# Turbulence and the Air-Sea Interface

## Workshop Agenda

**Monday August 14**

| | |
|---|---|
| 8:00 | Kickoff breakfast ..... Barb Hansford |
| 9:30 | Opening remarks ..... Jackson Herring |
| 9:45 | Ocean waves and the atmosphere .... Gerbrand Komen |
| 10:45 | Surface-wave effects on winds and currents ..... James McWilliams |
| 11:45 | Lunch |
| 1:15 | Wave propagation and wind-wave interaction ..... Mark Donelan |
| 2:15 | A global perspective on air-sea CO2 fluxes ..... Rik Wanninkhof |
| 3:15 | Break |
| 3:45 | The complex coastal zone ..... Larry Mahrt |
| 4:45 | *End of Session Day 1* |

## Workshop Agenda

**Tuesday August 15**

| | |
|---|---|
| 8:30 | Hidden Langmuir circulation ..... Sid Leibovich |
| 9:15 | Observations of the oceanic surface boundary layer: wind, waves, and Langmuir circulation ..... Jerry Smith |
| 10:00 | Break |
| 10:30 | Flows under a wavy surface: Numerical tests of the Craik-Leibovich theory of Langmuir cells ..... Hong Zhou, Stephen Monismith & Joel Ferziger |
| 11:15 | Possible evidence for the interaction of surface gravity waves with the earth's rotation through its effect on the near-surface shear ..... Eugene Terray |
| 12:00 | Lunch |
| 1:30 | Laboratory and field studies of the influence of wave breaking on turbulence and fluxes in the marine boundary layer .....Ken Melville |
| 2:15 | Bubble distributions in the ocean surface layer ..... Dave Farmer |
| 3:00 | Break |
| 3:30 | Numerical simulation of free-surface turbulent flows ..... Lian Shen & Dick Yue |
| 4:15 | The role of air/sea exchange in chemistry of the marine troposphere ..... Barry Huebert |
| 5:00 | *End of Session Day 2* |
| 6:30 | Banquet at Mesa Laboratory |

# Workshop Agenda

**Wednesday August 16**

| | |
|---|---|
| 8:30 | Observations of coupling between surface wind stress and sea surface temperature in the eastern tropical pacific ..... Steven Esbensen |
| 9:15 | Satellite observations of tropical instability waves ..... Dudley Chelton |
| 10:00 | Break |
| 10:30 | Observations of the marine atmospheric surface layer ..... James Edson |
| 11:15 | Interactions between wind, waves and turbulence ..... Stephen Belcher |
| 12:00 | Lunch |
| 1:30 | A quasi-inhomogeneous similarity theory for flux profile relations in the marine atmospheric surface layer ..... Gary Geernaert |
| 2:15 | The role of spray in the turbulent air-sea fluxes ..... Edgar Andreas |
| 3:00 | Regional coupled modeling ..... Jim Wilczak |
| 3:45 | *Adjourn* |

# Ocean Waves and the Atmosphere

Gerbrand J. Komen

*KNMI and University of Utrecht, The Netherlands*

This presentation attempts to give a frame of reference for discussion. It is not a comprehensive review of all relevant research. It will start with a historic overview of the development of the WAM model, a numerical model for the prediction of ocean waves. This development was carried out by an international group, the WAM (WAve Modeling) group, after an earlier project (SWAMP) had revealed a number of basic shortcomings in all existing wave models. The WAM model is based on integration of the energy balance equation, which gives a physical description of the evolution of the wave spectrum. Currently, the WAM model is widely and successfully used for operational wave forecasting, both globally and regionally. One of the source terms in the energy balance equation describes the transfer of energy and momentum from the atmosphere to the waves. The actual magnitude depends on the wind stress and the wave spectrum. Early versions of the WAM model had a minor shortcoming: for certain spectra the momentum flux to the waves exceeded the total stress. This stimulated studies of the boundary layer over waves.

An important aspect of the wave boundary layer is the wave stress $\tau_w(z)$, i.e. the stress supported by the wave-induced motion in the air. Miles' (1957, 1959) considered airflow over a monochromatic wave with a given mean wind profile. In this approximation waves extract momentum from the mean wind at the critical height, and the wave motion transports this down to the surface. Fabrikant (1976) and Janssen (1982) extended Miles' work to the case of a continuous wave spectrum and a background profile that is allowed to vary in time. In this way a set of equations result that describe the coupled evolution of both the atmospheric wind profile and the wave spectrum, each wave component extracting momentum at its own critical height and thereby modifying the wind profile. This approach still neglects turbulence, which is expected to have a restoring influence on the wind profile. This problem is overcome in studies seeking numerical solutions of the Reynolds equation (Gent and Taylor, Chalikov/Makin, Belcher, Makin/Kudryavtsev, and very recently Li, Xu and Taylor). A problem then is the description of the turbulent transport term. Belcher and Hunt introduced the concept of rapid distortion, which implies that local closure is not always appropriate. This was confirmed in numerical work of Mastenbroek (1996). This study confirmed the importance of advection of turbulent energy. The critical height did not seem to play a special role. Surprisingly, very recently Direct Numerical Simulations by Sullivan et al (2000) found a dynamically important region of closed streamlines around the critical height. In another study Kudryavtsev and Makin included the effect of air flow separation.

GCM's of the atmosphere, as used for weather and climate simulations, parameterize the surface boundary layer using Monin-Obukhov theory. This requires specification of the roughness length $z_0$. Janssen (1989, 1991) used his quasi-linear theory, supplemented with a mixing length term in the momentum equation, to obtain an expression for Charnock's constant $\alpha = z_0 g/u_*^2$ in terms of the momentum flux into the waves. This quantity can be computed as an integral over the wave spectrum. Its sensitivity to high frequencies has given additional relevance to studies of the spectral evolution of short waves (Plant, Hara, Donelan and many others).

