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Experimental Evaluation of the Atmospheric Energy Input to Sea Surface Waves

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LONG-TERM GOALS

Understanding the spatio-temporal structure and the dynamic influence of the surface waves signature in the wind is critical for the transition from the current empirical and phenomenological (dating back to Charnock (1956)), to a mechanistic description of air-sea interaction. Over the last decades, however, a number of observational studies attempting to detect statistical and dynamic manifestations of wave signature in the airflow have produced negative results. Weiler and Burling (1967) have failed to find "*a dominant peak at the frequency of the surface waves, although all spectra had appreciable energy about this frequency*". Schacher *et al.* (1981) determined that the measured kinetic energy dissipation rate over the ocean was virtually no different from that quantity measured over land. Van Atta and Chen (1970) found the second and third order structure functions of wind velocity over the ocean to be in close agreement with the original Kolmogorov theory, i.e. no wave influence was detected in the structure functions. As an important dynamic description of the atmospheric boundary layer, the kinetic energy balance has been studied repeatedly over waves (Edson and Fairall (1998), Taylor and Yelland (2000), Sjoblom and Smedman (2002)) to seek signs of surface motion penetration into the wind. Edson and Fairall (1998) have hypothesized that the lack of observable wave signature in the kinetic energy budget possibly stems from wave effects being confined to a thin layer over the surface, well below the positions of the measuring instruments used. Consistent with that hypothesis, later marine atmospheric boundary layer models, e.g. Hara and Belcher (2002), assumed small penetration height of the wave influence L, such that $kL << 1$ for wave effects of a surface mode of wave number k. Hasse and Dobson (1986) expected that wave-induced velocity in the wind would be difficult to observe with the turbulence always present. Phillips (1977) has opined the same regarding the observability of wave-induced pressure.

The central role of the wave-induced fields in air-sea interaction along with the multiple studies, some listed above, failing to detect wave influences in either airflow's kinematics or energetics, is a longstanding issue, possibly dissuading productive research on the subject. The analysis presented below addresses key aspects of that issue. Starting from the premise that the observational findings outlined above are correct, and using recent results, we arrive to alternative interpretations of these findings.

OBJECTIVES

Analysis of field data collected by recent experiments on *FLIP* demonstrates that wave-induced fields can be identified both robustly and uniquely, by separating them from turbulent fields. For instance, a conditional sampling filter $\left\langle x-\bar{x} \mid Arg(\eta+i\hat{H}\eta)\right\rangle$ (where x stands for a quantity measured in the wind, e.g. velocity, pressure or a passive scalar, η is the surface elevation and $(\eta+i\hat{H}\eta)$ is the analytic signal obtained from the time series of the elevation η) commonly identifies the phase-averaged counterpart of the wave-induced fields, a fact seemingly conflicting with experimental conclusions and opinions outlined above.

A goal pursued by this project is consistently to reconcile the apparent contradictions regarding the dynamic role and observability of wave signature in the wind. Considering that the direct observability of the wave-induced fields depends on the relative intensity of turbulence and wave effects, we seek an explicit form for that relative intensity and express it through the transfer functions of the wave-induced fields. For a wide range of conditions, the relative intensity of the wave-induced velocity is low, justifying the expectations of Hasse and Dobson (1986). Same analysis suggests, for a wide range of conditions, that the wave-induced pressure is dominant and directly observable, contrary to Phillips (1977). We will reinterpret the failure of Van Atta and Chen (1970) to find a surface wave signature in the structure functions of wind velocity. The discussion of the kinetic energy (KE) balance will show that, although the wave effects may extend to heights of the order of ten meters, the terms they generate in the KE balance equation are too small to detect by means of Edson and Fairall (1998) data analysis.

APPROACH

There is a good physical argument for choosing a linear and weakly nonlinear approach to describe the wave signature in the wind: the wave breaking effectively imposes a limit on wave slope thus preventing any strong nonlinearity. In the light of experimental results and theoretical arguments, we consider wave-mean-flow interaction to be the essential one.

We obtain the explicit form for the relative intensity of the wave-induced fields compared to turbulence, i.e. signal-to noise ratio. We obtain and analyze the explicit form of the structure functions of the velocity over waves and from there reinterpret the failure of Van Atta and Chen (1970) to observe wave signature in the velocity structure functions. We conduct perturbative analysis of the kinetic energy balance equation, which supports negative findings of Edson and Fairall (1998), yet that analysis suggests an alternative explanation for these findings.

