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On the Effect of Wind and Turbulence on Ocean Swell

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ABSTRACT

A quantitave review of processes contributing to the evolution of swell is proposed, combining direct interactions of swell with the wind and upper ocean turbulence, and interaction with shorter wind waves. The interaction with short waves is based on the extension of Hasselmann's (1971) theory for short wave modulation by long wave to the presence of variable wind stresses. Quantitative estimations of the various effects are performed based on the wave modulation model of Hara et al. (2003) and the wind-over-wave coupling model of Kudryavtsev and Makin (2004). It is found that the observations of swell decay in the Pacific (Snodgrass et al., 1963) are quantitatively consistent with the effects of wind stress modulation and direct wind to wave momentum transfer.

KEY WORDS: Waves, turbulence, wind, swell, modulation.

INTRODUCTION

The problem of swell forecasting on the coast of Morocco (Gelci, 1949) led Gelci et al (1957) to develop the first numerical spectral wave models. Half a century later, the forecasting of wind seas has made enormous progress but swells are still the least well predicted part of the wave spectrum (Rogers, 2002). Although these long period waves may be well generated in numerical wave models, what happens next is still much of a mystery. At the same time it is now well recognized that swells play an important role in air-sea interactions (e.g. Drennan et al., 1999; Grachev et al. 2003) and should impact the remote sensing of ocean properties. These new applications, along with the traditional problem of wave and surf forecasting, warrant a closer inspection of the theory and practical aspects of swell evolution.

It was recognized very early that viscosity had a negligible effect on waves of periods of about 10 s and longer (Lamb, 1932), so that, once generated, swells were supposed to dissipate slowly due to the action of the wind, as represented by Jeffrey's (1925) sheltering theory (Sverdrup and Munk, 1947). These ideas have been gradually abandoned and traded for eddy viscosity analogies (Bowden, 1950; Groen and Dorrestein, 1950) that are used today in some operational wave forecasting models (e.g. Tolman and Chalikov, 1996). The magnitude and the frequency dependence of the associated wave damping are calibrated using buoy and altimeter data, and no theory is available to predict these parameters. Other wave models wishfully assume that swell dissipates in the same way as the wind sea (WAMDI, 1988; Komen et al., 1994).

The validation studies on the spectral shape and magnitude of the dissipation are very few. Snodgrass et al. (1966) have demonstrated that swells of periods larger than 16 s are hardly attenuated when crossing the Pacific from south to north, although attenuation of shorter period waves was observed. There is also qualitative evidence of waves blown flat by strong opposing winds, without any satisfactory theory or good observations (Jenkins 2002). We therefore take advantage of recent developments in wave-turbulence interaction theory (Teixeira and Belcher, 2002; Ardhuin and Jenkins, manuscript submitted to J. Phys. Ocenogr.) and observation of short wave modulations by long waves (Hara et al., 2003) to review and combine the existing theories, including the much ignored 30-year old theory on swell-short wave modulations by Hasselmann (1971), and evaluate their relevance for swell forecasting.

The paper unfolds as follows. First the theory recent result for wave-turbulence interaction is recalled, followed by an extension of Hasselmann's (1971) theory for short wave modulation, including now the modulation of the wind forcing. Next, a semi-empirical parameterization is proposed for the short wave modulation, and the different effects are evaluated numerically for typical wind conditions. Perspectives for validation are discussed with our conclusions.

WAVE-TURBULENCE INTERACTION

Using rapid distortion theory, Teixeira and Belcher (2002) found that waves propagating in a turbulent field produced turbulent kinetic energy locally at the rate of

$$P_{ws} = \overline{u_a ' w'} \cdot \frac{\partial U_{sa}}{\partial z} \qquad (1)$$

where the Cartesian components of the fluctuating turbulent velocity are u_α' (α=1,2) and w' in the water, and the (horizontal) components of the Stokes drift are $U_{s\alpha}$. This expression may be considered obvious when compared to the usual production of TKE due to the mean current shear. However, (1) must be evaluated taking into account the moving surface. As a result the energy of the wave component with wavenumber $\vec{k}$ changes at the rate given by the non-dimensional growth/decay parameter *b*, so that the energy rate of change is of the form

