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THE EFFECTS OF ATMOSPHERIC WATER VAPOR ON THE LOCATION OF OCEAN FEATURES BY THE GEOSAT ALTIMETER

Water vapor in the atmosphere increases the round-trip travel time of Geosat altimeter pulses. Variations in water vapor along the satellite ground track cause changes in the ocean surface topography estimated by Geosat. Such changes can be interpreted as ocean features or can mask ocean features that are actually present. Using radiometer data from the Seasat satellite to estimate water vapor variability, we can assess the probability of such misinterpretations by using and interpreting Geosat data in the context of regional circulation models.

INTRODUCTION

Just as short-term variability in atmospheric circulation patterns constitutes changes in local weather, mesoscale variability in ocean circulation patterns may be considered as the weather of the oceans. Unlike atmospheric weather, however, which changes on time scales of days, ocean weather changes on time scales of weeks.

Fronts and eddies are found in many regions of the oceans on horizontal spatial scales of 100 to 300 km (i.e., the mesoscales). The current flow caused by the balance of the horizontal components of gradients of pressure and Coriolis forces (geostrophic flow) is accompanied by changes in ocean surface topography. For example, ocean surface topography changes by a meter or more across the Gulf Stream, and Gulf Stream rings exhibit height signatures from 20 to 50 cm or even greater.

One of the most important applications of satellite radar altimetry is the location of mesoscale circulation features. Mesoscale eddies are believed to account for much of the kinetic and potential energy of the oceans. A more complete understanding of the dynamics of ocean circulation has significant implications for climatic studies. Additionally, mesoscale circulation features affect underwater acoustic propagation and are therefore of operational interest to the Navy.

Figure 1A is a contour map of ocean surface topography caused by Gulf Stream circulation, as described by a regional circulation model developed at Harvard University.[1] The left-slanting line across the region between 56°W and 60°W longitude indicates a Geosat ground track. In Figure 1B, sea surface height as measured by the Geosat altimeter is plotted as a function of degrees latitude for the ground track segment shown in Figure 1A. The locations of the edge of the Gulf Stream and an associated ring are indicated in Figure 1B by the relatively sharp changes in altimeter-measured height.[2,3] These precise Geosat locations serve to constrain and reinitialize the circulation model, thereby improving predictive skill.

Unfortunately, atmospheric weather patterns can interfere with the location of circulation features. Atmo-

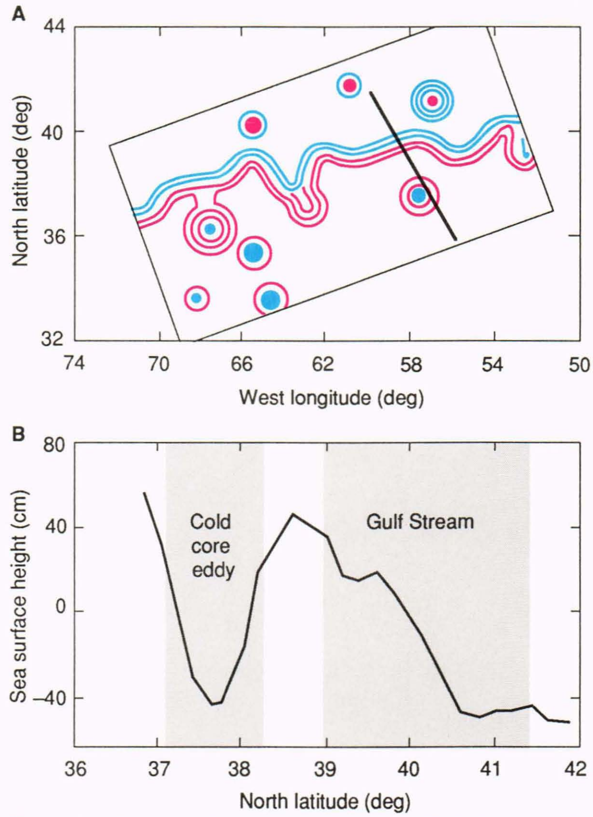

Figure 1. Ocean surface topography of the Gulf Stream region. A. Contour map of the topography caused by Gulf Stream circulation, as described by the Harvard model. The black lines represent a sea surface height equal to the height of the central axis of the Gulf Stream, the blue lines represent positive heights above the center of the Gulf Stream axis, and the red lines indicate heights lower than the Gulf Stream axis. The contour interval is 10 cm. For the rings, a blue center indicates a cold ring, and a red center indicates a warm ring. The left-slanting line between 56°W and 60°W longitude indicates a Geosat ground track. B. Elevations measured by the Geosat altimeter for the ground track segment shown in part A. The locations of the edge of the Gulf Stream and an associated ring are indicated by the relatively sharp changes in height. (Reprinted with permission from Ref. 2, pp. 18–20.)