WORK COMPLETED

A field experiment and theoretical analysis comprised the work under the project. The last field cruise of *FLIP* under this effort was conducted in December 2010. To avoid the experimental difficulties encountered during the June cruise, the platform took vertical position Nortwest of San Diego, CA unmoored and was carried freely by currents. The atmospheric conditions were mostly calm, with waves' standard deviation about 0.5m. The meteorological mast was instrumented with sonic anemometers, cups, vanes, measuring airflow velocity, sensitive barometers. Instruments for GPS and inertial navigation were positioned on the portside boom and over *FLIP*'s hull. We gratefully

acknowledge Ken Melville, UCSD, and Fabrice Veron, Univ. of Delaware, who kindly shared the signals from two laser altimeters registering wave elevation. The list of sensors in shown in Table 1. Drifting caused by currents brought the platform in proximity to the shallow waters of the coast and the measurements were interrupted before schedule, early on December 8 2010, followed by accelerated redeployment.

Table 1. List of instruments deployed during the field experiment in December 2010. The Laser Altimeters were kindly shared by Ken Melville (UCSD) and Fabrice Veron (Univ. Delaware).

Instruments	Quantity measured	Height/Location
7 Sonic Anemometers	Wind velocity, Air temperature	On the mast
5 RMY Prop. Anemometers	Wind speed & direction	At 5 levels on the mast
8 Pressure Instruments	Atmospheric pressure	On the mast
2 Wave Wires	Sea surface elevation	At the mast and at the middle of the boom
2 Laser Altimeters	Sea surface elevation	At the mast and at the middle of the boom
Infrared SST	Sea surface temperature	————
FLIP's Gyroscope	Heading	————
Boeing CMIGITS III	Platform Motion	On the mast, at 18m height
GPS Unit	GPS location and timing	————
8 Thermistors	Air temperature	5 on the mast, 3 in the water
Oxford Inertial Nav. Unit	GPS position, Motion	On the boom

RESULTS

A. Comparative intensity of the of wave effects and turbulence in the air flow.

The observability of wave-induced fields depends on the relative intensity of these fields and the turbulence. As a measure of the relative intensity, we choose the ratio between the spectrum of the wave-induced field $S_{\tilde{q}\tilde{q}}$ (where q stands for any of the velocities, the pressure or a passive scalar) and the spectrum of the corresponding turbulent field $S_{q'q'}$. Assuming the wave-induced fields to result from the waves displacing the mean flow streamlines, the wave-induced fields can be expressed through transfer functions $T_{\tilde{u}\eta}$, $T_{\tilde{v}\eta}$, $T_{\tilde{p}\eta}$ obtained from solving the Rayleigh equation

$(U-c)(\varphi''-k^2\varphi)-U''\varphi=0$, specifically, $\tilde{u}=-u_*\dfrac{(c/u_*)^2}{\kappa\Omega}ke^{-(c/u_*)-\xi}\varphi'\eta=T_{\tilde{u}\eta}\eta$,

$\tilde{v}=(i/\kappa)u_*k\varphi\eta=T_{\tilde{v}\eta}\eta$, $\tilde{p}=(\rho u_*^2)\dfrac{(c/u_*)^2}{\kappa^2\Omega}e^{-(c/u_*)-\xi}(\xi\varphi'-\varphi)k\eta=T_{\tilde{p}\eta}\eta$. Here φ is the wave-induced flow's stream function, c and k are the phase speed and the wave number for the considered wave mode, $u_*=\langle u'w'\rangle^{1/2}$ is the turbulent friction velocity, κ is the von Karman's constant, Ω is the

Charnock's parameter relating surface roughness and friction velocity, $\xi = \log(z / z_c)$ with z_c being the critical height. The relative intensity is then expressed as $\frac{S_{\tilde{q}\tilde{q}}}{S_{q'q'}} = \frac{\left|T_{\tilde{q}\eta}\right|^2 S_{\eta\eta}}{S_{q'q'}}$. In flows with developed turbulence the spectral variance of velocity scales as $S_{u'u'} = \alpha\varepsilon^{2/3}k^{-5/3}$ and of pressure as $S_{p'p'} = C_p\varepsilon^{4/3}k^{-7/3}$. A parameterization for the dissipation rate $\varepsilon = u_*^2 \frac{\partial \overline{u}}{\partial z} = \frac{u_*^3}{\kappa z}$ suitable for convectively neutral conditions (Panofsky and Dutton (1984)), when applied to the relative intensity ratio $\frac{S_{\tilde{q}\tilde{q}}}{S_{q'q'}}$ shows that the observability of wave fields is independent of the turbulent intensity u_* and depends, through the transfer functions $T_{\tilde{u}\eta}$, $T_{\tilde{v}\eta}$, $T_{\tilde{p}\eta}$, only on the wave age parameter c / u_* and the normalized distance to the undisturbed surface (z / z_c). Transfer function of the wave-induced vertical velocity and pressure, in magnitude and phase form, are shown in Figure 1. Deep valleys in the transfer functions magnitudes indicate the areas of the parameter with dominating turbulence, i.e. where the wave-induced fields are poorly observable.

