

Meteorological and Wave Measurements from a Stable Research Platform at Sea

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LONG-TERM GOALS

The approach that describes air-sea exchange as interaction between a flow and a rough surface, now considered traditional, dates back to the 1950s (Charnock, 1956). Within that approach, the complex exchange processes are condensed down to exchange coefficients, thus delivering computational efficiency in large-scale numerical modeling of air-sea meteorology. However, inability to distinguish between momentum and kinetic energy transferred to waves from those transferred to currents, as well as considerable variance in the experimental estimates of the drag coefficients, show some of the applicability limits for this traditional approach. Clearly, a short-term phase-resolved wave forecasting, a goal of the High-Resolution Wave-Air-Sea Interaction project, requires a more detailed mechanistic description of the marine boundary layer dynamics with a special focus on the elements distinctly introduced by the compliant interface and the sea surface waves. While wave dynamics on the water side has already been reduced to a computationally-intensive numerical problem (Friehe et al., 2007, section III.B), the complexity of which is determined by the number of nonlinearly interacting wave modes, the wind driving of the waves on the other hand, is less understood. Current challenges include gaps in theoretical knowledge and in techniques for numerical modeling. In particular, the observational validation for most of the wind-wave interaction mechanisms proposed so far in theoretical works is lacking. The purpose of this work is to advance our understanding on these open issues.

OBJECTIVES

A goal pursued by this project is to distill both field observations and physical analysis into a description for the structure and dynamics of the marine atmospheric boundary layer that will be suitable to incorporate in models for short-term wave prediction. Considering that the wave breaking limits the waves slope and thus prevents any strong nonlinearities in wind-wave interaction, as a physical framework of this study we select is the weakly nonlinear interaction dynamics proposed by Hasselmann (1965). The higher-order mechanisms in that hierarchy have been a subject of extensive theoretical studies in the last four decades, yet their presence and intensity has never been addressed experimentally. Some non-expandable mechanisms, such as flow separation, have received renewed interest in light of the work of P. Sullivan, NCAR. Detection of such mechanisms in measurements will be among our important objectives.

From applied perspective, we focus on experimental determination of the wind input to the waves, an essential physical factor in waves evolution. Our analysis has lead us to conclude that a widely adopted approach of exponential extrapolation to obtain atmospheric surface pressure from pressure

measurements in the wind, has a clear tendency of overestimating the surface pressure and may have caused substantial uncertainty in previous estimates of wind input to the waves. Here we propose an alternative that is free of the deficiencies of exponential extrapolation.

APPROACH

Meteorological and wave data acquired in June 2010 over the open ocean will be analyzed, along with data from previous experiments, to assemble a complete description of the marine boundary layer dynamics. As the 2010 data cover mostly conditions of high winds and developed wave fields, data from previous experiments will complement our study with information on low and moderate winds. The wind input results will be used to calibrate numerical models of wave evolution and marine boundary layer dynamics. The atmospheric pressure measurements will be extrapolated to the surface in a novel and more rigorous way, to evaluate the direct energy input to the waves occurring through form drag. The wind velocity measurements will be analyzed to identify wave-turbulence interaction and its contribution to the wave growth. Recent numerical results reported by Peter Sullivan, NCAR, have predicted instances of air flow separation in cases of extreme wave slope and surface roughness. We will seek to recognize signs of such phenomena in the data and estimate their influence on the wave field evolution.

The PI closely collaborates with other members of the project's team. The experimental component is carried out with Carl Friehe and Jesus Ruiz-Plancarte (UCI). The work on data assimilation, surface and boundary layer air flow modeling will be done with Eric Terril (UCSD) and Peter Sullivan (NCAR).