$$\frac{dE(\vec{k})}{dt} = S(\dot{k}) = b s E(\dot{k}), \qquad (2),$$

in this case $b = b_{turb}$, with

$$b_{turb}(\vec{k}) = -k \frac{r_a}{g r_w} u_*^2 \cos\tilde{q} \frac{\cosh(2kH)}{\sinh^2(kH)} \qquad (3),$$

where ρ_a and ρ_w are the air and water densities, respectively, *g* is the acceleration due to gravity, u_* is the friction velocity of the air flow, *H* is the water depth, and $\tilde{q}$ is the direction of the waves relative to the wind stress direction. Equation (3) takes the following limit for deep water,

$$b_{turb}(\dot{k}) = -k \frac{2 r_a}{r_w} \frac{u_*^2}{C^2} \cos\tilde{q} \qquad (4),$$

where *C* is the phase speed of the wave component of wavenumber *k*. The same expression was found by Ardhuin and Jenkins (op. cit.) using a Generalized Lagrangian Mean (Andrews and McItyre 1978) of the turbulent kinetic energy equation and assuming that the downward flux of horizontal momentum u_*^2 is not correlated with the wave phase. This assumption is, in a sense, very similar to the assumption made by Teixeira and Belcher (2002) that the turbulence is rapidly distorted by the wave motion.

SHORT WAVE – LONG WAVE INTERACTION THEORY

Although a three-dimensional (3D) set of equations is now available (e.g. Andrews and McItyre 1978), we shall use the simpler depth-integrated equations of Hasselmann (1971), also given in a slightly different form by Garrett (1976). These depth integrated equations can be obtained from Andrews and McIntyre's 3D equations for the Generalized Lagrangian Mean (GLM) momentum, or by vertical integration of the alternative GLM equations (Andrews and McItyre 1978), which gives Mellor's (2003) equations to second order in the wave slope (Ardhuin and Jenkins, manuscript submitted to J. Fluid Mech.), after subtracting a 3D wave momentum equation.

Hasselmann's (1971) result

Neglecting the modulation of the wind stress on the scale of the long waves, Hasselmann (1971, eq. 25) found that the rate of change of the long-wave energy is given by the work of the radiation stresses on the orbital velocity. Namely, the wave energy evolves with a modulation source term

$$S_{swlw} = \left\langle \frac{\partial t_{ab}^{rad}}{\partial x_b} \tilde{u}_a \right\rangle \qquad (5),$$

where $\tilde{u}_a$ is the orbital velocity of the long waves in the (horizontal) direction *a*, and t_{ab}^{rad} is the short wave radiation stresses, that can be expressed as $t_{ab}^{rad} = -0.5 r_w g e d_{a,b}$, with *e* the short wave surface elevation variance. Assuming that the short wave energy is weakly modulated by the long waves around its mean value e_0, and that the modulation is proportional to the long wave slope, we use the complex modulation transfer function (MTF) M_{swlw} to relate modulations with the long wave complex amplitudes Z_k and phases j_k

$$e = \int e_0 (k', \tilde{q}') \mathrm{Re}\left(M_{swlw} k Z_k e^{i j_k} + c.c.\right) dk' d\tilde{q}' \qquad (6),$$

where *k'* and $\tilde{q}'$ are the wavenumber and direction (relative to the wind stress direction) of the modulated short waves. Writing the source term in the form of equation (2), one obtains the long wave evolution parameter,

$$b_{swlw}(\vec{k}) = 0.5 k^2 \int e_0 (k', \tilde{q}') \mathrm{Im}(M_{smlw}) dk' d\tilde{q}' \qquad (7).$$

Therefore the long waves dissipate (β<0) if the short waves are larger on the forward face of the long waves (this will be defined as a positive phase of the MTF).

Wind stress modulation

Because Hasselmann (1971) wanted to show how the maser mechanism (Phillips, 1963; Longuet-Higgins, 1969) was canceled by the variation of the short wave potential energy, he neglected the modulation of the wind stress much weaker than the modulation of the short wave breaking. However, since we are now looking at the net higher order effect, such as given by eq. (7), the wind stress modulation may be relevant. This was already recognized by Garrett and Smith (1976). One may thus follow Hasselmann's (1971) derivation and realize that this wind stress modulation analysis, the following term, representing the work of the wind stress modulations on the wave orbital velocity, should be added to the long wave energy rate of change,

