OCEAN CURRENT DETECTION BY SATELLITE ALTIMETRY

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Abstract

Seasat provided 3 months of satellite altimeter data in 1978 with a precision of approximately 5 cm. In the western North Atlantic where a detailed gravimetric geoid model is available, these data yield realistic profiles of Gulf Stream dynamic heights. A Seasat-type mission could thus produce near-synoptic maps of the Gulf Stream path with surface current measurements accurate to perhaps 50 cm/s. Because of a lack of detailed geoid models for most ocean regions, however, solutions of sea height variability represent the most significant contribution of altimetry. The 25-day set of Seasat repeat-track altimeter data permits determination of global mesoscale variability with an accuracy of a few cm. The map generated from these data displays patterns which clearly define the mean paths of most major surface current systems.

1. Introduction

The Geos-3 and Seasat missions demonstrated the potential of satellite altimetry for ocean dynamics studies. Altimetric analyses of ocean dynamic topography are based on the approximate geostrophic balance maintained by ocean circulation. Surface currents are thus manifested as gradients of sea height relative to the equipotential surface, or geoid. Major currents such as those found at western ocean boundaries and in the Antarctic circumpolar region have the largest dynamic height signals, 100-150 cm. These strong currents shed rings which have lifetimes of years while maintaining sea height signatures of 50-100 cm. Equatorial currents are at the lower end of the sea height range with characteristic values of 10-30 cm, and the smallest features are the mid-ocean eddies with sea height signals of 5-20 cm. Seasat, with a precision of approximately 5 cm (Tapley, et al., 1982), was therefore capable of resolving virtually all mesoscale phenomena.

2. Gulf Stream Profiles

Altimeter observations, together with precise ephemeris data, yield profiles of the instantaneous sea surface. These profiles are composed of the static geoid plus dynamic sea height due

primarily to ocean circulation. (For simplicity, we will ignore the tidal signal, since it is usually of longer wavelength and does not interfere with the detection of mesoscale features). One can therefore attempt to recover dynamic sea height by simply subtracting a gravimetric geoid model from profiles of altimeter heights. Figure 1 shows a sample of Seasat altimeter data in the western North Atlantic in which we have made use of the detailed gravimetric geoid model of Marsh and Chang (1978). The residual profile shows a step of 115 cm associated with the Gulf Stream and other depressions and elevations which match the known locations of cold and warm rings (Cheney, 1982). Surface current speeds can be computed from the measured slopes. The steeply sloping Gulf Stream profile indicates a maximum speed of 235 cm/s, a value which is in agreement with the generally accepted speed of the Stream in this region.

In Figure 2 we demonstrate how the Seasat data could have been used to produce near-synoptic maps of the Gulf Stream. During the first half of the mission, the Seasat ground track produced a global grid with approximately 150 km spacing every 17 days. One of these 17-day cycles would yield 26 crossings of the Gulf Stream between Florida and 60°W. In Figure 2 we have summarized the Gulf Stream information which was derived from these Seasat data using the detailed geoid model. North edge locations are indicated together with the maximum speed where such a determination was possible. There were five cases in which ascending and descending passes intersected each other in the Gulf Stream, and at these locations the full velocity vector could be derived.

The Gulf Stream path depicted by the altimeter data in Figure 2 agrees closely (within 20 km in most cases) with analyses of satellite infrared imagery during this time. Even details such as the known seaward deflection off Charleston, South Carolina appear in the altimetric map, and the vectors shown are consistent with the Gulf Stream flow. It is difficult to assess the accuracy of the current speeds calculated from the altimeter profiles since there are no available surface measurements with which to compare. Although the speeds are clearly of the proper magnitude, the apparent variation from 140 to 255 cm/s between Florida and Cape Hatteras cannot be verified. Downstream of Cape Hatteras the speeds are more consistent, with the exception of

Fig. 1. Altimeter data from Seasat on August 6, 1978. When the profile is differenced with an accurate geoid surface along the same track, the result is dynamic topography due to geostrophic ocean currents (bottom profile). Comparison with independent observations of the Gulf Stream, rings, and "no anomaly" regions indicates good agreement. (From Cheney and Marsh, 1980.)

the easternmost value (345 cm/s) which seems too high. An estimate of the accuracy of the speed determination might be ± 50 cm/s, much of which is probably due to error in the geoid model.

3. Global Sea Height Variability

Detailed geoid models exist only in limited regions such as the western North Atlantic, the western North Pacific (Ganeko, 1982), and the North Sea (Brennecke, et al., 1982). Geoid-independent techniques for detection of ocean current variability have therefore been emphasized in recent work. Knowledge of the distribution of eddy energy is fundamental to understanding global ocean dynamics. All major currents exhibit mesoscale sea height variability

due to meandering, and the fields of migrating rings and eddies are a secondary source of time-dependent height fluctuations. Several different altimetric approaches have been demonstrated in solving for mesoscale variability. Huang, et al. (1978) examined the temporal variability of the Gulf Stream system by comparing GEOS-3 monthly mean surfaces with a longer-term mean, revealing general features of ring migration and Gulf Stream meandering. Cheney and Marsh (1981) evaluated GEOS-3 altimeter measurements at the intersections of ascending and descending ground tracks (where the geoid contribution cancels) and produced a map of sea height variability in the Gulf Stream region. A similar GEOS-3 variability map of the Gulf Stream system was produced by Douglas and Cheney (1981) by taking

Fig. 2. Chart of the Gulf Stream determined from 17 days of Seasat altimeter data. North edge crossings and current speeds were obtained after removing a detailed gravimetric geoid model from the altimeter profiles. Where satellite ground tracks intersect in the Gulf Stream the full velocity vector can be derived, as shown by arrows.

advantage of the fact that repeated altimeter profiles along identical ground tracks also contain the same geoid signals. In addition to providing reliable statistics on sea height variability, this last repeat-track method yields a description of sea height undulations along the ground track as a function of time, thereby permitting time series analyses, and generally offers the most complete information on mesoscale dynamics.

