An Apparent Wave Height Dependence in the Sea-State Bias in Geosat Altimeter Range Measurements

Donna L. Witter and Dudley B. Chelton

College of Oceanography, Oregon State University, Corvallis

The sea-state bias in Geosat altimeter range measurements expressed as a percentage of significant wave height (SWH) is examined as a function of SWH. The bias is shown to be approximately a fixed −3.5% of SWH for SWH smaller than about 4 m. For larger SWH, the bias decreases in magnitude approximately linearly to a value of about −1.5% of SWH for 6 m SWH. Because of this "saturation effect" associated with large SWH, estimates of the Geosat sea-state bias which have been based on the assumption of a fixed percentage of SWH are too small by up to 1.5% of SWH. The saturation effect is so large at high latitudes in the southern hemisphere (where about 1/4 of the SWH values exceed 4 m) that it apparently overwhelms any wind speed dependence in the sea-state bias suggested by several recent studies. The apparent SWH dependence found in this study appears to be the result of attitude and sea-state errors in the Geosat altimeter on-board tracking algorithm.

1. Introduction

To resolve sea surface height variability associated with geostrophic ocean currents, each component of error in altimeter range measurements must be corrected to within an accuracy of 2–3 cm. A large source of error in the range measurement is the sea-state bias, which consists of two parts, the electromagnetic (EM) bias and the skewness bias. Both components combine to drive altimeter estimates of mean sea surface height below true mean sea level. The altimeter range measurements must also be corrected for antenna mispointing effects that have been found to be approximately quadratically related to satellite attitude angle and SWH [*Hayne and Hancock*, 1990]. Although all of these biases are known to arise because of the presence of waves on the sea surface, the exact nature of these errors in the range measurement is not completely understood. Theoretical models often express the total sea-state bias in terms of quantities which are not recoverable from altimeter measurements [see *Jackson*, 1979; *Barrick and Lipa*, 1985; *Srokosz*, 1986], and hence these models cannot be used to correct the bias from altimeter data alone. Models derived empirically from altimeter measurements presently offer the best hope for obtaining an accurate correction.

Largely as a matter of convenience, the sea-state bias has generally been expressed as a fixed percentage of significant wave height [*Born et al.*, 1982; *Douglas and Agreen*, 1983; *Cheney et al.*, 1989; *Zlotnicki et al.*, 1989; *Nerem et al.*, 1990]. Uncertainty in the bias coefficient, a multiplicative factor of significant wave height (SWH), is the primary source of error in these estimates of the correction. For most applications, this coefficient is computed based on statistical fits to observations comprising a wide range of sea-state conditions – a method which does not differentiate between seas with the same SWH but with different physical characteristics (e.g., wind waves versus swell). In an attempt to improve on this representation of the bias correction, two models which parameterize the bias as a

function of both significant wave height and wind speed have recently been developed. *Ray and Koblinsky* [1991] have derived an empirical model which represents the bias correction as a linear combination of SWH and the product of SWH and wind speed, and a physically based model which expresses the bias correction in terms of SWH and pseudo wave age (a measure of wave development) has been proposed [see *Fu and Glazman*, 1991]. Empirical coefficients for the wave age model were computed by *Fu and Glazman* [1991] based on a subset of the Geosat observations.

In this paper, we analyze 25 months of southern hemisphere Geosat altimeter data to investigate the validity of an assumed constant sea-state bias coefficient over the full range of SWH. The details of this data set are summarized briefly in section 2. The nature of the sea-state bias is investigated separately for middle and high southern latitudes and the sea-state bias coefficient is examined as a function of SWH in section 3. Alternative possible explanations are considered in section 4 for an apparent SWH dependence in the bias found in section 3.

2. Geosat Data Set

Geosat data from 46 cycles of the Exact Repeat Mission (November 8, 1986 to December 31, 1988) were obtained from the NASA Ocean Data System (NODS) at the Jet Propulsion Laboratory. The altimeter-measured heights had been preprocessed by NODS to correct for wet and dry tropospheric range delays, ionospheric range delays, the inverse barometer effect, and solid earth and ocean tides [see *Zlotnicki et al.*, 1990]. The data were screened to eliminate observations with off-nadir pointing angles greater than 1° and to eliminate observations contaminated by sea ice. The contribution to the height measurement due to the marine geoid and a sinusoidal orbit error estimate were then removed as described by *Chelton et al.* [1990]. Only observations between 10°S and 65°S are analyzed in this study. This data set is well-suited for an investigation of the sea-state bias, since it includes the full range of wave heights and wind speeds found globally. Large wave heights and high wind speeds are particularly well represented since this region includes the Southern Ocean.

