Breaking Waves, Langmuir Circulation and Bubbles in the Mixed Layer

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LONG-TERM GOAL

Our goal is to use a combination of measurement and analysis to determine processes responsible for vertical transfer of heat, mass and momentum across the near surface of the ocean. Wave breaking and the role of turbulence and Langmuir circulation in redistributing bubbles are of particular interest.

SCIENTIFIC OBJECTIVES

The key scientific objectives are (i) to test models of turbulence in the upper few metres of the wind driven ocean, especially relating to the effect of wave breaking; (ii) to interpret MBL and related data showing thermal inhibition of Langmuir circulation; (iii) to determine the response of Langmuir circulation to misalignment between wind and waves.

APPROACH

We are using data acquired with a combination of acoustical, dissolved gas and temperature sensors during the Marine Boundary Layer experiment and related cruises. Doppler sonars were used to measure the organization of bubble clouds by Langmuir circulation and to measure the directional wave spectrum; a mechanically profiling thermistor was used to acquire temperature profiles over the upper 1m of the water column. Since the air-sea heat flux was independently measured, we use the high resolution temperature profiles to examine the turbulent diffusion of heat loss away from the surface (with PhD student J Gemmrich). Measurements of the orientation of the bubble clouds associated with Langmuir circulation are being used together with the orientation of the Stokes drift vector derived from the directional wave measurements to study the response of Langmuir circulation when the wind and waves are not in alignment (with PhD student V Polonichko). Models incorporating processes affecting the generation and evolution of bubble clouds are used to interpret measurements of bubble distributions.

WORK COMPLETED

The data acquired from the Marine Boundary Layer experiment have been analysed; the results have either been written up and submitted for publication or are close to that stage. During the completion of this work two PhD students, Johannes Gemmrich and Vadim Polonichko have completed their doctoral theses. Analysis of the large data sets acquired during MBL have led to insights on the structure of near surface thermal variability and resulting implications for the role of wave breaking in near surface turbulence, the effects of near surface stratification in inhibiting the formation of Langmuir circulation and resultant vertical mixing, and interaction between the Stokes drift and wind stress

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vectors when these are not aligned. Models have been developed for the analysis of small scale temperature variability in the upper ocean, including a mixing length model applicable in the wave enhanced turbulent layer in the upper few metres and an advection-diffusion model that illustrates the combined effect of turbulence and advection by Langmuir circulation on scalar properties in the upper ocean mixing layer. A model has also been developed to describe the interaction of Stokes drift and wind stress when the latter are not in alignment. The potential for application of the Radon transform in the analysis of circular acoustic imagery of bubble cloud distributions has been illustrated.

RESULTS

Properties of turbulence in the wind driven surface layer have been investigated. Measurements of the fine scale vertical profile of the temperature structure in the upper 2m were acquired with a profiling thermistor. Together with temperature measurements at fixed depths and acoustic Doppler imaging of bubble clouds, the temperature variability has been explained in terms of the combined effects of (i) near surface turbulent diffusion and (ii) advection associated with Langmuir circulation (see sketch in Figure 1). Since the air-sea heat flux was independently measured by bulk methods and the Langmuir circulation scales were known from acoustic observations, the temperature variability provided a tracer for inferring the properties of the near surface turbulence. Combining the Langmuir circulation and vertical turbulence results, model predictions can be made of the variability of measured temperatures as a function of depth. Maximum variability is predicted at a depth of 1-1.5m, consistent with the observations Figure 2). The results provide clear evidence of wave enhanced near surface values relative to a log-layer scaling, although indicating a smaller roughness scale than expected.
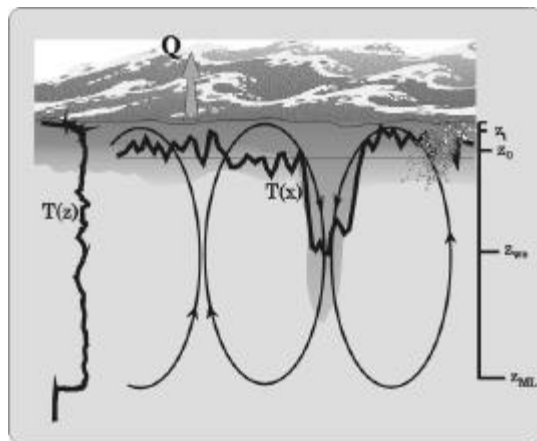