spheric water vapor reduces the propagation speed of the altimeter's radar pulse and appears to lengthen the path experienced by the pulse. The abrupt changes in atmospheric water vapor that sometimes accompany atmospheric fronts cause changes in the apparent measured range to the surface, and such changes may mimic ocean circulation signatures.

THE PHYSICAL PHENOMENON

The index of refraction for a material, n, is the ratio of the speed of light in a vacuum, c, to its speed in the material. The larger the index of refraction of a material, the slower that electromagnetic waves propagate through it. The Geosat altimeter fundamentally measures time differences—the time differences between the transmission of radar pulses and their reception after reflection from the ocean surface. From this time difference, the height of the altimeter above the surface is inferred. The slowing of the wave propagation speed by the atmosphere increases the round-trip travel time and makes the ocean surface seem further away.

Moreover, the atmosphere is not a vertically homogeneous medium; the index of refraction changes with altitude. The variation of the index of refraction with altitude can be described by a continuous function, $n(z)$, where z is the height above the surface. The one-way travel time, t, through the atmosphere is given by

$$t = \frac{1}{c} \int_0^{h_{sat}} n(z)\, dz \; , \qquad (1)$$

where h_{sat} is the geometric height of the satellite.

We are concerned here with the small increase in travel time caused by atmospheric water vapor. For any particular parcel of air, the index of refraction can be estimated by

$$n = \frac{Ae}{T^2} \; , \qquad (2)$$

where e is the partial pressure of water vapor in millibars, T is the temperature in kelvins, and $A = 1.373$ K^2/mbar at the Geosat radar frequency of 13.5 GHz.[4] Consequently, if the variations of both water vapor pressure and temperature with altitude are known, the increase in travel time and hence the height correction associated with atmospheric water vapor can be computed by using Equation 1.

The most direct means of determining these profiles is by using either balloon- or rocket-lofted radiosondes. Geosat, however, makes worldwide measurements, and it is impractical to acquire radiosonde data at more than a few locations along any Geosat ground track. Methods to infer the height correction associated with water vapor must therefore rely on more indirect schemes.

Saastamoinem[5] integrated Equation 1 by using the water vapor pressure and temperature at the surface to infer the profiles of vapor pressure and temperature with altitude. Specifically, he assumed that temperature in the lower troposphere decreases linearly with altitude according to the relation $T(z) = T_s + \Gamma z$, where T_s is the surface temperature and Γ is the adiabatic lapse rate. He also assumed that the partial pressure of water vapor varies adiabatically with altitude according to $e(z) = e_s[T(z)/T_s]^{-k}$, where $k = 4g/R\Gamma$. Here, e_s is the surface vapor pressure, g is gravitational acceleration, and R is the gas constant of dry air. The validity of this approach was recently confirmed by Bisagni,[6] who compared estimates of the increase in travel time based on radiosonde data with estimates derived from the Saastamoinem model, as initialized with surface temperature and water vapor pressure measurements in the western North Atlantic, and found agreement to about 5 cm.

On a global basis, water vapor corrections to the Geosat-measured height can be estimated by using atmospheric model predictions of surface temperature and water vapor pressure, produced operationally by the Fleet Numerical Oceanography Center (FNOC), to initialize the Saastamoinem model. This correction is routinely supplied with Geosat data on tapes produced by the National Oceanic and Atmospheric Administration.[7] The FNOC predictions, however, are produced on a 1° by 1° longitude–latitude grid. Even given a perfect model, these predictions do not have the spatial resolution to account for the type of abrupt water vapor change that could be mistaken for or mask a circulation feature.

An alternative approach to obtaining water vapor corrections involves the use of spaceborne microwave radiometers. By using the known absorption properties of water vapor at different frequencies, the total integrated water vapor in a column beneath the spacecraft can be measured.[8] Just as the Saastamoinem model permits the integration of Equation 1 if surface measurements of water vapor pressure and temperature are given, the increase in travel time experienced by an altimeter pulse can be inferred if the total columnar water vapor measured by a spaceborne radiometer is given.[4,9] Again, one must assume that the atmosphere behaves like an ideal gas and that tropospheric temperature varies linearly with altitude.

