A COMPARISON OF SEA STATE BIAS ESTIMATES FROM THEORY AND RECENT EMPIRICAL MODELS

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ABSTRACT

Two theoretical formulations of the sea state bias (SSB) by Srokosz (1986; hereafter S86) and Elfouhaily et al.(2000; hereafter E00) are applied to directional ocean wave spectra from WAM and from NDBC moored buoys collocated with Topex altimeter data. S86 SSB computations obtained for WAM with idealised ocean current fields reveal a quasi-linear relationship between the SSB coefficient and the r.m.s. wave slope, which remains valid for a wide range of wind/wave/current conditions. It is shown that the SSB coefficient is parameterised better in terms of slope, than significant wave height and wind speed as is presently used in empirical models.

The theoretical SSB for the buoys' 2D wave spectra are compared with estimates from five recent empirical SSB models calculated from the collocated Topex data. The magnitude of the E00 SSB shows a strong sensitivity to the choice of high frequency tail model used to extend the 2D wave spectra, and best agreement with empirical estimates is seen when the influence of short waves is minimal. Similarly, the long-waves-only S86 theory displays better agreement with the empirical SSB models than the E00 theory extended to include short waves effects. Thus, the sea state bias appears to be primarily governed by the slope of long gravity waves, presumably through its well-documented influence on the modulation of short waves.

Given a suitable high frequency tail, the E00 theory can adequately model the radar frequency dependence of the SSB, but at the expense of good quantitative agreement with the empirical SSB models. The E00 theory can introduce a new dependence of the SSB on the spectral peak period through its choice of short/long wave discrimination criterion, although no empirical evidence is available at this stage to establish the physical validity of this feature.

TWO SEA STATE BIAS THEORIES

Srokosz (1986)

A theoretical handle on the sea state bias was provided by the first two-dimensional sea state bias theory of Srokosz (1986) which estimates the skewness and electromagnetic bias for non-linear random surfaces. The necessary moments of the surface elevation and slopes are obtained from 2D wave number spectra under a weakly non-linear waves assumption, and related to the altimeter radar returns using the Geometrical Optics approximation.

Limitations
-> Weakly non linear approximation => the theory is strictly only valid for long waves

-> Geometrical optics => theory does not include a radar frequency dependence.

Elfouhaily et al (2000)

Elfouhaily et al. (2000) have recently proposed an improved theory based on Srokosz (1986) that allows for short wave/long wave interactions. The theory expresses the ssb coefficient in terms of the moments of both the long and the short waves and requires the spectrum to be divided into low and high frequency ranges (usually at 10*peak wave number).

Radar frequency dependence is introduced through the high frequency cut-off used to evaluate the integrals of the short wave spectrum.

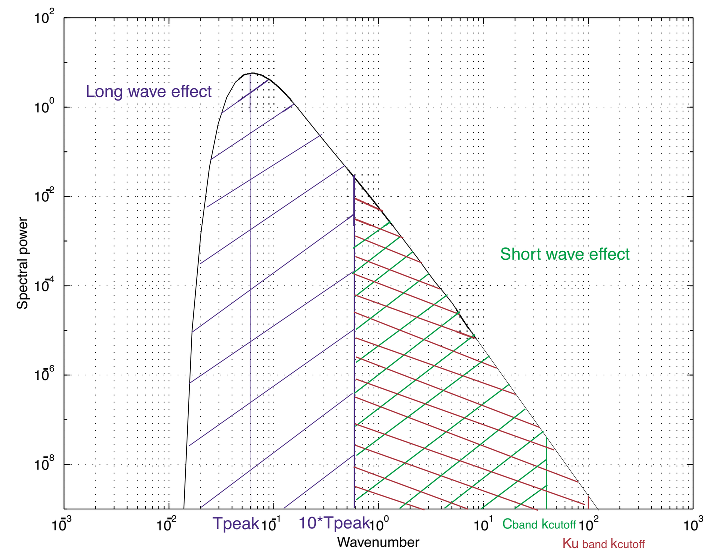


Figure 1: Two scale approach in Elfouhaily et al.(2000) for the calculation of the sea state bias coefficient. The moments of the spectrum are calculated separately for the long waves (blue) and the short waves (green/red), discriminated using the 10*Kpeak criterion. The radar frequency dependence of the ssb is introduced via the high frequency cutoff at Kcutoff = Kradar / 3.

