Direct estimation of sea state impacts on radar altimeter sea level measurements

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[1] A new sea state bias modeling approach is presented that makes use of altimeter-derived marine geoid estimates. This method contrasts with previous models that require differencing between repeat altimeter passes for SSB isolation, along with complex bivariate inversion, to derive a relation between wind speed, wave height and SSB. Here one directly bin-averages sea height residuals over the wind and wave correlatives. Comparison with the most current nonparametric repeat-pass model shows close agreement and provides a first validation of this simpler and more direct technique. Success is attributed mainly to extensive space and time averaging. Ease in implementation and benefits in working with absolute levels provide much appeal. Further advantages and potential limitations, centered on the need to effectively randomize large sea level anomaly components to expose the bias, are also discussed. *INDEX TERMS:* 1640 Global Change: Remote sensing; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4504 Oceanography: Physical: Air/sea interactions (0312); 6959 Radio Science: Radio oceanography; 4215 Oceanography: General: Climate and interannual variability (3309). **Citation:** Vandemark, D., N. Tran, B. D. Beckley, B. Chapron, and P. Gaspar, Direct estimation of sea state impacts on radar altimeter sea level measurements, *Geophys. Res. Lett.*, *29*(24), 2148, doi:10.1029/2002GL015776, 2002.

1. Introduction

[2] The SSB in a satellite altimeter's range measurement results in a sea level estimate that falls below the true mean. Modeled SSB correction uncertainty is thought to be 1.5–2 cm on average and can exceed 5 cm in high seas [*Chelton et al.*, 2001].

[3] A location's sea surface height (SSH) measurement, uncorrected for SSB, contains the geoid signal (h_g), the ocean dynamic topography (η), the SSB, and other measurement and correction factors (w):

$$SSH = h_g + \eta + SSB + w. \quad (1)$$

SSB modeling normally begins by eliminating the dominant marine geoid signal from equation (1) by differencing precise repeat measurements either along collinear tracks [*Chelton*, 1994] or at orbit crossover points [*Gaspar et al.*, 1994]. Repeating altimeter measurements typically occur within 3–17 days, thus longer-term variance in the large η term is also removed. Using the two additional radar altimeter products, radar cross section-derived wind speed (U) and significant wave height (SWH), SSB estimation relates time-dependent range differences to corresponding wave height and wind speed differences.

[4] While relatively successful, the development of empirical SSB models based on repeat-pass differences presents several limitations [*Gaspar et al.*, 2002]. Key among these is the need to develop a nonparametric model function to resolve nonlinearities obscurred within standard regression techniques operating on differenced data. In addition, residual error analysis can only be performed in the space of the differenced variables. Further, large amounts of data and complex, numerically-optimized inversions are also required to properly develop such a model.

[5] Another approach is to solve for SSB directly by imposing a constant *a priori* mean sea level at each altimeter observation location thus eliminating the geoid. While substantial errors residing within equation (1) discouraged this approach in the past, the TOPEX/Poseidon mission has now provided ten years of precise measurements along the same 254 ground tracks across the global ocean. This paper provides a preliminary demonstration of this approach using TOPEX data.

2. Methods

[6] Following equation (1), a long-term average for the sea surface at any referenced location k on an altimeter's ground track can be written as:

$$MSS_k = \left(h_g + \langle\eta\rangle + \langle SSB - SSB_{\mathrm{m}}\rangle + \langle w\rangle\right)_k \quad (2)$$

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where $\langle\rangle$ denotes the expectation computed over a given time period. SSB_m are the model-derived sea state range corrections employed in this surface determination, and w comprises all other error components (e.g. in sensor range corrections, interpolation errors, orbit, tides, atmospheric terms, etc...) built into the mean sea surface MSS_k estimate. Equation (2) assumes independence between source terms.