3. WAVE HEIGHT DEPENDENCE

In the most commonly applied sea-state bias model, the bias is expressed as

$$h_{ssb} = \alpha \cdot SWH, \qquad (1)$$

where h_{ssb} is the contribution to the height measurement due to the sea-state bias, and α is the bias coefficient. As noted in section 2, heights are expressed as deviations from the time-mean at each location and a one cycle per orbit sinusoidal fit to each ground track. These are referred to here as "relative" heights to distinguish them from raw heights inferred from altimeter range measurements. Empirical estimates of the sea-state bias must be derived based on these relative height data (see discussion in *Zlotnicki et al.* [1989]). To maintain consistency with this treatment of the height data, the SWH data must be processed similarly. Accordingly, the time-mean at each location and a least squares sinusoidal fit (with a wavelength of one cycle per orbit) were subtracted from the SWH data along each ground track. The resulting data are referred to here as "relative" SWH.

Previous studies of the sea-state bias in Geosat measurements have focused on obtaining a single sea-state bias coefficient assumed to be constant over the full range of SWH [*Cheney et al.*, 1989; *Zlotnicki et al.*, 1989; *Nerem et al.*, 1990]. In this section we examine the relationship between altimeter height and SWH measurements in more detail to evaluate the validity of the assumed linear relationship for all SWH. To investigate the stability of the results, the data are separated into northern (10°S–40°S) and southern (40°S–65°S) latitudinal bands and analyses are performed separately for each band. The 40°S dividing latitude was chosen to distribute the observations approximately evenly between the tropical-subtropical northern band (where wave heights and wind speeds are generally small) and the polar-subpolar southern band (where wave heights and wind speeds are generally larger).

Representative relative height and relative SWH data from the southern band are shown in Figure 1 for cycle 7 of the Geosat ERM (February 18 to March 7, 1987).
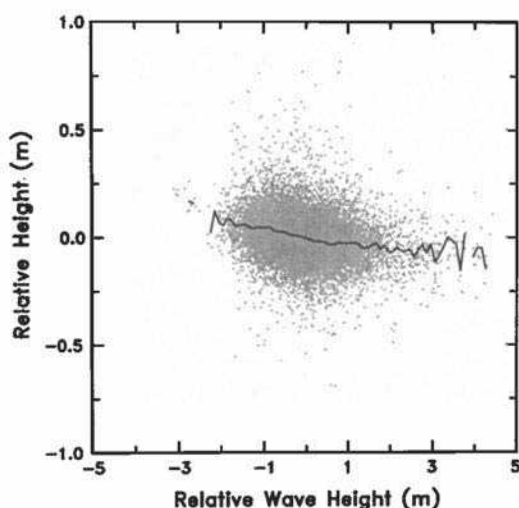

Fig. 1. Relative height and relative SWH data for the latitude band 40°S–65°S from cycle 7 of the Geosat Exact Repeat Mission (February 18 to March 7, 1987). Each data point represents an average over 70 km in the along-track direction. The solid line shows the average relative height in each 0.1 m relative SWH bin.

Each point on the plot represents an average over a group of 10 consecutive measurements (70 km in the along-track direction); negative values appear on both axes since relative values are, by definition, deviations from the long-term mean and a sinusoidal fit at each location. The scatter shown in Figure 1 results from a combination of variability due to (1) true dynamic sea level changes, (2) residual height errors, including those associated with the sea-state bias, as well as errors in other components of the altimeter height measurement, and (3) errors in the altimeter estimate of SWH. It is immediately apparent from scatter plots such as Figure 1 that any systematic, SWH-dependent component of the height estimate is small compared with variability due to other sources. This is fortunate, as a close relationship between relative height and relative SWH in Figure 1 would imply an overwhelming sea-state bias, which would make it difficult to detect sea level variability associated with ocean circulation using altimetry.

The systematic, SWH-dependent component of the height measurement can be isolated by averaging all relative height values as a function of relative SWH. For the data plotted in Figure 1, averaging in SWH bins of width 0.1 m produces the profile indicated by the solid line. This averaging effectively eliminates random height fluctuations due to other sources, thus focusing on variability in the height measurement due to a SWH-dependent bias. For bins containing a sufficiently large number of observations, the non-zero slope of the averaged profile indicates a clear relationship between relative height and relative SWH; relative height decreases approximately linearly with increasing SWH. The erratic behavior near the ends of the profile is due to sampling variability from the small numbers of observations in the extreme relative SWH bins. The linear bias coefficient α in (1) for this particular cycle of the Geosat ERM is given by the slope of the profile in Figure 1; the negative slope indicates a negative bias (i.e., toward wave troughs).

