OS51C HC: 318 A Friday 0830h

Air-Sea Exchange IV

Presiding: **R Wanninkhof,** NOAA Atlantic Oceanographic and Meteorological Laboratory**; W Drennan,** RSMAS/University of Miami

OS51C-01 0830h INVITED

Air-Sea Fluxes in High Winds

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The destructive nature of high wind events along our coastlines has a profound impact on society. Over the ocean, episodic high wind events contribute significant fractions of the total flux of momentum and energy across the air-sea interface. This statement is based on scaling arguments that predict a momentum flux that increases as the wind speed squared. This has been substantiated by numerous observations of measured drag coefficients that generally increase with wind speed, which implies that the momentum flux increases somewhat faster than the wind speed squared. Therefore, even infrequent storms can strongly impact the structure of the upper ocean in many regions of the world, and impact processes at the ocean bottom along continental shelves (e.g., sediment transport and benthic biological processes). However, direct observations of momentum flux over the ocean are extremely scarce at winds above 20 m/s. There are even fewer measurements of heat and mass fluxes under these winds. As a result, there is no definitive understanding of the transfer coefficients for heat and mass even under moderate winds. The uncertainty in the drag and transfer coefficients at high winds has hampered our ability to accurately predict the intensity of extreme storms such as tropical cyclones and hurricanes. For example, modelers have shown that simple extrapolation of existing formulations to high winds does not produce realistic hurricanes. In fact, these simulations predict that the ratio of the drag to enthalpy coefficient must become less than 1 to obtain realistic hurricane winds, i.e., the frictional drag of the ocean must decrease and/or the energy input must increase at extreme winds.

Investigations of processes that could explain this predicted behavior have been severely hampered by the lack of direct flux measurements. Some of these processes include the generation and re-entry of sea-spray and the modulation of ocean surface characteristics due to extensive wave breaking and bubble entrainment. Even at moderate winds, direct measurements of the heat and moisture flux above 15 m/s are still required to improve our understanding of the transfer coefficients. Clearly, the scarcity of measurements is not driven by a lack of interest but rather by the difficulties associated with direct measurement of the turbulent flux in the marine environment. These difficulties include flow distortion, motion contamination, and the corrosive and contaminating effects of sea spray. However, in recent years, a number of groups have made significant process at addressing these issues and computing fluxes from a number of platforms. This talk presents the analysis of several data sets taken by the air-sea interactions groups at WHOI and NOAA/ETL. The data has been taken on ocean-going ships, moored buoys, the R/P FLIP, a coastal research platform, and at a coastal observatory facing the north Atlantic. The high wind data contains numerous direct measurements of the fluxes above 15 m/s and a number of measurements above 20 m/s. Whenever possible the data sets are combined with information describing the sea state. The drag and transfer coefficients computed from these measurements will be compared with previous and newly developed parameterizations including those that attempt to account for sea state, wave age, and the role of sea spray. Some ideas on how to extend these observations to even higher winds will be discussed.

OS51C-02 0845h

A Bulk Turbulent Air-Sea Flux Algorithm for High-Wind, Spray Conditions

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In high winds, breaking waves and whitecaps disrupt the ocean surface; spray proliferates. Because these spray droplets start with the same temperature and salinity as the surface water, they effectively increase the ocean's surface area and may thereby enhance the exchange of any constituent normally transferred across the air-sea interface. My interest here is in how spray affects the air-sea exchange of momentum and sensible and latent heat.

I will present a bulk turbulent flux algorithm that accounts for both the interfacial and spray routes by which sensible and latent heat cross the air-sea interface. The algorithm is appropriate for 10-meter wind speeds up to a least 30 m/s. To model the interfacial fluxes, the algorithm uses the COARE bulk flux algorithm (Fairall et al., 1996), with some high-wind-speed modifications. The spray component of the algorithm results from tuning Andreas's (1992) theoretical spray model with heat flux data from HEXOS, the experiment to study Humidity Exchange over the Sea (DeCosmo et al., 1996).

When spray droplets are formed, they accelerate quickly to the local air speed. This process extracts momentum from the wind. When the spray droplets ultimately crash back into the ocean, they transfer this momentum to the sea surface and therefore also, potentially, enhance the surface stress. Although this spray momentum flux is small for wind speeds less than 30 m/s, it increases as the fourth power of the friction velocity, while the usual wind-driven, interfacial stress increases only as the square of the friction velocity. Consequently, as the wind speed approaches 60 m/s, in hurricanes for example, the interfacial and spray momentum fluxes become comparable.