ECMWF runs a coupled atmosphere/ocean-wave model for medium-range weather prediction. Each time step output from the atmospheric model is used to force the WAM model. At the same time the wave spectrum provided by the WAM model (including a parameterization of the short wave part of the spectrum) is used to compute the surface roughness, which is transferred to the atmospheric model. In this way consistency is obtained between the wave stress in the atmospheric model and the momentum flux going into the waves. In our presentation we will compare Janssen's parameterization of $\alpha$ with more recent approaches. We will also discuss experimental information from field observations, such as carried out during HEXOS and by the RRS Discovery and others. Yet another issue is the impact of wave coupling. A number of sensitivity studies have been carried out. In these studies runs with a wave-dependent Charnock parameter were compared with control simulations with a constant Charnock parameter. In individual cases (cyclogenesis; Doyle, Lionello) the difference was quite large but also related to the sensitivity of the atmosphere to small initial perturbation. Statistical studies eliminating this (Janssen, Weisse, Doortmont) still find a small but significant impact of the waves on the atmosphere. In particular, Janssen obtained a small improvement of the forecast skill.

Much work remains to be done. Models of the wave boundary layer should be extended and compared (Reynolds vs DNS; air/flow separation; the role of small scale "background roughness") and verified against laboratory and possibly field observations. Field observations of the stress should be repeated with detailed simultaneous measurements of the sea state. More comprehensive studies of the cost benefit relation of two-way coupling in operational weather forecasting would be of use. In the long term better understanding of the wave boundary layer should lead to improvements in wave prediction models.

## Surface-Wave Effects on Winds and Currents

James C. McWilliams

*Department of Atmospheric Sciences and Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA 90095-1565*
*and*
*National Center for Atmospheric Research, Boulder, CO 80307*

Surface gravity waves strongly deform the air-sea interface over wavelengths as large as 100 m, comparable in size to energetic components of winds and currents in the adjacent marine boundary layers. These near-surface flows are altered in several important ways due to the presence of the waves. Through a generalization of the perturbation theory of Craik & Leibovich, we understand how wave-averaged "vortex forces" in the ocean induce Langmuir circulations and otherwise alter the velocity and tracer distributions. In both air and water, "wave pumping" excites wave-correlated rotational motions that carry the vertical momentum and energy fluxes through a near-surface layer with a thickness comparable to the dominant surface wavelength; in this context the critical layer where the mean wind speed equals the wave phase speed plays an important role, as advocated by Miles. Finally, in the ocean, "wave breaking" enhances the near-surface mixing and dissipation above the levels predicted by Monin-Obukhov similarity forms. The theory and representation of these effects are reviewed, supporting Large-Eddy Simulations are shown, and future directions are speculated about.

# Wave Propagation and Wind-Wave Interaction

Mark A. Donelan

*Rosenstiel School of Marine and Atmospheric Science, University of Miami, Division of Applied Marine Physics, Miami, FL 33149-1098*

Insofar as wind-generated waves are the "roughness elements" enabling or enhancing the coupling between atmosphere and ocean, a full description of the wavenumber directional spectrum of these waves is a necessary condition for progress in understanding the mechanical link between air and water. Standard approaches to the measurement of directional spectra yield the frequency-direction spectrum, in which Doppler shifting of short waves on the orbital velocities of long waves or on currents map the principle roughness elements (10 m to 10 cm wavelengths) into smeared and shifted frequency bins. Here the Wavelet Directional Method (Donelan et al., 1996) is employed to yield (directly) the wavenumber spectrum and modulational effects of long waves on short. The existence of "equilibrium" and "dissipation" ranges in the spectrum is explored. Wavelet methods are also employed to reveal the effect of steepness and breaking on the induced pressure pattern in air flow over waves.

## A Global Perspective on Air-sea CO2 Fluxes

Rik Wanninkhof

*Ocean Chemistry Division, Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami FL 33149*

Improved understanding of near surface turbulent processes controlling air-sea CO2 fluxes is of critical importance to forecast changes in oceanic CO2 uptake. Current estimates are based on global mass balance constraints and rudimentary parameterizations with gas transfer. Small scale flux estimates and large scale constraints have not always been reconcilable but with improved techniques and better understanding of the inherent differences and limitations of approaches better agreement is being obtained.

On global scale the oceanic CO2 uptake is determined by mass balance constraints using the carbon isotope 14C or by the fraction of anthropogenic CO2 that remains in the atmosphere compared to what is released. In the latter method the separation between terrestrial uptake and oceanic uptake is accomplished using the unique 13C isotopic signature of the fossil fuel and the known isotopic fractionation between the reservoirs. A similar but largely independent approach is to use the changes in O2/N2 ratio in the atmosphere.

Local air-sea gas exchange estimates have been determined by a variety of in situ mass balance methods and by studies in controlled environments such as wind-wave tanks. In the latter case the work often has been interpreted in a theoretical framework and applied to natural systems. The scales of investigation range from $m^2$ to $10^3$ $km^3$. For tracer studies in the natural environment the response time of the measurements has been at least several days. Recently, direct flux measurements in the atmospheric marine boundary layer have increased the frequency to about 1/2 hour greatly enhancing our ability to relate gas fluxes directly to surface forcing.

The gap between large-scale constraints and small-scale investigations is being narrowed by improvements in techniques to downscale the constraints and by upscaling the (field) investigations. Using (inverse) models and water column transport estimates it is possible to determine CO2 fluxes at basin to sub-basin scale. By relating the small scale results to "robust" turbulence parameters, preferably those that can be sensed remotely, these studies can be extrapolated to larger scale.