$$S_{inm} = \left\langle T_a^a \tilde{u}_a \right\rangle \qquad (8).$$

In order to be consistent with the previous term, we wish to express the stress modulation with a modulation transfer function applied to the swell spectrum. A proper description requires a theory for the atmospheric boundary layer above waves, as given by Kudryavtsev and Makin (2004). However, in order to understand this process a first estimation can be made by assuming that the wave-induced wind stress is proportional to the short wave energy *e* as well as the square of the relative wind speed $(U_{10}\text{-}c)^2$ where *c* is the short wave phase speed, including the apparent current for the short waves, which here is the swell orbital velocity. For a single swell component we have,

$$T_a^a = \langle T_a^a \rangle \left(1 + \mathrm{Re}\left(M_{swlw} k Z_k e^{i\varphi_k} + c.c. \right) - \frac{2\tilde{u}_a}{U_{10} - \bar{c}} \right) \quad (9).$$

Therefore eq. (8) can be re-written as,

$$S_{inm} = \left(b_{inm1} + b_{inm2} \right) s E\left(\vec{k}\right) \quad (10),$$

with

$$b_{inm1} = \frac{\rho_a}{\rho_w} \frac{\cos\tilde{\theta}}{C^2} \int \frac{g S'_{in}}{C'} \mathrm{Re}\left(M_{smlw} \right) dk' d\tilde{\theta}' \quad (11),$$

where gS'_{in} / C' is the momentum source for the modulated short waves of wavenumber k' and direction $\tilde{\theta}'$. If M_{swlw} is constant, and this is a rather strong assumption, then (11) simplifies as,

$$b_{inm1} = \frac{\rho_a}{\rho_w} \frac{\tau^w}{\tau} \frac{u_*^2}{C^2} M_{swlw} \cos\tilde{\theta} \quad (12),$$

with τ^w/τ the order one fraction of the wave-induced stress to the total wind stress, and

$$b_{inm2} = -\frac{\rho_a}{\rho_w} \frac{u_*^2}{C^2} \frac{2C}{U_{10} - \bar{c}} \quad (13),$$

where C is the long wave phase speed and $\bar{c}$ is a short wave mean phase speed. Strictly speaking that term should be expressed with an integral over k' and $\tilde{\theta}'$. It is clear that the first term S_{inm1} is very similar to S_{turb} and opposes the effect of wave-turbulence interactions, generating swells that follow the wind and dissipating swells that oppose the wind.

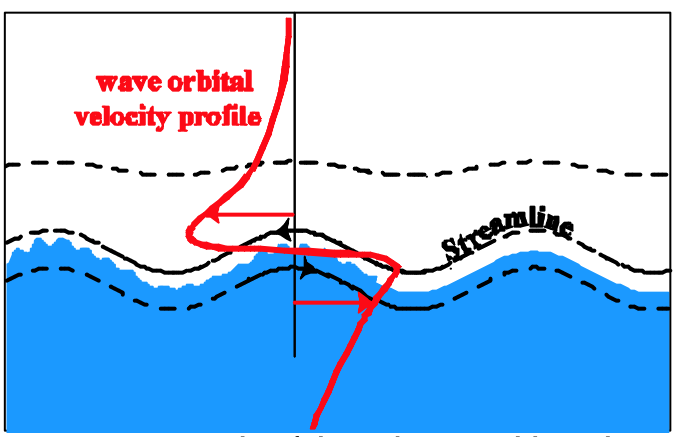

Figure 1: Basic principles of the wind stress modulation due to roughness modulation and long waves orbital velocity. Velocities are shown in a fixed frame of reference.

The second term in S_{inm} represents the modification of the wind stress due to the jump in wave orbital velocity near the surface (Figure 1). This term tends to dissipate the long waves as it increases the apparent wind felt by the short waves, for swell against the wind, and decreases the apparent wind for swell following the wind.