WORK COMPLETED

An extensive preparation for the field experiment included designing and building deployment gear, testing of instruments and developing of data acquisition and data processing algorithms and software. Starting June 1, 2010 FLIP moved to the site selected for the experiment Northwest of San Francisco, at 33.3365N and 123.4289W. Site's climatology of high winds and large waves significantly extended the time necessary for deployment. Atmospheric conditions and sea state included wind gusts up to 21 m/s and significant wave heights up to 18 feet. The lower part of the mast has been repeatedly submerged with some repairable damage. Among the essential components of the meteorological array were the instruments measuring airflow velocity (sonic anemometers, cups, vanes), pressure sensors, and the units for GPS tracking and inertial navigation. Total of 57 units were deployed and 142 signals were acquired continuously, most of them listed in Table 1. The instrumented mast and the persistent whitecapping on the sea surface are shown in Figure 1. We gratefully acknowledge Ken Melville, UCSD, and Fabrice Veron, Univ. of Delaware, who kindly shared the signals from two laser altimeters registering wave elevation. Strong current first led to excessive drag and tilt on FLIP that later caused the main mooring line to snap. Measurements had to be discontinued on June 19, before the scheduled end date, followed by accelerated redeployment.

RESULTS

A. Wave influences in the pressure and velocity fields.

Out preliminary analysis of the data set was in part inspired by the recent findings of Peter Sullivan, NCAR, whose modeling results indicated a significant distinction between the structures of velocity

and pressure fields in the wavy boundary layer (Sullivan *et al.*, 2010). Namely, modeling results find that the wave influence in pressure is more pronounced than in velocity, a fact with potentially significant implications on the dynamics of wind-wave coupling. Such findings agree with earlier field observations, e.g. from the RED and CBLAST experiments. A consistent interpretation is pursued within this project.

Instruments	Quantity measured	Height/Location
12 Sonic Anemometers	Wind velocity, Air temperature	10 on the mast, 2 on the boom
10 RMY Prop. Anemometers	Wind speed & direction	At 10 levels on the mast
10 Pressure Instruments	Atmospheric pressure	8 on the mast, 2 on the boom
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
Krypton Hygrometer	Atm. humidity	On the mast, at 11.3m height
Infrared SST	Sea surface temperature	—————
Leosphere Windcube	Wind Profiles in the ABL	
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

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

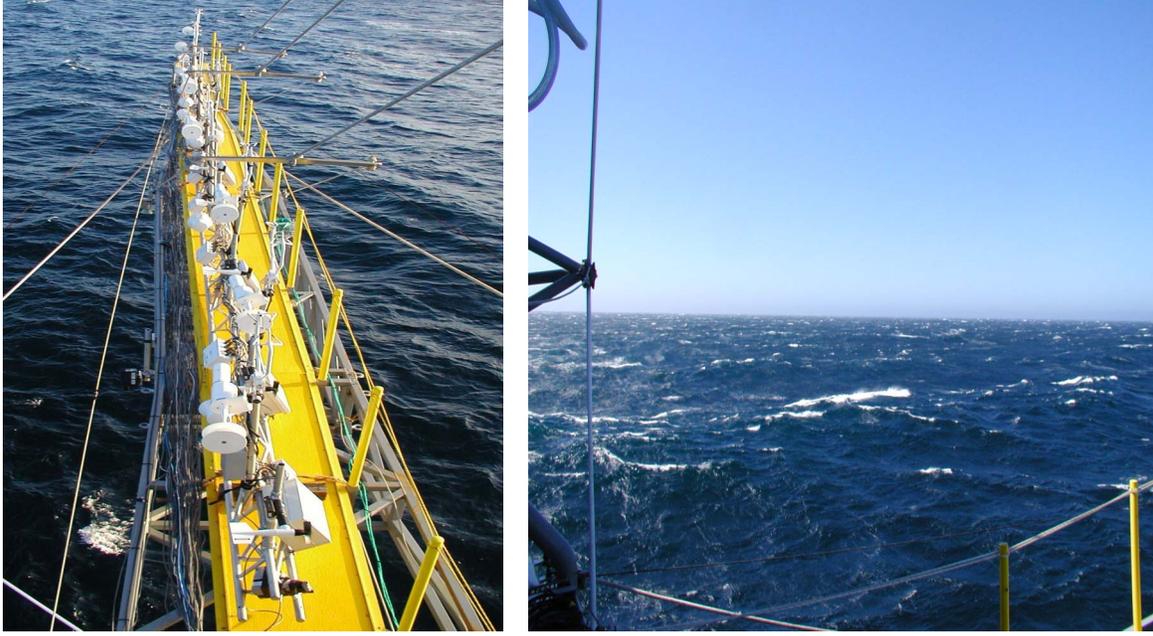


Figure 1. The instrumented mast on the port boom (left) and the persistent whitecapping on the sea surface at high winds (right).

