JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, C02009, doi:10.1029/2008JC005117, 2009

Reply to comment by Paul A. Hwang on "A study of the slope probability density function of the ocean waves from radar observations" by D. Hauser et al.

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Received 10 September 2008; revised 29 October 2008; accepted 3 December 2008; published 12 February 2009.

Citation: Hauser, D., G. Caudal, S. Guimbard, and A. Mouche (2009), Reply to comment by Paul A. Hwang on ''A study of the slope probability density function of the ocean waves from radar observations'' by D. Hauser et al., *J. Geophys. Res.*, *114*, C02009, doi:10.1029/2008JC005117.

1. Introduction

[1] In response to the comment of *Hwang* [2009], this paper presents an addendum to the study published by *Hauser et al.* [2008] on the mean square slopes (mss) derived from radar observations (at C-band and incidence angles between 7 and 21°). Different sea state conditions are sorted out (swell, wind sea, and mixed sea) and their possible impact on mean square slopes is analyzed. It is found that swell encountered in condition of moderate wind (6–12 m/s) seems to affect only weakly the radar-derived mean square slope and mainly in the crosswind direction. Under light wind (<6 m/s) where only swell conditions were encountered, the sensitivity of the mss to wind speed is much larger than in wind sea conditions (either pure or mixed). In wind sea cases, there is no significant difference for the mss-wind relationship between pure wind sea and mixed sea cases with dominant wind sea part. Compared to mss estimated from *Hwang* [2009] and *Hwang* [2005] parameterizations, the radar-derived mss are in good agreement for intermediate wind speed (4–7 m/s), but larger at light wind (<4 m/s) and smaller at moderate to strong wind (>7 m/s). This conclusion is the same whatever parameterization of Hwang is used (mixed sea or pure wind sea). Although the effect of swell cannot be excluded at light winds, sorting the radar data by type of sea conditions does not help to reconcile the mss calculated from *Hwang* [2005] parameterizations and the radar-derived ones at strong winds. The best agreement of the radar-derived mss remains with the mss derived from the *Elfouhaily et al*. [1997] parameterization.

[2] In their study, *Hauser et al.* [2008] (hereinafter referred to as HCGM08) presented an analysis of the mean square slope (mss) of ocean waves as estimated from C-band radar observations at small incidence. A large part of the paper was devoted to the analysis of the relationship between mss and wind speed as obtained from radar observations, and to comparisons with various former results presented in the literature. In his comment, *Hwang* [2009] criticizes the fact that HCGM08 did not take into account in their analysis, the presence of background long waves. In particular *Hwang* [2009] suggests that the discrepancy between the results of HCGM08 and those of *Hwang* [2005] (hereinafter referred to as H05) could be due to the presence of long waves. Therefore, in this Reply we reanalyze our data by sorting them according to sea state conditions. We first present in section 2 the sea state conditions and separate our conditions in three classes (swell, pure wind sea, mixed sea with dominating wind sea part). We then reanalyze in section 3.1 our mss results sorted according these different sea state conditions. In section 3.2, we compare these results with those of H05 taking into account the apparent cutoff wave number associated with our radar observation conditions. Finally, we conclude in section 4.

2. Sea State Conditions Corresponding to the Data Set of *Hauser et al.* [2008]

[3] The VALPARESO data set (see *Mouche et al.* [2005] for more details) is composed of 15 flights of the C-band radar Système de Télédétection pour l'Observation par Radar de la Mer (STORM) over the Atlantic Ocean and English Channel. Each flight covered about 250 km to 300 km and flew over a meteo-oceanic buoy called Pharos (48°31′42″W, 5°49′03″W) which provided each hour atmospheric parameters (including wind speed and direction) and the 1-D spectrum of ocean waves. To investigate the impact of background waves on the relationship between mean square slope and wind speed, we use the adimensional parameters η^* and ω^* as proposed by *Hwang* [2009],

$$\eta^* = \frac{\eta^2 g^2}{U^4}, \omega^* = \omega_p U/g \qquad (1)$$

where ω_p is the angular peak frequency, η^* the wave height variance, and U the reference wind speed. The adimensional height variance and peak frequency are estimated using the 1-D spectra (provided over 31 frequency bands between 0.035 and 0.375 Hz), and wind speed is taken as the one measured at the measurement height (10.7 m) without correction for stability (we checked independently that