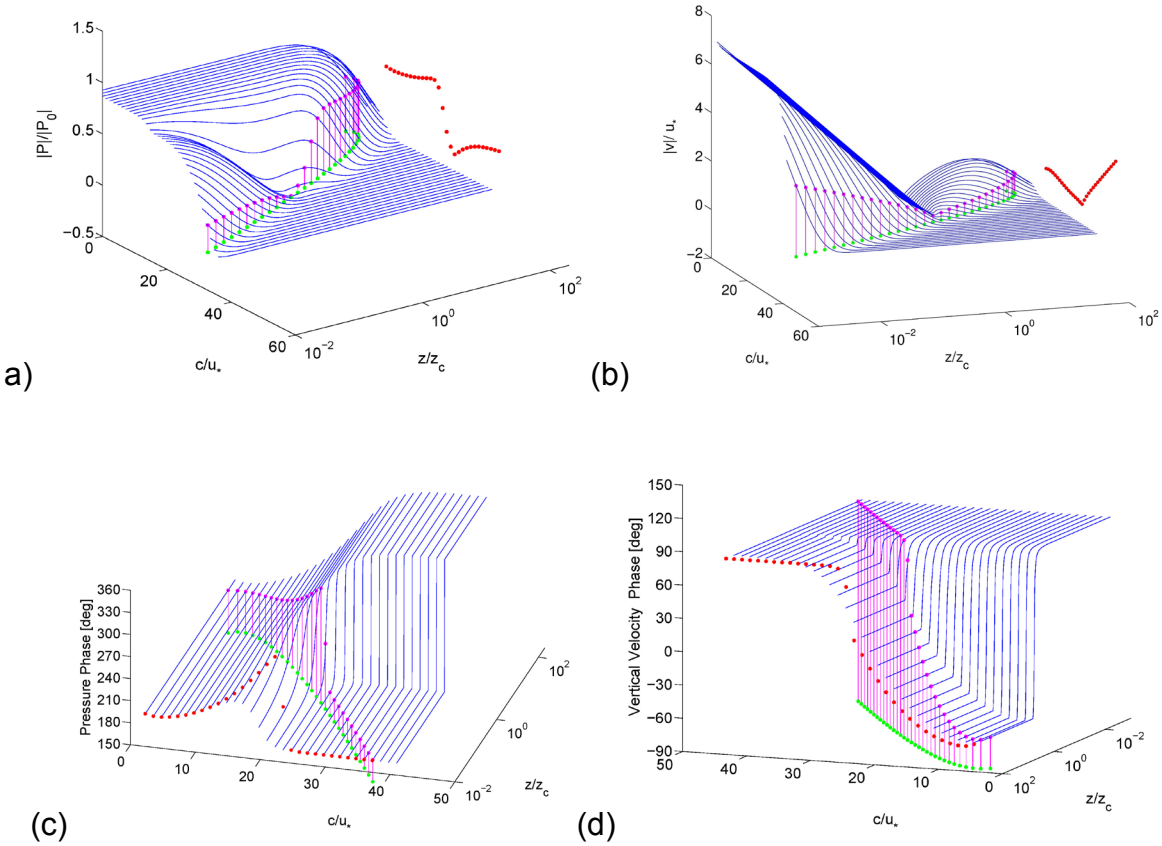

Figure 1. Transfer functions (TF) of the wave-induced vertical velocity and pressure as a function of the distance to the surface in units of critical height (z/z_c) ***and the wave age parameter*** (c/u_*) ***. The transfer functions are complex-valued, thus the plots show (a) magnitude of pressure TF normalized by the pressure on the surface, (b) the magnitude of the vertical velocity TF, (c) the phase of the pressure TF, and (d)) the phase of the velocity TF. The phases are all referenced to the phase of the waves. The green dots in the*** $(z/z_c, c/u_*)$ ***plane show the variation of*** (z/z_c) ***with the change of*** (c/u_*) ***when*** (z) ***is fixed. The red dots in the vertical plane*** $(c/u_*, TF)$ ***show a curve that is experimentally measurable by an instrument at a fixed height.***