One could observe that for uncorrelated waves and turbulence the correlation function of the measured velocity $B_v^m(\vec{r}_1, \vec{r}_2)$ and pressure $B_p^m(\vec{r}_1, \vec{r}_2)$ split into turbulent $B_v^t(\vec{r}), B_p^t(\vec{r})$ (where $\vec{r} = \vec{r}_1 - \vec{r}_2$) and wave-induced terms $B_v^w(\vec{r}_1, \vec{r}_2)$ and $B_p^w(\vec{r}_1, \vec{r}_2)$, i.e. $B_{\{v,p\}}^m(\vec{r}_1, \vec{r}_2) = B_{\{v,p\}}^t(\vec{r}) + B_{\{v,p\}}^w(\vec{r}_1, \vec{r}_2)$. Recalling that the structure $D(\vec{r})$ and correlation $B(\vec{r})$ functions of the same random field are related as

$B(\vec{r}) = B(\vec{0}) - \frac{1}{2}D(\vec{r})$, and that for the inertial subrange of developed turbulence the turbulent structure functions scale as $B_v^t(\vec{r}) = C_v^2 r^{2/3}$ for velocity and $B_p^t(\vec{r}) = C_p^2 r^{4/3}$ for pressure, one arrives to these forms of the correlation functions

$$B_v^m(\vec{r}_1, \vec{r}_2) = \left[B_v^t(\vec{0}) - \frac{1}{2} C_v^2 r^{2/3} \right] + B_v^w(\vec{r}_1, \vec{r}_2)$$

$$B_p^m(\vec{r}_1, \vec{r}_2) = \left[B_p^t(\vec{0}) - \frac{1}{2} C_p^2 r^{4/3} \right] + B_p^w(\vec{r}_1, \vec{r}_2)$$

These suggest that the turbulence in pressure decays faster with separation distance (exponent (4/3)) than it does in velocity (exponent (2/3)). Consequently, the influence of the boundary, i.e. the waves, will be more pronounced and propagate further in the flow in pressure than in velocity, as has been observed in low to moderate wind conditions. At high winds, however, two circumstances occur simultaneously: (i) there is a lowering of the critical layer in the air flow, which roughly determines the vertical extent of the wave-induced pressure and (ii) there is increased turbulent intensity. Consequently, turbulence also starts to dominate the pressure signal and no clear wave signature is observed, as indicated by the pressure spectrum in Figure 2.

B. Determining wind-to-wave energy input from measurements of pressure in the airflow

Pressure distribution on the sea surface determines the rate of wind-to-wave energy transfer $\langle \tilde{p} \dot{\eta} \rangle$.

However, direct measurements of the atmospheric pressure on the surface are impractical, considering that the sensitive instrument will have to be protected from wetting, and that the film serving that purpose will distort the pressure readings. Also, avoiding spurious pressure readings from dynamic pressure requires a specific pressure port (inlet) whose disks should be kept parallel to the mean flow (Hristov, 2008). This requirement is difficult to meet when both the position and the orientation of the instrument are vigorously driven by the surface's motion. Furthermore, as the pressure on the surface does not directly determine the structure of the airflow above, information on the surface pressure carries little or no information on the wind-wave generation dynamics. Instead, pressure measurements in the airflow are free of the experimental limitations mentioned above and can reveal more of the wind-wave coupling mechanism, yet for estimating wind-wave energy transfer rate these have to be extrapolated down to the air-water interface. The extrapolation method, essential for proper determination of the wind input to the waves, is proposed for this project and is outlined below.