This overview will cover the global constraints and process studies to determine air-water CO2 transfer. It will point to the necessity of improving our mechanistic understanding of the processing controlling the exchange. It is only with this understanding that reasonable forecasts of future oceanic CO2 uptake, and possible changes with environmental change, can be made.

# The Complex Coastal Zone

Larry Mahrt

*College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon*

Air-sea interaction in the coastal zone is influenced by shoaling and wave breaking, growing young waves, diurnally varying local circulations and nonequilibrium boundary layers. Offshore flow of warm air over cold water is particularly complex. Turbulence near the surface may collapse leading to decaying wave field. Turbulence advected from land at higher levels may be significantly stronger than the near surface turbulence.

The complexities of the coastal zone are interpreted in terms of the bulk aerodynamic relationship, the validity of Monin-Obukhov similarity theory and the relationship of the roughness length to wave state. Unique features of the weak wind case will be discussed.

# Hidden Langmuir Circulation

S. Leibovich, T. Haeusser, and R. Bhaskaran

*Sibley School of Mechanical & Aerospace Engineering, Cornell University, Ithaca, New York 14853*

The principal observable signatures of Langmuir circulation (LC) rely on near-surface Lagrangian tracer patterns. We discuss Lagrangian patterns, including 'Y-junctions' and their relation to Eulerian patterns. The analysis forming the basis of the discussion is a set of amplitude equations derived from the Navier-Stokes equations valid for mildly supercritical conditions. The basic state considered is the Ekman layer modified by the surface wave vortex force as originally treated by Huang (JFM, 91, 1979). The Coriolis force causes the LC instability to be in the form of propagating waves. Other physical circumstances also can lead to a similar propagating property for the Langmuir circulation. A substantial parameter range exists where Lagrangian markers are not organized due to cross-roll propagation, yet LC is active. Mixing then occurs without the tell-tale surface signature.

# Observations of the Oceanic Surface Boundary Layer: Wind, Waves, and Langmuir Circulation

Jerry Smith

*Scripps Institution of Oceanography, UCSD, La Jolla CA 92093-0213*

Fluxes of momentum, energy, heat, moisture, etc. across the air/sea interface are linked to waves, wave breaking, and to quasi-coherent motions spanning the boundary layers above and below. Motions in the oceanic mixed layer are linked to shears across the thermocline, to wind stress, and to waves and wave breaking. An ongoing challenge is to formulate a simple yet effective parameterization of air/sea fluxes in terms of easily observed and modeled parameters. There is hope that this puzzle will yield to the dual effects of improved understanding and measurement techniques. Measurements of wind, waves, stratification, and mixed layer motions have been made at several locations in the open ocean over the past decade, including large-scale experiments coordinating measurements from Doppler sonars, sonic anemometers, directional wave arrays, and various other instruments. With these data sets, we are investigating basic scaling relationships between variables of dynamic significance. For example, the observed size, orientation, and velocity scales associated with "Langmuir circulation" (a commonly observed form of wind-driven motion in the oceanic boundary layer) are related to the observed strength and direction of the wind and waves and to the mixed layer depth. The *rms* surface velocity associated with Langmuir circulation ($V_{rms}$) scales closely with either the wind speed or the surface Stokes' drift velocity due to the presence of waves. Since these are highly correlated (at about 95%), it is hard to distinguish which is the dynamically relevant parameter. To investigate this, we need good wind, wave, and surface velocity measurements over a range of conditions, including a wide variety of stages of wave development and of alignment angles (between the mean wind and wave directions). To describe joint wind and wave effects in these experiments, eddy-flux wind measurements were made, collocated and synchronized with wave height and slope measurements. Scaling both the *rms* velocity ($V_{rms}$) and the Stokes' drift ($U_s$) by the wind friction velocity ($u_*$), we can examine and verify what combination of $U_s$ and $u_*$ best fit the data. The results to date (three separate wind events) show that $V_{rms}$ favors the Stokes' drift alone, once Langmuir circulation is detected. A new puzzle remains: the scaling factor relating $V_{rms}$ to $U_s$ is tightly constrained (statistically) within each wind event, yet varies between wind events by far more than the apparent uncertainty (it varies by a factor of about 5 among the three events). There is some "missing factor" (and associated physics?) that varies significantly from one storm to the next. A similar puzzle exists concerning the "drag coefficient" over water: over the handful of storms that have both sufficient measurements and sufficient variation in the wind/wave ratios, it is seen that the drag coefficient varies tightly with the waves (wave height, say) within an individual storm; however, the "constant of proportionality" varies between storms by a factor of up to 3. Using "wave age" (the ratio of wind speed to wave phase speed) rather than wave height is not the solution: in one storm wind and waves rise together, yielding constant wave age, while the drag coefficient increases by more than 2.5 over the same period. Two classes of hypotheses for these discrepancies exist: (1) "Local," where an additional local factor such as wind-wave angle, bubble content near the surface, etc. may explain the variations; and (2) "Non-local," where the variations arise due to (for example) large-scale convergence/divergence of wave energy. While the former class of hypotheses can be addressed by re-examining data or with modest small-scale experiments, the latter will require considering (and observing!) the structure of the winds and waves (etc.) over the scales of the entire storm and resulting oceanic response.