2D WAVE SPECTRA and SSB IMPLEMENTATION

WAM directional wave spectra were obtained for an idealised deep-water current field which included (a) an idealised north-going curved jet stream of dimensions and magnitude comparable to those of the Gulf Stream, and (b) a cyclonic eddy comparable to mesoscale cold core eddies. This configuration offered the maximum number of combinations of relative wind/wave/current directions. Wave spectra were extracted at 15 grid points selected to best sample the effect of these features on the ocean wave spectra. The idealised current grid was submitted to a variety of wind and sea state scenarios. Here, we present results for a three-day storm event, consisting of an increasing-and-decreasing easterly wind (3 to 21 to 3 m/s) blowing over a pre-existing northerly swell (10 s period). Wave spectra were extracted at all 15 output points every six hours, resulting in 11 time steps over the duration of the storm.

Directional buoy spectra were obtained from three NDBC moored buoys respectively in the Hawaii, Gulf of Mexico and Gulf Stream area. The directional buoy data were collocated within 100 km and 1 hour of the Topex altimeter overpasses.

Implementation: Both the WAM and the buoy directional spectra span frequencies between 0.04 and 0.4 Hz and 360 degrees in azimuth. The spectra were extended towards higher frequencies using (a) an f^{-5} tail and (b) the Elfouhaily et al (1997) spectrum. This latter directional spectrum is wind and fetch dependent and its collation with the buoy spectrum made use of the buoy wind speed and direction information.

PARAMETERISATION OF THE SSB WITH SLOPE

Empirical characterisations of the SSB coefficient generally parameterise it in terms of the significant wave height, SWH, and the wind speed, U10. This is done because SWH and U10 are the two geophysical parameters that are routinely obtained from altimeter data, in addition to the height (range). However, the altimeter U10 is obtained empirically from the backscattered power σ^0, which is known to depend on the surface wave slope variance (Barrick, 1974)

Figure 2 shows the SSB results for the three NDBC buoys against wind speed, SWH and rms slope. The SSB coefficient shows better correlation with slope than with either U10 or SWH.

Figure 3 shows the SSB results obtained for the WAM run 6 (3-day storm evcent with swell) against rms slope. The same quasi-linear relationship is also observed, thus indicating that the parameterisation with slope remains valid over a wide range of wind/wave/current conditions.