[7] An individual height residual, $\Delta h_k = SSH_k - MSS_k$, used in SSB estimation is thus:

$$\Delta h_k = (SSB + (\eta - \langle\eta\rangle) - \epsilon_{SSB} + (w - \langle w\rangle))_k \qquad (3)$$

where $\epsilon_{SSB} = \langle SSB - SSB_m\rangle$ at any k defines the time-independent SSB modeling error within MSS_k. Note that the many realizations forming every MSS_k and ϵ_{SSB} differ from the arbitrary sample denoted in equation (3). Next, let dynamic sea level variability $(\eta - \langle\eta\rangle)$ be joined with $(w - \langle w\rangle)$ to form a noise term ϵ. By design, the geoid term cancels out to give:

$$\Delta h_k = (SSB + \epsilon_{SSB} + \epsilon)_k \qquad (4)$$

Error terms on the right side of the equation depend upon the quality of the estimates used to build MSS_k including, to some extent, the accuracy of the SSB model(s) used.

[8] An empirical bivariate SSB model is readily built by defining MSS_k globally and then computing the mean height bias at discrete bins across the (U, SWH) domain. Each bin holds the average over height residuals for all locations (k, ij), meeting the condition that altimeter-derived wind and wave height estimates fall within a (U_i, SWH_j) bin having width (ΔU, ΔSWH), given as:

$$SSB(U_i, SWH_j) = \langle (SSH_{ij} - MSS)_k \rangle \qquad (5)$$

The ϵ terms are dropped in equation (5) under a tentative assumption of weak dependency on sea state effects and assumed convergence of η and w terms towards zero mean values under long-term global averaging.

[9] Implementing this formula using TOPEX NASA altimeter (TOPEX hereafter) data is straightforward. The sea surface height residuals used are interpolated, georeferenced values computed along the TOPEX track using an established mean sea surface [*Wang*, 2001]. This surface merges multiple years and several satellite mission data sets (TOPEX, ERS, and Geosat) along the mean tracks of TOPEX [*Koblinsky et al.*, 1998], spanning a time period from 1986 to 1999. The large time period and number of repeat measurements lead to precise geoid determinations along the TOPEX track. This provides not only a reference mean sea level for oceanic studies, but also a low noise *MSS* along the altimeter's ground track that was not available in past SSB investigations.

[10] Prior to computing Δh_k, TOPEX measurements are corrected for all geophysical and instrumental effects and the original SSB (version 2.0 algorithm [*Gaspar et al.*, 1994]) is removed from each height estimate. These estimates are given at 1-s along-track intervals ($\sim$every 6 km) and interpolated to fixed georeferenced track locations. All Poseidon-1 altimeter and any erroneous (using conventional data quality flagging) TOPEX estimates are eliminated. Pairing of the NASA/GSFC Altimeter Pathfinder dataset with both TOPEX radar cross section σ_0 and *SWH* data is accomplished using the same georeferencing interpolation. The 10-m wind speed is calculated from σ_0 using the modified Chelton and Wentz algorithm [*Witter and Chelton*, 1991]. One 10-day TOPEX cycle of pathfinder data prepared in this manner provides 350,000–400,000 samples. For direct comparison to the most current SSB model [*Gaspar et al.*, 2002] (NP02 hereafter), cycles 21–131, April 1993–April 1996, are examined. The number of samples used in this 3-year average exceeds forty million. For demonstrations here, data are not spatially subsampled to insure independence. Data set size would contract by a factor of 7–10 with such sampling. By comparison, the NP02 crossover set contains 633,000 points for the same period.

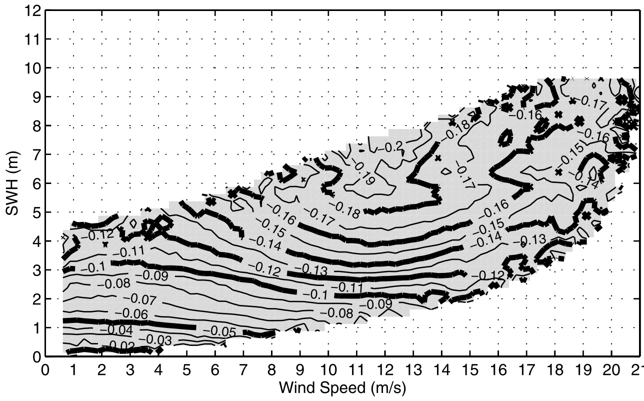

Figure 1. Isolines for the global TOPEX SSB estimate (in meters) obtained from bin-averaging into boxes of width (0.25 m/s, 0.25 m) over the (U, SWH) domain.

