Measurements of EM Bias: Wave Slope and Altitude Effects

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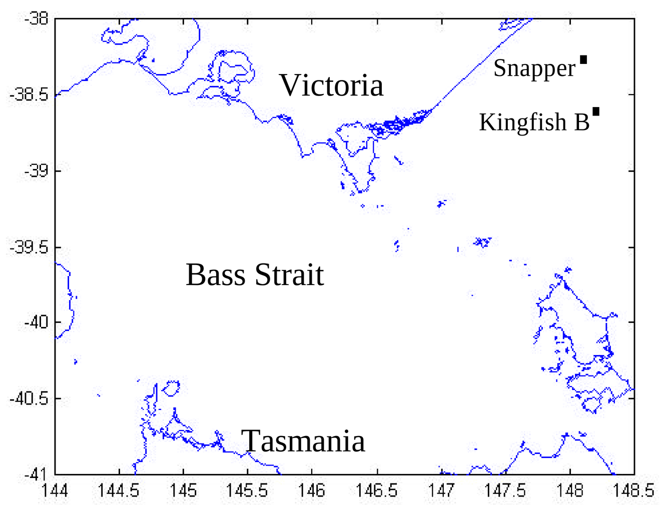
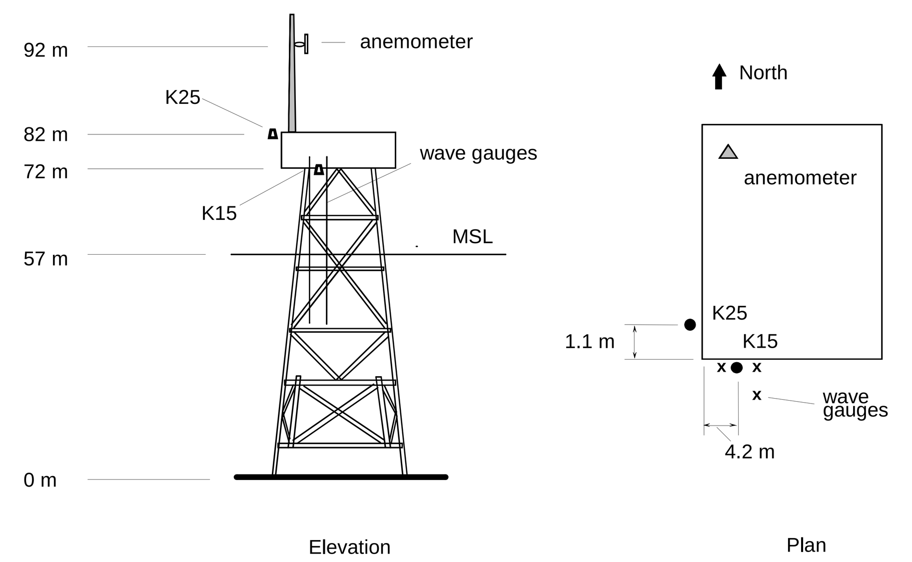
Introduction

Measurements of em bias at Ku band (14GHz) were made from a platform in Bass Strait during the austral winter of 1992. Two Ku-band Doppler scatterometers were installed on the Snapper platform at 15 and 25m above MSL in 57m of water 30 km off the coast of Victoria, Australia. Approximately two months of data were collected and included microwave backscatter, microwave Doppler velocity, along with supporting wind and wave measurements. The normalized em bias $\beta = \varepsilon/Hs$, where ε is the em bias and Hs is the significant wave height, is usually correlated with the wind speed and significant wave height; however, this leads to significant anomalies at at low wind speeds where β typically has a finite value at zero wind speed, presumably due to the effects of residual waves and swell generated at remote locations. These measurements were carried out to examine em bias in strong wind and wave conditions at a site exposed to the Southern Ocean, to investigate improved parameterizations of the bias, and to study the effect of small altitude differences on em bias measurement.



Site of the experiment. All microwave measurements were made from the Snapper platform. Some meteorological measurements were made from Kingfish B, 45km SSE.

