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The Effect of the Degree of Wave Development on the Sea State Bias in Radar Altimetry Measurement

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The effect of the degree of wave development on the sea state bias (SSB) in Geosat altimeter height measurement is evaluated. Theoretical considerations suggest that the altimetric SSB is generally not a linear function of significant wave height but depends also on other factors of wave development. Of particular interest is its dependence on wave age, defined as the ratio of the phase speed of the dominant ocean waves to ocean wind speed. We estimate wave age rather crudely, on the basis of the significant wave height ($H_{1/3}$) and wind speed measured by the altimeter. Under general conditions when the sea is not in equilibrium with the wind, this estimate may not correspond to the wave age in a strict sense and hence is called "pseudo wave age" in this paper. Nevertheless, the pseudo wave age is a rough indicator for the degree of wave development. The general trend in the dependence of the SSB on pseudo wave age, as found by analyzing 2.7 years' worth of Geosat data, agrees well with the theoretical prediction: for a given $H_{1/3}$, the SSB decreases as the degree of the wave development (measured by the pseudo wave age) increases. This empirical trend is modeled as SSB$=A(\xi/\xi_m)^M H_{1/3}$, where ξ and ξ_m are the pseudo wave age and its average value, respectively; $A = 0.013 \pm 0.005$, and $M = -0.88 \pm 0.37$. Statistically, this model performs slightly better than a standard model (i.e., SSB $= \beta H_{1/3}$ with β being a constant). In terms of the global rms error the improvement is by 1.6 cm. However, because the degree of wave development varies with the season and geographical location, this small improvement could become important for more accurate altimetric missions in the future when the centimetric, basin-scale signals are the focus of the study.

1. INTRODUCTION

A radar altimeter is used for making precise measurements of the altitude of a spacecraft above the sea surface. Subtracting this altitude from the height of the spacecraft relative to the center of the Earth, one can determine the geocentric sea level height. Altimetric measurement of sea level is a powerful tool for studying the global ocean circulation and its changes and other various geophysical problems [e.g., *Douglas et al.*, 1987; *Fu et al.*, 1988]. In this paper we discuss an aspect of the accuracy of altimeteric measurement in relation to the conditions of the sea state.

A radar altimeter measures its altitude by tracking the arrival time of the radar return pulse which is reflected mainly by the specular facets (i.e., the horizontal wave facets) of the wind-disturbed sea surface. The arrival time is directly related to the mean height of the sea surface specular facets over the radar footprint, thus yielding an estimate of the mean height of the sea level over the radar footprint. The reader is referred to *Barrick and Lipa* [1985] and *Chelton et al.* [1989] for a detailed discussion of the altimeter sea level tracking method.

To simplify the altimeter tracking method, the sea state model used in altimeter design normally assumes the statistics of the sea surface elevation field (due to wind-generated gravity waves) to be Gaussian. The fact that the sea surface elevation is not exactly a Gaussian random field causes errors in the altimeter-measured sea level height. Such errors are known collectively as the sea state bias, hereinafter denoted by SSB. The following factors determine the major components in the SSB.