Profiles such as that shown in Figure 1 were generated separately for the northern and southern bands for each of the 46 cycles of the ERM analyzed here. For each band, the average of the 46 individual profiles are plotted in Figure 2a for all relative SWH bins containing more than 40 observations. Note that much of the sampling variability at the extreme values of relative SWH is eliminated in these overall average profiles. The one-parameter expression (1) for the sea-state bias can be seen to be a good approximation for the SWH-dependent component of the bias for relative SWH from about −2 m to about 0.5 m. For this range of relative SWH, the relationship between relative height and relative SWH is very nearly linear and the bias coefficient (given by the slope of the profile) is similar in the northern and southern bands. For relative SWH greater than 0.5 m, both profiles flatten out (particularly for the southern band). This flattening is a robust feature of profiles from both latitude bands (see, for example, Figure 1) and is therefore not an artifact of sampling variability in bins with high relative SWH values. The sensitivity of the sea-state bias to SWH is evidently reduced at high relative SWH values.

Since the bias coefficient is estimated from the slope of profiles such as Figure 2a, α depends strongly on the range of relative SWH values included in the data set used
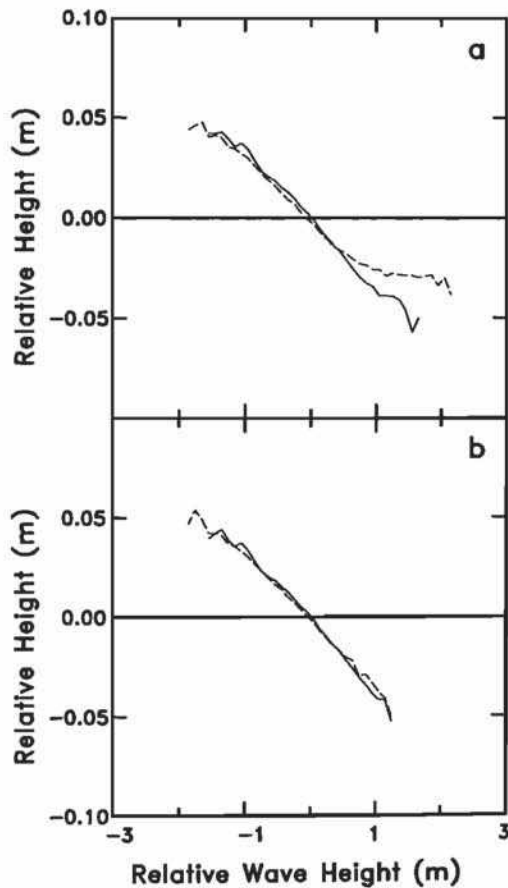
Fig. 2. The 46-cycle averaged relative height profile for latitude bands 10°S–40°S (solid line) and 40°S–65°S (dashed line). Relative heights are shown only for relative SWH bins containing more than 40 observations from at least five Geosat cycles. Profiles were computed based on data including (*a*) the full range of SWH values and (*b*) only SWH values between 0 and 4 m.
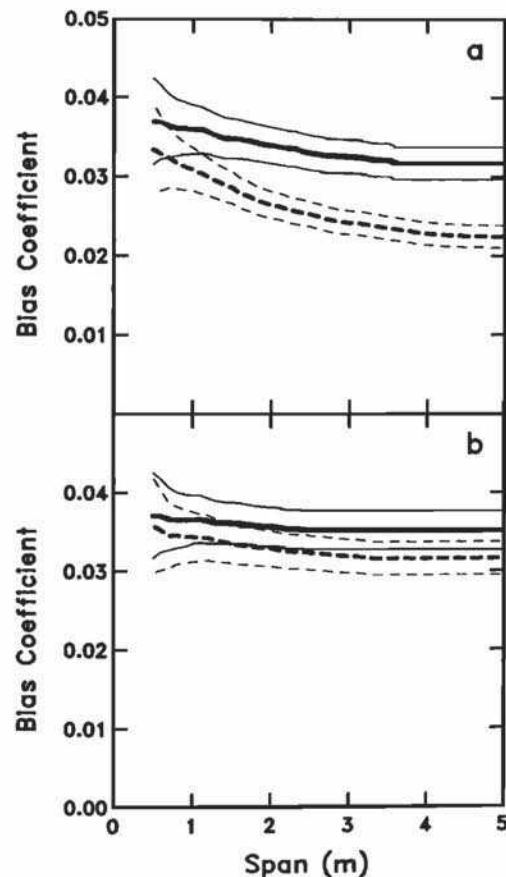