Although the simple form of (10) is interesting for understanding the basic sources of the wind stress modulation, it is based on assumption that are certainly too simple. The same phenomenon that gives rise to S_{inm2} was modeled by Kudryavtsev and Makin (2004), using a k-l turbulent clodure in a model of the air flow above the waves. In particular they find a larger values for S_{inm2} due to their expression of the near-surface stress as an eddy viscosity times a shear. The modulation of the eddy viscosity brings an increase of that term by a factor $\left[1 + \cos^2\tilde{\theta}\right]$ (see their equation A25) and the relative velocity U_{10}-$\bar{c}$ in (9) is replaced by $\bar{u}_l$, the wind speed at the height of the inner layer which is now well defined for any wave component Their estimation of the wind stress modulation also yields another smaller term that is proportional to $\cos\tilde{\theta}\left[1 - \ln(kl) / \ln(l / z_0)\right]$, where l is the inner layer thickness, due to the profile of the wave-induced velocity in the air. That extra term is typically 5 times smaller for periods larger than 10 s and a wind speed of 10 m/s. The result of Kudryavtsev and Makin (2004) reads,

$$b_{inm2} = \frac{\rho_a}{\rho_w} \frac{u_*^2}{C^2} \left[1 + \cos^2\tilde{\theta}\right] \left\{ \cos\tilde{\theta} \left[1 - \frac{2\ln(kl)}{\ln(l / z_0)} \right] - \frac{2C}{\bar{u}_l} \right\} \quad (14).$$

Direct work of wind on the swell

Finally, Kudryavtsev and Makin (2004) also estimated the direct effect of winds on swell through the pressure-slope correlations, and found a wind input source term of the form (their equation A29),

$$b_{in} = 2 \frac{\rho_a}{\rho_w} \left[1 + \cos^2\tilde{\theta}\right] \frac{U(z = 1/k)}{\bar{u}(z = l)} \Phi \frac{u_*^2}{C^2} \quad (15),$$

where U is the wind speed in the frame of reference moving with the wave crest, $\bar{u}$ is the wind speed in a fixed frame of reference, and Φ is a correction function that allows a matching of the wave-induced vertical velocity to known asymptotes. For our applications to long period swells Φ is close to 1.

ESTIMATION OF THE SHORT WAVE AMPLITUDE MODULATION

As we have seen, the amplitude modulation function M_{swlw} plays a central role in the growth or decay of long wave energy. A quantitative model is required for the swell-induced modulations of both the short waves, that carry most of the energy at the peak of the wind sea, in order to evaluate S_{swls}, and the modulation of the shorter wind waves, that carry most of the wave-induced stress. Unfortunately there is no available measurement of such modulations.

The nearest data available are observations of the modulation of 3.5 and 5 Hz waves by Hara et al. (2003) do show some variation of the modulation phase from about -10 to about 30 degrees that may be related to the different wind-wave angle conditions in which their observations were performed. However, the MTF amplitude is relatively stable, around 2 to 4. One should however take these measurements with caution since they are based on time series and the intrinsic frequency of the short waves is determined from the measured frequency assuming that all waves propagate in the same direction. In this processing the modulation of the short wave frequency was not taken into account, which may be a reasonable approximation when the long waves have small amplitudes. However, that approximation should break down for moderate to large waves as were observed for the case of wind against the long waves (their data on day 131). In that case, assuming a (conservative above 50 rad/m) f^{-4} spectral tail, a (conservative) 10% Doppler modulation in the short wave frequency would result in a real MTF of 2.3 if a MTF of 1 is observed. Indeed, waves that have the same frequency of long waves crests and troughs can have intrinsic frequencies different enough to yield a significant high (respectively low) bias to the MTF for long waves propagating toward (respectively away from) the measurement platform. Other estimations of this MTF using radar measurements have produced values up to 10 (Kudryavtsev et al., 2003) but it is difficult to separate the radar cross section enhancement due to wave breaking and steeper slopes from the actual modulation of the wave amplitude. Such a problem also occurs with Hasselmann's (1971) original estimation of the swell dissipation based on upwind/downind radar cross section ratios. It is thus unfortunate that no better estimation of the MTF has been published.

The most solid result in Hara et al. (2003) is probably their qualitative validation of a theoretical expression for the MTF, based on the conservation of action for the short waves. Based on a short wave spectral shape of the form, valid for the scales of the modulated waves,

$$E\left(k',\tilde{\theta}'\right) = E_0 u_*^{n_3} k^{-n_1} \cos^{n_2}\tilde{\theta}' \qquad (16),$$