For a non-Gaussian sea state, the mean height of the sea surface specular facets is generally lower than the mean height of the sea level. This bias is called the electromagnetic bias, or EM bias for short, because it is caused by an intrinsic property of sea surface in reflecting electromagnetic waves. The phenomenon of EM bias was first discovered by *Yaplee et al.* [1971] from radar observations made on a tower. They reported that the sea surface radar cross section was found to be higher at wave troughs than at wave crests. This subject has been extensively discussed in the literature ever since. The reader is referred to *Walsh et al.* [1989] for a review on the subject. Theoretically, EM bias can be expressed as $-(\gamma/8)H_{1/3}$, where γ is a combination of second- and third-order mixed statistical moments of the sea surface elevation and its horizontal gradient [e.g., *Jackson*, 1979; *Barrick and Lipa*, 1985; *Srokosz*, 1986]. The minus sign indicates that the bias is toward the wave troughs. Theoretical estimate of the EM bias ranges from 3% to 5% of $H_{1/3}$, depending on the assumption of the wave spectrum [*Walsh et al.*, 1989]. Unfortunately, this γ parameter cannot be directly estimated from the shape of the altimeter return pulse, called waveform (E. Rodriguez and B. Chapman, Ocean skewness and the skewness bias in altimetry: A Geosat study, submitted to *International Journal of Remote Sensing*, 1990, hereinafter referred to as Rodriguez and Chapman (1990)). Aircraft observations have indicated that the EM bias is a function of radar frequency, and is typically 3% of $H_{1/3}$ at 10 GHz and 1% of $H_{1/3}$ at 36 GHz [*Walsh et al.*, 1989]. Recent tower observations indicated that the EM bias is about 3% of $H_{1/3}$ at 14 GHz, with significant dependence on wind speed [*Melville et al.*, 1991].

Another component of the SSB arises from the fact that the skewness of the sea surface elevation makes the radar return waveform deviate from the shape assumed by the on-board altimeter height tracker, resulting in a bias in the altimetric measurement of the mean height of the specular facets. This component is thus called skewness bias. The existence of the skewness bias is due to a deficiency in the

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altimeter design; if the altimeter height tracker can be designed to track the mean height of the specular facets for a non-Gaussian sea, then there will be no skewness bias.

To a first-order approximation the skewness bias can be estimated as $-(\lambda/24)H_{1/3}$, where λ is the skewness of the sea surface elevation [*Srokosz*, 1986; *Lagerloef*, 1987; *Rodriguez*, 1988]. The minus sign indicates that the bias is also toward the troughs. Rodriguez and Chapman (1990) have recently demonstrated that the skewness bias can be corrected for by analyzing altimeter waveforms, from which the skewness parameter can be derived. The skewness parameter they estimated was typically between 0.1 and 0.2, yielding a skewness bias of 0.4–0.8% of $H_{1/3}$, which is considerably smaller than the EM bias.

Many investigators have studied the effects of sea state conditions on altimetry by examining the correlation between altimeter sea level measurement and $H_{1/3}$. It is found that the overall SSB (a combination of the skewness bias and the EM bias plus other sea-state-related errors) is about 2% of $H_{1/3}$ for both the GEOS 3 [*Douglas and Agreen*, 1983] and the Geosat altimeters [*Cheney et al.*, 1987] and about 7% of $H_{1/3}$ for the Seasat altimeter [*Born et al.*, 1982; *Hayne and Hancock*, 1982]. It is believed that the higher values for Seasat are due to certain peculiarities in the ground processing unique to Seasat. The values for GEOS 3 and Geosat are considered the norm for the altimeteric SSB. In all the cases, the estimated percentage coefficient has a rather large standard deviation. This is expected because in theory the coefficients for both the skewness bias and the EM bias are dependent on the sea surface elevation probability density function (pdf), which varies with the sea state conditions.

It is generally believed that the degree of "Gaussianity" of the sea surface elevation pdf is dependent on the degree of wave development. Newly generated waves are more skewed than older waves and thus less Gaussian. This concept leads to the notion that the SSB should be a function of wave age, hereinafter denoted by ξ. Wave age, defined as $\xi = C/U$ where C is the phase speed of the dominant wave and U is the wind speed [*Kinsman*, 1965], is a measure of the degree of wave development.

Recent analysis of the Geosat altimeter data [*Glazman and Pilorz*, 1990] showed considerable correlation of the radar cross section with wave age. Theoretical studies [*Glazman*, 1986; *Glazman and Weichman*, 1989] and analyses of other microwave remote sensing observations [*Glazman et al.*, 1988] have indicated that the degree of wave development, expressed in terms of wave age, represents a basic characteristic of air-sea interactions that greatly affects the statistical properties of a rough sea surface. The question we pose for the present study is the following: Can we detect from altimeter data a dependence of the SSB on wave age or a similar parameter characterizing the degree of wave development?