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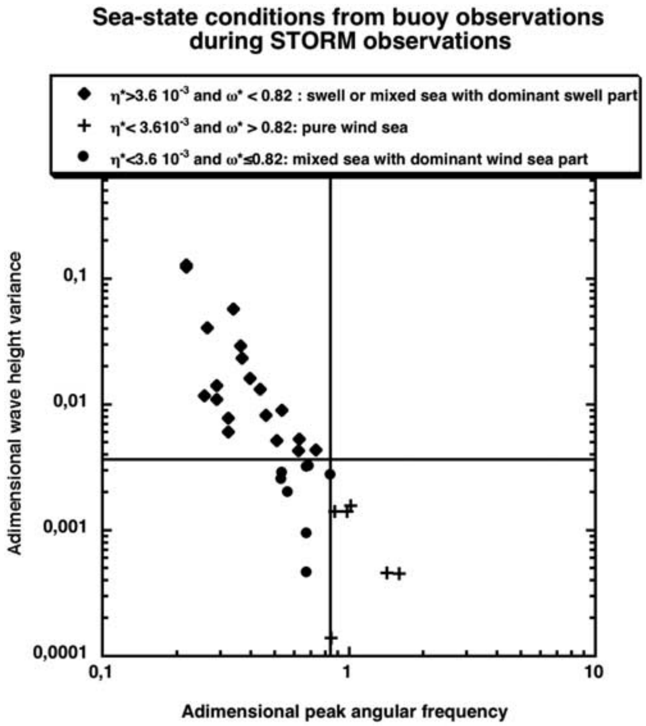


Figure 1. Adimensional parameters η^* and ω^* (equation (1)) estimated from the buoy observations collected during the STORM flights. The different symbols correspond to the limit values of η^* and ω^* ($3.64\ 10^{-3}$ for η^* and 0.82 for ω^*).

correction for stability in the cases corresponding to the STORM observations lead to deviation of less than 0.30 m/s from the measured wind). In the following we also consider that the adimensional parameters estimated at the buoy location characterize the sea state over the whole STORM trajectory. Although this is an approximation, we checked from wind and wave height fields from the WAM model (operational results from ECMWF) that variations along the STORM trajectory would not change the classification.

[4] Figure 1 shows the adimensional parameter η^* versus ω^* for the Pharos observations acquired during the STORM observations (2 to 3 data from Pharos during each flight). Using the same criterium as proposed by *Pierson and Moskowitz* [1964] and used by *Hwang* [2009], i.e., limit of fully developed wind waves for $\eta^* = 3.64\ 10^{-3}$ and $\omega^* = 0.82$, we first sort the swell cases (diamonds in Figure 1) as those with $\eta^* > 3.64\ 10^{-3}$ and $\omega^* < 0.82$. The analysis of 1-D spectra show that these swell conditions include pure swell conditions and mixed sea cases with a dominating swell part. In the following these two classes are merged together in the analysis.

[5] Data in Figure 1 with $\eta^* < 3.64\ 10^{-3}$ and $\omega^* > 0.82$ are shown as (+) marks. This class corresponds to pure wind sea, according to the criterium of *Pierson and Moskowitz* [1964]. Although the number of cases is not very large, the adimensional parameters in this case seem to follow the empirical growth law proposed by *Hwang* [2006] and plotted by *Hwang* [2009] in his Figure 1. This confirms that we can consider them as wind sea cases.

[6] Finally data with ($\eta^* < 3.64\ 10^{-3}$ and $\omega^* < 0.82$) (shown as circle symbols in Figure 1) correspond to our third class. By examining the 1-D spectra, we could conclude that this class corresponds to mixed seas with dominating wind-sea part.

[7] Comparing to Figure 3 of *Hwang* [2009], it is clear that our sea state conditions are quite different from those of H05: first, H05 did not observe cases similar to our swell cases (pure swell or swell-dominated mixed cases); second our mixed sea cases are quite different from those of *Hwang* [2009] when we refer to the adimensional parameters η^* and ω^*; finally our pure wind sea cases are clearly separated from our mixed sea cases in this η^* (ω^*) relationship, whereas those of Hwang may have the same adimensional relationship as his mixed sea cases.

[8] This must be kept in mind in the following for comparisons with the results of H05 and analysis of the impact of background waves of the relationship between mss and wind speed.