Fig. 3. Bias coefficients for the one parameter model computed as a function of the span width of relative SWH values included in the data set. Span values on the horizontal axis indicate the maximum and minimum relative SWH on the span (e.g., a span value of 0.8 m corresponds to relative SWH values between ±0.8 m). Coefficients and their one standard deviation uncertainties are shown for the latitude band 10°S–40°S (solid lines) and 40°S–65°S (dashed lines). The coefficients were estimated based on data including (*a*) the full range of SWH values and (*b*) only SWH values between 0 and 4 m.

in least squares determination of the coefficient. Figure 3 shows estimates of α for the northern and southern bands as a function of the range of relative SWH values used to compute the coefficient. Each estimate of the bias coefficient was calculated from weighted least squares fits of (1) to the averaged profiles in Figure 2*a*. The weighting for each relative SWH bin in Figure 2*a* was proportional to the inverse of the relative height standard deviation in that bin and only bins containing observations from more than eight Geosat cycles were included. This weighting procedure yields a simple estimate of the uncertainty of the bias coefficient [see *Draper and Smith*, 1981]. The error bars shown in Figure 3 correspond to the one standard deviation uncertainty in estimates of α.

As shown in Figure 3*a*, the magnitude of the bias coefficient decreases as the span width increases, particularly in the southern band. The flattening of the profiles in Figure 2*a* at large values of relative SWH reduces the slope of a least squares fit straight line through wide spans of relative SWH. For the northern band, the negative slope decreases from –0.036 for a 1 m span to –0.032 for 5 m span. For the southern band, the slope decreases from –0.031 to –0.022 for the same span widths.

A physical interpretation of the flattening is difficult when the data are presented in terms of relative SWH as

in Figure 2*a*; each relative SWH value corresponds to a wide range of true SWH values. However, the average true SWH value corresponding to each 0.1 m relative SWH bin (Figure 4) suggests an explanation for the flattening. In both bands, high relative wave heights are generally associated with high true wave heights, although individual measurements may deviate from this trend. The flattening at high relative SWH in Figure 2*a* may therefore indicate a reduced sea-state bias at high true SWH values.

To investigate this possibility, altimeter SWH observations were grouped into true SWH bins of width 0.5 m and an estimate of the bias coefficient was computed for each bin. Observations from the two latitude bands were combined to increase the number of data points in each bin, thus decreasing uncertainty in estimates of α. The resulting estimates of the bias coefficient and their uncertainties are shown in Figure 5*a*. For reference, the distribution of SWH observations is shown in Figure 5*b*. The bias coefficient ranges from –0.032 to –0.037 for SWH values between 0 and 3.5 m. For larger SWH, the coefficient decreases in magnitude approximately linearly to a value
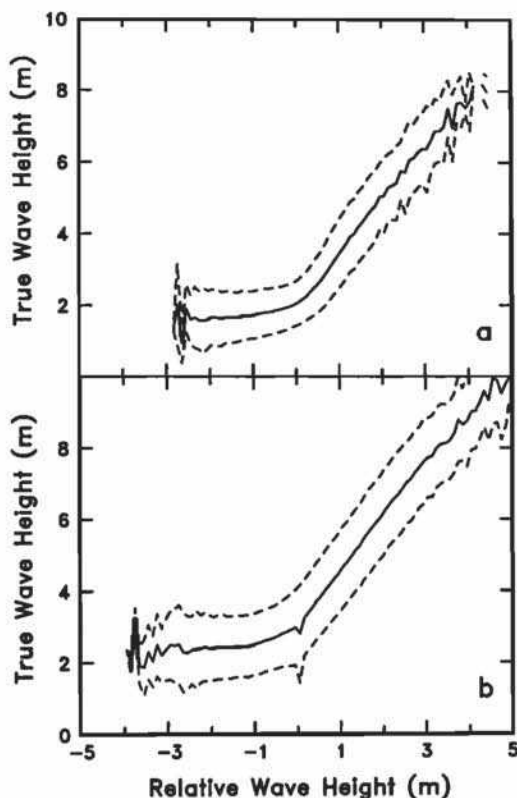
Fig. 4. Average altimeter-measured SWH for each 0.1 m relative SWH bin (solid line) for (a) 10°S–40°S and (b) 40°S–65°S. Standard deviations about these averages are given by the dashed lines.
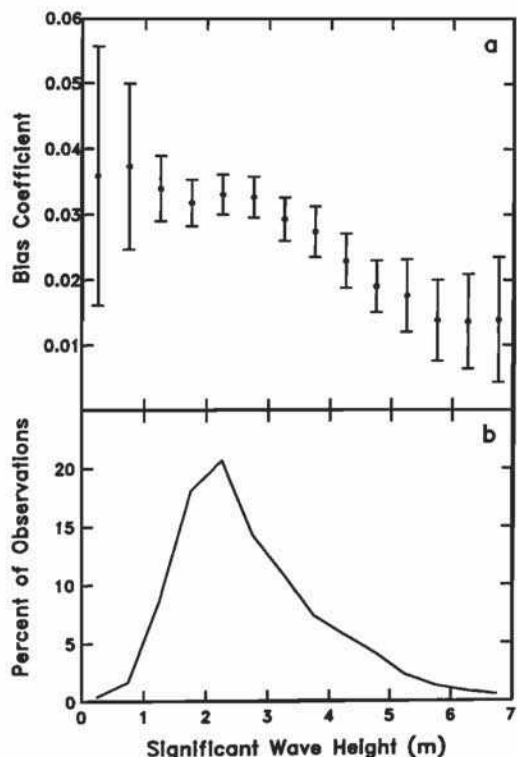