# Flows under a Wavy Surface: Numerical Tests of the Craik-Leibovich Theory of Langmuir Cells

H. Zhou, S. G. Monismith, and J.H. Ferziger

*Departments of Civil and Environmental, and Mechanical Engineering, Stanford University, Stanford, CA 94305-4020*

We will present results of LES computations of flow under a wavy surface, in which the wavy surface was used to model the effect of surface gravity waves on laminar and turbulent Couette flows. For the sake of comparison, we also calculated the same flows with a flat surface instead using Craik-Leibovich (CL) theory to model the effects of waves. In order to make this comparison "fair" however, surface stresses applied in cases in which the waves weren't explicitly included were augmented by an amount equal to the viscous stress developed in the near-surface Stokes layer in the presence of waves. For all non wavy computations we used stresses appropriate to laminar flows.

For the laminar case, flows computed using the CL theory were essentially the same as flows computed using waves and no averaging. For the turbulent case, both the CL case and the wavy case are significantly different from the comparable Couette flow in a number of ways, most notably, because significant vertical momentum transport is accomplished by the LCs, turbulent Reynolds stresses and hence TKE production are reduced relative to values typical of the base flow. On the other hand, while the CL model yields results that are similar to those seen for the wavy flow, secondary flows seen in the CL case are stronger than those seen in the wavy case. One reason for this difference may be the fact that the wave stresses that develop in the turbulent case are roughly twice as large in the turbulent case as in the laminar case, behavior that may be attributed to the fact the flow near the free surface is turbulent. It appears that in general, wavy Couette flows are described by two parameters: a turbulence Reynolds number $Re_* = u_* h/\nu$ ($u_*$ = shear velocity of applied stress, $h$ = depth of box, and $\nu$ = viscosity), and a wave Reynolds number, $u_s h/\nu$ ($u_s$= Stokes drift velocity at surface), the combination of which gives the Langmuir number, $La$. Thus, because of its enhanced surface stress, $Re_*$ was larger in the wavy case than in the CL case, which, we can hypothesize, may lead to a weakening of the Langmuir cells (or a strengthening of the Couette flow). To test this hypothesis, computation of a CL case with the same value of $Re_*$ as our wavy case is currently underway.

These results suggest that further progress on Langmuir cell dynamics and the use of CL theory as a model of wave-turbulence interactions in LES calculations may require more careful evaluation of the near surface flow structure, particularly with regard to the parametric inclusion of surface wave breaking. Additionally further exploration of the way flow behavior changes as a function of $Re_s$ and $Re_*$ would be useful for understanding why in some cases the LCs are relatively organized and persistent and why in other cases, LCs are observed to be more ephemeral.

# Possible Evidence for the Interaction of Surface Gravity Waves with the Earth's Rotation Through Its Effect on the Near-Surface Shear

Eugene A. Terray

*Department of Applied Ocean Physics and Engineering Woods Hole Oceanographic Institution*
*Woods Hole, MA 02543*

The mechanics of surface gravity waves on a rotating ocean, and the implications for upper ocean currents is an old problem dating back at least to Ursell (1950). He pointed out that if the waves are statistically homogeneous and steady, the mean Lagrangian current vanishes, and hence a reverse Eulerian current must be set up to balance the Stokes drift, $\mathbf{U_s}$, of the waves. Hasselmann (1971) subsequently analyzed the dynamics in an Eulerian frame, showing that the interaction with the earth's rotation causes the waves to become rotational at order $f/\omega$, producing a vertical Reynolds shear stress whose divergence drives an Eulerian current. He further showed that the stress divergence takes the form $-\mathbf{f} \times \mathbf{U_s}$.

The importance of this interaction for basin–scale oceanic circulation was recently emphasized by McWilliams and Restrepo (1999), who estimated that the net transport is modified from the wind–driven Ekman value by O(30–40%) at mid– to high–latitudes. Unfortunately, such values are close to the observational uncertainty in estimates of the vertically–integrated mass flux. However, the wave stress is expected to modify the vertical current distribution to an extent that may be observable (McWilliams *et al.*, 1997).

In this note we revisit observations of near–surface shear taken in the winter of 1988–1989 on the northern California shelf (at 38°N), near Point Arena (Santala, 1991). Using a simple turbulence model to describe the vertical mixing, we find that the mechanism discussed above is consistent with the observed asymmetry between the along– and cross–wave shear. We conjecture that these observations might be a consequence of wave forcing.

### References

Hasselmann, K. (1970): Wave–driven inertial oscillations. *Geophys. Fluid Dyn.*, **1**, 463–502.

McWilliams, J.C., P.P. Sullivan and C.–H. Moeng (1997): Langmuir turbulence in the ocean. *J. Fluid Mech.*, **334**, 1–30.

McWilliams, J.C. and J.M. Restrepo (1999): The wave–driven ocean circulation. *J. Phys. Oceanogr.*, **29**, 2523–2540.

Santala, M.J. (1991): Surface–Referenced Current Meter Measurements. Ph.D. dissertation, MIT/WHOI Joint Program in Oceanography.

Ursell, F. (1950): On the theoretical form of ocean swell on a rotating earth. *Mon. Notices Roy. Astron. Soc.*, **6**(1), 1–8.

# Laboratory and Field Studies of the Influence of Wave Breaking on Turbulence and Fluxes in the Marine Boundary Layer

W. Kendall Melville

*Scripps Institution of Oceanography, UCSD, La Jolla CA 92093-0213*

Despite the major recent advances in our ability to measure turbulence in the marine boundary layer, especially within the surface wave layer, it remains very difficult to directly measure the role of breaking; as a source and sink of turbulent kinetic energy, and in the flux of momentum from waves to surface currents. This difficulty arises because, in the field, the effects of breaking occur randomly over both fast and slow time scales, and over short and long length scales. In the laboratory we can generate breaking waves that are repeatable in the mean, and separate the waves, the currents, coherent structures and the turbulence (Melville, Veron & White, 2000). However, Rapp & Melville (1990) also showed that even without detailed turbulence measurements, "black box" studies in the laboratory in which fluxes into and out of the breaking region are measured can provide very good estimates of the bulk effects of breaking. In this talk, I will present the case that an improved understanding of breaking in the field is best obtained from a combination of both laboratory and field measurements.