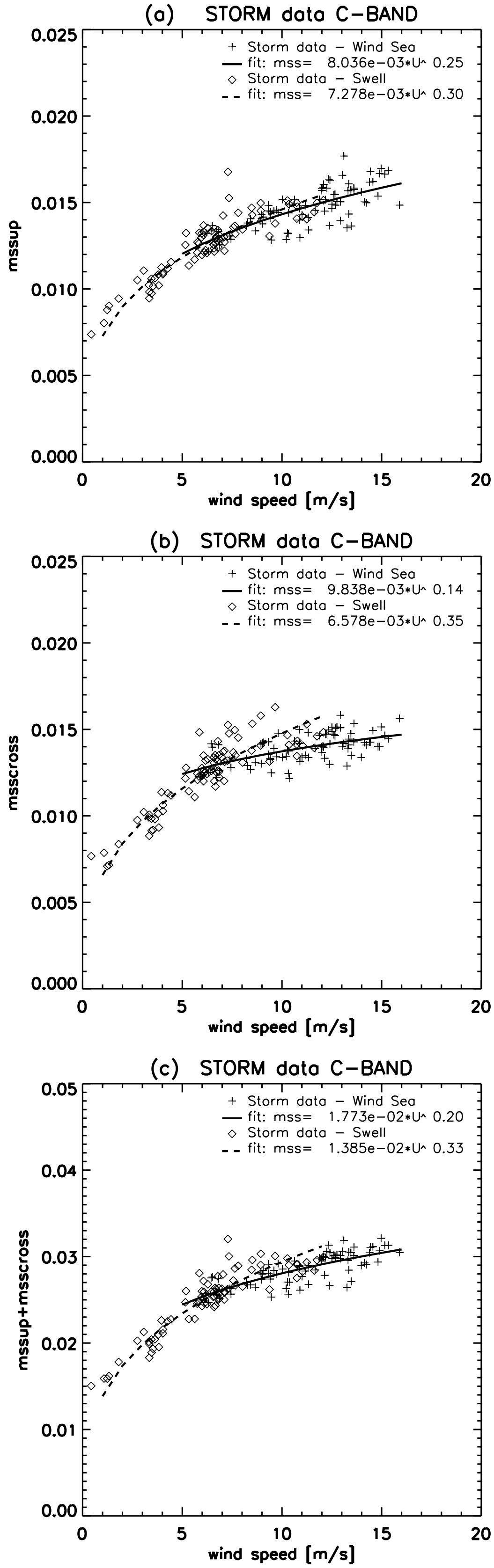
3. Reanalysis of STORM mss Taking Into Account Sea State Conditions

3.1. Radar-Estimated Mean Square Slope Versus Wind Speed, in Swell and Wind Sea Conditions

[9] Figures 2a, 2b, and 2c show the STORM-derived mean square slope (using the method presented in HCGM08) versus wind speed, in upwind, crosswind directions as well as for the total mss. We recall here that wind speed was also derived from radar cross section measured at incidence 32.5°, using the same data set as for deriving mss. Plus (+) symbols correspond to STORM data acquired during conditions of wind sea (pure wind sea or mixed sea with dominant wind sea part) measured at the Pharos buoy. Diamonds symbols correspond to STORM data acquired during conditions of swell (pure swell or mixed sea with dominant swell part).

[10] Figure 2 first shows that different wind speed ranges are associated with different sea state conditions. For wind less than 6 m/s, only swell conditions are observed; for wind stronger than 12 m/s, only wind sea cases are observed; in the [6–12] m/s wind speed range (and only in this range) both conditions of wind sea and conditions of swell are encountered. This implies that discussion about the impact of the background long waves on the mss has to be limited with our data to the range of wind speed between 6 and 12 m/s.

[11] In this range of wind speed [6–12 m/s], the mss derived in the upwind direction (Figure 2a) are very similar for both sea state classes (swell or mixed sea). In contrast, in the crosswind configuration (Figure 2b), mss in swell cases are larger than in wind sea cases (maximum difference of 13% for a 12 m/s wind). Figure 2c shows the total mean square slopes (sum of upwind and crosswind values). In the [6–12 m/s] wind speed range, the total mean square slopes in swell cases are only 7% larger (in average) than those in wind sea cases. *Vandemark et al.* [2004] also analyzed the effect of sea state conditions on radar-derived mean square slope (Ka-band radar, nadir observations). In this range of wind speed they found larger values of mss for open sea conditions with respect to coastal conditions (about 10% difference at 12 m/s wind). Although the classes of sea state conditions are not defined with the same method, and in spite of the very small difference between our two classes, both analyses are consistent.