The velocity and pressure variation induced in the water by deep-water waves exhibits vertical exponential decay. In previous works (Donelan, 1999), (Hasselmann and Bosenberg, 1991) authors have assumed an analogous behavior for the wave-induced motion on the air side and have used that assumption to extrapolate pressure measurements within the airflow down to the interface. This assumption, however, is inconsistent with the presence of singular point in the air flow and may considerably overestimate the wind-wave energy input. Namely, the height where the mean wind speed matches the phase speed of the wave carries dynamic significance and the vertical structure of

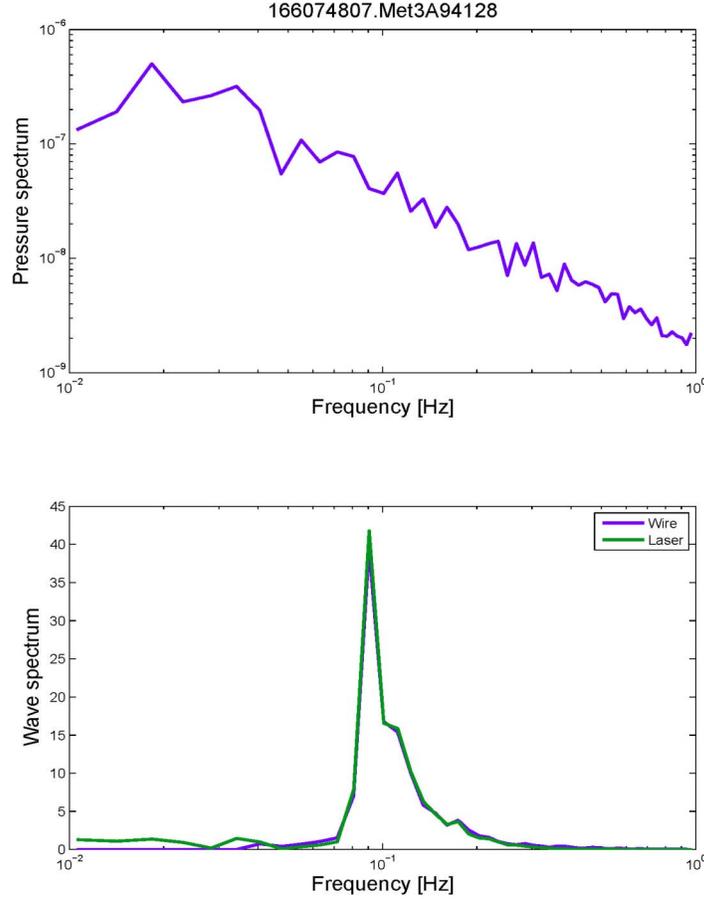


Figure 2. A spectrum of the atmospheric pressure (upper plot) and a wave spectra produced by a wave wire (blue) and laser altimeter (green), shared by Ken Melville (UCSD) and Fabrice Veron (Univ. Delaware) (lower plot). At the high wind conditions encountered throughout the experiment, the wave signature in the pressure is weak, a consequence of the lowered critical layer and increased turbulent intensity.

the wavy boundary layer is profoundly influenced by that critical layer singularity. The critical layer theory (Miles, 1957), (Hristov *et al.*, 2003) properly accounts for the role of the matching height and shows vertical behavior for the pressure that is distinctly different from exponential. Specifically, for a range of wave ages, the pressure shows virtually no vertical decay and change in phase up to the matched height. Within the critical layer theory, the stream function $\phi(z)$ of the wave-induced flow satisfies the Rayleigh equation $\xi(\phi'' - \phi) - \xi''\phi = 0$, with $\xi = \log(z/z_c)$. Expressing the pressure

through wave-age parameter $\xi_0 = -c\kappa/u_*$ and the solution $\phi(z)$, i.e. $p = (\rho_a g) \frac{e^{\xi_0 - \xi}}{\Omega} \left(\xi \left(\frac{d\phi}{d\xi} \right) - \phi \right) \eta$,

where Ω is the Charnock's roughness parameter, one could relate the wave-coherent pressure at a given height $p(\xi)$ to the pressure at the surface $p(\xi_0)$ as $p(\xi_0) = T(\xi, \xi_0)p(\xi)$. The transfer function