In this paper we use the Geosat altimeter data to demonstrate that the SSB is related to a parameter that is closely related to wave age and can be estimated from the wind speed and $H_{1/3}$ measured by altimetry. We call this parameter "pseudo wave age." A SSB model that incorporates the effects of pseudo wave age is also constructed.

In the next section, the concept of pseudo wave age and its estimation from altimeter data is discussed. An empirical model that relates the SSB to pseudo wave age is also described. The Geosat data and the data processing technique are described in section 3. The results are summarized in section 4, and the conclusions are presented in section 5.

2. Pseudo Wave Age and the SSB Estimated From Altimeter Data

On the basis of results from the Joint North Sea Wave Project (JONSWAP) [*Hasselmann et al.*, 1976], one can derive the following empirical relationship between wave age and a nondimensional fetch [e.g., *Glazman et al.*, 1988]:

$$\xi = Gs^b \tag{1}$$

where $G = 0.056$, $b = 0.3$, and s is a nondimensional fetch defined as

$$s = gX/U^2 \tag{2}$$

where U is wind speed, g is the acceleration of gravity, and X is the dimensional wind fetch. Based on the JONSWAP spectrum, X is related to the significant wave height and wind speed as follows:

$$X = 3.4 \times 10^5 \frac{gH_{1/3}^2}{U^2} \tag{3}$$

Using (1)–(3), one can thus obtain an estimate for ξ from altimeter-measured significant wave height and wind speed. However, (1)–(3) are valid only when the sea state can be described by the JONSWAP spectrum, which was derived from near-coastal, fetch-limited observations. Can one use (1)–(3) under more general conditions in the open sea?

From buoy observations of ocean wind and waves from numerous locations in the open sea, *Glazman and Pilorz* [1990] found that (1)–(3) were valid for a near-equilibrium sea if the coefficients in (1) were modified to the following: $G = 0.062$, $b = 0.31$. However, the parameter X can no longer be interpreted as the wind fetch when the JONSWAP spectrum does not apply. Instead, X should be interpreted as a generalized fetch that represents a measure of the wave development in a similar fashion as the wind fetch.

Under more general conditions when the sea is not in equilibrium with the wind, for instance, in the presence of swells, the parameter ξ estimated from (1)–(3) (with $G = 0.062$, $b = 0.31$) would be an overestimate for the wave age of the wind waves; hence ξ is referred to as the "pseudo wave age" in this paper. The symbol ξ will be used to represent both the wave age and the pseudo wave age depending on the context. The pseudo wave age takes the effects of swells into account in characterizing the degree of wave development. Because swells are "old waves" generated in the far field, their shapes are less skewed and their statistics are more Gaussian than those of wind waves. The presence of swells should therefore result in an increased degree of wave development as represented by the pseudo wave age. We therefore use (1)–(3) (with $G = 0.062$, $b = 0.31$) to estimate the pseudo wave age as a parameter characterizing the degree of wave development for a more general sea state that is a mixture of wind waves and swells.

The SSB is usually expressed in the form, SSB $= -\varepsilon H_{1/3}$. The dependence of ε on pseudo wave age is to be determined empirically from the Geosat data. R. E. Glazman and M. A. Srokosz (Equilibrium wave spectrum and sea state bias in satellite altimetry, submitted to *Journal of Physical Ocean-*

ography, 1990) have recently developed a theory relating ε to wave age for an equilibrium sea. They used a generalized power law wave number spectrum for an equilibrium sea [see *Glazman and Weichman*, 1989] to evaluate the non-Gaussian statistical parameters λ and γ as functions of wave age. Their results suggest that the relation between ε and ξ is of the following form:

$$\varepsilon \propto \xi^{-p} \tag{4}$$

where p is of the order of unity. Whether this relation can be extended to the more general case of a nonequilibrium sea characterized by the pseudo wave age is not clear, but it certainly suggests the following simple form for an empirical evaluation of the effect of wave development on the SSB:

$$\text{bias} = A\left(\frac{\xi}{\xi_m}\right)^M H_{1/3} \tag{5}$$

where ξ_m is the globally averaged pseudo wave age, which was found by *Glazman and Pilorz* [1990] and confirmed in the present work to be close to 2.3 (see section 4). The two constants, A and M, are to be determined by applying a regression analysis based on (5) to the Geosat altimeter data; namely, optimal values for A and M are sought to minimize the variance of the difference between repeat altimeter sea level observations.

To make the SSB correction to altimeter-measured sea level height, denoted by η, one needs to add the bias obtained from (5) to η to arrive at the corrected sea level height, denoted by h, i.e.,

$$h = \eta + A\left(\frac{\xi}{\xi_m}\right)^M H_{1/3} \tag{6}$$

To the extent that the SSB is uncorrelated with the true sea level or with other errors in the altimeter sea level measurement, the variance of h should be less than that of η. Therefore A and M are determined by minimizing the following quantity:

$$\sum_{n=1}^{N} (\delta h_i)^2 \tag{7}$$

where δh_i is the difference between the ith pair of repeat altimeter sea level observations, and N is the total number of pairs used in the calculation. Equation (6) is used to evaluate δh, i.e.,

$$\delta h = (\eta_1 - \eta_2) + A\left\{\left(\frac{\xi_1}{\xi_m}\right)^M [H_{1/3}]_1 - \left(\frac{\xi_2}{\xi_m}\right)^M [H_{1/3}]_2\right\} \tag{8}$$

where the subscripts 1 and 2 are used to label the two observations from a given pair of repeat altimeter measurements. The data and procedures used to obtain a solution for A and M are described in the next section.

3. The Data and Procedures

Geosat was launched by the U.S. Navy in March 1985. It carried a K_u band (13.5 GHz) altimeter with a primary objective of mapping the details of the marine geoid. In November 1986, Geosat was maneuvered into a 17-day repeat orbit for oceanographic applications, marking the beginning of the Geosat Exact Repeat Mission (ERM). The ERM data have been processed and distributed by the National Oceanic and Atmospheric Administration (NOAA) [*Cheney et al.*, 1987]. This data set, containing sea level, significant wave height, and σ_0 (the normalized radar backscatter coefficient) has been further processed and grouped into passes [*Zlotnicki et al.*, 1989]. Each revolution is broken into an ascending pass (from the minimum latitude to the maximum latitude) and a descending pass (from the maximum latitude to the minimum latitude). All the data from a given pass have been gridded to a fixed set of latitudes (with an along-track grid size of 7 km) to facilitate the computation of the difference between repeat observations. The following corrections supplied in the NOAA data by *Cheney et al.* [1987] are applied to the data: Fleet Numerical Oceanography Center (FNOC) wet and dry tropospheric range delays, ionospheric range delay from a model, ocean and Earth tides from models, and the inverted barometer effect from FNOC sea level pressure. To avoid the undesirable effect of large off-nadir pointing, the data with off-nadir pointing angle greater than 1° were discarded from the data base used in our study.