The water vapor height corrections made from satellite radiometers are particularly useful if they can be made from the altimeter spacecraft itself because this method ensures that the radiometer and altimeter sample the same part of the atmosphere at the same time, thereby minimizing the necessity of spatial and temporal interpolation. Even if the inferred water vapor correction is not perfectly accurate, the radiometer measurement is precise and will reveal changes in water vapor as the satellite ground track crosses an atmospheric front.

Radiometer measurements made by instruments such as the special sensor microwave imager on board a Defense Meteorological Satellite Program platform and the operational vertical sounder of the television infrared observation satellite (TIROS) can be useful in interpreting Geosat altimeter data.[10] The special sensor microwave imager has a ground resolution of 25 km and a swath width of nearly 1440 km, and the TIROS operational vertical sounder has a resolution between 20 and 60 km, depending on its position within its 2240-km swath.[11] The resampling and interpolation required to remap the data onto the Geosat ground track at the Geosat overpass time are difficult, however, and can introduce their own additional errors.

The Seasat satellite was equipped not only with a radar altimeter but also with a scanning multichannel microwave radiometer (SMMR) able to measure total columnar atmospheric water vapor with a horizontal resolution of about 50 km.[12] Figure 2 is a histogram of the difference between the SMMR-estimated water vapor correction to the Seasat altimeter range measurement and the corresponding correction based on estimates of surface pressure and temperature derived from FNOC predictions. The data shown consist of about 350,000 independent comparisons obtained over the entire three-month Seasat lifetime for all regions of the Earth.

The FNOC predictions are consistent with the SMMR-based water vapor correction estimates to within a mean difference of a fraction of a centimeter, which is certainly small when compared with the Geosat height measurement precision of 3 cm.[13] The predictions, however, do not account for a considerable amount of variability in water vapor that occurs on the horizontal scales required to resolve ocean mesoscale features. The standard deviation of the difference between SMMR- and FNOC-based water vapor corrections is more than 5 cm, consistent with the results of Tapley et al.[9] Much of this variability is associated with the finer horizontal spatial scales measured by the SMMR. The salient point to be emphasized is that even if FNOC-derived water vapor predictions were perfect, they are not made at a resolution high enough to be useful in detecting mesoscale circulation features.

VARIABILITY ASSESSMENT

Investigators at APL and Harvard University have developed new and highly useful techniques to process and interpret Geosat height signatures (Ref. 14 and Porter et al., elsewhere in this issue). Basically, these techniques involve the incorporation of Geosat-measured height variations into Harvard's regional ocean circulation model. The Geosat data are used to adjust the location of circulation features in the model. Of importance to our discussion is that these techniques involve looking for the abrupt changes in Geosat height measurements on horizontal spatial scales consistent with mesoscale circulation. Slow variations of the water vapor correction on horizontal scales greater than 300 km are not relevant to this application.

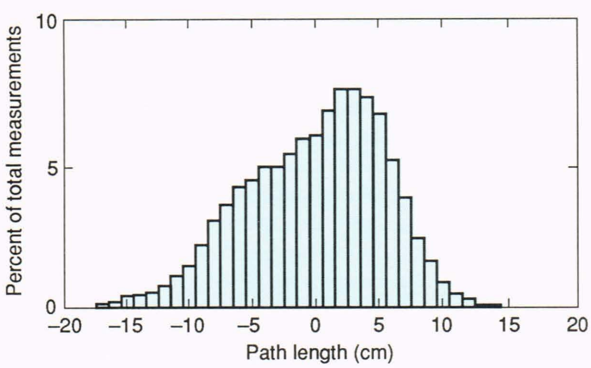

Figure 2. Histogram of the difference between SMMR- and FNOC-based water vapor corrections to an altimeter height measurement of the Earth. The mean is 0.06 cm, and the standard deviation is 5.5 cm; there were 350,000 measurements taken.