3. Results and Discussion

[11] Overall direct SSB results are now compared with the NP02 crossover model obtained for the same three year TOPEX period. Figure 1 shows the bin-averaged residual SSH data over the (U, SWH) domain with a bin width of 0.25 m/s in U and 0.25 m in SWH. Results are only computed for bins containing at least 200 samples. The shaded area corresponds to this dense data region. Contours are used to visualize the features. Note that this is the first reported direct (non-differenced) realization of on-orbit sea state bias impacts. Moreover, the results are directly in a tabular form that mimics the current NP model output format. While not shown, the crossover-based NP02 model solution looks nearly identical to Figure 1.

[12] A limitation encountered in this or the crossover method comes in resolving the absolute model reference to better than a small cm-level uncertainty. For NP02, only SSB differences are observed so that the SSB can only be determined to within a constant. This crossover method imposes an arbitrary bias estimate near the median in the joint (U, SWH) distribution to determine the overall SSB solution, and then shifts the solution at all grid points to satisfy $SSB(0, 0) = 0$. In the present approach, a bias is also observed. One theory is that an imperfect overall offset in SSB_m leads to a nearly constant offset value for the direct solution over the model domain. As shown later, time dependence in η may also play a role.

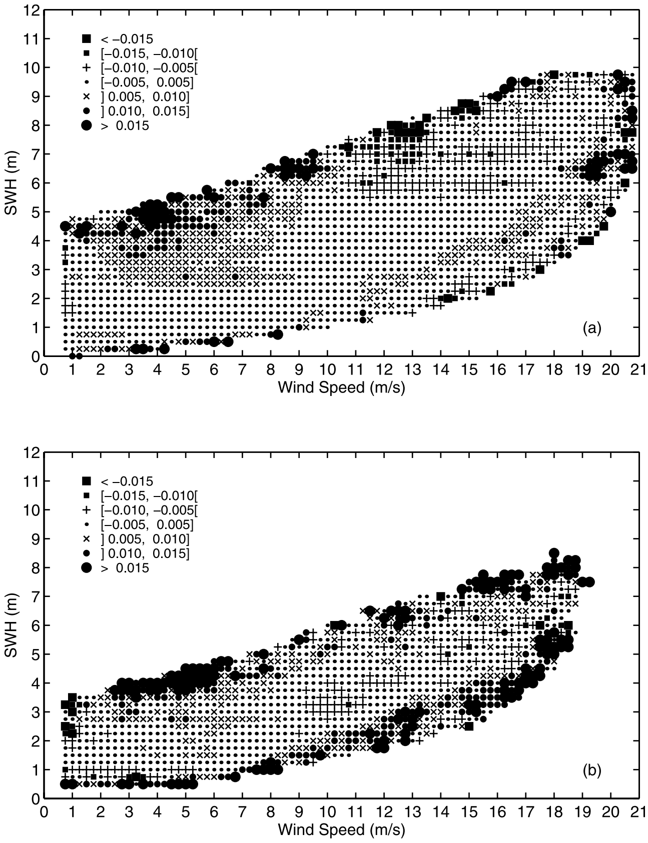

Figure 2. Difference (in meters) between the shifted bin-averaged map and the *Gaspar et al.* [2002] model grid. Bin-averaged estimates were computed using (a) a 3-year subset, TOPEX cycles 21–131; and (b) a 10-cycle subset, cycles 75–85.

[13] Due to these issues in absolute reference, a small level shift between the directly-obtained residual map and the NP02 model solution is not unexpected. Direct comparison with the NP02 model grid is made in Figure 2a after adjusting the present SSB estimates to match NP02 at the median bin (7.75 m/s, 2.0 m). The shift used is 16 mm. Examination of other points across the dense data zone indicates that the shift value varies by only a few mm. Results of Figure 2a represent the difference between the two methods. It is found that 86% of the bin-averaged SSB estimates differ by less than 10 mm and 57% by less than 5 mm. Best agreement is obtained where the data is densest, i.e. over most TOPEX observations. This high level of agreement is exceptional and helps to corroborate this recent NP02 model. The agreement also serves as validation for the use of this alternate direct approach to estimate SSB.