Fig. 5. (a) Average bias coefficients with ±1 standard deviation error bars as a function of SWH for the one parameter model (1) computed based on data from 10°S–65°S. The SWH bin size is 0.5 m. (b) The distribution of observations as a function of SWH.

of about –0.015 for 6 m SWH. Since large wave heights occur infrequently at subtropical latitudes, bias coefficients for SWH values larger than 4 m were computed based primarily on observations from the southern band.

Figures 4 and 5a suggest that the flattening in the averaged profiles of Figure 2a is due to a "saturation effect" in the sea-state bias associated with large SWH. As a simple test of this hypothesis, SWH values larger than 4 m were eliminated and the averaged profiles were recalculated for both latitude bands. This range of SWH values comprises 96% of all observations from the northern band and 74% of all observations from the southern band. The flattening at high relative SWH is negligible in the resulting profiles (see Figure 2b) and the profiles for the northern and southern bands are nearly identical. In addition, estimates of the bias coefficient obtained based on these profiles no longer depend strongly on the span width used to compute the coefficient (see Figure 3b); for spans larger than 1 m, α only varies from –0.037±0.003 to –0.035±0.002 in the northern band and from –0.034±0.003 to –0.032±0.002 in the southern band.

Since the Geosat bias coefficient is a strong function of true SWH, a single value of α cannot be used for the full range of SWH values. Otherwise, the apparent SWH-dependent component of the bias will be underestimated for measurements with small SWH values and overestimated for measurements with large SWH values. For SWH values between 0 and 4 m, which account for most of the wave heights observed globally, fixing the bias coefficient at about –0.035 is appropriate; this is the average of the values for the two latitude bands in Figure 3b. With the exception of Nerem et al. [1990] (for which the uncertainty of the estimated bias coefficient is very large), this value is larger in magnitude than those obtained by all previous studies using Geosat altimeter data (see Table 1). It is apparent from Figure 3 that these differences can largely be accounted for by the fact that previous estimates have been based on wide ranges of relative SWH. As shown above, the bias coefficient appropriate for the range over which the sea-state bias and SWH are linearly related is underestimated if Geosat observations with high SWH values are included in the data set.

TABLE 1. Previous Estimates of the Bias Coefficient for Geosat Measurements

	α		
Zlotnicki et al. [1989]			
Global	-0.028		
Acc sector (see text)	-0.029	±	0.003
Nerem et al. [1990]	-0.036	±	0.015
Ray and Koblinsky [1991]	-0.026	±	0.002
Fu and Glazman [1991]	-0.014	±	0.006

4. DISCUSSION

The risk of purely empirical models such as that developed here is that the apparent SWH dependence in the sea-state bias found in section 3 may be unrelated to SWH. Without a sound physical model, the saturation effect could equally well be due to any other phenomenon that is correlated with SWH. We have therefore considered several alternative explanations for this behavior, including

possible effects of wind speed and wave type and effects of other geographically dependent errors in the altimeter range measurements. The possibility of a wind speed dependence has previously been suggested from empirical analyses of tower-based radar measurements [*Melville et al.*, 1991], aircraft radar measurements (E.J. Walsh, personal communication, 1989) and Geosat altimeter data [*Ray and Koblinsky*, 1991]. Because these studies have consistently found an increase in the magnitude of the sea-state bias coefficient with increasing wind speed, the original intent of this study was to verify this relationship at high southern latitudes where wind speeds are the largest in the world.