The lack of a radiometer aboard Geosat may adversely affect the retrieval of ocean features when using either no water vapor corrections or corrections derived from FNOC predictions. To ascertain the potential problem that water vapor may pose for mesoscale circulation feature detection, we examined the SMMR-derived water vapor corrections used for the Seasat altimeter. At the time of this study, SMMR data were the most readily available. Additionally, because Geosat is a near repeat of the Seasat ground track, the Seasat SMMR sampled the water vapor field in a manner similar to Geosat. We also considered the FNOC-based corrections because they are routinely applied to Geosat altimeter height data. It is important to remember that the mean value of the water vapor height correction is not relevant to mesoscale feature detection. If the effect of water vapor is large but constant, it will not be mistaken for an oceanic feature.

Water vapor height corrections estimated by the SMMR and FNOC for the five geographic regions shown in Figure 3 and the entire Earth were examined. The five regions are listed as follows, along with indications of the reasons for our interest in them.

1. GIUK Gap: In the Greenland–Iceland–United Kingdom (GIUK) Gap region, APL and Harvard collaborators have expended considerable effort to successfully extract small, circulation-induced height signals in the 10- to 30-cm range over 100-km spatial scales.
2. Gulf Stream: This western boundary current region contains both large mesoscale circulation signatures and a high mean level of water vapor. The Gulf Stream

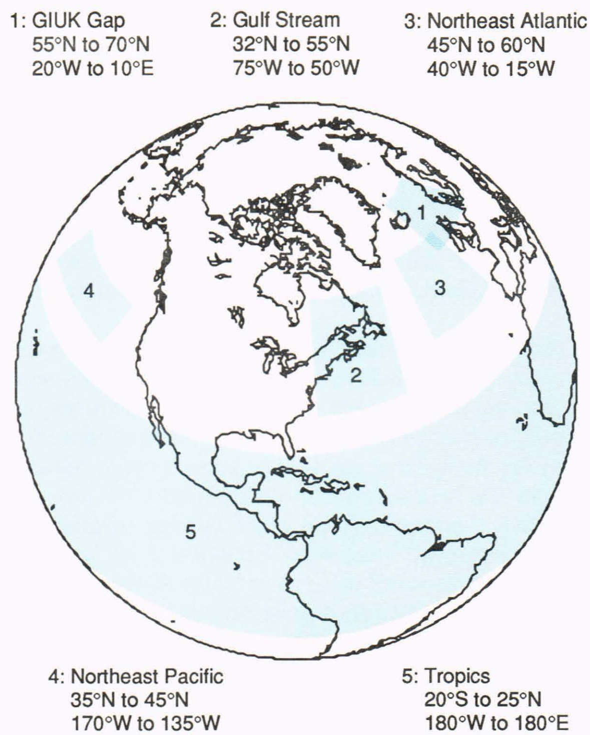

Figure 3. Specific regions of the Earth examined in addition to the Earth itself.

itself has a height signature on the order of 1 m, whereas rings have height signatures of 20 to 50 cm or larger.

3. Northeast Atlantic: A major circulation experiment named Athena was conducted in this region of the North Atlantic in 1988.[15] This region exhibits sea surface height variations on the order of 40 cm over 100 km.

4. Northeast Pacific: The Northeast Pacific region, similar to the GIUK Gap, exhibits small frontal signals on the order of 5 to 30 cm in height over 100 km that pose a demanding test of the ability of various altimeter data-processing techniques to locate ocean features.

5. Tropics: The tropics are of interest not because of mesoscale circulation, but because this region exhibits large water vapor corrections and may have large spatial gradients in water vapor.

Water vapor height corrections along the Seasat altimeter ground track that were estimated by the SMMR and FNOC were extracted for segment lengths of 100, 200, 300, 500, and 1000 km. These segments composed our basic data set. Figure 4 is an example of the variation of the water vapor height correction over a 300-km segment from the Northeast Pacific region. The black line is the SMMR water vapor correction, the red line is the FNOC-derived correction, and the blue line is the difference between the two corrections. If we assume that the more accurate SMMR gives the true water vapor correction (at least at the SMMR's resolution), then the difference signature represents the residual water vapor signal that would remain in an altimeter signature after applying the FNOC-derived water vapor correction.

The abrupt change of 18 cm in the water vapor height correction over about 150 km within the 300-km segment, as shown in Figure 4, would, if mistaken for a front, lead one to deduce an ocean current of 20 cm/s, an energetic feature. This water vapor signature is the type that poses a problem for the location of mesoscale features from Geosat data. The question is "How likely are such events?" We can use data segments like the one shown in Figure 4 to address this question.