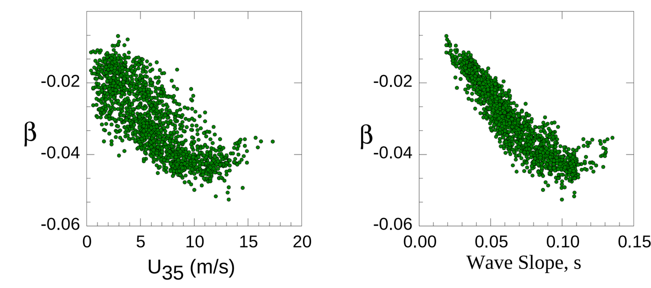


Layout of instrumentation on the Snapper platform

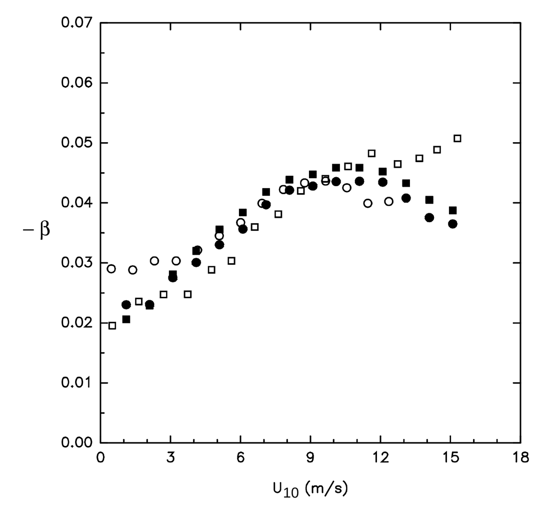
Conclusions

Tower-based measurements of em bias show that correlations of the normalized bias $\beta = \varepsilon/Hs$ with a measure of the longer wave slope, s, are superior to the standard correlations with wind speed. This might be expected on the basis of both dimensional reasoning and on the theory of short-wave modulation by longer waves. We find that the dependence of the bias on wave slope is liner for smaller slopes, before reaching a local maximum at an rms slope, s, in the range 0.12-0.14. (Note that s is scale dependent an for these measurements correspond to waves of frequency 1 Hz and smaller.) Comparison of the measured bias with that predicted by Arnold (1992) based on a short-wave modulation model agree to with an error of 20-40% that depends on the scattering theory and model assumptions about the form of the short wave spectra.

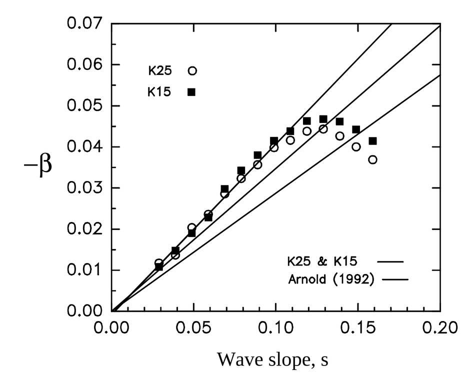
We find that the em bias measured at 15m elevation is approximately 9% greater than that measured from 25m. We find that the normalized standard deviation of the backscatter at 15m is approximately 8% greater than that at 25m, qualitatively consistent with the differences in the measured bias, and the larger footprint of the scatterometer at 25m. Complete resolution of this altitude effect awaits detailed measurements of the small-scale structure of the ocean surface at scales less than several meters.



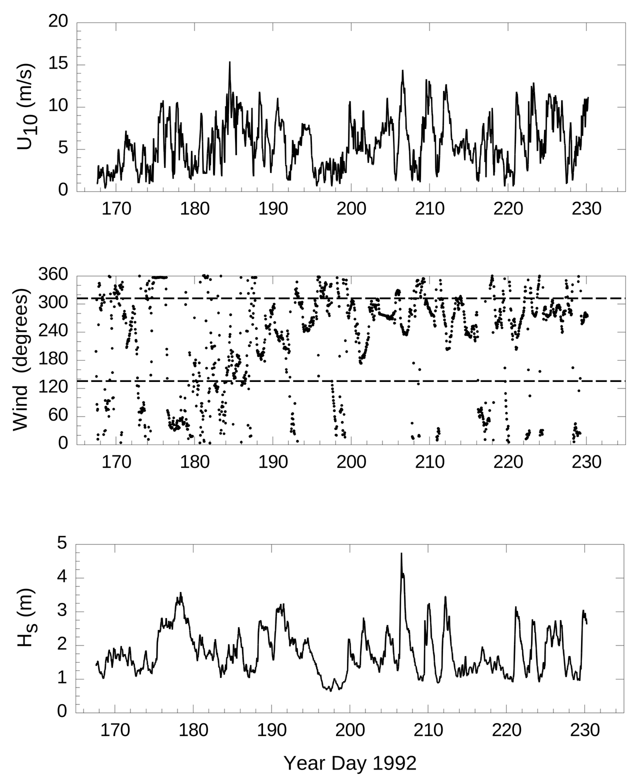
Scatter plots of hourly averages of normalized bias plotted against the 35m wind speed and the wave slope parameter. (In this and subsequent figures the rms wave slope s is based on the K15 values which were up to 12% greater than those measured with the K25 scatterometer. The difference is due to the larger footprint of K25.) Two improvements of the slope parameter over the wind speed become immediately apparent. Firstly, the points approach the origin with no intercept at zero slope. Secondly, the scatter is reduced especially at smaller values of the bias.