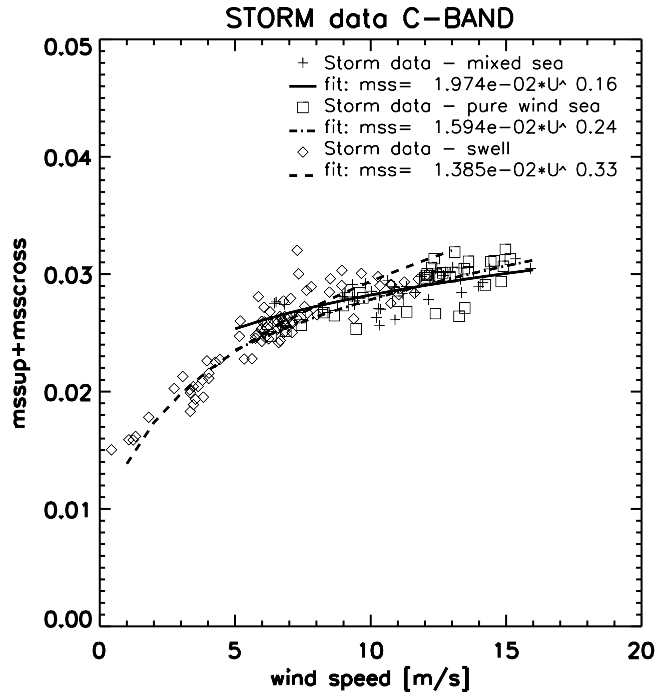


Figure 3. Same as Figure 2c except that the data in wind sea conditions are separated in two subsets: pure wind sea with square symbols, and mixed sea with dominant wind sea part with plus signs).

[12] In light wind conditions (<6 m/s) where only swell cases were observed, the sensitivity of mss with wind speed is the largest. This higher sensitivity of mss with wind at light wind was already mentioned by HCGM08. This fact is also consistent with the results of *Vandemark et al.* [2004] for any of their sea state conditions (open sea, coastal and inland) (their Figures 7 and 9) although they find that for a given wind speed, mss from Ka-band radar observations increase from inland to coastal and open ocean conditions.

[13] Figure 3 presents the same analysis as presented in Figure 2c above, but sorting further the wind sea cases in two subsets as explained in section 2. These two subsets cover the same range of wind speed (6–16 m/s). Pure wind seas and mixed seas are respectively square symbols and crosses in Figure 3. Figure 3 shows that there is no significant difference for the radar-derived mean square slopes obtained in these two sea state conditions.

3.2. Comparisons With H05 Results

3.2.1. Estimation of Cut Off Limit Using *Hwang* [2005, 2006] Spectra

[14] In his comment *Hwang* [2009] contests the choice of HCGM08 regarding the apparent cutoff wave number (k_d)

Figure 2. Mean square slope estimated from STORM observations at C-band versus wind speed (see HCGM08 for details) in (a) upwind, (b) crosswind, and (c) as total values. Figures 2a and 2b are equivalent to Figures 5a and 5b of HCGM08, except that two different symbols are used for separating wind sea and swell conditions. The fits are applied on each subset of data. Same convention for Figure 2c.