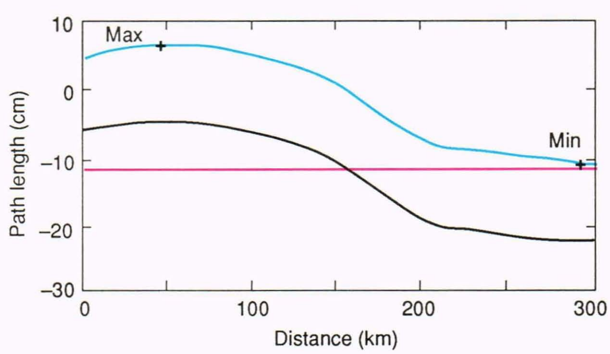

Figure 4. Example of an abrupt change of 18 cm in the water vapor height correction over about 150 km within a 300-km segment from the Northeast Pacific region. If mistaken for a front, this change would lead one to deduce an ocean current of 20 cm/s, an energetic feature. The black line is the SMMR water vapor correction, the red line is the FNOC-derived correction, and the blue line is the difference between the two corrections. The points marked "max" and "min" indicate the maximum and minimum values of the height correction, respectively.

Let $W_d(x)$ represent the variation in the difference between the SMMR and FNOC water vapor corrections as a function of distance x. Figure 4 shows two points labeled "max" and "min" that mark the maximum, W_d^{max}, and minimum, W_d^{min}, values of the height correction within this segment, respectively. The greatest change in the residual water vapor correction signature in the segment, Δ_d, is given by

$$\Delta_d = |W_d^{max} - W_d^{min}| \ . \tag{3}$$

The value of this maximum change in the water vapor correction was calculated for each of the segments compiled from the Seasat data.

For each of the six regions studied, Figure 5 shows a set of cumulative probability distributions indicating the likelihood of finding a path length change, Δ_d, equal to or greater than the abscissa; the five curves for each region correspond to the segment lengths shown in kilometers. The distributions do not, however, directly predict the probability of a water vapor event either causing a fictitious circulation feature to appear in the altimeter data or masking the presence of an existing feature.

The solid black curve for the GIUK Gap region in Figure 5 indicates that for the 1662 segments of 100 km extracted from this region, a 1% probability existed that the maximum change in the water vapor correction was greater than or equal to about 6 cm in any particular segment. The other curves for the GIUK Gap region in Figure 5 demonstrate that the longer the segment considered, the greater the probability of having a large excursion in the water vapor correction. Longer segments contain variations that occur on both long and short horizontal spatial scales, but only variations on the smaller scales concern us here.

The graphs in Figure 5 reveal that for all the regions, the probability of finding a water vapor correction change of 10 cm or greater in any particular altimeter ground track segment of 200 km is at most 2%; larger water vapor signatures are even less common. These small probabilities do not tell the complete story, however. Assessing the probability of the misinterpretation of Geosat data is very dependent on how those data are used and interpreted.

Even though the probability is small of finding a water-vapor-induced height change of consequence within any particular segment, if Geosat altimeter data are used as a coarse means to promiscuously scour large expanses of ocean for frontal features, the probability of encountering water vapor events that could mislead us somewhere in that search becomes greater. The low probabilities given in Figure 5 do not justify ignoring the potential problems of water vapor.

Although the collaborative work between APL and Harvard has employed various techniques of processing Geosat altimeter data to locate the position of ocean features, the interpretation of these features has been performed not *ex nihilo*, but rather in the context of a regional circulation model.