[14] One potential advantage to the present method is the ability to develop an SSB model using less data gathered over a shorter period of time. This capability could benefit development of SSB models for TOPEX follow-on altimeters such as Jason−1 and −2. To examine this, the time period for TOPEX averaging is reduced to respectively 1 year and 10 cycles. Comparison of NP02 to shorter one year averaging periods within cycles 21–131 gives results similar to Figure 2a with 84% of the bins having ΔSSB under 10 mm and 54% under 5 mm. Figure 2b shows SSB differences obtained when averaging data over only 100 days, cycles 75–85. 77% of the bins yield ΔSSB under 10 mm and 49% under 5 mm. Again, the largest ΔSSB occurs at the limits of the dense data region. Different values for the absolute shift were applied with respect to the time frames, from 13 and 18 mm. Agreement between the 3-year NP02 map and the 10-cycle data is remarkable. NP02 comparison to other 10-cycle estimates exhibit a similar level of agreement. This suggests that there is enough data collected within 100 days to develop a reasonable first estimate of the sea state bias mapping for the densest (U, SWH) data region while a 1-year period provides an extended mapping.

[15] The model intercomparisons suggest that this direct approach has merit and that, at least to first-order, the assumptions presupposed for equation (5) hold. To delve slightly deeper, sample global $\langle \Delta h_k \rangle_{ij}$ data for U =7.75 m/s and SWH = 2.0 m (±0.125 m/s, 0.125 m) are given in Figure 3, as collected from 1993–1996. The sea state bias of 7 cm is apparent. Scatter indicates a substantial 8 cm standard deviation, but also that the distribution has a quasi-Gaussian shape. The distribution is symmetric, yet peaked. As noted, more than 250,000 samples reside in this bin. Recalling equations (2)–(4) it is seen that numerous factors form a given Δh_k. This includes geophysical and instrumental corrections, along with dynamic topography, and also includes the averaging that goes into MSS_k. Thus the distribution of Figure 3 presents the compounding of many space and time-variant processes. The observed distribution kurtosis in the presence of a huge sample population may be due in part to correlation amongst some of these terms. Similar distributions are observed across the data dense portion of the 2D map. Asymmetry begins to appear as one nears the domain's edges indicating that the randomizing process may break down. Little deviation amongst distribution variances is observed across the bins shown in Figure 2a.

[16] Variability in the table offset value discussed above is of O(mm) but still of concern in context of corrections applied within precision altimetry. Preliminary study suggests that variance sources include deterministic dynamic topography variation and mean sea level rise. These in addition to an effective offset that may carry through from SSB_m and MSS_k. Figure 4 illustrates global sea level variance observed at the 10–30 day time scale within an SSB_{ij} bin (U =7.75 m/s, SWH =2.0 m). Annual and semi-annual

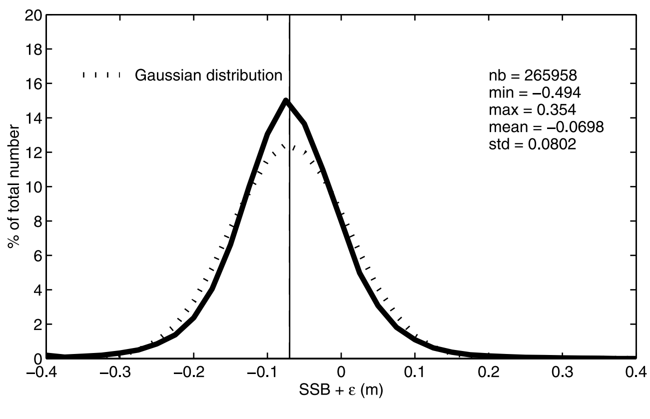

Figure 3. Histogram of TOPEX residual SSH observations at 7.75 ± 0.125 m/s in U and 2.0 ± 0.125 m in *SWH*. Statistics, including number of samples, are noted, and a Gaussian function carrying the same variance is shown.