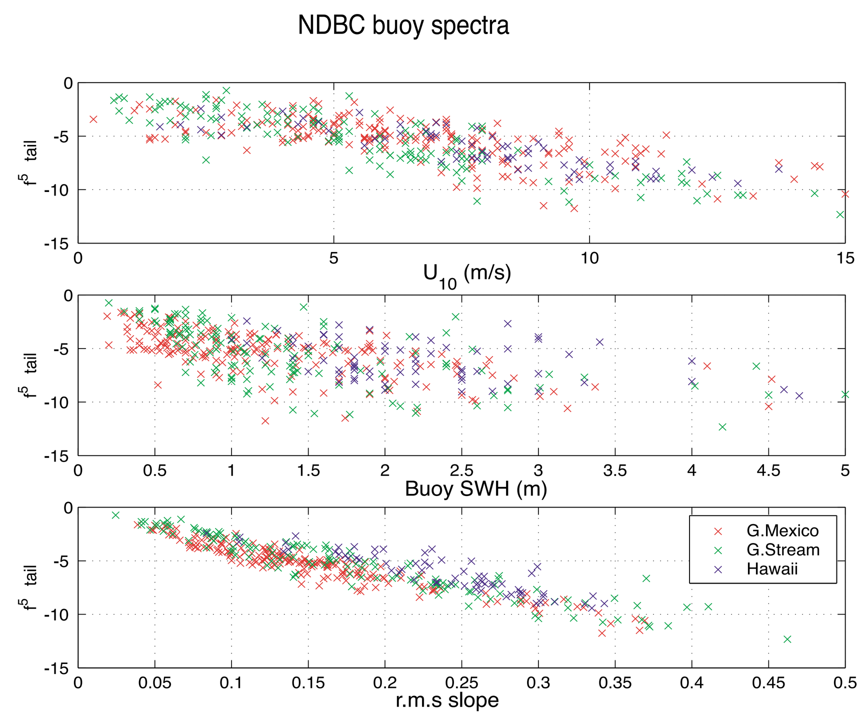


Figure 2: Theoretical ssb coefficient (in %) after Srokosz (1986) calculated for three NDBC directional buoys and an f^{-5} spectral tail extension shown against: Top: buoy wind speed, Middle: buoy SWH, Bottom: r.m.s. slope.

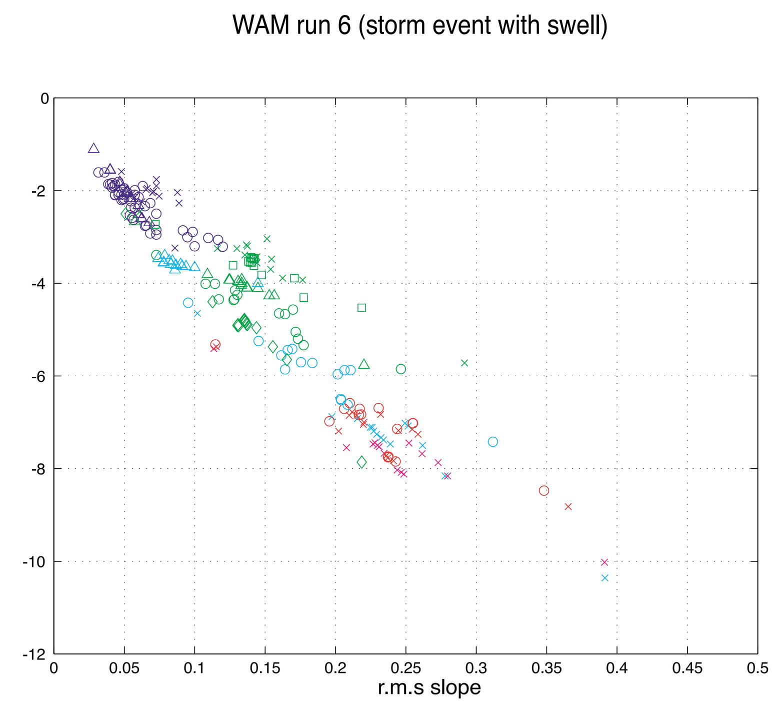


Figure 3: Theoretical ssb coefficient (in %) after Srokosz (1986) calculated for WAM run 6 (3 day storm event in the presence of swell) directional buoys and an f^{-5} spectral tail extension shown against r.m.s. slope.

COMPARING THE THEORY WITH EMPIRICAL SSB MODELS at Ku-band

Today's altimeter sea surface height measurements are routinely corrected for sea state bias errors. There is a wide range of corrections available, ranging from parametric formulations obtained from either global satellite cross-over studies (Gaspar et al., 1994) or instrumented tower experiments (Melville, 1991), to more recent similarly-derived non-parametric models (Gaspar et al., 2001; Millet et al., 2001). These empirical models have in common the fact that all rely on altimeter wind speed and SWH measurements to retrieve the SSB coefficient.

Figure 4 presents the theoretical SSB results calculated with both SSB theories for the NDBC directional spectra against the SSB coefficients calculated with various empirical models and the collocated altimeter wind speed and SWH measurements. The results are shown for an f^{-5} tail extension (Figure 4a) and for an Elfouhaily et al. (1997) spectral tail (Figure 4b).

We find that:
-> the magnitude of the E00 SSB coefficient is systematically too low, regardless of the empirical model chosen for the comparison.
-> in contrast, the S86 SSB results generally produce the right order of magnitude with respect to all empirical models, (and in particular, with Melville et al. (1991) and Millet et al. (2001)).