In 1985, Phillips formulated a statistical description of breaking based on $\Lambda(\vec{c})d\vec{c}$, the average length of breaking fronts per unit ocean surface area in the velocity range, $(\vec{c}, \vec{c}+d\vec{c})$. Once $\Lambda(\vec{c})$ is known, other important quantities associated with breaking can be determined. In the context of surface wave dynamics, the most important of these is wave dissipation. From simple physical arguments to describe laboratory measurements of 2D breaking waves, Duncan (1981) showed that the dissipation per unit length of breaking front is given by $b\rho_w c^5/g$ , where $b$ was a constant. Using this result, it follows that the dissipation due to breaking fronts in the speed range $(c, c + dc)$ , $(c)$, is given by $b\rho_w g^{-1}\Lambda(c)c^c dc$. Melville (1984) showed that very general inertial estimates of dissipation, along with an assumption of geometrical similarity of unsteady breakers, led to the same fifth moment with the factor $b$ a function of a characteristic wave slope, and an order of magnitude smaller than that found by Duncan for quasi-steady waves. Thus to within a numerical factor $b$, given $\Lambda(c)$, the wave dissipation can be determined. In a similar fashion the momentum flux from waves to currents can be determined once $\Lambda(c)$ and $b$ are known.

I will present recent field measurements of $\Lambda(c)$ using image sequence analysis of airborne video from the Shoaling Waves Experiment (SHOWEX), and show how it may be combined with laboratory measurements of $b$ to give estimates of wave dissipation and momentum flux due to breaking waves that generate whitecaps.

(Work supported by ONR and NSF.)

# Bubble Distributions in the Ocean Surface Layer

David Farmer

*Institute of Ocean Sciences, Sidney, BC*

At higher sea states breaking waves inject bubbles into the ocean surface layer. The resulting bubble clouds, especially their time evolving spatial properties and bubble radius spectra, provide evidence of the roles of turbulence and advection in shaping the bubble distribution. Detailed observation of spatial patterns acquired with imaging sonars, along with in situ measurements of bubble radii, dissolved gases, the directional wave field, fine scale temperature variability and related properties provide a basis for model comparisons. Simple 1-dimensional analytic models capture the essence of bubble injection, buoyant rise and bubble dissolution following a breaking event, but numerical methods are required to explore the detailed response to advection and turbulence. A Monte Carlo simulation with randomly distributed injection events is implemented, together with a subsurface circulation consistent with measured Langmuir cell characteristics. The model calculations capture several aspects of the resultant bubble cloud characteristics and provide insight on near surface turbulence and advective processes in the wind driven surface layer.

# Numerical Simulation of Free Surface Turbulent Flows

Lian Shen & Dick K. P. Yue

*Department of Ocean Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139-4307*

We develop a suite of numerical capabilities for simulations of turbulent flows near the air-sea interface: (a) for small free-surface deformations, a boundary interface tracking method (BITM) which solves the incompressible Navier-Stokes equations subject to the viscous free-surface boundary conditions, with the kinematic boundary condition requiring the interface remains a material surface, and the dynamic boundary condition requiring a stress balance across the interface; (b) for steepening/breaking surface waves, an Eulerian interface capturing method (EICM), which treats the air and water together as a system with varying density, viscosity and diffusivity, with the air-water interface captured by a level set function; and (c) for highly-mixed air-water flows, a Lagrangian large-eddy tracking method (LLETM) based on smoothed particle hydrodynamics, in which the motions of designated fluid particles are tracked during momentum exchange through inertial and viscous forces.

Through numerical simulations, substantial understanding of free-surface turbulence (FST) has now been obtained especially for the relatively low Froude number case. We identify conceptually and numerically a multi-layer structure in the turbulent flows near the free surface. The inner surface layer is caused by the tangential free-surface dynamic boundary conditions and the outer blockage layer is due to the kinematic boundary condition. The dynamics of vortex connection to the free surface within the free-surface boundary layers are elucidated. We also examine the effects of the inner and outer layers on the turbulence statistics of length scales, Reynolds-stress balance, and enstrophy dynamics, which show clearly the different turbulence mechanisms operating in the respective near-surface scales. To characterize and quantify the turbulent diffusion process near the free surface, we develop a similarity theory. The theoretical predictions on the shape and time-scaling behavior of the mean flow, as well as the scaling relations for the thickness of free-surface boundary layers, are well confirmed by numerical results.

From direct numerical simulations (DNS) we obtain important insights into the subgrid-scale (SGS) modeling for the large-eddy simulation (LES) of free-surface turbulent flows. It is found that the amount of energy transfered from the grid scales to the subgrid scales reduces significantly as the free surface is approached. This is a result of energy backscatter associated with the fluid vertical motions. The free-surface region is highly anisotropic at all the length scales while the energy backscatter is carried out by the horizontal components of the SGS stress only. Based on the physics of FST, we develop two novel SGS models, a dynamic free-surface function model (DFFM) and a dynamic anisotropic selective model (DASM). We also model for the first time the surface SGS flux and the dynamic SGS pressure, which are unique to the free-surface problems. Our physics-based SGS models are shown to substantially improve the predictions of free-surface turbulent flows over existing models.