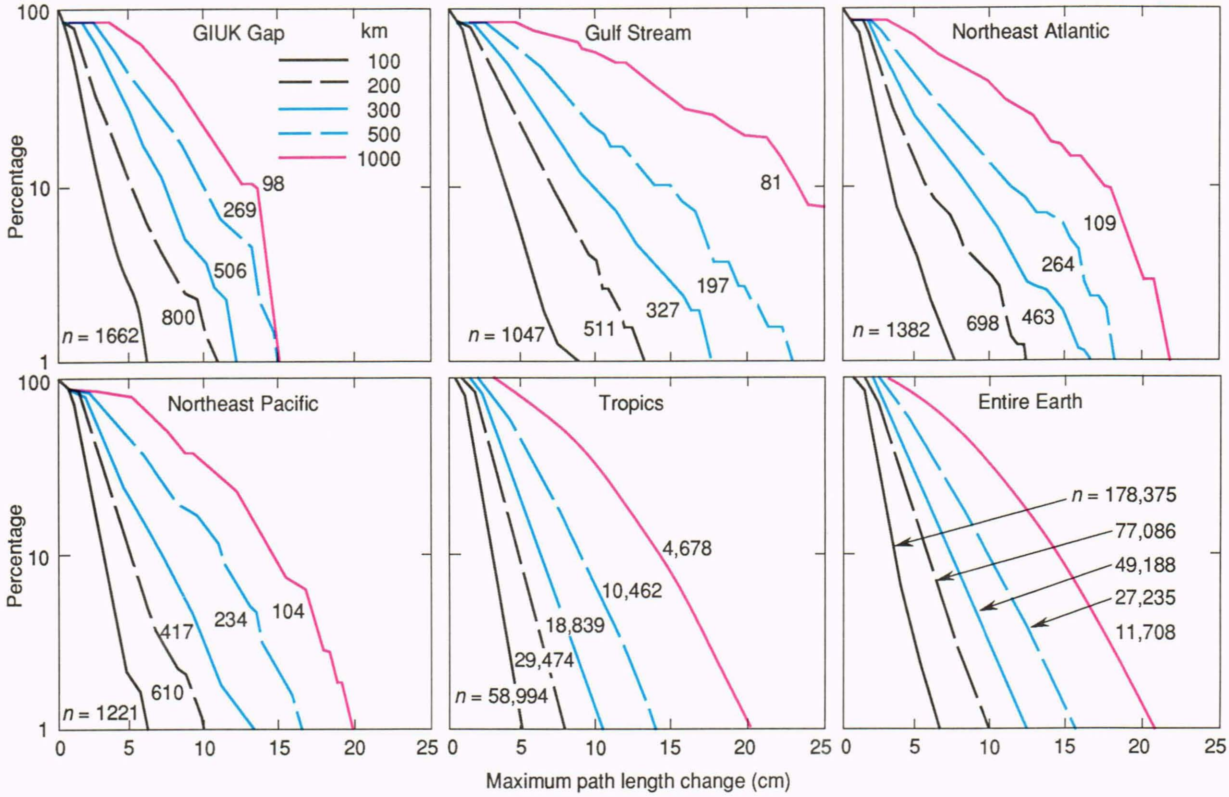

Figure 5. The probability of finding a change in the difference between the SMMR and FNOC water vapor corrections greater than the abscissa for the segment lengths shown in kilometers for the various regions studied. The values of *n* on the graphs are the numbers of segments used to calculate the probabilities. The percentage along the *y*-axis refers to the percentage of segments having a maximum height change greater than or equal to the abscissa.

As an example of how Figure 5 is to be used, let us assume we are concerned about water-vapor-induced path length changes of 10 cm that occur on horizontal scales of 200 km or less. A change of 10 cm is chosen because many circulation features of interest have signatures larger than this, and, given the 3-cm precision of the altimeter, looking for much smaller features would be difficult. Further assume that we are using Geosat to locate frontal positions to within a meander range of 1000 km. Then, the probability of encountering a potentially misleading water vapor event equal to or greater than 10 cm is the probability of finding such an event in one or more of nine 200-km segments. We use nine because of the five 200-km segments that fit into 1000 km and the four overlapping 200-km segments that account for water vapor changes extending across adjacent 200-km segments. We would not, however, use the curve for 1000 km in Figure 5. The probabilities taken from this curve include water vapor changes that occur on horizontal scales greater than, as well as smaller than, 200 km.

In the GIUK Gap region, the meander range of the dominant front, which is tied to the Iceland–Faeroe ridge, is about 200 km. The search for the front is thus limited to a small region. The probability of encountering a 10-cm change or greater in the water vapor correction is given by the 200-km curve for the GIUK Gap region in Figure 5, or about 2%.

The Harvard circulation model, as currently implemented in a subset of the Northeast Pacific area, can use Geosat altimeter data to help locate fronts as small as 10 cm. Let us assume the worst: that the positions of the fronts are not known at all to within the 600-km domain of the model. The probability of finding a 10-cm water vapor event or larger on scales less than 200 km is the probability of such an event occurring in one or more of five 200-km segments. According to Figure 5, the probability of finding such an event within any particular 200-km segment in the Northeast Pacific region is slightly less than 2%. Therefore, the probability of a water vapor event within the 600-km domain of the model is about 10%.