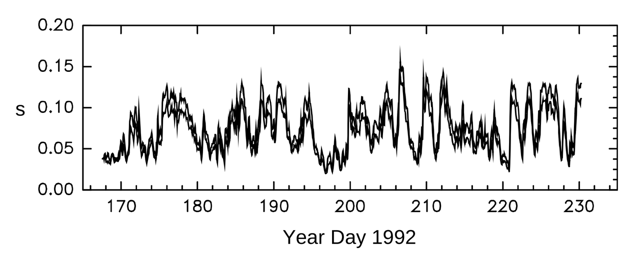
It is usual to correlate the normalized bias, here $-\beta$, with U10, the wind speed at 10m. This is shown here with results binned in 1 m/s increments for three tower-based Ku-band experiments: SAXON - CLT, (Melville et al., 1991),□ ; Gulf of Mexico Experiment (GME), (Arnold et al, 1994), ○ ; This experiment, Ku at 15m ,■ ; Ku at 25m, ● . In the wind speed range from 3-12m/s there is generally good quantitative agreement between the three data sets. Each experiment shows that the normalized bias at zero wind speed is a significant fraction of that at the higher wind speeds. For the GME and this experiment there is a clear maximum at a wind speed in the range 9-11m/s, while SAXON-CLT shows only a local maximum around 11m/s before continuing to increase. In this experiment there was a small but discernible dependence of the normalized bias on the altitude of the scatterometer with the measured at 15m being up to 5% greater than that at 25m.

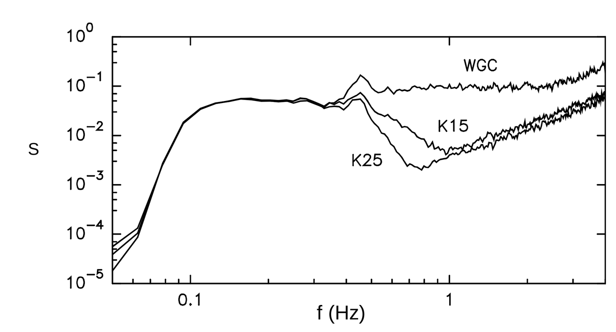


The linear sections of the plots of the K15 and K25 bias versus rms wave slope, s, are nearly identical and given by $\beta = -0.47$ s. This result is consistent with the modulation of short waves (the scatterers) by longer waves having a characteristic slope, s. Since the work of Longuet-Higgins and Stewart (1960), it is well known that the amplitude and wavenumber of the short waves are greatest at the crest and the modulation of these parameters is, to leading order, proportional to the slope of the longer waves. Based on the Gulf of Mexico experiment (Arnold et al., 1995), Arnold et al. (1990) and Arnold (1992) proposed a short wave modulation model leading to the result that $\beta = -\alpha m$, where m is a modulation parameter, which on the basis of the hydrodynamic modulation theory is equal to the rms wave slope, s, of the long waves and α is a dimensionless constant that depends on the details of the scattering theory and the directional spectrum of the short waves. Arnold (1992) suggested that α is in the range (-1.15,-1.39). The range of Arnold's predictions are plotted on the figure.



The em bias experiment at two elevations ran from June 16 to August 19, 1992 when the lower scatterometer was rotated to 45 degrees incidence angle for another experiment. Measured wind speeds ranged up to 15m/s, with significant wave heights up to 4.8 m. The instrumentation was mounted on the SW corner of the platform, so to avoid interference effects due to the platform , only data corresponding to wind directions of 225 +/- 90 degrees were analyzed. The wind direction measurement on the Snapper platform failed on day 188 and was replaced by that from the Kingfish B platform for the rest of the experiment. Wave heights were measured using the Doppler capability of the scatterometers to measure the vertical component of the orbital velocity of the wave. This procedure was tested against direct measurements of wave heights using wire wave gauges.





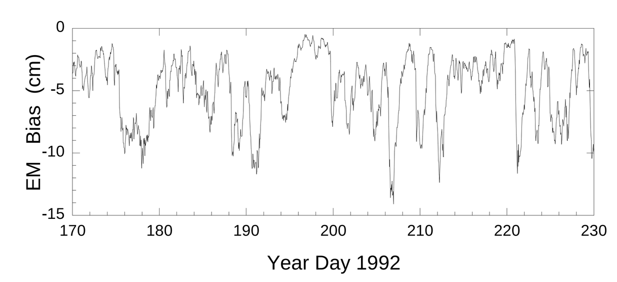
No matter what the physical details of the processes leading to em bias, simple dimensional analysis suggests that the normalized bias β should be a function of a characteristic slope s say, of the wind waves and swell. In this experiment we initially deployed a small array of wire wave gauges over a base line of approximately one meter, but seals found the wires ideal for relieving their itches, and the wires did not last long. In order to obtain some measure of the wave slope we used the wave height measurement and the linear dispersion relationship for deep-water waves to estimate a wave slope s, and a spectral density S(f) for waves larger than the scatterometer beam sizes on the surface: 1.7 m and 2.8 m for the 15 (K15) and 25m (K25) scatterometers, respectively. These figures show an example comparison of "slope spectra" computed from the wire wave gauge record, and the scatterometer wave height measurements following Cox & Munk (1956):