Shown in Figure 1 are 16 passes from which the data used in this investigation were selected. These passes cover the global oceans from 60°S to 50°N and encompass a wide range of sea state conditions at any given time of year. Within a given pass a temporal mean sea level computed from 57 repeats (2.7 years' worth of data) was first removed from each grid. The dominant error in the residual sea level is the temporally varying component of the orbit height error. This error has a dominant wavelength of 40,000 km (the length of a revolution) and an rms amplitude of 3 m for Geosat. Error of this magnitude would seriously degrade the estimate of the SSB. To reduce this error, each repeat of residual sea level data was fit to a sinusoid model (with wavelength of 40,000 km) of the orbit error with the amplitude and phase of the sinusoid determined by a least squares procedure. This sinusoid was then removed from the data. A nine-point median filter was applied to the residual sea level, significant wave height, and σ_0 to reduce measurement noise. Then the three parameters were subsampled every ninth point. The smoothed Brown model [*Dobson et al.*, 1987] was used to convert σ_0 to wind speed, which was then used with significant wave height to compute the pseudo wave age according to (1)–(3) (with $G = 0.062$, $b = 0.31$). At a given grid point, one can generate numerous pairs of simultaneous observations of the three parameters: sea level η, significant wave height $H_{1/3}$, and pseudo wave age ξ. For each pass, a total of 50,000 such pairs were generated as the data base for evaluating the SSB model given by (5) through the use of (7) and (8).

An optimization routine from the MATH/LIBRARY of *IMSL* [1987], called UMINF, was used to obtain a solution for A and M for each pass. This routine was based on a quasi-Newtonian method to search iteratively for an optimal solution. The robustness of the solution was tested by perturbing the initial guess, which normally sets both A and M equal to zero. For each of the 16 passes, a stable solution was always obtained.

To obtain a benchmark against which one can evaluate the impact of the degree of wave development on estimating the SSB, we have also applied to the data a model that takes no account of the effect of wave development, i.e.,

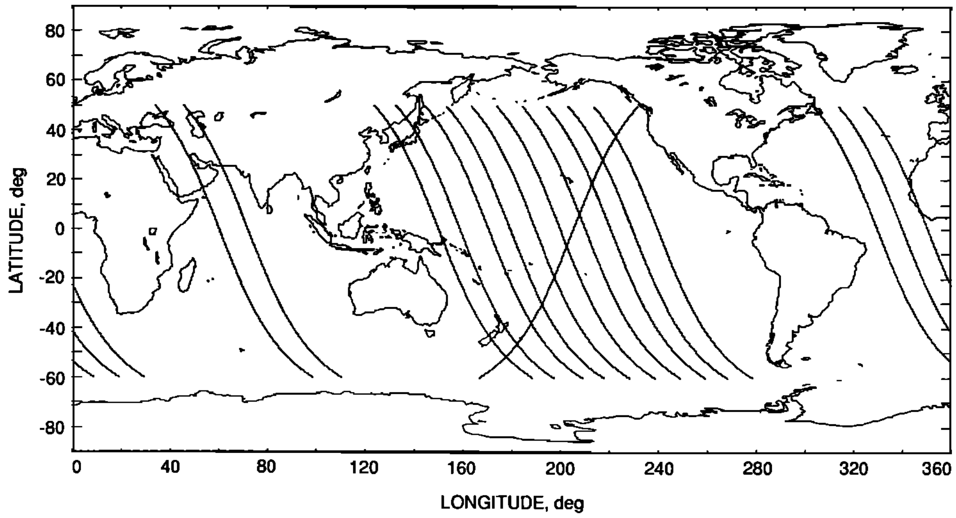

Fig. 1. Map of the ground tracks of the 16 Geosat passes used for the study. Only the ocean data were used.

$$\mathrm{SSB} = \beta H_{1/3} \tag{9}$$

where β is a constant. This is a standard model used in most of the previous investigations [e.g., *Born et al.*, 1982; *Douglas and Agreen*, 1983].

4. RESULTS

Before proceeding to the results of the SSB calculations, we would like to describe briefly the statistics of the sea state parameters (significant wave height, wind speed, and pseudo wave age) as revealed by the data. Displayed in Figure 2 are the histograms of the three parameters from an ascending pass with its equatorial crossing at 189.9 degrees east. About 10,000 data were used in each histogram. The average values are 2.5 ± 1.1 m (significant wave height), 7.0 ± 2.5 m s^{-1} (wind speed), and 2.3 ± 1.4 (pseudo wave age). The uncertainties are standard deviations. Statistics obtained from other passes are similar. The large values of pseudo wave age that are greater than 4 are primarily due to swells.