Figure 1: Sketch of fine scale temperature effects in the wind driven surface layer. The upwards heat flux Q results in cooling of the surface waters. Strong vertical mixing reduces the thermal gradient to small, but still measurable values. This effect is further modulated by Langmuir circulation which tends to draw down the cooler surface water into convergence zones. The result is a combined effect of advection and diffusion in which turbulent transfer has a predominant effect in determining the vertical variability and Langmuir circulation introduces horizontal variability.
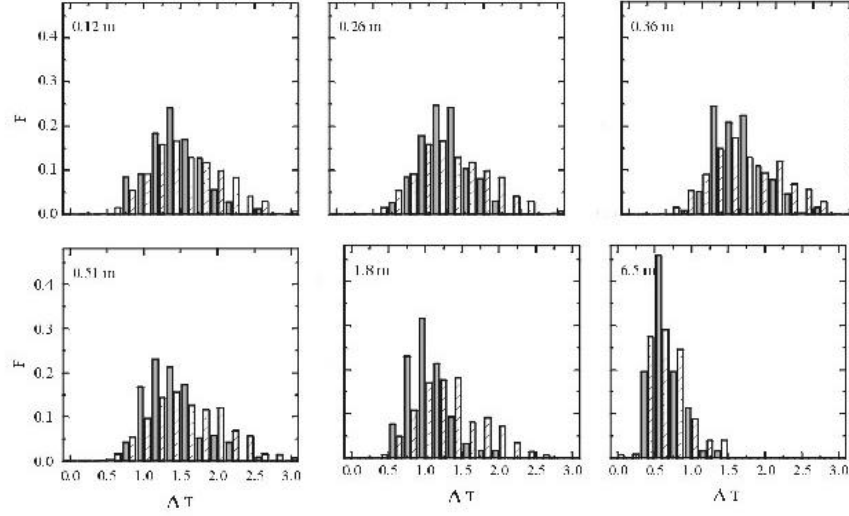
Figure 2: Comparison of observed (solid) and modeled (pattern) temperature fluctuations at different depths. Modeled variability arises from the introduction of Langmuir circulation and allows for wave induced enhancement of turbulent diffusion near the surface. These results allow a test between combinations of Langmuir circulation and different turbulence models. It is only when we use a model for wave enhanced near surface turbulence, as inferred from the temperature profile data, that maximum temperature variability at a depth of 1.0-1.5m is predicted, consistent with the measurements.
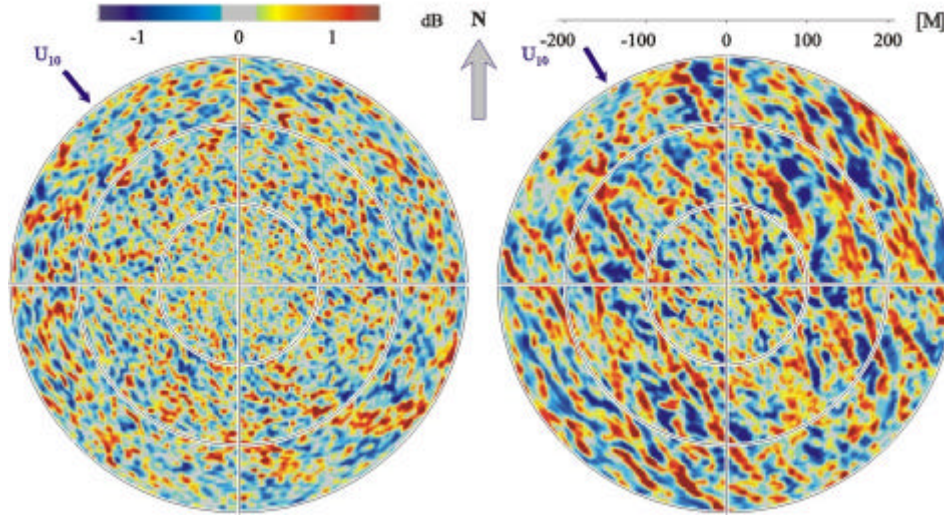