Of course, as one looks for smaller and smaller circulation features whose positions are unknown to within larger and larger areas, the probability of being misled by water vapor grows. For example, if one looks for mesoscale circulation features of 5-cm height, which may be common in the Northeast Pacific region, and if one has no idea of the position of these features to within 2000 km, then an 88% probability exists of finding a water vapor signature of this magnitude in the Northeast Pacific region. The curves given in Figure 5 provide the means of assessing these probabilities for different uses of Geosat data. The use of these statistics has been explained more thoroughly by Monaldo.[16]

A change in the water vapor correction as large as the 1-m change that characterized western boundary currents was never experienced in the Seasat SMMR data set we examined. It is, therefore, highly unlikely that water vapor will ever interfere with the location of the Gulf Stream. Similarly, Gulf Stream rings are so large that even over rather large meander ranges, the likelihood of encountering similarly sized water vapor correction changes is negligibly small. The circulation features in the Northeast Atlantic region are similar to Gulf Stream rings in size and magnitude. Thus, water vapor is generally not a problem in this region either.

The manner in which Geosat data are to be processed is extremely important in evaluating the impact of water vapor. At least three techniques can be used to remove short-scale geoid signatures from altimeter data before searching for mesoscale circulation features (see Porter et al., elsewhere in this issue).

The first technique involves subtracting a current Geosat track of height data from a previous collinear track of data. The geoid signature is stationary, so it subtracts out. If the previous track is selected properly, the feature in the current track should stand out in the difference signal.

The second technique involves calculating the mean Geosat height signature from many repeat cycles over the same ground track. The mean height data include height variations due to both the geoid and the mean circulation. Subtraction of a current Geosat track from this mean removes the geoid signature. If the mesoscale feature in the current set of data resembles the mean circulation signal, however, then subtracting this mean significantly reduces the circulation signal magnitude. In this context, water vapor events smaller than those usually considered could be mistaken for circulation features.

The third technique is to generate a synthetic geoid from altimeter data. The mean Geosat height signature is subtracted from the mean oceanography signal, as calculated by a regional ocean feature model, to form the synthetic geoid. Future Geosat passes over a ground track for which a synthetic geoid has been computed can be differenced with this synthetic geoid. The residual signal can then be ascribed to circulation signatures. Again, if performed properly and if the circulation model is adequate, this technique can avoid both reduction in the size of the signature and potential confusion with smaller water vapor events. Porter et al. (elsewhere in this issue) provide a more thorough discussion of the various altimeter signal-processing techniques.

Signal-processing techniques have been mentioned here to emphasize that judging the impact of water vapor on Geosat altimeter data requires an understanding of the context in which the data will be used and the processing techniques to be employed. It is expected that when using the "difference-from-the-mean" technique, the reduced circulation signatures could suffer additional interference from spatial gradients in atmospheric water vapor.

CONCLUSIONS

The presence of water vapor in the atmosphere can cause changes in the sea surface topography estimated by Geosat radar altimetry; such changes can confuse the interpretation of mesoscale circulation signatures. If used in the context of circulation models having limited domains over which frontal positions are unknown, water vapor gradients are not likely to interfere with the location of fronts having elevations as small as 10 cm.

Of the regions we considered here, the GIUK Gap and the Northeast Pacific regions pose the greatest challenge. Because of the small meander range of the front in the GIUK Gap region, the probability of a water vapor event being confused with an ocean feature is about 2%. In the Northeast Pacific region, if the positions of the fronts are not known to within the 600-km domain of the Harvard model, the probability of a 10-cm water vapor event or larger is 10%.

In assessing the probabilities of such events by using the data given in this article, care must be taken to consider the techniques that are in use for any particular Geosat application. For very energetic events, that is, 30 cm or greater, water vapor should pose minimal problems in feature location.

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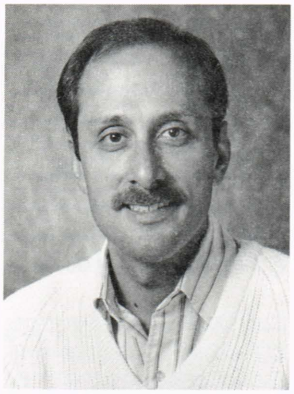

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