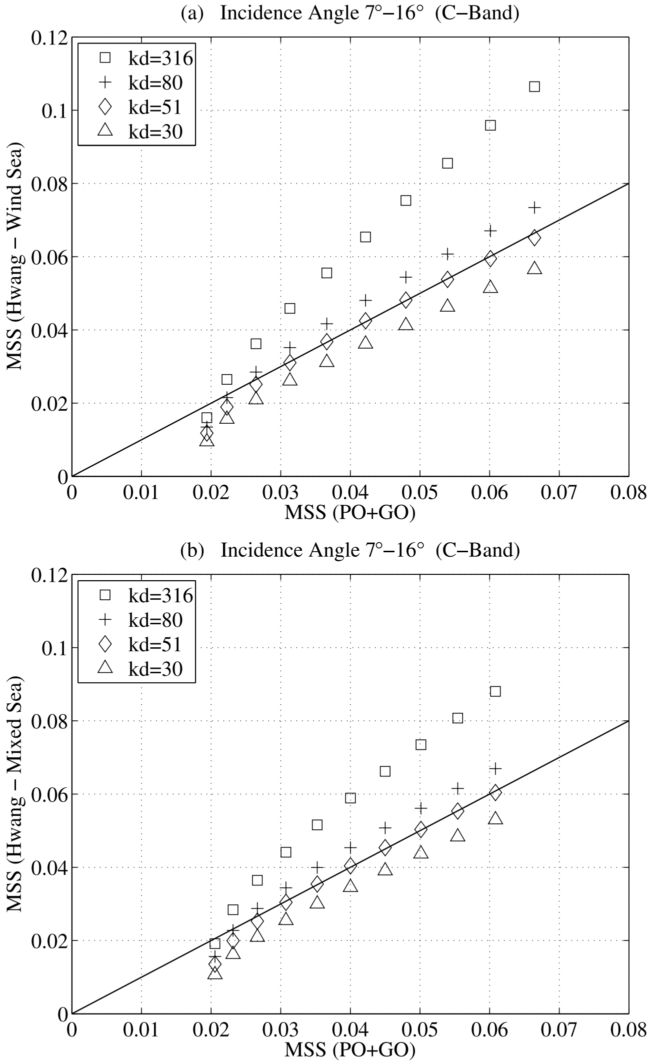


Figure 4. Total mean square slope estimated from the spectra of *Hwang* [2005] for short waves and *Hwang* [2009] for long waves, as a function of the total means square slope estimated from simulated radar cross sections in conditions of STORM observations (C-band, incidence 7–21°; see HCGM05 for details on the method). The different symbols are for different values of the wave number limit k_d used in the integration of the surface spectrum. (a) Surface spectrum for wind sea conditions and (b) surface spectrum for mixed sea conditions.

corresponding to the longest waves contributing to the radar-derived mean square slope. In particular *Hwang* [2009] suggests that the k_d value should be 4.7 times the electromagnetic wave number, as suggested from *Jackson et al.* [1992].

[15] First we would like to recall that an objective method was used by HCGM for estimating the cutoff wave number associated with the STORM observations. The same type of method was previously used by *Jackson et al.* [1992] and *Thompson et al.* [2005], but applied for other conditions of radar observations. Although the method is similar, the results for k_d differ because the configuration of radar observations differs in both wavelength and incidence range: C-band and incidence between 7° and 21° for HCGM08, Ku-band and incidence between 0 and 15° for *Jackson et al.* [1992].

[16] Second we assess here the choice of HCGM08 for k_d by extending the results shown in their Figure 2, to simulations performed using the wave spectra of H05 for wind sea and mixed sea conditions. Figure 4 is similar to Figure 2 of HCGM08, but the mean square slopes are calculated for the Hwang spectra (H05 for waves with wave number > 1 rad/m, *Hwang* [2009] for wave number < 1 rad/m). Figures 4a and 4b are respectively for the wind sea and mixed sea cases as classified by H05. In each case, the mean square slope inverted from simulated radar cross sections using the Hwang spectra as input, is compared to the mean square slope calculated directly from the Hwang spectra integrated up to a frequency limit corresponding to a certain k_d value. Results are plotted for four values of k_d (30, 51, 80, 317 rad/m). Figure 4 shows that whatever the sea condition is (wind sea or mixed sea) the best agreement is obtained for 51 rad/m, i.e., for the same k_d value as estimated by HCGM08 using other surface wave spectra.

[17] Thus, we confirm that a wave number of 51 rad/m is a reasonable value of the cutoff that must be applied to the surface spectra for comparisons of mss with our radar-derived values.

3.2.2. Comparisons With Mean Square Slope From *Hwang* [2005, 2009] Spectra

[18] Figure 5 shows the radar-derived mss (same data points as in Figure 2) with the mss-wind relationships overlaid. These latter are calculated from the parameterizations of *Hwang* [2005] for the short wave range (wave number > 1 rad/m) and from *Hwang* [2009] for the long wave part (wave number < 1 rad/m), and taking into account