References

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OS51C-03 0900h

Effect of Wind Speed on Aerosol Fields Generated by Breaking WavesA Scanning Lidar Investigation

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We have been monitoring time dependent 3-D marine aerosol fields as a function of meteorological parameters with a multi-wavelength scanning lidar at Bellows Air Force Station (AFS) on NE side of Oahu, Hawaii. These measurements include extensive field investigations during the ONR sponsored Shoreline Environment Aerosol Study (SEAS) program, April 21-30, 2000. The focus of these studies was to provide a long-term database to evaluate and model the effect of aerosols generated up to 100 m above the sea surface on optical transmission and visibility in coastal areas.

Here we describe our measurements of salt-aerosol plumes generated at a reef at ∼1.6 km from the lidar, and their effect on the aerosol extinction coefficient. The lidar is located at the University of Hawaiis Atmospheric Research Site at Bellows AFS.

A set of vertical lidar scans were collected during the SEAS experiment on April 24, 2000, under normal trade wind conditions.. The meteorological parameters during these scans were wind direction 48-52^{O}E, wind speed=8.1-8.3 m/s, RH=82-84% and temperature=23.4^{O}C. Plumes of salt spray were observed to rise to heights of about 50 m above the reef. A time sequence of vertical scans at three wavelenghts (355, 532, 1064 nm) were taken under light wind conditions (∼2 m/s) over the same reef on March 20, 2001. Large salt plumes more than 600 m high were found to develop. The much greater height of these plumes suggests that they are being dispersed less rapidly at the lower wind speed, allowing them to rise to greater heights. Earlier data collected at Bellows (Sharma et al., 2001) showed reef plumes rising to ∼120 m/s in winds of ∼5 m/s, indicating a consistent trend of increasing plume height with decreasing wind speed.

The 532-to-355 nm extinction coefficient ratios indicate that there is no significant wavelength dependence in and out of the plume. However, the 1064-to-532 nm extinction coefficient ratios are smaller outside the plume than in it, suggesting that the size of aerosol particles decreases outside the plume.

URL: http://www.soest.hawaii.edu/lidar

OS51C-04 0915h

Near-Surface Turbulence in the Presence of Breaking Waves

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Breaking surface waves are believed to be a major pathway for the energy input from the atmosphere to the ocean and a source of enhanced turbulent kinetic energy levels in the near-surface layer. Increased turbulence levels relate to enhanced air- sea exchange processes. However, the direct link between enhanced turbulence levels and wave breaking has not been shown yet.

During the recent FAIRS experiment in the North Pacific we deployed three orthogonal short-range acoustic Doppler profilers, originating ∼1m beneath the free surface, to obtain high-resolution velocity profiles beneath breaking waves. The high spatial (6 mm) and temporal (20 Hz) resolution allow us to estimate turbulent kinetic energy dissipation directly from wave number spectra, without the requirement of Taylors assumptions of frozen turbulence. Acoustic resonators are used to assess the near-surface bubble field and give information on the air entrainment through wave breaking. The turbulence and bubble field measurements are linked to breaking events via simultaneous video recordings, which also provide estimates of size and speed of the breaking wave. A broad suite of scanning sonars, monitoring the wave field and larger scale mixed layer structures such as Langmuir circulation, supplement the turbulence measurements. Results showing enhanced turbulence levels linked to wave breaking and the detailed structure of the turbulence and bubble field associated with breaking waves will be presented. Implications for air- sea exchange processes will be discussed.

OS51C-05 0930h

Measurements of Wave Breaking: Kinematics, Dynamics and Air-Sea Interactions

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Wave breaking plays an important role in determining the air-sea fluxes of mass (gas, aerosols/spray), momentum and energy. Breaking limits the height of surface waves and transfers momentum flux from the wave field to currents. The energy lost from the wave field is available to mix the surface layers of the ocean. Small gravity-capillary waves may break with no significant air entrainment, but larger gravity waves entrain air as whitecaps. The classical description of whitecaps has been in terms of whitecap coverage: the fraction of sea surface covered by foam; however, of more interest are the kinematics and dynamics of breaking. In this paper we present airborne measurements, from the SHOWEX and RED experiments, of the kinematics of breaking in terms of $Lambda(c)dc$, the average length of breaking crests with speeds in the range $(c, c + dc)$, a measure first introduced by Phillips (1985). We show that airborne imagery and image processing techniques, including PIV, can be used to measure $Lambda(c)$ and its first 5 moments, which are interpreted in terms of the kinematics and dynamics of breaking. The significance of the results for surface-wave and air-sea interaction processes will be discussed. Research sponsored by ONR.

