

Spatial Variation of Wind Stress and Wave Field in the Shoaling Zone

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LONG-TERM GOALS

Existing atmospheric models for predicting surface stress and turbulence in the shoaling zone fail because of their inability to properly account for wave age, shoaling, and boundary layer development. Accurate model simulation of surface stress and turbulence above the air-sea interface is important for a number of applications including understanding wave growth and decay. Our goals are:

1. to measure the spatial variation of the wind, surface stress, and ocean wave fields in the shoaling zone and to provide quality-controlled data to the shoaling community; and
2. to study the relationship between the spatially varying mean wind, surface stress, turbulence structures, and surface wave fields in order to model effects of wave age, shoaling, and internal boundary layer development on the drag coefficient and momentum transfer.

OBJECTIVES

The key to achieving our goals is the development of a data archive containing simultaneous observations of the spatially varying wave, wind, and stress fields in the shoaling zone. At the start of this project, instrument systems for making such observations did not exist. Over the last five years, we have achieved our first objective which was to develop and demonstrate an efficient data acquisition system to measure the spatial variation of the wind, surface stress, and ocean wave fields in the shoaling zone. This report focuses on instrument system development and its application in the Shoaling Waves Experiment (SHOWEX).

APPROACH

The LongEZ (registration N3R) is a pusher-engine research aircraft that has been used extensively to

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acquire data for a variety environmental research projects (Fig. 1). This aircraft has proven to be especially powerful in studying the spatial variability of air-sea exchange. The instrument suite and data acquisition system are used to measure mean properties of the atmosphere as well as turbulent fluxes of heat, moisture, and momentum. Remote sensors were specifically added for SHOWEX to determine wave field properties such as wave height, roughness, phase speed, and directional spectra.



Fig. 1. LongEZ N3R over the North Carolina coastline during a SHOWEX flight.

The “best” aircraft turbulence (BAT) probe was developed by scientists and engineers from NOAA’s Air Resources Laboratory and Airborne Research Australia. The BAT housing consists of a 15-cm diameter carbon-fiber hemisphere mounted on a tapered cone which is mounted on the nose of the aircraft. The housing contains solid-state pressure sensors used to measure differential and static pressure from pressure ports on the hemisphere. These measurements provide the pressure distribution over the hemisphere from which the air relative velocity may be computed. Ground relative velocities are provided by differentially-corrected GPS data which provides three-dimensional velocity with an accuracy of roughly 4 to 5 cm s⁻¹. High frequency measurements are made from three orthogonally-mounted accelerometers. These devices are used to augment GPS data to 50 Hz. Wind velocities are derived by taking the difference between vectors of air and ground relative velocity. Aircraft attitude (pitch, roll, heading) is measured using a Trimble Advanced Navigation System (TANS) vector GPS. The TANS consists of four antennas mounted on the BAT probe housing, wings, and rear of the cockpit. Using carrier-phase interferometry, the position of three antennas is measured relative to a master antenna.

Air temperature measurements are acquired by redundant fast-response micro-bead thermistors. A NOAA-designed open-path infrared gas analyzer measures turbulent fluctuations of water vapor. Three sets of radiometric sensors measure both upwelling and downwelling radiation. A Radiation and Energy Balance Systems radiometer provides measurements of net (long and short wave) radiation. Upward looking and downward looking Li-Cor photosynthetically active radiation sensors measure the incoming and reflected portion of the visible solar spectrum. Upward and downward looking Everest Interscience infrared radiometers are used to measure sky and sea surface temperature.

A laser altimeter array and a NASA-designed 36-GHz (Ka-band) scatterometer were used to determine long and short surface wave characteristics, respectively. The data obtained from these remote sensors provide wave information from small capillary waves to long swells coupled with measurements of wind stress and turbulence. An array of three Riegl laser altimeters were used to determine ocean wave characteristics such as wave height, roughness, phase speed, and directional spectra. The array consists of three downward looking lasers mounted on the vertices of a 1-m equilateral triangle. Two are mounted under either wing while the third is mounted in an instrument pod below the aircraft fuselage. The lasers operate at a pulse repetition frequency of approximately 2 KHz. Thirty-eight individual pulses are averaged down to a rate of 50 Hz to reduce noise. The focal length of the lasers was set to 15 m providing a nominal accuracy of ± 2 mm. At a typical flight speed of 50 m s⁻¹, the laser array can determine wave characteristics for wavelengths greater than 5 to 6 m. The low-power nadir-pointing scatterometer is also mounted in the instrument pod. This sensor is used to infer short wave

characteristics by relating backscatter intensity to the mean-square slope (variance) over wave scales from 0.01 to 1 m. Coincident laser altimeter measurements provide the precise range information for computation of the normalized radar cross section. Visual and infrared images of whitecaps were acquired by the Modular Aerial Sensing System (MASS) developed by W. Kendall Melville (SIO). These measurements are used to determine the temporal evolution of breaking waves. The MASS sensors were mounted in the rear portion of the instrument pod.