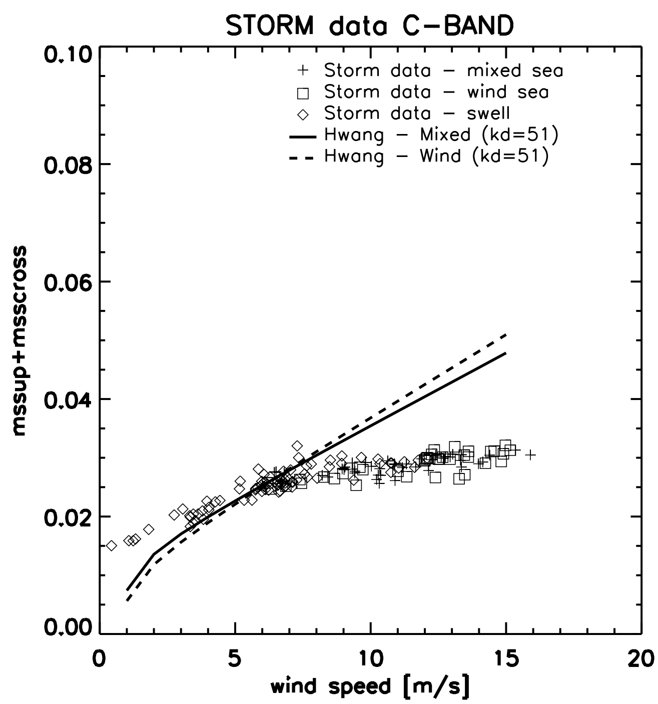


Figure 5. Same as Figure 3, but with overlay of the mean square slope estimated from the *Hwang* [2005] and *Hwang* [2009] parameterizations. Dot-dashed line is for pure wind sea and dashed line is for mixed sea. In both cases the mss is estimated by integrating the analytical form of the spectrum out to wavelengths corresponding to k_d = 51 rad/m.

the cutoff wave number of 51 rad/m. Hwang's parameterization for pure wind sea (dashed-dotted line) and mixed sea (dashed line) are shown in Figure 5.

[19] In very light wind conditions (<4 m/s), the radar-derived mean square slopes are significantly larger than those derived from both parameterizations of Hwang. For winds between 4 and 7 m/s they are very close to those derived from Hwang's parameterization. Finally for winds stronger than 7 m/s, the deviation between the radar-derived mss and those obtained from Hwang's spectra is quite significant (up to 1.5 times smaller at 12 m/s which is the strongest wind of the Hwang's data set).

[20] Comments on this comparison are similar whatever Hwang's parameterization is considered (mixed sea or wind sea). Indeed, both parameterizations of Hwang lead to very similar mss when filtered at 51 rad/m. This could have been anticipated from Figure 3 of H05. Significant differences between the two sea state conditions of Hwang could only be evidenced for larger k_d (corresponding to high-frequency radar observation or optical conditions).

[21] For light winds ($\leq$4 m/s), the presence of swell may be the reason for the difference between the two types of results (HCGM08 and Hwang's results) but this is difficult to assess because of the lack of both wind sea and swell cases in the same data set in this wind speed range. At moderate to strong wind (7–12 m/s), the difference between the two sets of results cannot be attributed to sea state conditions, since both sets of data concern pure and mixed sea cases (but not swell conditions).

4. Summary

[22] In summary, swell encountered during the HCGM observations in condition of moderate wind (6–12 m/s) seems to impact only slightly the radar-derived mean square slope, and mainly in the crosswind direction. In wind sea cases, the relationship between radar-derived mean square slopes and wind speed is independent of the type of wind sea (either pure wind sea or mixed sea). These conclusions arise from an interesting but nevertheless limited set of observations (15 aircraft flights). Compared to the conclusions of *Vandemark et al.* [2004], which were based on a much wider data set, our results indicate a smaller impact of background waves. However, the method for sorting out the different sea state conditions is different.

[23] Taking into account the 51 rad/m cutoff wave number associated to the HCGM08 radar observations, the HCGM08 radar-derived mss are in good agreement with H05 results but only in the 4–7 m/s wind speed range. At light winds (<4 m/s) larger values of mss are obtained by HCGM08. The role of swell cannot be excluded but is difficult to assess with the available data sets. At strong winds (>7 m/s) the smaller values of mss obtained by HCGM08 cannot be explained by difference in sea state conditions as suggested by *Hwang* [2009]. A similar difference was mentioned by HCGM08 in comparisons with mss obtained from *Kudryavtsev et al.* [2003] spectrum filtered at 51 rad/m (see Figure 6d of HCGM08). Finally, from the different comparisons proposed by HCGM08 and in this paper, we conclude that the *Elfouhaily et al.*'s [1997] spectrum gives the best agreement with the radar derived values of total mss (see Figure 6b of HCGM08).

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