OS51C-06 0945h

Eddy correlation measurements of CO2 flux over a large lake

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Measurements of the fluxes of CO2, heat and momentum, along with supporting meteorological, surface wave and water-side turbulence data, were made from a small ship on Lake Ontario. During the two field seasons, a wide range of wind speed, stability and fetch conditions were experienced. Here we report on the measurements and compare the mass transfer rates observed with recent measurements using direct and indirect methods. The effect of wave properties and turbulent dissipation rates(in the water) on the mass transfer rates is clarified.

OS51C-07 1030h

Coherent Structures Generated by Microscale Wave Breaking and Air-Sea Gas Transfer

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Microscale breaking waves are short wind waves that break without air entrainment. At moderate wind speeds microscale breaking waves play an important role in generating near-surface turbulence and controlling air-water gas transfer. We report on a series of experiments conducted in a wind-wave flume at the Harris Hydraulics Laboratory (University of Washington, Seattle) designed to investigate the importance of microscale breaking waves in enhancing air-water gas transfer rates. Non-invasive experiments were performed at wind speeds ranging from 4 m/s to 11 m/s and at a fetch of 5.5 m. The skin-layer or water surface temperature was measured using an infrared (IR) imager and particle image velocimetry (PIV) was used to obtain simultaneous measurements of the two-dimensional velocities immediately below the water surface. Analysis of the velocity data showed that coherent structures (i.e. strong vortices) were generated in the crest of microscale breaking waves and that the turbulent kinetic energy was significantly enhanced above the wave troughs. The properties of the coherent structures were used as input to the surface renewal model in order to predict air-water gas transfer velocities. The predicted gas transfer velocities were found to be comparable with measured bulk gas transfer velocities. We found that at wind speeds greater than 7 m/s more than 80% of the waves were microscale breaking waves and that microscale wave breaking contributed more than 85% of the total turbulent kinetic energy and air-water gas flux. These combined results reinforce the conclusion that microscale wave breaking is the dominant mechanism that controls the rate of air-sea gas transfer at moderate wind speeds.

OS51C-08 1045h

Velocity Structure and Turbulent Streses Directly Below Wind-Forced Ocean Waves

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Surface gravity waves play a critical intermediate role in transferring momentum into the ocean. Laboratory measurements of dissipation under breaking suggest that high dissipation events associated with wave breaking have short lifetimes (OT, the wave period) and shallow (O1-2 A, the wave amplitude) depth distribution, making it difficult to infer dissipation rates from observations deeper in the water column. These large excesses in near-surface dissipation rates under wind waves, orders of magnitude above law of the wall scaling, have also been observed by several investigators in field observations. However the kinematics of breaking oceanic wind waves remain poorly understood, as it is very difficult to measure the velocity field very close to the wave surface, in the shallow depth range directly forced by the wind-wave breaking.

A high resolution bistatic geometry, coherently sampled acoustic Doppler profiler has been developed to measure the velocity field in small scale oceanic boundary layers. This instrument has been successfully used to study the mean current and oscillatory wave bottom boundary layers in the surf zone and inner shelf in the last 5 years. A slightly modified, upward-looking version of this instrument is now being used to measure the velocity field immediately below ocean wind waves and shoaling waves. The system noninvasively measures three component velocity profiles with 1cm vertical bins over a 1.5m range, starting 0.5m above the instrument frame at a 40 Hz sample rate. These velocity profiles provide profiles of Reynoldss stresses and shear measurements allowing shear production associated with intermittent micro-breaking and breaking events to be estimated in a surface-following coordinate system.

Examples of bubble density and velocity time-series, Reynolds stress and shear production will be shown from trial deployments in Monterey Bay to illustrate progress in separating small magnitude turbulent events associated with wave breaking from the largely irrotational wave field. The rapid depth decay of turbulence events associated episodic small scale wave breaking events can be clearly seen in the stress profile time-series.

OS51C-09 1100h

Air-Sea Momentum Flux and Equilibrium Surface Wave Spectrum

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Recently, we have developed an analytical model of the equilibrium range of ocean surface wave spectra. The model predicts that the shape of the equilibrium spectrum is determined uniquely by a single parameter called "sheltering wavenumber". In this presentation, we show how the air-sea momentum flux (drag coefficient, equivalent surface roughness) is influenced by the equilibrium range of surface wave spectra. For mature seas at moderate to high winds, the drag coefficient is mainly determined by a single parameter called "sheltering wave age". If this parameter is assumed to be independent of wind speed, the model predicts that the normalized equivalent roughness (Charnock's constant) is indeed a universal constant. At lower wind speeds, the drag coefficient also depends on viscosity and surface tension of water. The model results are compared with recent field observations and numerical results based on a wave prediction model.