WORK COMPLETED

Three SHOWEX field studies were successfully conducted in the vicinity of the U. S. Army Corps of Engineers Field Research Facility located in Duck, North Carolina. Fourteen missions (53 flight hours) were conducted in November 1997 during the first pilot study. Twenty-three missions covering 75 flight hours were flown by N3R in the second pilot study in March 1999. Twenty-seven missions (105 flight hours) were flown in November and December 1999 during the SHOWEX intensive field study. N3R flew under various atmospheric and wave field conditions. In order to assess changes in atmospheric turbulence and the ocean wave field through the shoaling region, repeated transects were flown both perpendicular and parallel to the coastline at various altitudes. Soundings were also conducted during each flight to assess the vertical structure of the marine atmospheric boundary layer.

RESULTS

The shoaling zone is clearly defined by the decrease of the mean square slope (mss) of short waves (< 1 m) and the increase of the mss of long waves (> 1 m) with off-shore distance. For on-shore flow, the spatial variation of the surface stress J is small in the shoaling zone. The friction velocity u_* is strongly correlated with the mss . Similarly, the neutral drag coefficient C_{DN} is well correlated with the atmospheric bulk Richardson number R_B .

For stable off-shore flow of warm air over cool water, the momentum flux decreases rapidly with distance for the first few kilometers offshore and gradually reaches equilibrium values 10 km offshore. This observed decrease in the momentum flux with travel time from the coast is predicted using a characteristic timescale of the turbulence in boundary layer over land. This suggests that, close to the coast, advection and decay of residual turbulence strongly influence the air-sea momentum exchange. In this case, similarity theory does not adequately predict the flux due to dependence on upstream conditions. The residual turbulence advected from land becomes partially detached from the sea surface leading to a momentum flux and turbulence maxima aloft. Contrary to the usual concept of a boundary layer, the downward momentum flux increases with height. Further data analysis has revealed a frequent near collapse of turbulence with very small J and roughness lengths z_o which are less than predicted smooth flow values. The very small z_o are partly due to reduction of the downward momentum flux by stable stratification. N3R data also show the usual minimum of the z_o and C_{DN} for wind speeds ~ 5 m s⁻¹. Much larger values of z_o exist for weaker wind speeds which are partly due to the influence of swell when large differences in the direction of the mean wind vector and J exist. The ultra-smooth cases are most likely to occur with a combination of intermediate wind speeds and stable stratification in contrast to earlier studies where smooth flow effects were associated with weak winds. For unstable offshore flow of cool air over warm water, advection and decay of residual turbulence also occur. However, the relative contribution to the total turbulence level is less due to buoyancy generation of turbulence over the ocean. Unlike the stable case, the momentum flux for unstable flows

is relatively invariant with off-shore distance or travel time, and decreases with height as in traditional boundary layers.

N3R data have also shown a direct correlation between changes in the *mss* and the mean wind speed due to atmospheric roll vortices in unstable conditions. These aircraft data provide direct evidence of the wind impacts on the sea surface for regions as small as several hundred meters and almost one-to-one correlation for the larger scale eddies on the order of 1 to 2 km. Higher (lower) wind almost always equates with increased (decreased) slope variance. Continuous wavelet transform analysis shows a strong coherence between short-scale *mss* and the mean wind speed.

IMPACT/APPLICATIONS

The technology used on N3R is being used adapted for other air-sea interaction research studies. N3R is currently being used in the ONR-sponsored Coupled Boundary Layer Air-Sea Transfer (CBLAST) Departmental Research Initiative (DRI) to study air-sea interaction in light wind regimes. The BAT probe is being adapted for use on NOAA P3 aircraft for turbulence measurements in hurricanes. Finally, the same technology used in the BAT probe is being extended to develop a surface-based omni-directional pressure port anemometer. This extreme turbulence (ET) probe will be used to measure sensible heat and momentum flux during hurricane landfall.

TRANSITIONS

The atmospheric and sea surface data acquired from the three SHOWEX field studies are being used to address spatial variability of the wind, surface stress, and ocean wave fields in the shoaling zone. These data suggest parameters such as drag coefficient are strongly dependent upon wind direction, atmospheric stability, and wave state. These data will be used to better refine model parameterizations in coupled air-sea models. These data are being cooperatively analyzed by colleagues Douglas C. Vandemark, Jielun Sun, Larry Mahrt, Pierre D. Mourad, and W. Kendall Melville.

RELATED PROJECTS

Although funded separately, this project is a cooperative effort with Douglas C. Vandemark (radar scatterometer development and analysis, N00014-97-F-0179), Jielun Sun (data interpretation, N00014-98-1-0245), Larry Mahrt (data interpretation, N00014-97-1-0279), Pierre D. Mourad (SAR intercomparisons, N00014-97-1-0278), and W. Kendall Melville (wave breaking).

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