As can be seen from Figure 6, large SWH is generally associated with high wind speed. The correlations between wind speed (computed using the algorithm described by *Witter and Chelton* [this issue]) and SWH are 0.49 and 0.58 for the northern and southern latitude bands, respectively. Based on these high positive correlations and the suggested relationship between wind speed and the bias coefficient from previous studies, the magnitude of the bias coefficient is expected to increase with increasing SWH. This is the opposite of the result obtained in section 3. Indeed, binning the sea-state bias coefficient α in (1) as a function of wind speed shows the magnitude of the bias coefficient to be approximately constant for wind speeds up to about 10 m/s and to decrease approximately linearly for higher wind speeds (Figure 7). Previously argued wind speed effects evidently cannot account for the saturation effect found here. We note, however, that all of the studies of wind speed effects to date have emphasized SWH values less than 4 m. It is not clear that these results can be extrapolated to the higher wave heights found at high southern latitudes.
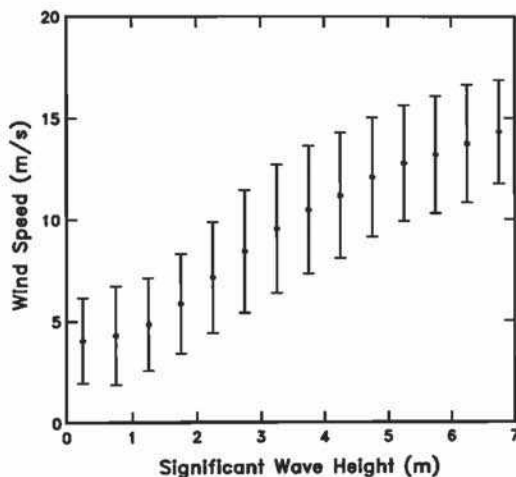

Fig. 7. As in Figure 5, except as a function of wind speed at 10 m above the sea surface for wind speed bin sizes of 2 m/s.

Fig. 6. Average wind speeds at 10 m above the sea surface with ±1 standard deviation error bars plotted as a function of SWH for SWH bin sizes of 0.5 m.

A second possible explanation for the apparent SWH dependence of the bias coefficient is that large waves at high southern latitudes may have different physical characteristics than waves elsewhere in the world ocean. Such a difference might not be surprising since oceanographic and meteorological conditions are so unique in the Southern Ocean. However the possibility of a "wave type" dependence in the sea-state bias can be addressed
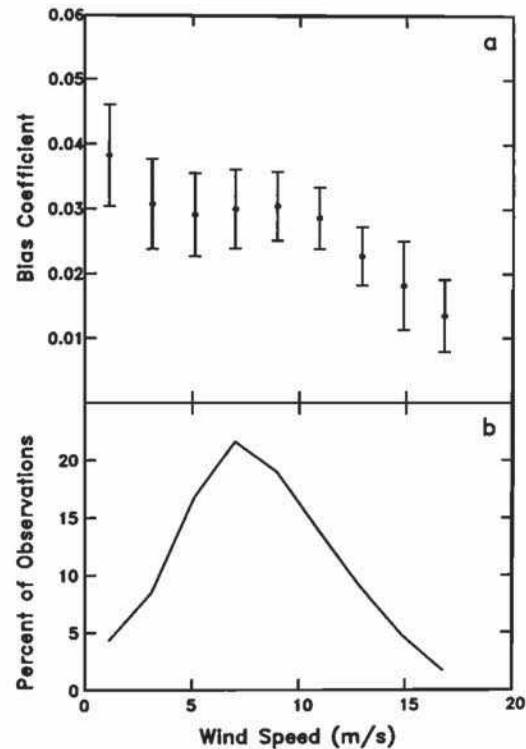
to only a limited degree from Geosat data alone since the only sea surface characteristics that can be inferred from altimeter data are SWH and wind speed (inferred from the normalized radar cross section).

A physically based model for the sea-state bias which attempts to account for the effects of wave type has recently been developed [see *Fu and Glazman*, 1991]. In this model, the sea-state bias is expressed as a multiplicative function of SWH and pseudo wave age, where pseudo wave age (a proxy for the degree of wave development) is estimated directly from altimeter SWH and wind speed observations [see *Glazman and Pilorz*, 1990]. The physical basis for the wave age model is essentially that young waves are more skewed than old waves and consequently result in a greater overall sea-state bias due to an increase in the skewness bias contribution. The magnitude of the sea-state bias coefficient is therefore expected to increase with decreasing wave age. Using the formulation for wave age cited by *Fu and Glazman* [1991], we computed a correlation of −0.68 between wave age and wind speed in both latitude bands. The wave age model therefore predicts an increase in the magnitude of the bias coefficient with increasing wind speed and thus offers a physical explanation for the wind speed dependence suggested from the tower, aircraft and Geosat data as discussed above. Unfortunately, the wave age model fails to explain the saturation effect found here for the same reason that the wind speed model was unsuccessful. We note, however, that the coefficients for the wave age model were derived empirically from a somewhat restricted Geosat data base which emphasized wave heights smaller than 4 m [*Fu and Glazman*, 1991]. As with the wind speed effects discussed above, extrapolating the wave age model to wave heights larger than 4 m may not be justified.