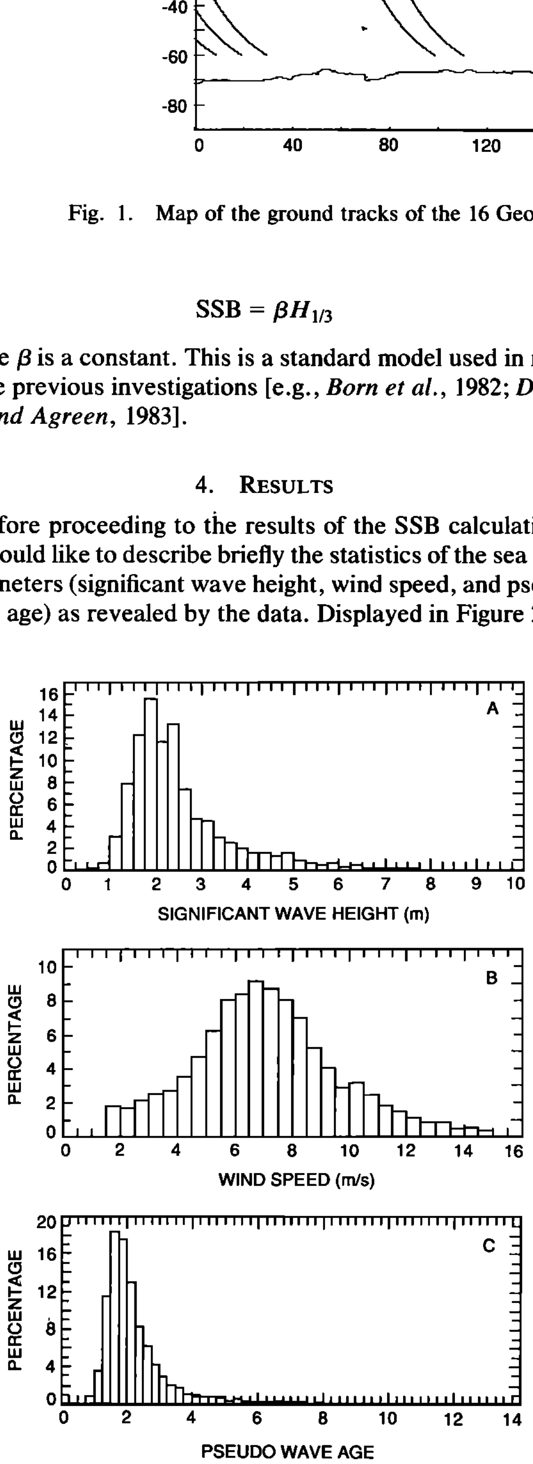

Fig. 2. Histograms of the sea state parameters: (*a*) significant wave height, (*b*) wind speed, and (*c*) pseudo wave age.

Displayed in Figure 3 are scatter plots of ξ versus U and ξ versus $H_{1/3}$. These plots are also typical of all the passes. Note that ξ is a strong function of U when U is less than 6 m/s. At low wind speeds, the presence of swells is responsible for the large values of ξ. The value of ξ decreases with U rapidly until U reaches about 6 m s^{-1}, reflecting the establishment of a wind wave field. When U is greater than 6 m s^{-1}, ξ varies much slower with U and eventually settles at values between 1 and 2. At high wind speeds, the growing wind waves maintain a somewhat constant ξ. There seems to be no systematic relationship between ξ and $H_{1/3}$.

The main results of the investigation are summarized in Table 1. The first column lists the designations of the 16 passes selected for the study. Each designation consists of a numeral and a letter. The numeral represents the east longitude (multiplied by 10) of the equatorial crossing of a given pass. The letter indicates whether the pass is ascending (A) or descending (D). The second and third columns list the solutions for A and M, respectively. The fourth and fifth columns contain the rms sea level variability before and after the SSB correction based on (5), respectively. Shown in the sixth column are the solutions for β in (9). The last column presents the rms sea level variability after the SSB correction based on (9).