It gives,

$$M_{smlw} = \frac{\int_{-\pi/2}^{\pi/2}\left[\left(n_1 - C_g'/C' + 3\right)\cos^2\tilde{\theta}' - n_2\sin^2\tilde{\theta}' + \beta_r^{\,2} n_3 M_u\right]\frac{\cos^{n_2}\tilde{\theta}'}{1+\beta_r^{\,2}}d\tilde{\theta}'}{\int_{-\pi/2}^{\pi/2}\cos^{n_2}d\tilde{\theta}'} + i\beta_r \frac{\int_{-\pi/2}^{\pi/2}\left[\left(n_1 - C_g'/C' + 3\right)\cos^2\tilde{\theta}' - n_2\sin^2\tilde{\theta}' - n_3 M_u\right]\frac{\cos^{n_2}\tilde{\theta}'}{1+\beta_r^{\,2}}d\tilde{\theta}'}{\int_{-\pi/2}^{\pi/2}\cos^{n_2}d\tilde{\theta}'} \qquad (17)$$

where M_u is the modulation function for u_*, which, if constant over the wavenumber of the modulated waves would be,

$$M_u = \frac{\rho_w}{2\rho_a}\frac{C^2}{u_*^2}\left(\beta_{inm1} + \beta_{inm2}\right) \qquad (18),$$

and β_r is a non-dimensional relaxation parameter for the short wave energy, that Hara et al. (2003) assumed equal to the short wind-wave growth parameter,

$$\beta_r \approx 0.04\frac{u_*^2 k'^2}{\sigma'^2}\cos^2\left(\tilde{\theta}'\right) \qquad (19)$$

For the present problem, where only an order of magnitude is sought for the different terms, we may chose a spectral shape defined by equation (14) with n_1=3 and n_2=2, and n_2=1. These values should be applicable to our two domains of interest: the wind sea peak and the inertial range. One obvious difficulty is that M_{swlw} is a function of M_u and that M_u is a function of M_{swlw}, due to the feedback mechanism that is thought to account for most of the short wave modulation (Kudryavtsev et al. 1997). For the sake of simplicity we shall assume that M_u is equal to 5 (Hara et al. 2003), and therefore only use (17) to estimate the imaginary part of M_{swlw} that gets into (7). In that case the relevant short waves are around the peak of the wind sea so that $\beta_r << 1$ and the term in brackets in the numerator of (17) is dominated by M_u. Using $E(f)=1.4\times10^{-2}U_{10}(2\pi)^{-3}g f^{-4}$, one gets,

$$\beta_{swlw}\left(\vec{k}\right) = 4.2\times10^{-7}\, g k^2 u_*^2 U_{10} M_u f_{hf}^{-1} \qquad (20)$$

where f_{hf} is the lower integration limit for frequency of the modulated waves, that we shall take as the maximum of the wind sea peak frequency and 4 times the modulating frequency, f_{hf} = Max{f_p,4 $(gk)^{1/2}$}.

SWELL EVOLUTION

Summarizing the previous findings, we have seen that the evolution of swell in the presence of shorter waves can be described with the equations of Hasselmann (1971), that allow a consistent description of the exchange of momentum and energy between short and long waves. An extra sink of energy, due to interactions with turbulenced is added in that system of wave interactions. The long waves have a total growth rate that is the sum of the growth rates given by each of these processes,

$$\beta_{tot} = \beta_{swlw} + \beta_{inm1} + \beta_{inm2} + \beta_{in} + \beta_{turb} \qquad (21)$$

The first term β_{swlw} correspond to the effect described by Hasselman (1971), the following two, β_{inm1} and β_{inm2}, represent the effects of roughness and orbital velocity modulations in the wind input, β_{in} is the direct momentum input to the waves (due to non-separating sheltering and described Kudryavtsev and Makin (2004), and finally, β_{turb} is the work ot the Stokes shear against the turbulent flux (Ardhuin and Jenkins, op. cit.).

We now only consider β_{turb} given by (3), $\beta_{inm2}+\beta_{in}$ given by (14) and (15), and β_{swlw} given by (20). We do not consider here β_{inm1}, not because it is negligible, but because it is very similar to β_{turb} (between -β_{turb} and -2β_{turb} if one applies directly the values of M_{swlw} measured by Hara et al., 2003).