$$S(f_i) = \frac{(2pf_i)^4}{g^2}\Phi(f_i)$$

where $$s = \left[\frac{1}{N}\sum_{i=1}^{N}\frac{(2pf_i)^4}{g^2}\Phi(f_i)\right]^{1/2}$$

and $\Phi(f_i)$ is the wave height frequency spectrum.

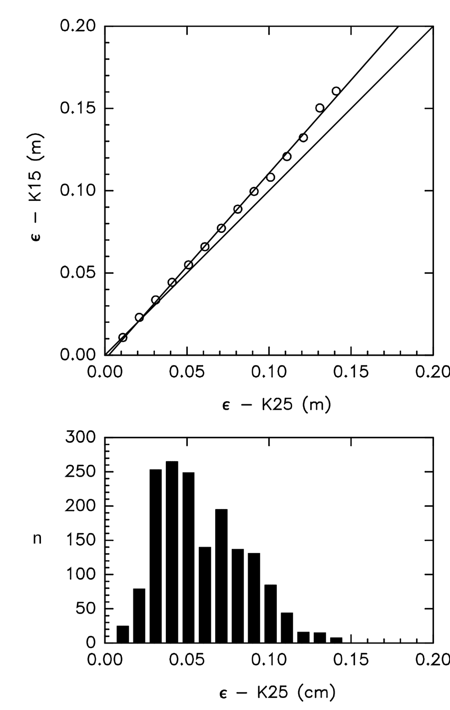
Note that s is divergent unless a suitable cut-off is specified. Note also that both scatterometers track the wire wave gauge up to 0.4 Hz, with the effect of the spot size becoming apparent for for K25 at 0.75Hz and that for K15 at 1 Hz.

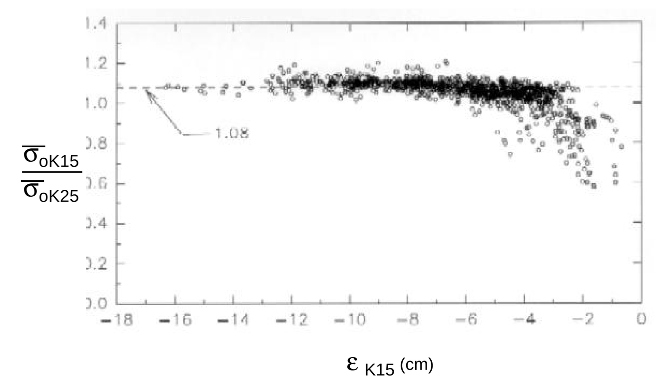


The em bias ε is defined by

$$e = \frac{\frac{1}{N}\sum_{n=1}^{N} s_o(t_n)h(t_n)}{\frac{1}{N}\sum_{n=1}^{N} s_o(t_n)}$$

where σ_o is the scatterometer cross-section , and η is the surface displacement, each as a function of time. If σ_o and η are uncorrelated then the em bias is zero, but the em bias in radar altimeters is typically negative at microwave frequencies corresponding to increased backscatter at the troughs of the waves when compared with the crests. This figure shows hourly averages over the course of the experiment with biases as large as - 15cm when Hs was approximately 5 m.





A comparison of the em bias measured by K15 and K25 shows that the tow values are proportional, but K15 is consistently about 9% greater than K25. In order to investigate the source of this difference, it is convenient to define the em bias in terms of the normalized scattering cross section $\bar{\sigma}_o$, where

$$\bar{s}_o = \frac{s_o}{\frac{1}{N}\sum_{n=1}^{N} s_o(t_n)}$$

Then the em bias, ε, is given by

$$e = \frac{1}{N}\sum_{n=1}^{N}\bar{s}_o(t_n)h(t_n)$$

where η is the surface displacement due to the waves. Now measurements of η using K15 were approximately 4% greater than those from K25; insufficient to explain the difference. However, the standard deviation of σo for K15 over one hour samples is consistently higher than for K25 by approximately 8%, except at the smaller values of em bias. This result is shown in the adjacent figure. The most likely cause of this difference is the effect of the increasing spot size on the surface relative to the coherence length scale of the scatterers as the scatterometer elevation increases. Confirmation of this effect would require detailed measurements of the ocean surface structure at scales less than O(1) m.

Acknowledgments

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