A third possible explanation for the apparent SWH dependence of the sea-state bias found in section 3 is a geographical dependence. Although there is no reason to expect a true geographical effect on the sea-state bias, Geosat data at high southern latitudes are known to be contaminated by antenna pointing errors which must be corrected to obtain accurate range estimates [see *MacArthur et al.*, 1987; *Chelton et al.*, 1990]. These pointing errors, which are unique to the Geosat passive gravity gradient stabilization system, are believed to be the result of a torque applied to the satellite by solar radiation pressure as Geosat emerged from the Earth's shadow during each orbit. Such pointing errors are not expected to occur on satellites with active attitude control systems such as Seasat, ERS-1 and TOPEX/Poseidon.

The effects of antenna mispointing on Geosat altimeter range estimates has been documented by *Hayne and Hancock* [1990]. Errors in the altimeter range measurement arise due to the combined effects of attitude and sea-state on the on-board tracking algorithm which identifies the point on the radar return (the so-called waveform) corresponding to mean sea level (see *Chelton et al.* [1989] for a description of altimeter sea level tracking). For reasons that are not completely understood, these sea level tracking errors have been found empirically to depend approximately quadratically on attitude and SWH. Tracking errors in Geosat height data can thus be expected to be particularly large at high southern latitudes where both attitude angle and SWH are large. As in all previous studies of sea-state bias from Geosat data, the Geosat data analyzed here were not corrected for the attitude and sea-state tracking errors described by *Hayne and Hancock* [1990]. The apparent SWH dependence in the sea-state bias found in section 3 may therefore reflect a geographical dependence due to sea level tracking errors at high southern latitudes. Such an explanation is attractive from the point of view that it would explain why the saturation effect found here has not been found in previous studies, none of which have emphasized the Southern Ocean as does this study.

As noted in section 2, Geosat observations with attitude angles exceeding 1° have been excluded from the analyses presented here. Inspection of Figure 4b in *Hayne and Hancock* [1990] reveals that antenna mispointing and SWH result in range errors that are indeed consistent with the saturation effect found in section 3. The positive values of the correction imply that the tracking errors are negative (i.e., the same sign as the EM and skewness biases). For attitude angles less than 1°, the tracking error has a maximum at SWH values of around 5 m; for larger SWH, the tracking error decreases with increasing SWH, similar to that found in section 3.

Although tracking errors can at least qualitatively explain the saturation effect found in this study, it does not seem to us that it would be fruitful to attempt a quantitative explanation based on the parameterizations of the tracking error presented by *Hayne and Hancock* [1990]. Their estimates of the biquadratic fit of tracking error to attitude and SWH are based on a rather limited sampling of all possible attitude angle and SWH combinations (see their Figure 2). To determine whether extrapolation of the coefficients derived thus far is valid for the combinations of attitude and SWH values found at high southern lat-

itudes, the computationally intensive waveform retracking procedures used to estimate these tracking errors should be applied to a much broader range of attitude and SWH values.

5. CONCLUSIONS

From the analysis presented in section 3, it is apparent that a systematic sea-state bias in altimeter range measurements is easily isolated from other sources of measurement errors and oceanographic variability by appropriate binning of the data. Such a procedure shows the Geosat sea-state bias to be approximately a constant −3.5% of SWH for SWH as large as about 4 m. For larger SWH, however, the magnitude of the empirical bias coefficient decreases. Because of this saturation effect, the magnitude of other estimates of the Geosat sea-state bias coefficient, which have been based on least squares analysis of the full range of wave heights, are too small.

The apparent wave height dependence in the Geosat sea-state bias found in section 3 is rather surprising. Other recent empirical analyses of Geosat data have focused on an apparent wind speed dependence in the bias, but have found no indication of a wave height dependence. This is probably because these previous studies have been based primarily on observations with wave heights smaller than 4 m. For this range of SWH, the present investigation found no wave height dependence in the bias coefficient. If indeed any wind speed dependence in the sea-state bias exists, it is evidently overwhelmed in this analysis of southern hemisphere data by the apparent SWH dependence found in section 3.