As indicated in Table 1, the solution for A varies from 0.008 to 0.023 with an average of 0.013 and a standard deviation of 0.005; the solution for M varies from −0.33 to −1.70, with an average of −0.88 and a standard deviation of 0.37. Note that the estimated values for M are always negative and of the order of unity, as predicted by the theory discussed in section 2. A scatter plot of M versus A is displayed in Figure 4, showing the spread of the solutions. No significant relationship between A and M can be seen. The variability of the solutions is primarily caused by the

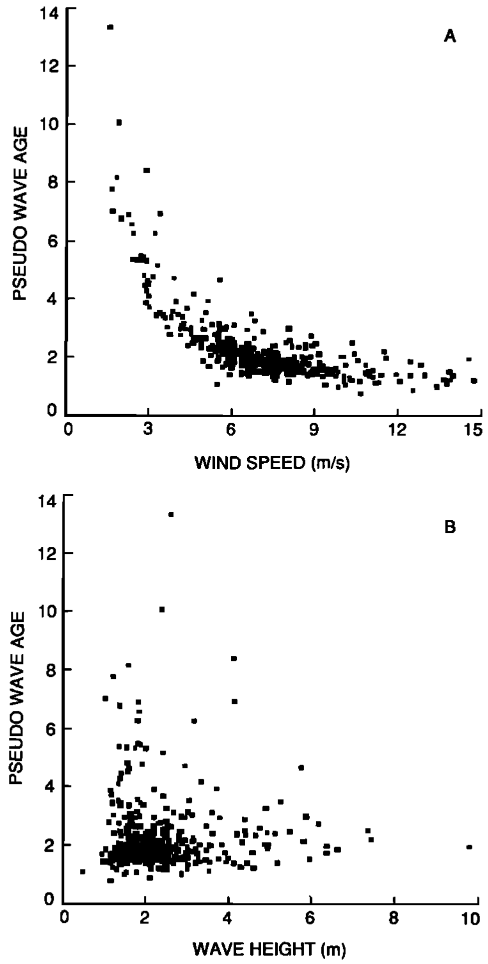

Fig. 3. Scatter plot of pseudo wave age versus (*a*) wind speed and (*b*) significant wave height.

residual errors in the data and the geographical dependence of the sea state characteristics.

The negative values for M have confirmed the notion that the SSB is smaller for older seas. By analyzing the Geosat waveform data, Rodriguez and Chapman (1990) found that

TABLE 1. Summary of Parameter Estimation

Data	A	M	E_1, cm	E_2, cm	β	E_3, cm
2400A	0.008	−1.70	11.43	11.18	0.010	11.37
1795A	0.012	−1.11	15.37	15.08	0.014	15.24
2297A	0.009	−1.23	11.51	11.36	0.007	11.47
2208A	0.012	−1.04	12.66	12.38	0.010	12.57
2105A	0.015	−0.51	13.32	13.13	0.015	13.17
1899A	0.020	−0.77	16.17	15.64	0.022	15.81
1707A	0.016	−0.45	17.58	17.41	0.017	17.45
1500A	0.011	−1.28	15.87	15.68	0.013	15.78
0718A	0.011	−0.59	12.11	11.98	0.011	12.02
1589A	0.023	−0.81	18.38	17.93	0.028	18.11
3404A	0.010	−0.88	13.21	13.14	0.008	13.17
3507A	0.019	−0.73	13.42	13.09	0.020	13.21
3300A	0.018	−0.66	14.09	13.86	0.017	13.93
0600A	0.009	−0.65	16.36	16.27	0.010	16.30
2002A	0.011	−1.28	15.34	15.10	0.009	15.27
2054D	0.010	−0.33	16.11	16.03	0.010	16.04

See text for explanation of column headings.