# The Role of Air/sea Exchange in Chemistry of the Marine Troposphere

Barry J. Huebert

*Department of Oceanography, University of Hawaii, Honolulu, HI 96822*

The turbulent exchange of material across the air-sea interface plays a major role in several aspects of marine tropospheric chemistry. Perhaps the most well known of these impacts is the effect of marine biogenic dimethylsulfide (DMS) on the whiteness of clouds. The CLAW hypothesis (Charlson et al., 1987) postulated that increased emission of DMS from the ocean would cause increased concentrations of sulfate aerosol, which might therefore increase the number of cloud droplets and thus cloud albedo. To realistically model the possible feedbacks in the climate system, this system has to be represented properly. Among the major uncertainties is how the DMS emission flux depends on wind speed and the nature of the air-sea interface. The supply of marine ammonia may also influence the formation of particles from DMS.

The ocean is also a significant source of biogenic volatile organic compounds (VOCs), which can be present in the marine BL at concentrations high enough to react with a significant fraction of the $OH$ and thus affect the oxidation capacity of the atmosphere. Condensible organic vapours may participate in the nucleation of new particles as well as in their growth. Organic material sources include the sea surface organic microlayer, the condensation of oxidized VOCs (many of them from the sea), and primary processes that release biological aerosols (e.g. bacteria and cell fragments) to the atmosphere.

Reactive halogen species (in particular $BrO$ and $IO$) may play major roles in FT and BL photochemistry. It is now widely believed that these oxidants (which react with some molecules even faster than the OH radical does) are released from sea salt after reaction with ozone, making the supply of sea salt particles important for computing photochemical reaction rates. The emission of marine biogenic halogens - in particular $CH_3Cl$ and $CH_3Br$ - also contribute to the halogen budgets of both the stratosphere and the troposphere. In addition, shorter-lived organic and inorganic halogen compounds are either emitted directly from the oceans (e.g., $CH_2Br_2$, $CHBr_3$, $CH_3I$) or produced indirectly via photochemical transformation of precursor species. These compounds can contribute to $O_3$ destruction in the troposphere. The impact of reactive halogen species on tropospheric ozone is exemplified by the polar "Tropospheric Ozone Holes" occurring during springtime in the Arctic and Antarctic boundary layers. It is possible that marine halogens also affect stratospheric ozone.

Quantifying turbulent transfer of gases and aerosols across the air-sea interface is therefore central to understanding many aspects of tropospheric gas and aerosol chemistry.

# Observations of Coupling Between Surface Wind Stress and Sea Surface Temperature in the Eastern Tropical Pacific

Steve Esbensen & Dudley Chelton

*College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon*

Satellite measurements of surface wind stress from the QuikSCAT scatterometer and sea surface temperature (SST) from the TRMM Microwave Imager are analyzed for the three-month period 12 July through 20 October 1999 to investigate ocean-atmosphere coupling in the eastern tropical Pacific. Oceanic tropical instability waves (TIWs) with periods of 20-40 days and wavelengths of 1000-2000 km perturb the SST fronts that bracket both sides of the equatorial cold tongue, which is centered near 1S to the east of 130W. These perturbations are characterized by cusp-shaped features that propagate systematically westward on both sides of the equator. The space-time structures of these SST perturbations are reproduced with remarkable detail in the surface wind stress field. The wind stress divergence is shown to be linearly related to the downwind component of the SST gradient with a response on the south side of the cold tongue that is about twice that on the north side. The wind stress curl is linearly related to the crosswind component of the SST gradient with a response that is approximately half that of the wind stress divergence response to the downwind SST gradient. The perturbed SST and wind stress fields propagate synchronously westward with the TIWs. This close coupling between SST and wind stress supports the Wallace et al. (1989) hypothesis that surface winds vary in response to SST modification of atmospheric boundary layer stability.

# Satellite Observations of Tropical Instability Waves

Dudley Chelton

*College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon*

A well-known feature of ocean variability in the eastern tropical Pacific and Atlantic is the existence of 20–40-day variability with wavelengths of 1000–2000 km and westward phase speeds of about 0.5 m s$^{-1}$. These very energetic signals were first discovered in the mid 1970s from satellite observations of westward propagating perturbations of the sea surface temperature (SST) field a few degrees north of the equator along the north side of the equatorial cold tongue. The wave-like signals are interpreted as surface signatures of unstable waves that draw their energy primarily from the horizontal shear of the equatorial current system. Vertical shear also plays a role. Energy transfers indicative of both barotropic and baroclinic instability have been observed from in situ observations of the velocity field. The 20–40-day variations are thus referred to as "tropical instability waves" (TIWs).

The amplitudes of TIWs vary annually and interannually in association with variations of the shears of the equatorial current system. TIWs exist in both the Pacific and the Atlantic but have not been observed in the Indian Ocean. The waves appear in May or June and persist until February or March in the Pacific but only until October or November in the Atlantic. Pacific TIWs are weak or absent altogether during El Niño years when the horizontal and vertical shears of the velocity field are weak.

Recent observations have revealed kinematic features of TIWs that question some of the traditional notions about TIWs. In particular, satellite observations of sea surface height indicate cross-equatorial coherence of TIW-related variability. The amplitude is much smaller south of the equator, but the southern hemisphere variability is usually phase locked with the northern hemisphere variability. The observed tendency for symmetric cross-equatorial phase structure is inconsistent with the predicted antisymmetric phase structure predicted from nearly all instability analyses. However, a symmetric phase structure is consistent with the phase structure of stable, free equatorially trapped Rossby waves modified by the mean background equatorial current system. The relatively constant amplitude of Pacific TIWs over periods of 6 months or more raises further questions about the relevancy of instability analyses.