As shown by Kudryavtsev and Makin (2004) the effects of the the wind stress modulation and direct wind input for the swell are highly dependent on the relative directions of swell and wind, with higher attenuations for opposing winds compared to following winds, in particular for the wind input term (figure 2). The other processes considered here are generally weaker. In particular the wave modulation mechanism of Hasselmann (1971) is generally negligible since at high frequencies (young waves) it will be generally dwarfed by wave breaking (there is no swell at the frequencies where it dominates). The effect of wave turbulence appears to dominate the dissipation of waves with frequencies just above the wind sea peak (propagating in the wind direction). It will thus be quite important to evaluate the wind stress modulation term due to the short wave modulation to see which of β_{inm1} or β_{turb} dominates a the wind sea peak. However, for the lower frequency swells the present theory makes -β_{turb} one order of magnitude smaller than the $b_{\mathrm{inm2}}+b_{\mathrm{in}}$.

Looking at the problem of swell propagation it appears that the combination of these two effects has the right magnitude to explain the wave attenuation observed by Snodgrass et al. (1966). Comparison with existing parameterizations in wave models suggests that WAM-Cycle 4 probably overestimates swell dissipation, because the wind speed at the time of the measurements by Snodgrass et al. (1966) was typically less than 10 m/s.

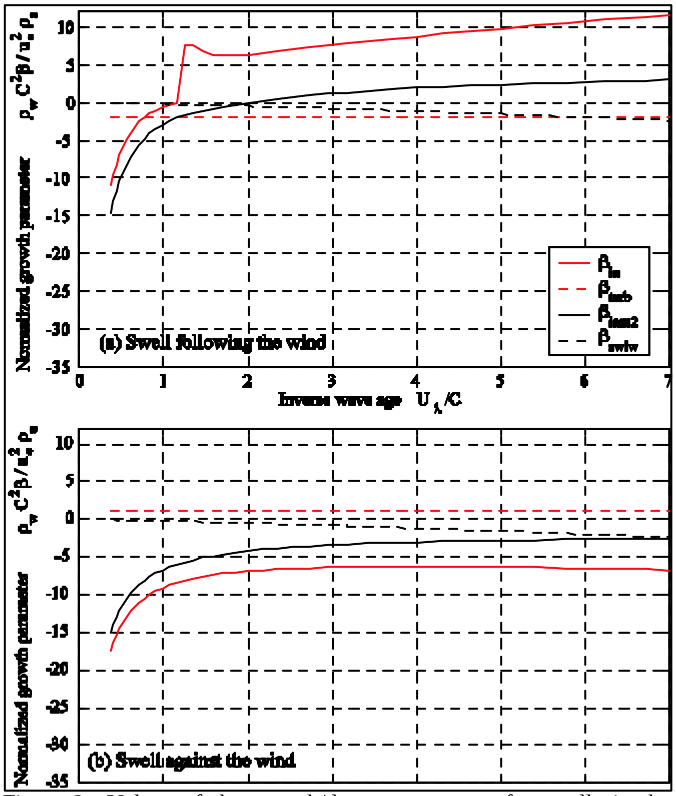

Figure 2: Values of the growth/decay parameters for swells in the presence of opposing and following winds of 10 m/s.

The same reasoning would suggest that Wavewatch III (Tolman and Chalikov, 1996) probably underestimates swell dissipation. The large difference in long wave dissipation between parameterization in WAM-Cycle 4 and Wavewatch III probably covers the range of possible situations.

CONCLUSIONS

A coherent description was given of swell attenuation and growth due to the effects of the wind, short wave modulations and turbulence. The present analysis of wind stress modulation is preliminary so that conclusions about waves at and just above the wind sea peak cannot be made without further work. For the case of lower frequency swells in the presence of winds, our analysis suggests that the wind speed and the wind direction relative to the swell propagation direction are the two most important parameters that control swell dissipation. Further, the theory of Kudryavtsev and Makin (2004) for the wind stress modulation and wind input give reasonable orders of magnitudes for the decay of swell energy, at least for the case of swells following the wind. This theory relies on the estimation of the inner layer depth based on the arguments of Belcher and Hunt (2003), which may overestimate this depth (see the review by Janssen 2004). The implications of that controversy in the present framework clearly requires further attention. More analysis of wave attenuation with known wind fields will be necessary to further verify the present parameterizations.

Future work should also address the compatibility of the present theory with laboratory measurements. Kudryavtsev and Makin (2004) had to multiply their wave decay/growth parameter by a factor 5 to obtain good agreement with the data reported by Donelan (1999). It is not clear at this stage if this multiplication by 5 is due to the fact that Kudryavtsev and Makin (2004) neglected effects that are important for laboratory conditions (e.g. Chen and Belcher, 2000). Our analysis does not support such a correction for field conditions.