B. Structure function of the wave-induced fields.

In order to explain Van Atta and Chen's (1970) failure to observe wave signature in the structure function of velocity, here we analyze the structure functions from wave-mean flow interaction perspective outlined above. Considering that any measured quantity q (which stands for either of velocities, pressure, or a passive scalar) in the wind consists of a turbulent q' and a wave-induced $\tilde{q}$ components, i.e. $q = q' + \tilde{q}$, and that q' and $\tilde{q}$ are statistically independent and uncorrelated, i.e. $\langle q'\tilde{q}\rangle = 0$, one could easily show that the structure function $D_q(\vec{r}_1,\vec{r}_2) = \left\langle [q(\vec{r}_1) - q(\vec{r}_2)]^2 \right\rangle$, like the q fields themselves, is also separable into turbulent and wave-induced parts, i.e.

$$D_q(\vec{r}_1,\vec{r}_2) = D'_{q'}(\vec{r}_1,\vec{r}_2) + \tilde{D}_{\tilde{q}}(\vec{r}_1,\vec{r}_2),$$

with $\tilde{D}_{\tilde{q}}(\vec{r}_1,\vec{r}_2) = \left\langle [\tilde{q}(\vec{r}_1) - \tilde{q}(\vec{r}_2)]^2 \right\rangle$ and $D'_{q'}(\vec{r}_1,\vec{r}_2) = \left\langle [q'(\vec{r}_1) - q'(\vec{r}_2)]^2 \right\rangle$. The wave-induced part $\tilde{D}_{\tilde{q}}(\vec{r}_1,\vec{r}_2)$, sought after in Van Atta and Chen's (1970) study consists of two local terms, $\left\langle \tilde{q}^2(\vec{r}_1)\right\rangle + \left\langle \tilde{q}^2(\vec{r}_2)\right\rangle$ and a non-local term, $2\left\langle \tilde{q}(\vec{r}_1)\tilde{q}(\vec{r}_2)\right\rangle$. As outlined above, the wave-induced fields $\tilde{q}$ are expressed through the transfer functions $T_{\tilde{q}\eta}$ and the wave spectra. Thus, we arrive to a general form for both local and nonlocal terms, i.e.

$$\left\langle \tilde{q}(\vec{R}_1,Z_1)\tilde{q}(\vec{R}_2,Z_2)\right\rangle = \int e^{i\vec{k}\cdot(\vec{R}_1-\vec{R}_2)} \mathrm{T}_{\tilde{q}\eta}(Z_1,\vec{k})\mathrm{T}^*_{\tilde{q}\eta}(Z_2,\vec{k}) S_{\eta\eta}(\vec{k})d\vec{k}\,.$$

The latter offers an explanation for Van Atta and Chen's (1970) failure to observe wave modification of the structure functions. Unlike the turbulent structure function $D'_{q''} \propto \left|\vec{r}_1 - \vec{r}_2\right|^{\alpha}$, that is spherically symmetric, the wave-induced structure function is highly anisotropic, strongly dependent on the relative direction of the wave field $\vec{k}$ and the line connecting the points $\vec{R}_1$, $\vec{R}_2$ and has a distinct role for the vertical separation $Z_1 - Z_2$. Therefore, measurements conducted in selected directions may be insensitive to any wave signature. Measurements of the structure function averaged over all the directions, i.e. assuming isotropic behavior, are likely to suppress any wave affect below the sensitivity threshold, thus making any wave effects undetectable. In addition, for a broad range of values for the wave-age parameter (c/u_*) the transfer functions show strong vertical decay, also capable of bringing the wave effects below the threshold of experimental sensitivity.