Figure 3: Comparison of two acoustic images of bubble clouds acquired during the Marine Boundary Layer experiment, the left hand image near the beginning of the storm (U_{10} = 10.3 m/s) and the right hand one four hours later (U_{10} = 14.7 m/s), showing the transition between random bubble cloud distributions and the more organised structures that evolve once Langmuir circulation takes over. In the left hand case, near surface stratification inhibited development of Langmuir circulation; in the second example, Langmuir circulation has overcome the stratification.
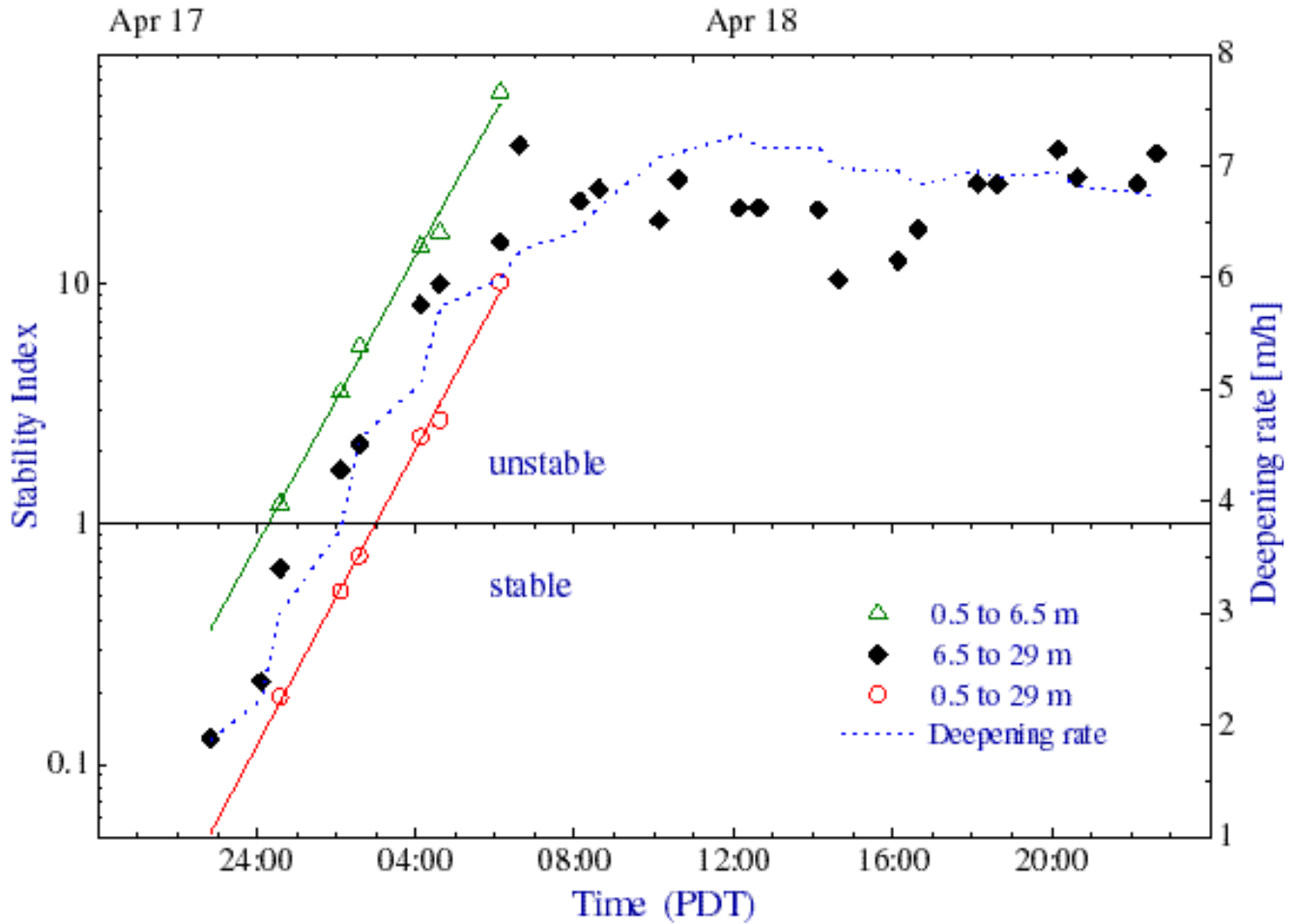
Figure 4: Time evolution, during the storm corresponding to Figure 3, of a Langmuir Froude number F_L defined as: $F_L = R_s(u_*)^2/h\mathbf{Db}$ where R_s is a wave Reynolds number relating the Stokes drift speed, Stokes e-folding scale and turbulent viscosity, h is the depth scale and $\mathbf{Db}$ the magnitude of the buoyant layer, and u_* is the water friction velocity. The turbulent viscosity is determined from the measured vertical velocity in convergence zones using a modeled relationship between vertical velocity and Langmuir number. As the Langmuir Froude number exceeds unity, the flow becomes unstable and mixes vertically. The left and right hand images in Figure 3 correspond to ~00h and 04h, thus straddling the transition from stable to unstable flow.