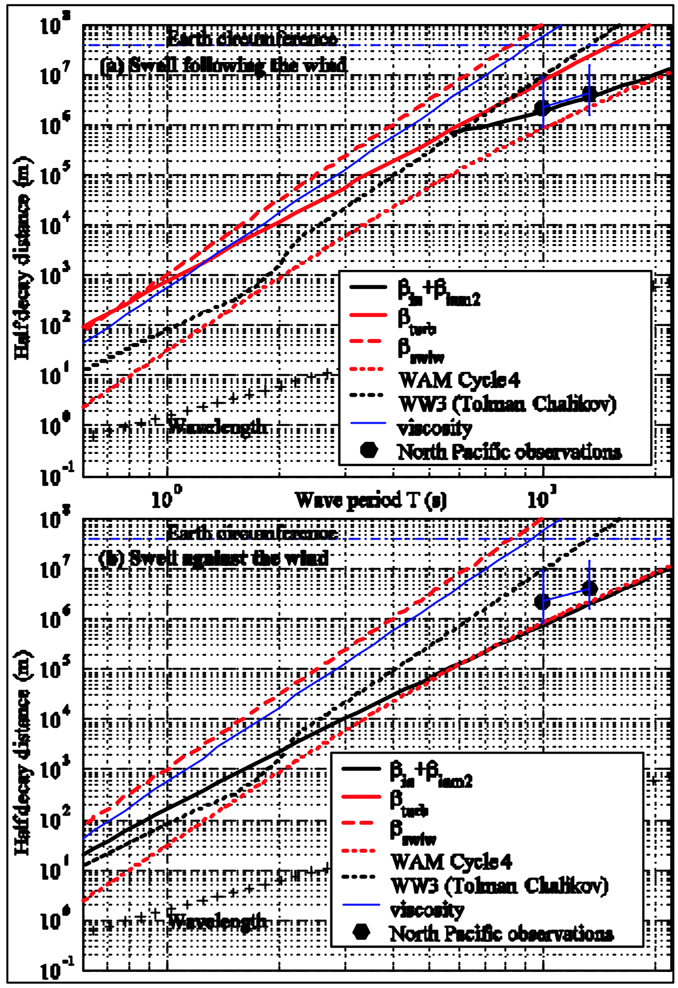

Figure 3: Decay scales for the wave energy for different processes for (a) swell following the wind and (b) swell against the wind. Observations of Snodgrass et al. (1966) as well as Lamb's (1932) theory for viscous decay are indicated for comparison.

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REFERENCES

Andrews, DG, and McIntyre, ME (1978), "An exact theory of nonlinear waves on a Lagrangian-mean flow," *J. Fluid Mech.*, Vol. 89, pp.

609-646.

Belcher SE, and Hunt, JCR (1993), "Turbulent shear flow over slowly moving waves", *J. Fluid Mech.*, Vol. 251, pp. 109-148.

Bowden, KF. (1950), "The effect of eddy viscosity on ocean waves," *Phil. Mag.*, Vol. 41, pp. 907-917.

Chen, G, and Belcher , SE (2000), "Effects of Long waves on wind-generated waves," *J. Phys. Oceanogr.*, Vol. 30, pp. 2246-2256.

Donelan, MA (1999). "Wind-induced growth and attenuation of laboratory waves," in *Wind over wave couplings*, edited by Sajjadi, SG, Thomas, NH, and Hunt, JCR, Clarendon Press, pp. 183-194.

Drennan, WM, Graber, HC, and Donelan, MA (1999). "Evidence for the effects of swell and unsteady winds on marine wind stress," *J. Phys. Oceanogr.*, Vol. 29, pp. 1853-1864.

Garrett, C (1976), "Generation of Langmuir circulations by surface waves - a feedback mechanism", *J. Mar. Res.*, Vol. 34, pp. 117-130.

Garrett,C, and Smith, J (1976) "On the interaction between long and short surface waves," *J. Phys. Oceanogr.*, Vol. 6, 925-930.

Gelci, R (1949), "Généralités sur les méthodes de prévision de la houle", *Bull. Comité Central Océanogr. Etude Côtes*, Vol. 1, 11-14.