The most likely explanation for the apparent SWH dependence in the sea-state bias found here is errors due to effects of attitude angle and sea-state in the on-board sea level tracking algorithm. Present parameterizations of these tracking errors have not been verified for the combinations of attitude and SWH values characteristic of high southern latitudes. A significant waveform retracking effort such as described by *Rodriguez and Chapman* [1989] or *Hayne and Hancock* [1990] is therefore necessary in order to eliminate tracking errors from the Geosat range measurements. An effort of this magnitude is beyond the scope of the present study. The important conclusion to be drawn from this investigation is that any higher order study of the EM and skewness biases in Geosat range measurements (e.g., searches for wind speed or wave height dependences) cannot be undertaken until attitude and sea-state tracking errors are more thoroughly investigated and removed from the data.

REFERENCES

Barrick, D.E., and B.J. Lipa, Analysis and interpretation of altimeter sea echo, *Adv. Geophys.*, 27, 61–100, 1985.
Born, G.H., M.A. Richards, and G.W. Rosborough, An empirical determination of the effects of sea state bias on Seasat altimetry, *J. Geophys. Res.*, 87, 3221–3226, 1982.

Chelton, D.B., E.J. Walsh, and J.L. MacArthur, Pulse compression and sea level tracking in satellite altimetry, *J. Atmos. Oceanic Technol.*, *6*, 407–438, 1989.

Chelton, D.B., M.G. Schlax, D.L. Witter, and J.G. Richman, Geosat altimeter observations of the surface circulation of the Southern Ocean, *J. Geophys. Res.*, *95*, 17,877–17,903, 1990.

Cheney, R.E., B.C. Douglas, and L. Miller, Evaluation of Geosat altimeter data with application to tropical Pacific sea level variability, *J. Geophys. Res.*, *94*, 4737–4747, 1989.

Douglas, B.C., and R.W. Agreen, The sea state correction for Geos 3 and Seasat satellite altimeter data, *J. Geophys. Res.*, *88*, 1655–1661, 1983.

Draper, N.R., and H. Smith, *Applied Regression Analysis*, 2nd ed., 709 pp., John Wiley, New York, 1981.

Fu, L.-L., and R. Glazman, The effect of the degree of wave development on the sea-state bias in radar altimetry, *J. Geophys. Res.*, *96*, 829-834, 1991.

Glazman, R., and S.H. Pilorz, Effects of sea maturity on satellite altimeter measurements, *J. Geophys. Res.*, *95*, 2857-2870, 1990.

Hayne, G.S., and D.W. Hancock, Corrections for the effects of significant wave height and attitude on Geosat radar altimeter measurements, *J. Geophys. Res.*, *95*, 2837–2842, 1990.

Jackson, F.C., The reflection of impulses from a nonlinear random sea, *J. Geophys. Res.*, *84*, 4939–4943, 1979.

MacArthur, J.L., P.C. Marth, and J.G. Wall, The Geosat radar altimeter, *Johns Hopkins APL Tech. Dig.*, *8*, 176-181, 1987.

Melville, W.K., R.H. Stewart, W.C. Keller, J.A. Kong, D.V. Arnold, A.T. Jessup, M.R. Loewen, and A.M. Slinn, Measurements of electromagnetic bias in radar altimetry, *J. Geophys. Res.*, *96*, 4915-4924, 1991.

Nerem, R.S., B.D. Tapley, and C.K. Shum, Determination of the ocean circulation using Geosat altimetry, *J. Geophys. Res.*, *95*, 3163–3179, 1990.

Ray, R.D., and C.J. Koblinsky, On the sea-state bias of the Geosat altimeter, (in press), *J. Atmos. Oceanic Technol.*, 1991.

Rodriguez, E., and B. Chapman, Extracting ocean surface information from altimeter returns: the deconvolution method, *J. Geophys. Res.*, *94*, 9761–9778, 1989.

Srokosz, M.A., On the joint distribution of surface elevation and slopes for a nonlinear random sea, with an application to radar altimetry, *J. Geophys. Res.*, *91*, 995–1006, 1986.

Witter, D.L., and D.B. Chelton, A Geosat altimeter wind speed algorithm and a method for altimeter wind speed algorithm development, *J. Geophys. Res.*, this issue.

Zlotnicki, V., L.-L. Fu, and W. Patzert, Seasonal variability in global sea level observed with Geosat altimetry, *J. Geophys. Res.*, *94*, 17,959–17,969, 1989.

Zlotnicki, V., A. Hayashi, and L.-L. Fu, The JPL-Oceans 8902 version of the Geosat altimetry data, *JPL Tech. Rep., D–6939*, 1990.

D. B. Chelton and D. L. Witter, College of Oceanography, Oregon State University, Oceanography Admin. Bldg. 104, Corvallis, OR 97331.