C. Kinetic energy balance in the marine atmospheric boundary layer.

We analyze the Kinetic Energy balance in order to reinterpret Edson and Fairall's (1998) negative findings regarding wave influence in that balance. When the KE balance equation

$$\frac{\partial \overline{E}}{\partial t} = -\langle uw\rangle \frac{\partial \overline{U}}{\partial z} + \frac{g}{\overline{\theta}}\langle w\theta\rangle - \frac{1}{\rho}\frac{\partial}{\partial z}\langle wp\rangle - \frac{\partial}{\partial z}\langle Ew\rangle - \varepsilon$$

is perturbed by the surface motion, both the shear turbulence generation term $\langle uw\rangle \frac{\partial \overline{U}}{\partial z}$ and the "pressure transport" term $\frac{1}{\rho}\frac{\partial}{\partial z}\langle wp\rangle$ split into turbulent and wave-induced parts, specifically

$$\langle uw\rangle \frac{\partial \overline{U}}{\partial z} = \langle u'w'\rangle \frac{\partial \overline{U}}{\partial z} + \langle \tilde{u}\tilde{w}\rangle \frac{\partial \overline{U}}{\partial z},$$

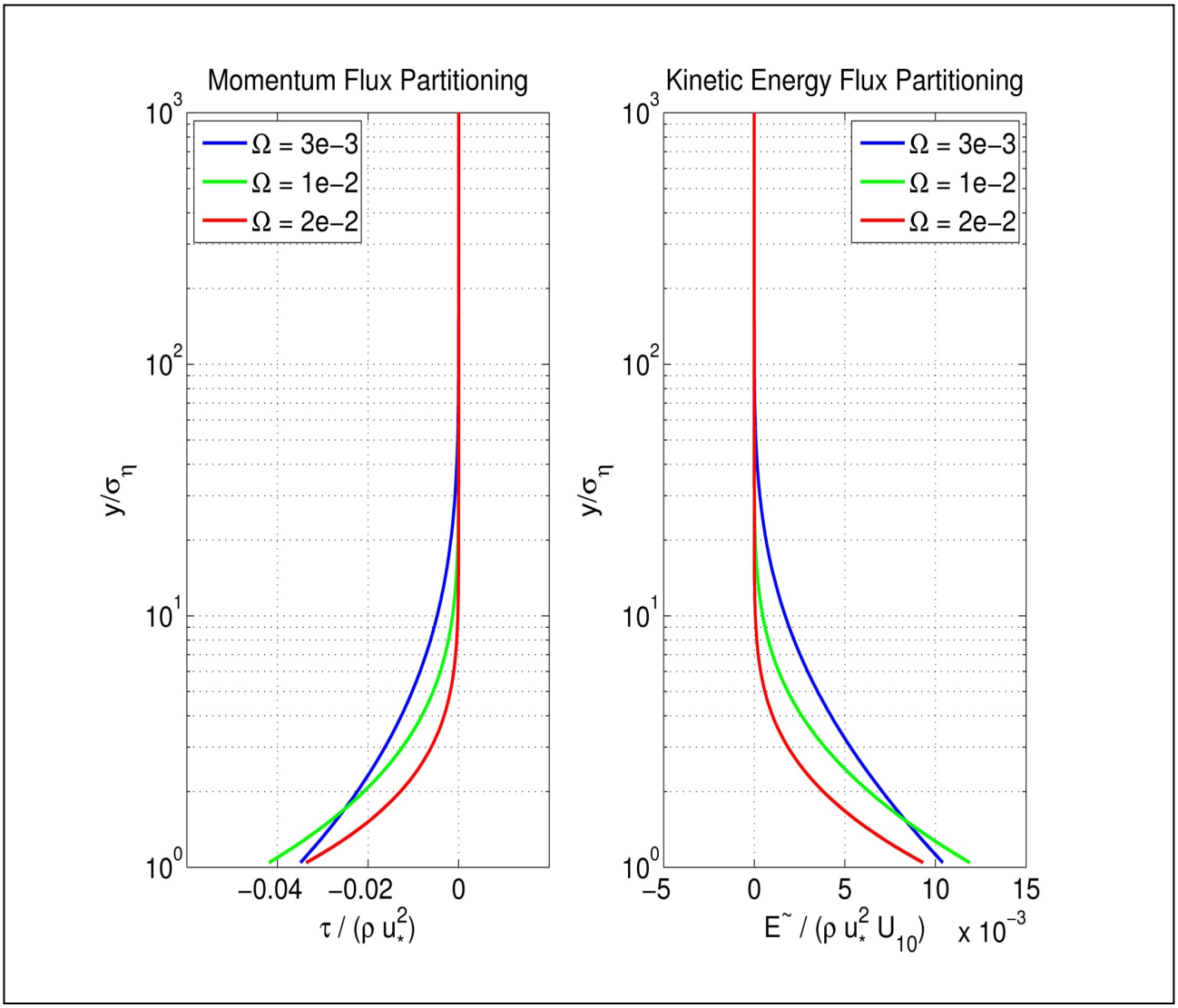

Figure 2.Vertical profile of the partitioning of the momentum flux (left) and of the kinetic energy (right). The color indicates the value of the Charnock's roughness parameter Ω**.**