Gelci, R, Cazalé, H, and Vassal, J (1957), "Prévision de la houle. La méthode des densités spectroangulaires," *Bull. Comité Central Océanogr. Etude Côtes*, Vol. 9, pp. 416-435.

Grachev, AA, Fairall, CW, Hare, JE, Edson, JB, and Miller, SD, "Wind stress vector over ocean waves," *J. Phys. Oceanogr.*, Vol. 33, pp. 2408-2429.

Groen, P, and Dorrestein, R (1950), "Ocean swell: its decay and period increase," *Nature*, Vol. 165, pp. 445-447.

Hara, T, Hanson, KA, Bock, EJ, and Uz, BM (2003), "Observation of hydrodynamic modulation of gravity-capillary waves by dominant gravity waves," *J. Geophys. Res.*, Vol. 108, pp. 3028.

Hasselmann, K (1971), "On the mass and momentum transfer between short gravity waves and larger-scale motions," *J. Fluid Mech.*, Vol. 4, pp. 189-205.

Janssen, P (2004), "The interaction of ocean waves and wind," *Cambridge University Press, Cambridge, U.K.*, 300 pp.

Jeffreys, H (1925), "On the formation of water waves by wind," *Proc. Roy. Soc. London*, vol. A107, pp. 189-206.

Jenkins, AD (2001), "Do strong winds blow waves flat?" *Proc 4th Int. Symp Ocean Wave Meas. Anal. (WAVES)*, ASCE, San Francisco, Vol 1, pp 494-500.

Komen, GJ, Cavaleri, L, Donelan, M, Hasselmann, K, Hasselmann, S, Janssen, PAEM (1994) "Dynamics and modelling of ocean waves," Cambridge University Press.

Kudryavtsev, VN, Mastenbroek, C, and Makin, VK (1997), "Modulation of wind ripples by long surface waves via the air flow: a feedback mechanism", *Boundary Layer Meteorol.*, Vol. 83, pp. 99-116.

Kudryavtsev, VN, Hauser, D, Caudal, G, and Chapron, B (2003). "A semiempirical model of the normalized radar cross-section of the sea surface 2. Radar modulation transfer function," *J. Geophys. Res.*, Vol. 108, pp. 8055.

Kudryavtsev, VN, and Makin, VK (2004), "Impact of swell on the marine atmospheric boundary layer," *J. Phys. Oceanogr.*, Vol. 34, pp. 934-949.

Lamb, H (1932), "Hydrodynamics," 6th edition, Cambridge University Press, Cambridge, England, 738 pp.

Longuet-Higgins, MS (1969), "A nonlinear mechanism for the generation of sea waves," *Proc. Roy. Soc. London*, Vol. A311, pp. 371-389.

Mellor, G. (2003). "The Three-Dimensional Current and Surface Wave Equations", *J. Phys. Oceanogr.*, Vol. 33, pp. 1978-1989.

Phillips (1963), "On the attenuation of long gravity waves by short breaking waves," *J. Fluid Mech.*, Vol. 16, pp. 321-332.

Rogers, WE. (2002). , "An investigation into sources of error in low frequency energy predictions," *Formal Report* 7320-02-10035, Oceanography division, Naval Research Laboratory, Stennis Space Center, MS, 63pp.

Snodgrass, FE, Groves, GW, Hasselmann, K, Miller, GR, Munk, WH, and Powers, WH (1966), "Propagation of ocean swell across the Pacific," *Proc. Roy. Soc. London*, Vol. A249, pp. 431-497.

Sverdrup, HU, and Munk, WH (1947), "Wind, sea, and swell: theory of relations for forecasting", U. S. Hydrographic Office report 601.

Teixeira, MAC, and Belcher, SE (2002), On the distortion of turbulence by a progressive surface wave, *J. Fluid Mech.*, Vol. 458, pp. 229-267.

Tolman, HL (2002). "Validation of WAVEWATCH-III version 1.15", *Tech. Rep.* 213, NOAA/NWS/NCEP/MMAB.

Tolman, HL, and Chalikov, D (1996), "Source terms in a third-generation wind wave model," *J. Phys. Oceanogr.*, Vol. 26, pp. 2497-2518.

WAMDI Group (1988) "The WAM Model - A third generation ocean wave prediction model," *J. Phys. Oceanogr.*, Vol. 18, pp. 1775-1810.