Observations of the surface wind field pose additional interesting questions about the energetics and thermodynamics of TIWs. Satellite observations of the surface wind field reveal that the wind stress is high over warm water and low over cold water, consistent with previously hypothesized modifications of the surface wind field through SST-induced changes of boundary layer stability. These TIW-related perturbations of the wind field generate strong wind stress curl anomalies that feed back on the TIWs. The SST-induced changes of the wind field also result in heat flux anomalies that play an important role in the thermodynamics of TIWs. The significance of the wind stress and heat flux forcing of TIWs is not yet understood.

Another puzzling characteristic of TIWs is that they often disappear abruptly in February or March in the Pacific and in October or November in the Atlantic. The turbulent dissipation that evidently plays a role in the demise of TIWs is surprisingly strong; the transition from a well-developed wave field to conditions in which there is no evidence of TIWs occurs over a period of less than a few weeks. To add to the confusion, the TIWs in the Pacific sometimes persist from one year to the next.

There are clearly many different aspects of TIWs in need of additional theoretical understanding.

## Observations of the Marine Atmospheric Surface Layer

James Edson

*Department of Applied Ocean Physics and Engineering Woods Hole Oceanographic Institution*
*Woods Hole, MA 02543*

The data collected from the FLIP mast during the Marine Boundary Layers Experiment allows us to compute all the terms of the KE budget. This data is being used to compare the measured profiles of the dissipation rate with their Monin-Obukhov similarity (MOS) predictions. We have found that our dissipation estimates are adequately predicted by MOS in the surface layer above the WBL. However, the results indicate that there is a significant difference between our dissipation measurements and their MOS predictions within the WBL. The dissipation is lower than predicted by traditional wall-layer scaling over developing seas, and the magnitude of the dissipation deficit is directly related to the energy input to the waves and currents. Interestingly, our results indicate that there is still a balance between production and dissipation near the surface - its just that neither term obeys their MOS predictions. Higher in the WBL, the transport terms becomes significant and are required to balance all terms in the KE budget. The talk will address these findings and their possible impact on marine surface layer turbulence in coastal waters versus the open ocean. It will also briefly discuss how these findings relate to their oceanic counterparts.

# Interactions between Wind, Waves and Turbulence

Stephen E. Belcher

*Department of Meteorology, University of Reading, UK*

The aim of this talk is to review a conceptual picture of turbulent boundary layer flow over a sinusoidal surface wave and to show how the results are now being used to understand air flow over more complex waves and to understand the role of turbulence in water beneath the wave.

Scaling arguments show that turbulent boundary layer flow over a sinusoidal wave divides naturally into two regions. Within an inner region, close to the wave surface, the turbulence is close to local equilibrium with the mean-flow velocity gradient and so eddy-viscosity models can be used. Above the inner region, in the outer region, the turbulence is advected over the wave rapidly and is subjected to a rapid distortion. Observations support this view. Erroneously using an eddy-viscosity model in the outer region produces values for the turbulent stresses that are much too large by a factor $U_0/u_*$ (where $U_0$ is the wind speed and $u_*$ is the friction velocity). These findings have a strong bearing on the computed values of the wave-induced growth. Analytical models accounting for the inner and outer regions show that wave growth is largely controlled by a non-separated sheltering mechanism; the critical layer mechanism is of secondary importance. Large Eddy Simulations need to resolve turbulence in the inner region to correctly compute the wave growth.

The results of these studies have recently been applied to more complex situations, when more than one wave component is present. In such cases the long wavelength waves extract momentum from the wind leaving a smaller turbulent momentum flux to force growth of shorter waves. Using this notion of sheltering, we have explained why a long paddle-generated wave inhibits growth of short wind waves. In addition, we have constructed a new model for the equilibrium range of wind wave spectra that correctly satisfies momentum conservation.

Finally, we have begun to apply these ideas to turbulence in the water flow beneath the waves. In this case the second order Stokes drift of the waves tilts and stretches turbulent vorticity in the horizontal perhaps linking to the generation of Langmuir circulations.

# A Quasi-inhomogeneous Similarity Theory for Flux Profile Relations in the Marine Atmospheric Surface Layer

Gary L. Geernaert

*National Environmental Research Institution, Roskilde, Denmark*

The underlying framework behind the bulk aerodynamic parameterizations for air-sea fluxes is the Monin-Obukhov similarity (MOS) theory. According to MOS theory, one must assume that the domain is both steady state and horizontally homogeneous, for all parameters which act as indicators of governing processes. In this way, the surface layer also becomes a constant flux layer, thus simplifying the derivation of flux coefficients from the profile relations. Measuring and subsequently parameterizing the flux coefficients has however been challenging. In many research studies, efforts have been placed on relating the wind stress to wave state, with results which in turn may be used to improve parameterizations of flux coefficients (e.g., the drag coefficient). In addition, the diabatic relations which are used to adjust the logarithmic profiles and bulk parameterizations exhibit large uncertainty. Fixed offshore towers, ships, buoys, and low flying flying aircraft have been the most popular platforms employed in air-sea interaction process studies. However, in order to build the best parameterizations, much emphasis has been placed on measuring in regions with the greatest variety of windspeeds, wave states, stratifications, etc. Given the ease of deployment and maintenance of platforms and given the wide variability of conditions encountered, coastal zones have become among the favorite regions of study. There is, however, a dilemma in using coastal zones. While coastal zones exhibit a wide variability of environmental conditions, they also exhibit dramatic spatial variability of all state parameters which are used to describe the flux processes. For example, windspeed, surface wave state, and atmospheric stratification are each strong functions of fetch, and they are all interrelated. Furthermore, the assumption of horizontal homogeneity behind MOS theory is increasingly violated as one moves to smaller and smaller fetch. Perhaps as a consequence of the systematic violations of MOS theory, measurements of the drag coefficient as well as flux coefficients for heat, moisture, and trace gases (including deposition velocities) contain uncertainties which are unacceptably high. It is noted herein that there are other sources of uncertainty associated with sampling. In this paper, the flux profile relations outlined in the original MOS theory are extended, in order to consider weakly varying systematic variabilities of state variabilities. In this analysis, the assumption of homogeneity behind MOS theory is merely relaxed, yet only to the degree to which the logarithmic profiles as the starting point are somewhat preserved. Starting with the momentum equation, it is shown that a vertical flux divergence