Figure 4a: Theo. ssb (%) v. Empirical ssb (%) for f^{-5} tail

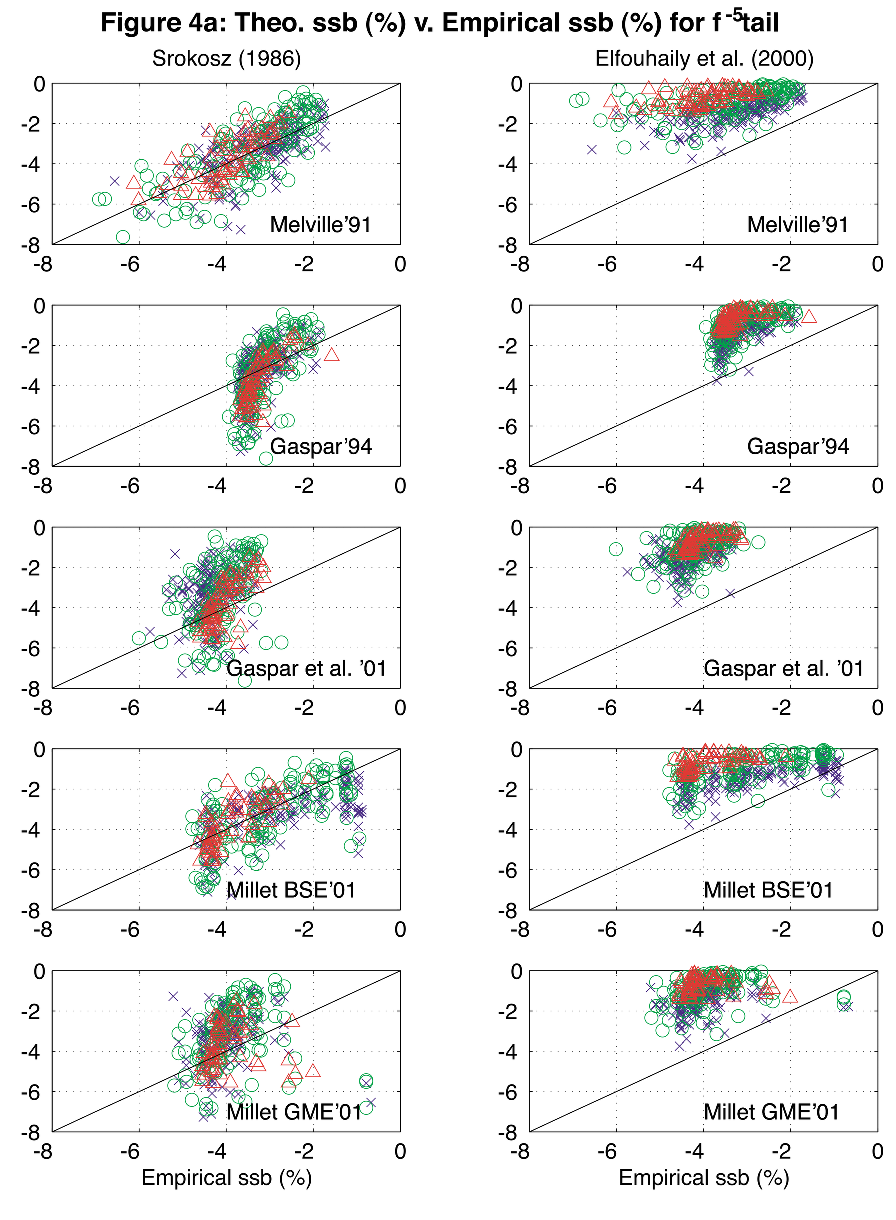
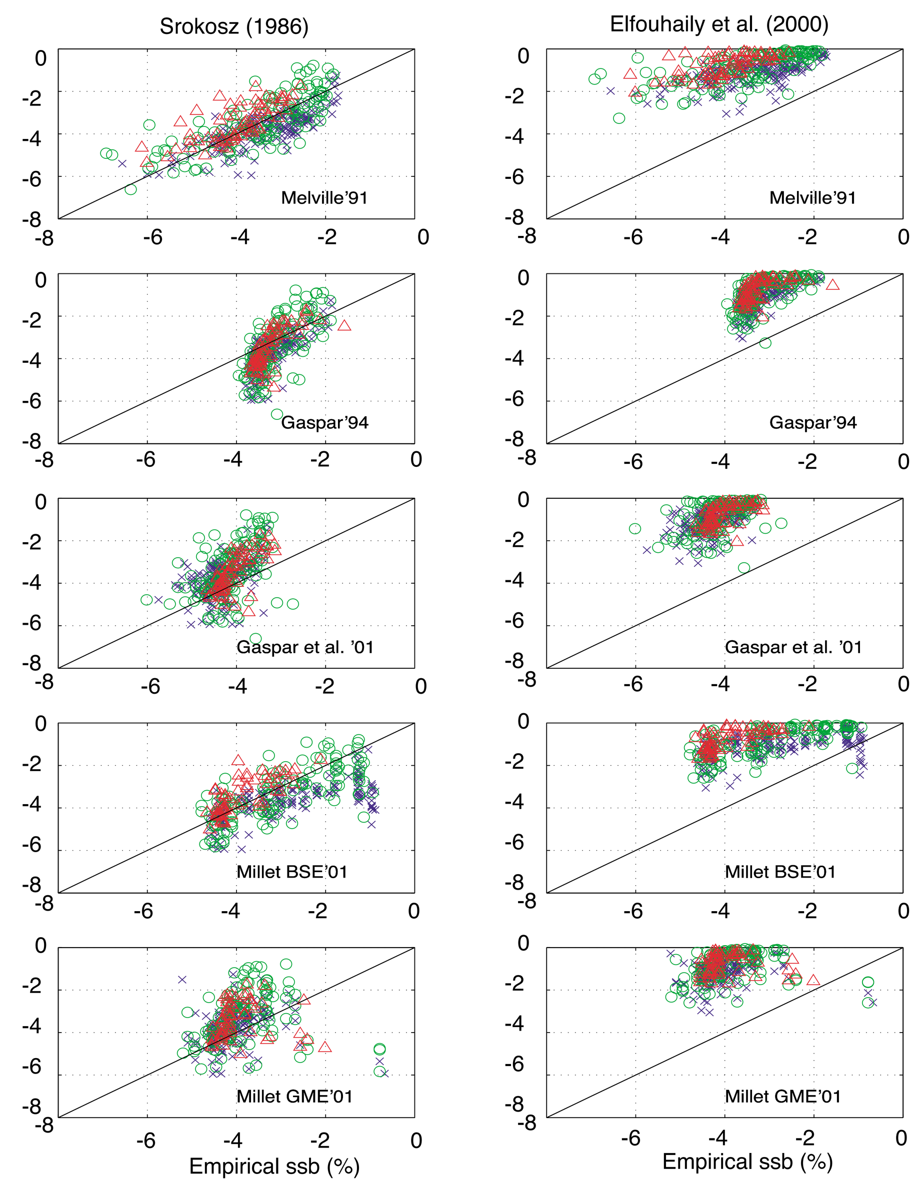