$$\frac{1}{\rho}\frac{\partial}{\partial z}\langle wp\rangle = \frac{1}{\rho}\frac{\partial}{\partial z}\langle w'p'\rangle + \frac{1}{\rho}\frac{\partial}{\partial z}\langle \tilde{w}\tilde{p}\rangle .$$

The rest of the terms in the KE balance remain unperturbed by the waves, since $\langle \tilde{w}\tilde{\theta}\rangle = 0$ as $\tilde{w}$ and $\tilde{\theta}$ are always in quadrature and $\langle E\tilde{w}\rangle$ is a higher order term, excluded from this perturbative analysis. Using the explicit forms shown above of the transfer functions of the wave-induced fields, and accounting for the discontinuity of the momentum flux at the critical height, one concludes that the wave-induced terms balance each other, i.e.

$$-\langle \tilde{u}\tilde{w}\rangle \frac{\partial \overline{U}}{\partial z} - \frac{1}{\rho}\frac{\partial}{\partial z}\langle \tilde{w}\tilde{p}\rangle = 0.$$

The physical interpretation of this result is straightforward. The equation expresses the fact that kinetic energy extracted by the wave-induced fields $\langle \tilde{u}\tilde{w}\rangle$ from the mean flow gradient $\frac{\partial \overline{U}}{\partial z}$, is directly delivered to the waves through the "pressure transport" $\frac{1}{\rho}\frac{\partial}{\partial z}\langle \tilde{w}\tilde{p}\rangle$. Therefore, the KE balance is separable into turbulent and wave-induced parts.

Furthermore, the fraction of the wave-induced momentum flux is calculated explicitly for the case of a Phillips spectrum, $S(k) = \frac{1}{2}k_p^2\sigma_\eta^2 k^{-3}$

$$\frac{\tilde{\tau}(y)}{\rho u_*^2} = \frac{4\sigma_\eta^2 k_p^2}{\Omega\kappa^2}\int_{-\infty}^{-\log(y/y_0)} w_0^2\,\Im[\varphi'(w_0)]dw_0,$$

as well as the fraction of the wave-induced kinetic energy flux

$$\frac{\tilde{E}(y)}{\rho u_*^3} = \frac{4\sigma_\eta^2 k_p^2}{\Omega\kappa^3}\int_{-\infty}^{-\log(y/y_0)} w_0^3\,\Im[\varphi'(w_0)]dw_0$$

where $\tilde{\tau}(y) = -\rho\langle \tilde{U}(y)\tilde{W}(y)\rangle$ is the total (spectrally integrated) wave-induced momentum flux at height y, $\tilde{E}(y) = -\rho c\langle \tilde{U}(y)\tilde{W}(y)\rangle$ is the total (spectrally integrated) wave-induced kinetic energy flux at height y, $w_0 = -\kappa c/u_* = -\log(y_c/y_0)$ is a negative wave age and φ is a solution of the Rayleigh equation $\varphi'' - k^2\varphi - (U-c)^{-1}U''\varphi = 0$. The numerical solutions showing $\frac{\tilde{\tau}(y)}{\rho u_*^2}$ and $\frac{\tilde{E}(y)}{\rho u_*^3}$ for the Phillips spectrum are shown in Figure 2. Clearly, the separability of the KE balance into turbulent and wave-induced parts, along the wave-induced fluxes fraction being small, suggests that the waves influence is too weak to disturb the structure of the turbulent flow, and thus it is undetectable with the analysis of Edson and Fairall (1998).

IMPACT/APPLICATIONS

The presented results are intended to consistently reconcile longstanding apparent discrepancies between experimental findings, opinions and theoretical results. We hope they will advance the basic science of the air-sea interaction and will be helpful in building operational models for short-term wave modeling and forecasting. The information on the structure and dynamics of the marine atmospheric boundary layer (MABL) will advance the description and modeling of signal propagation over the ocean.

RELATED PROJECTS

The PI is unaware of any related projects.

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