of momentum flux may be attributed to horizontal gradients of windspeed, roughness, and atmospheric stratification. The analysis suggests that the horizontal gradient of windspeed is likely to be the most important cause of flux divergence in coastal zones, and it is substantially important in the first 25 km of the coastline. The drag coefficient, in turn, is substantially affected, especially for upwind fetches less than 10 km. In addition, the flux profile relations (and the flux coefficients) for temperature and gases are shown to be dependent upon horizontal gradients of windspeed, roughness, stratification, concentrations, chemical reactions, etc. Since the results to be presented are based on model calculations, there is a tremendous need for data to confirm and/or evaluate the relative importance of the various "quasi-inhomogeneous" terms which will be discussed. The presentation concludes with a set of concrete recommendations for various new research directions, including both theoretical and experimental work. Specific recommendations will focus on ways to improve the methods and procedures for interpreting over-water flux profiles and air-sea fluxes, based on observed mean quantities.

# The Role of Spray in the Turbulent Air-Sea Fluxes

Edgar L. Andreas

*U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire*

Sea spray, presumably, should influence the air-sea exchange of heat and moisture when the total surface area of the spray becomes a significant fraction of the area of the underlying sea surface. Evidence of such influence, however, has remained elusive. In this talk, I will review the characteristics of sea spray that are important for understanding spray's role in air-sea exchange. I will then describe a theoretically based microphysical model for the heat and moisture that sea spray can transport across the air-sea interface and will compare this model to eddy-correlation data from HEXOS (the Humidity Exchange over the Sea Program). This analysis shows how to partition the heat fluxes between interfacial and spray contributions and, thereby, reveals for the first time a spray signature in air-sea heat flux data. In essence, these results suggest a new air-sea heat flux parameterization that explicitly acknowledges spray's role in air-sea heat exchange in winds above 15 m/s.

The ultimate objective of this research is to learn how to parameterize the turbulent surface fluxes of heat, moisture, and momentum in high winds, especially in tropical and extra-tropical storms. I will close with some ideas on how to extrapolate the HEXOS results to hurricane-strength winds and will show some preliminary results when parameterizations for spray enthalpy and momentum flux are used in a simple model of a tropical cyclone.

# Regional Coupled Modeling

James Wilczak

*NOAA/Environmental Technology Laboratory, Boulder, CO*

The potential importance of running atmosphere and ocean models as a coupled system, as a function of the spatial and temporal scales that are to be predicted, will be discussed. These scales range from climate, to weather, and down to simulations of the microstructure of the air-sea interface. We then will focus on the "weather scale" range of atmospheric and oceanic forecasts, and discuss the circumstances in which coupling can lead to improved predictions.

Specific examples demonstrating the effects of direct coupling of the atmosphere and ocean within a Regional Coupled Modeling system (RCM) will then be presented. The RCM consists of an atmospheric (Penn State/NCAR regional atmospheric mesoscale model, MM5), oceanic (Princeton Ocean Model, POM) and wave model (WAM or WaveWatch3) that are run as a tightly coupled system, with information being exchanged at each time step of the ocean and wave models. The examples chosen include the effects of waves, sea-spray, and mesoscale variations in upper-ocean heat content. The results presented come from simulations of hurricanes, as the coupling between the atmosphere and ocean can become increasingly important in high wind speed events that have significant mesoscale structure.

Surface wave effects are examined by comparing hurricane intensity predicted with the full RCM, in which the surface roughness length is provided by the wave model, with simulations using a Charnock type parameterization of the surface roughness length. Although the wave model allows for large spatial variations in the stress that can be attributed to spatial variations in an effective Charnock "constant", the overall effect of the wave model on cyclone intensity remains relatively small.

The effect of sea-spray on atmospheric events is a highly controversial issue, due in large part to the difficulty of making spray measurements. To evaluate the effect of spray we implement a spray parameterization within the RCM based on the Fairall/Kepert model. If it is assumed that all spray droplets evaporate before they can fall back to the sea, spray changes the partitioning between sensible and latent heat flux but does not appreciably change the total enthalpy flux. Although the thermodynamic structure of the lower atmosphere will differ, the change in the partitioning between sensible and latent heat fluxes is found to make relatively little difference on cyclone intensity. If instead one allows for some fraction of the spray droplets to fall back to the sea before evaporate, sea-spray can significantly increase the sensible heat flux, and this is found to result in potentially very large increases in hurricane intensity.

Sub-surface oceanic mesoscale temperature structure is also found to potentially have a significant effect on cyclone intensity. This results from its regulation of the change in sea surface temperature as the cyclone extracts heat from the ocean and as oceanic turbulent mixing across the thermocline both act to cool the SST. Simulations demonstrate that the temporal scales of passing cyclones can be sufficiently long so that hurricane intensity can be modified by the presence of warm core rings shed by the Loop Current in the Gulf of Mexico.