Figure 4b: Theo. ssb (%) v. Empirical ssb (%) for E97 tai



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HIGH FREQUENCY SPECTRAL TAILS and SSB

Figure 5 shows the relation between SSB coefficient and rms slope using both SSB theories and various spectral tails extensions. We see that:
-> the quasi-linear relationship between ssb and slope observed in Figure 2 and 3 remains valid for the Srokosz (1986) theory regardless of the tail chosen.
-> the Elfouhaily et al. (2000) results display some clustering for the f^{-5} tail case which can be related to the use of a peak period dependent criterion to discriminate long/short waves contributions (i.e. large peak period means a larger proportion of the spectra in assigned to short wave efects, thus smaller (in magnitude) ssb coefficients)

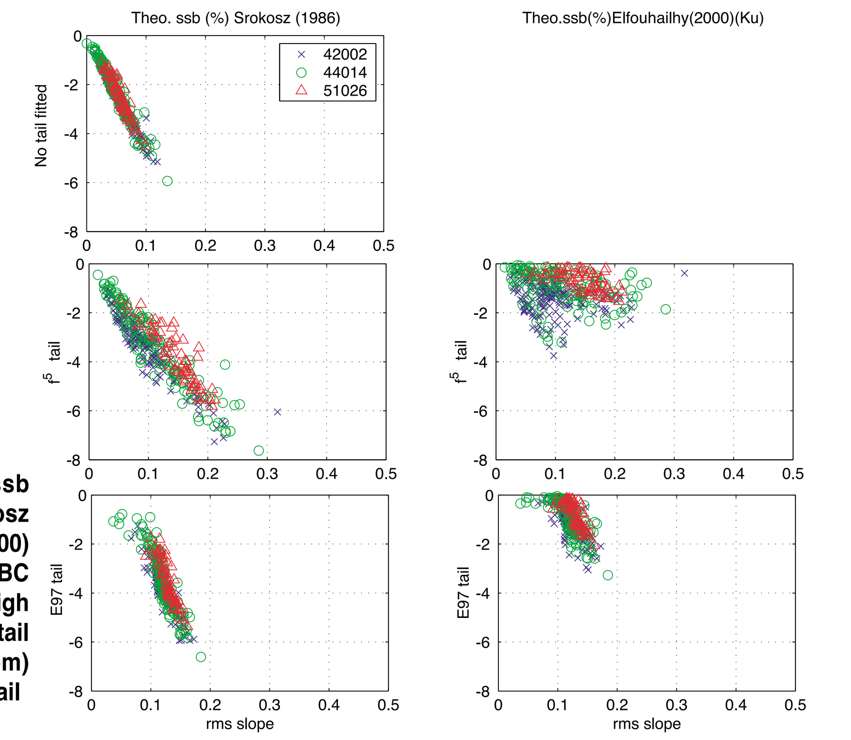

Figure 5: Theoretical ssb coefficient (in %) after Srokosz (1986) and Elfouhaily et al (2000) against rms slope for three NDBC directional buoys and three high frequency tail cases: (top) no tail (middle (f^{-5} tail) and (bottom) Elfouhaily et al (1997) spectral tail

CONCLUSIONS

Overall, this work suggests that the SSB may be better parameterised in terms of the slope of long gravity waves. This is supported by the observation that the long-waves-only S86 theory produces adequate SSB estimates in good quantitative agreement with today's empirical SSB models (Figure 4). There is a degree of controversy attached to applying to short gravity waves a SSB theory developed under the weakly non-linear waves approximation. However, the weak dependence of the S86 SSB magnitude on the short waves (Figure 5) and the consequent goodness of fit with empirical SSB regardless of the high frequency tail does lend support to the above approach. A tentative explanation for this may be found in laboratory and theoretical findings which indicate a clear relationship between the modulation of short waves and the slope of the long waves (Miller et al., 1991).

The E00 SSB theory extended to short waves displays, unsurprisingly, a strong sensitivity to the energy in the short wave part of the spectrum. This makes it difficult to assess the validity of this new formulation given that no consensus has yet been reached as to the precise description of the high frequency spectrum. It is noted though that best agreement with the empirical SSB models occurs once again when the influence of short waves is minimal, in support to the argument that SSB is predominantly influenced by long waves.

The practical implementation of the E00 theory calls for a long-wave/short-wave dividing criterion. Setting this to 10 times the peak wave number, as suggested in E00, introduces an indirect dependence of the SSB on the peak wavelength, with major repercussions on the magnitude of the SSB coefficient (Figure 5). At present, it is difficult to decide if this dependence of the SSB on peak wavelength is indeed real, as current empirical SSB models do not include such dependence. It is hoped that further empirical studies into the spatial distribution of SSB in the global ocean may be able to establish a physical basis for a dependence of SSB on ocean wave spectrum peak wavelength.

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