The role of near surface mixing has been further investigated with a data set in which wind driven vertical exchange is initially suppressed during a storm by the presence of a buoyant surface layer. In coastal environments it is not uncommon to find near surface stratification which is part of the larger scale advection commonly observed in thermal imagery. This was a noticeable feature of the MBL site. During one storm it was observed that the thermal stratification was present before the wind picked up and was sufficient to inhibit development of Langmuir circulation. This is apparent in the acoustic images acquired with the SEASCAN imaging sonar and shown in Figure 3. Initially the bubble cloud patterns were essentially random; later they became organised and aligned with the wind. Using the thermally derived measurements of turbulence described above, the transition between stratification (Fig 3 left) and Langmuir organization (Fig 3 right) has been explained through the balance between buoyancy and the torque generating Langmuir circulation. This calculation is expressed in terms of a

Langmuir Froude number that incorporates turbulent viscosity derived from Li & Garrett's numerical calculations based on the Craik-Leibovich model. Figure 4 shows the Langmuir Froude number during the transition from stable to unstable conditions.

Acoustical images of the organisation of bubble clouds by Langmuir circulation have provided a data set with which to examine the orientation of the circulation relative to the Stokes drift and wind vectors when these are not in alignment. The Stokes drift vector was deduced from acoustic Doppler measurements of the surface wave field. Two-dimensional acoustic images of the bubble clouds were analysed with the Radon transform to deduce the degree of organisation and the preferential alignment (Figure 5). When the wind stress and Stokes drift were out of alignment, the resulting orientation of the Langmuir circulation lay between these vectors. The results are generally consistent with a model that
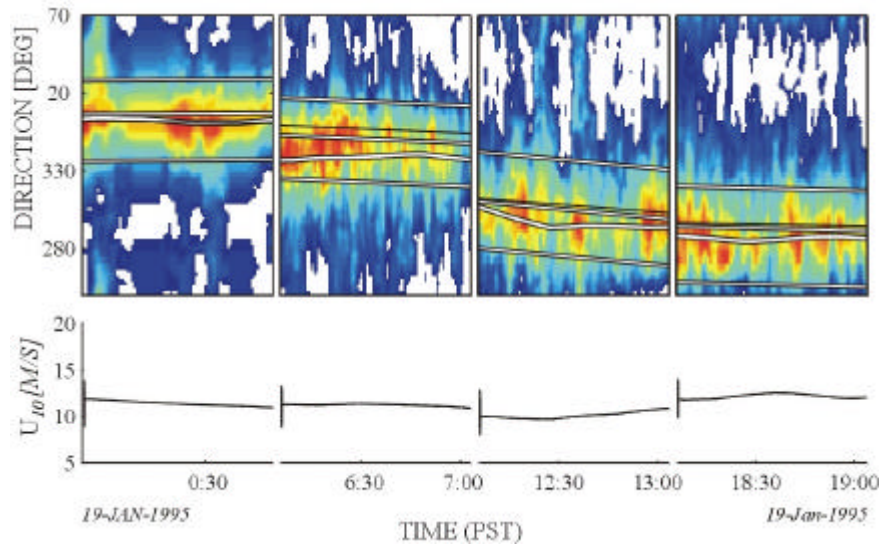

Figure 5: The normalised directional intensity (background color - red is high, blue/white is low) derived from 2-d sonar images of the horizontal bubble cloud distribution similar to those in Figure 3 together with corresponding wind speed. Thick hollow line shows wind direction, green lines mark the direction of maximal growth (center line) and half level values, black line marks Stokes drift direction derived from the directional wave spectrum. Significant misalignment occurs between 0600 and 0630h when the wind changed direction.

allows for wind and wave misalignment within the Craik-Leibovich formulation and show that the predominant variable affecting cell orientation is the ratio of the Stokes drift to the mean Eulerian shear.

IMPACT/APPLICATION

The near surface structure and its response to changing wind and wave conditions helps to determine the vertical transport of key oceanographic variables such as heat, mass and momentum. A particular example is the turbulent and advective transport of bubbles, from their creation in breaking waves to their escape to the surface or their loss through dissolution. As well as contributing to the air-sea transport of gas, bubbles have a profound effect on the acoustical environment of the surface layer. The measurements and analysis summarized here contribute to our understanding of this near surface

environment and thus to our ability to model and predict characteristics of the upper ocean boundary layer. For example, models of near surface bubble distributions depend on prescribed conditions of turbulent diffusivity and advection. We have found that an advection-diffusion model can provide a consistent interpretation of observed near surface temperature structure; this can serve as a background environment upon which to model bubble distributions. Some of the results are at variance with expectations, for example the smaller surface roughness scale inferred from our temperature profiles. Such discrepancies motivate further analysis and the design of more complete measurement approaches.

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