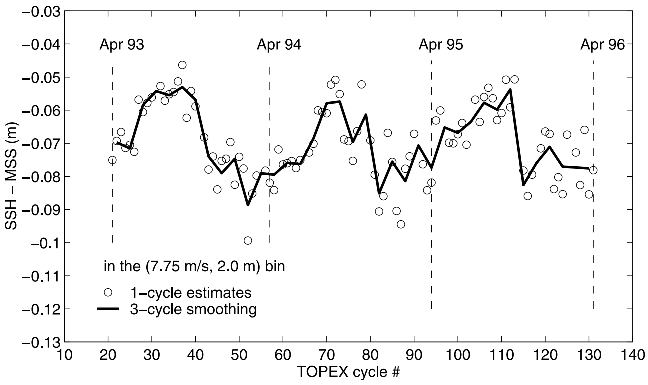

Figure 4. Single cycle (10 days) estimates of ($\langle SSH_k - MSS_k \rangle$) in the bin centered at (7.75 m/s, 2.0 m) and a curve depicting the 3-cycle running average.

harmonics observed in these residual data show interannual surface variability that correlates with global-average sea surface temperature variation [*Minster et al.*, 1995]. Moreover, superimposed upon this variability is a longer-term mean sea level variation. *Nerem and Mitchum* [2001] report that the rate of change of global mean sea level derived from 6 years of TOPEX/Poseidon data, 1993–1998, is +2.5 mm/year. Thus both the global dynamic topography and the mean sea level rise may affect SSB estimates in terms of an absolute offset versus time. The effect should not alter the overall SSB mapping. This hypothesis was checked for bins across the data rich zone and indeed similar amplitude and temporal variance are observed. However, examination of the fringe (*U*, *SWH*) bins exhibits divergence, perhaps suggestive of spatial undersampling (i.e. localized to a small region).

[17] These observations are reported to point out that more work is warranted to clarify when and where this simple averaging approach is applicable and accurate for either operational or more physically-based SSB investigations. Computation over a height residual population sufficient to extract the small SSB signal from numerous other sources is the central requirement. It is clear from Figure 4 that the time extent used to estimate SSB should, at minimum, acknowledge potential SSB table offset variability. This and past crossover studies presuppose, for pragmatic reasons, the (*U*, *SWH*) correlation with SSB. Use of the present technique in this vein may be subject to bias via (*U*, *SWH*) self-correlation if there is large systematic error in SSB_m used in equation (2). Validation via intercomparison suggests limited impact for this TOPEX demonstration where the model of *Gaspar et al.* [1994] predominates in MSS_k estimates. But sensitivity to this error is readily assessed via modification of the surface reference and will be examined. Other areas of future inquiry include collocation of the sea surface anomaly data with ancillary wind and wave parameters in lieu of (*U*, *SWH*). Study of the binned residual distribution statistics vs. a new correlative parameter suite under this versatile approach may yield new insight on variability unresolved within the standard (*U*, *SWH*) modeling.

4. Conclusion

[18] This is the first reported direct (non-differenced) realization of on-orbit altimeter SSB impacts. The technique relies upon averaging over a numerous realizations to isolate the small SSB signature. Results from a 3-year global average mirror that obtained using satellite crossover differences and subsequent nonparametric model inversion. It is also shown that an accurate SSB estimate can be obtained over most of the altimeter-derived (*U*, *SWH*) domain with as little as 100 days of data, a substantial improvement. Direct intercomparison corroborates two separate empirical TOPEX SSB derivations, but observed mm-level offsets and estimate differences for infrequently observed locations in the (*U*, *SWH*) domain highlight the need for future refinement.

[19] There is no question that this direct method is simpler to implement from numerous perspectives, foremost the avoidance of complex and numerically-intensive nonparametric inversion. Moreover, one is now working directly with the height residual and its correlatives, rather than time-dependent differences in all terms. These points, among others, suggest the benefit that direct assessment may have in speeding studies to evaluate the relative importance of additional characteristics of sea state beyond altimeter-derived (*U*, *SWH*). For instance, direct regression of TOPEX height residuals against global model-derived long wave products, unobtainable using the altimeter, are in progress and may identify remaining SSH variance. Further, the sparse time-sampling approach of Figure 2a can also be applied spatially, where basin-scale evaluation of the sea state impacts now becomes more tractable. It is also likely that this SSB methodology is applicable to altimeters aboard ERS, Envisat, or Geosat Follow-On platforms with use of an appropriate mean surface reference.

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