OS51C-10 1115h

Wave-supported fluxes of momentum and energy to the sea surface, measured at sea from a SWATH vessel during SHOWEX 99

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A newly-designed measurement system was deployed on the SWATH (Small Waterplane Area Twin Hull) vessel CCGS Frederick G. Creed during SHOWEX 99 to measure the air pressure sea surface slope correlations required to estimate the wave-supported fluxes of momentum and energy to the sea surface. The system consisted of an array of vertically pointing IR lasers for measuring sea surface elevation and slope and a vertical array of highly sensitive air pressure sensors, Pitot tubes and hot film wind turbulence sensors to measure the turbulent pressure and wind vector near the sea. The measurements were part of the SHOaling Wave EXperiment (SHOWEX 99) and were carried out in November and December 1999 on the continental shelf near Duck, NC. This represents the first time such measurements have been attempted from a moving vessel in the open sea. This paper describes the outcome of the initial analysis of the pressure-wave slope correlations. The wave-supported momentum inputs are scaled by the total momentum flux and related to the wave age parameter (U/c-1)2 where U is wind speed and c wave phase speed, and compared with earlier measurements made from fixed sites in enclosed environments (wind wave tanks, bays). These direct measurements of the wind forcing will help realize the overall SHOWEX goal of determining all the terms (wind input, nonlinear interactions, propagation and dissipation) in the wave action transport equation, thus putting realistic constraints on the modeling of wave development in a shoaling environment.

OS51C-11 1130h

Direct Measurements of Wavenumber Spectra of Ocean Waves Using Air-Sea Interaction Spar Buoys in SHOWEX

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Three air-sea interaction spar (ASIS) buoys were deployed in coastal waters off Duck, North Carolina during the SHOWEX experiment. The buoys acquired continuous time series of wave elevations using a nested 8-wire gauge array, observations of meteorological variables (wind velocity and stress, atmospheric stability), and near-surface oceanographic variables (near-surface currents and water temperature). The nested array of capacitance wire wave gauges and motion sensors coupled with the Wavelet Directional Method (WDM) allows us to define the wavenumber directional spectrum with unprecedented accuracy down to wavelengths of 10 cm. The traditional use of 3 m discus buoys has produced frequency-direction spectra for waves longer than 6 m, in which the shorter waves are Doppler shifted. Our method provides three significant advantages over conventional methods: (i) it yields wavenumber spectra; (ii) it allows calculation of rapidly changing wave directional properties as waves shoal; and (iii) it yields no ambiguity of wave direction for platforms with a mean advective velocity.

Combining the frequency-direction and wavenumber spectra will allow us to examine the dispersion relation and deduce currents as a function of the depth. The currents will be compared to surface current measurements from a HF radar system illuminating the same location as the ASIS buoys.

OS51C-12 1145h

Numerical Modeling of Sea Surface Directional Wave Spectra in Hurricane Bonnie (1998) using WAVEWATCH-III

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The Hurricane Bonnie (1998) directional wave spectra obtained from NASA Scanning Radar Altimeter (SRA) on 24 August 1998 in the open ocean, and on 26 August when the storm was approaching Wilmington, NC are compared with results of a third-generation ocean wave model, WAVEWATCH-III. This is the first detailed comparison of the spatial distribution of the sea surface directional wave spectra in surface wave model simulations with observations in both open ocean and landfall hurricane cases.

The simulated maximum wave height in the open ocean case reaches 12 m, agreeing well with the SRA observations and buoys. It was gradually reduced by the distributed wave energy dissipation across the shelf as the hurricane approached the shore. The variation of the hurricane translation speed from 2 m/s at 06 UTC, 24 August to 8.1 m/s prior to landfall affected the distributions of the wave height as well as the directional spectrum. The effect of bathymetry at landfall was also an important factor determining the wave fields. The model and SRA spectra are in a good agreement in the open ocean. The peak wave direction and frequency and the spatial variation of spectra in all four quadrants relative to the storm center are simulated quite well. For the landfall case, however, the simulated peak frequencies displayed noticeable disagreement with the SRA observations, probably due to the models limitations of resolving shallower depths.