two other concurrent developments - the World Ocean Circulation Experiment (WOCE) and the maturing technology of global ocean modeling, TOPEX/POSEIDON is creating enormous opportunities for making significant advancement in the understanding of global ocean dynamics. The high accuracy of TOPEX/POSEIDON would help calibrate and improve other less accurate missions such as ERS-1 and 2 and enhance their value for large-scale circulation studies. To achieve the ultimate goal of understanding the ocean’s role in climate, the observation provided by TOPEX/POSEIDON must be sustained with consistent quality. Plans are in place to extend the mission from 3 to at least 6 years as long as the flight hardware is functioning. A series of follow-on missions to extend the TOPEX/POSEIDON data stream to the indefinite future is being studied jointly by NASA, NOAA, and the French CNES (Centre National d'Etudes Spatiales). The prospect of having a combination of various altimeters with at least one of them having the TOPEX/POSEIDON accuracy holds great promise for ocean circulation research in the next decade. This series of altimetry missions will become a key element of a global ocean observing system for unraveling the ocean’s role in climate change.

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