$T(\xi, \xi_0)$ takes the form:

$$T(\xi; \xi_0) = \frac{\xi_0}{e^{\xi_0 - \xi}} \frac{\left(\left(\frac{d\phi}{d\xi} \right) \Big|_{\xi=\xi_0} - 1 \right)}{\left(\xi \left(\frac{d\phi}{d\xi} \right) - \phi \right)}.$$

Application of this transfer function to sampled time series requires the discrete-time filter counterpart of that function, commonly in z -transform representation $F(z) = \frac{b_0 + b_1 z^{-1} + \dots + b_n z^{-n}}{1 + a_1 z^{-1} + \dots + a_m z^{-m}}$. Such a counterpart filter can be obtained by selecting the order of the filter (n, m) and requiring that the discrepancy ε between the amplitude and phase responses of the complex-valued analog prototype $T(\xi; \xi_0)$ and the discrete form $F(z)$

$$\varepsilon(b_0, b_1, a_0) = \sum_{\Omega} \left| (1 + a_1 e^{i\omega}) T(\omega) - (b_0 + b_1 e^{i\omega}) \right|^2$$

is minimized. Choosing, for instance, $n = 1, m = 1$, and necessitating that the derivatives at the minimum should vanish, leads to these equations for determining the coefficients $\{b_0, b_1, a_1\}$:

$$\frac{\partial \varepsilon}{\partial b_0} = \sum_{\Omega} \left[2b_0 + (e^{i\omega} + e^{-i\omega}) b_1 - (e^{i\omega} T + e^{-i\omega} T^*) a_1 - (T + T^*) \right] = 0$$

$$\frac{\partial \varepsilon}{\partial b_1} = \sum_{\Omega} \left[(e^{i\omega} + e^{-i\omega}) b_0 - (T + T^*) a_1 - (e^{i\omega} T^* + e^{-i\omega} T) \right] = 0$$

$$\frac{\partial \varepsilon}{\partial a_1} = \sum_{\Omega} \left[(e^{i\omega} T + e^{-i\omega} T^*) b_0 - (T + T^*) b_1 + 2TT^* a_1 + (e^{i\omega} + e^{-i\omega}) TT^* \right] = 0$$

Above, ω is the frequency measured in radians per sample. The set of coefficients $\{b_0, b_1, a_1\}$ depends on the distance of the instrument from the surface, the wind's friction velocity u_* , and the pressure signal's sampling frequency. Considering that the pressure p_m measured in the airflow broadly consists of a turbulent p_t and a wave-induced \tilde{p} terms, i.e. $p_m = p_t + \tilde{p}$, the filter $F(i\omega)$ applied to the wave-induced component $\tilde{p}(\xi)$ produces the wave-coherent pressure at the surface $\tilde{p}(\xi_0)$, suitable for calculating the wind-to-wave energy transfer rate $\langle \tilde{p}(\xi_0) \dot{\eta} \rangle$. For computational efficiency, one may skip the separation p_m into a turbulent p_t and a wave-induced \tilde{p} parts. Using either $F(i\omega) \otimes p_m(\xi)$ or $\tilde{p}(\xi_0)$ should produce the same energy transfer estimate, i.e. $\langle \tilde{p}(\xi_0) \dot{\eta} \rangle = \langle \dot{\eta} F(i\omega) \otimes p_m(\xi) \rangle$. Since the turbulent component $p_t(\xi)$ and its (unphysical) filtered counterpart $F(i\omega) \otimes p_t(\xi)$ are both uncorrelated with the waves, i.e. $\langle F(i\omega) \otimes p_t(\xi), \dot{\eta} \rangle = 0$, $F(i\omega) \otimes p_t(\xi)$ will not contribute to the energy transfer rate.

IMPACT/APPLICATIONS

The results of this research are expected to advance the basic science of the air-sea interaction and will be applied to operational models for short-term wave modeling and forecasting. The information on the structure and dynamics of the marine atmospheric boundary layer (MABL) and the statistics of the

ocean surface will advance the description and modeling of signal propagation over the ocean. The profound physical similarities between propagation of radar signals over the ocean and acoustic signals in the water will extend possible applications to the acoustic domain.

RELATED PROJECTS

The PI is unaware of any related projects.

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