Fortunately, Seasat's orbit during the last 25 days of the mission produced a set of global, repeated ground tracks every 3 days. From these 8-9 overlapping sets of altimeter profiles the sea height variability can be determined to within an accuracy of a few cm. The method used is illustrated in Figure 3. The ground tracks were

broken into arcs approximately 2000 km in length and a linear trend was removed from each pass. This removes both relative orbit error and long wavelength tide modeling errors. Shallow water regions (less than 1000 m) were deleted from the analysis to avoid possible contamination by short wavelength coastal tides and storm surges. After the adjustment the rms variability could be computed at each 1-second point (every 7 km) along the satellite track. The sample in Figure 3 transects the Agulhas Current south of Africa and displays the largest sea height variability found in the Seasat data set. The individual profiles show the wave-like undulations of a feature which is probably an intense eddy formed at the western extremity of the Agulhas. Peak-to-peak amplitude of the eddy is 120 cm, producing rms variability of 40 cm.

Fig. 3. Analysis of eight Seasat altimeter profiles with identical ground tracks south of Africa. After removal of a linear trend from each to account for orbit error, sea height variability due to mesoscale features can be computed directly. This series shows the largest amplitude feature seen in the Seasat data. The double peak of 30-40 cm variability is believed to be due to an eddy which has formed at the western extremity of the Agulhas Current and which is migrating parallel to the ground track. Peak-to-peak amplitude of the feature is 120 cm.

Approximately 400 Seasat ground track segments such as this were processed yielding nearly 125,000 measurements of sea height variability around the world. These values were input to an interpolation routine to obtain a uniform 2° grid of global values which were then contoured to produce the map shown in Figure 4. (Maximum variability values such as those occurring in the high-energy western boundary currents are damped considerably by the interpolation process, but the patterns of high and low variability are retained.)

The global map of mesoscale sea height variability in Figure 4 shows patterns which are quite realistic based on our knowledge of ocean circulation. Largest values define the paths of five major currents: the Gulf Stream, Kuroshio, Agulhas, Antarctic Circumpolar, and the Falkland/Brazil confluence. As expected, higher variability is most prevalent in the western parts of the oceans. This is best demonstrated in the North Atlantic where the Gulf Stream completely dominates the mesoscale eddy field between the North American coast and the Mid-Atlantic Ridge. The South Atlantic is nearly a mirror-image of the North Atlantic except that the high variability generated by the Falkland/Brazil confluence does

not extend seaward as far as the Gulf Stream. There is also a marked contrast between the highly variable western North Pacific, which is dominated by the Kuroshio, and the quieter eastern region, with the dividing line occurring near the dateline. Highest variability in the Southern Hemisphere is found off South Africa in the Agulhas Current region whose magnitude and horizontal scale are similar to the Gulf Stream. Extending eastward from the Agulhas is a series of maxima which surround the Antarctic continent and clearly trace out the path of the Antarctic Circumpolar Current.

A remarkable feature of the map is the predominance of values less than 5 cm over vast regions. Of all 125,000 global variability values, 61% were less than 5 cm, 34% were in the 5-10 cm range, and only 5% were greater than 10 cm. This broad background of low variability permits some relatively small amplitude signals to be seen. For example, equatorial currents in both the North Pacific and North Atlantic are clearly visible as zonal bands of maxima even though they fall in the 5-7.5 cm range. Other current systems detectable in the map are the Somali Current, the East and West Australia Currents, and the Iceland-U.K. Gap front.

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Fig. 4. Global mesoscale sea height variability measured by the Seasat altimeter, 15 September to 10 October 1978. The North Atlantic and North Pacific are dominated by the highly energetic Gulf Stream and Kuroshio systems which extend seaward some 4000 km. In the Southern Hemisphere the Agulhas Current below Africa and the Falkland/Brazil Current confluence off South America are apparent. High variability due to the Antarctic Circumpolar Current extends in a nearly continuous band around the polar oceans.

4. Conclusions

Satellite altimetry has the potential to play a significant role in ocean circulation studies through its capability for rapid, global observation of sea surface topography. Where detailed geoid models are available, reasonably accurate dynamic height profiles of western boundary currents can be produced, and near-synoptic maps of current velocity can be obtained. At the present time, however, the primary contribution of altimetry is in the determination of sea height variability. Of the different techniques that have been applied, the repeat-track method provides the most complete information. We have used this technique in an analysis of the Seasat repeat-track data and have produced a global variability map which provides a strikingly realistic view of ocean circulation and mesoscale energetics.

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