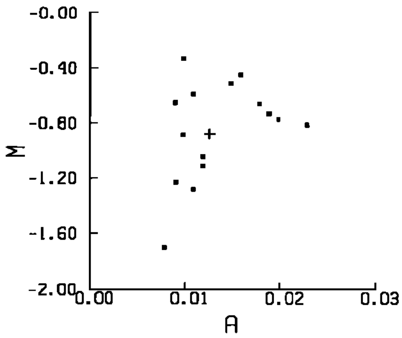

Fig. 4. Scatter plot of M versus A (the two parameters in equation (5)). The plus indicates the average M and A.

the skewness bias decreased with increasing wave age. They also found a similar behavior in the EM bias obtained from aircraft observations. On the basis of the analysis of Geosat data [*Ray and Koblinsky*, 1990] and offshore tower observations [*Melville et al.*, 1991], SSB was also found to increase with wind speed. As is shown in Figure 3, the pseudo wave age decreases rapidly with wind speed at low wind speeds, indicating that the SSB should increase with wind speed at low wind speeds. Therefore the effects of wind speed on the SSB may be explained in terms of the relationship between wind speed and the degree of wave development, at least at low wind speeds (less than 6–8 m s^{-1}).

Application of the SSB correction according to (5) has reduced the rms sea level variability as indicated in Table 1. The amount of rms sea level variability accounted for by the SSB can be estimated as $\langle (E_1^2 - E_2^2)^{1/2} \rangle$ where E_1 and E_2 denote the rms sea level variability before and after the correction, respectively, and angle brackets denote averaging over the 16 passes. Based on the values listed in Table 1, $\langle (E_1^2 - E_2^2)^{1/2} \rangle = 2.5$ cm.

The average solution for β in the model given by (9) is 0.014 with a standard deviation of 0.006. This is in good agreement with the result of *Cheney et al.* [1987] but is quite different from the result of *Ray and Koblinsky* [1990], who reported a value of 0.026 ± 0.002. At present, we do not have a good understanding of the discrepancy with the latter. Note that the rms sea level variability after this correction (denoted by E_3) is slightly higher than E_2 derived from the application of (5). The amount of rms sea level variability accounted for by the SSB according to (9) can be estimated by $\langle (E_1^2 - E_3^2)^{1/2} \rangle$, which yields a value of 1.8 cm. The improvement of (5) over (9) in estimating the SSB can be estimated by $\langle (E_3^2 - E_2^2)^{1/2} \rangle$, which yields a value of 1.6 cm.

5. CONCLUSION

The results of this study suggest that the pseudo wave age is a useful parameter in determining the SSB in altimeter measurement of sea level. The bias can be modeled as $A(\xi/\xi_m)^M H_{1/3}$ with $A = 0.013 \pm 0.005$ and $M = -0.88 \pm 0.37$. For a given significant wave height, the bias increases with decreasing pseudo wave age. This result is consistent with the notion that younger seas (with lower pseudo wave age) tend to have a more non-Gaussian sea surface elevation pdf and hence a larger SSB than older seas (with higher pseudo wave age).

The rms sea level variability is reduced after the SSB correction. Statistically, the SSB model including the pseudo wave age effect performs slightly better than a model without that effect by improving the accuracy of global SSB estimation by 1.6 cm. However, the inclusion of the pseudo wave age effect can make a more significant difference in certain occasions. For instance, a sea state with $H_{1/3} = 4$ m can have a wide range of pseudo wave age values (see Figure 3*b*), resulting in a bias varying from 11 cm (if $\xi = 1$) to 3 cm (if $\xi = 4$). For most applications of the Geosat altimeter data, the inclusion of the pseudo wave age effect in the SSB correction perhaps is not necessary, because the improvement is most likely overwhelmed by other sources of errors. However, because the degree of wave development varies with the season and geographical location, this small improvement could become important for more accurate altimetric missions in the future when the centimetric, basin-scale signals are the focus of the study.

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