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The final extension to this award was terminated 9 months in (september 2000) due to the departure of the Principal investigator, Dr David Rogers. A subsequent modification was awarded to allow Dr Ian Brooks to wind-down the project in an orderly fashion and complete some work in progress.

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13. ABSTRACT (*Maximum 200 words*)

This study analyzed observational data from field programs in the Persian Gulf and off the coast of California; characterizing the spatial variability of marine atmospheric BL structure in the coastal environment, and the processes that control that structure. Significant results concern the scaling of turbulence under stable conditions – a commonly quoted form for the temperature scale is shown to be formally invalid. The spatial variability of radar propagation conditions over near-coastal waters has been shown to be significant, and the errors in propagation assessment resulting from a failure to account for this variability shown to be unacceptably large. The boundary-layer flow along the coasts of Oregon and northern California during summer are shown to be close to critical over very wide areas, and supercritical over significant regions around every major headland along the coast. The spatial variability of wind stress its curl is found to be large along the coast; the latter is closely tied to sea surface temperature distributions through its modulation of cold upwelling. Stable conditions were widespread and persistent over the cold coastal waters; significant discrepancies between measured and parameterized fluxes were observed within the stable regions.

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Final Report
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Marine Boundary-Layer Processes in the Littoral Zone

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1. Preamble

This grant commenced March 1, 1997 with David P. Rogers as Principle Investigator, and has undergone 3 extensions and 1 modification. During the final extension Ian M. Brooks was named as a Co-PI; the final modification funded Ian Brooks to wind-down these activities following the departure of David Rogers from SIO in September 2000.

2. Project Activity

The original focus of this program was the analysis of data collected during two aircraft-based field programs: SHAREM-115 and Coastal Waves 96, with a view to characterizing atmospheric boundary layer process in the littoral zone and their effect upon spatial variability. The ultimate goal of this research was to improve the predictability of boundary layer conditions in the coastal environment.

SHAREM-115 took place during April 1996 in the Persian Gulf. Five research flights were conducted by the UK Meteorological Research Flight C-130 Hercules alongside a US naval exercise. Our analysis of these data focused on fundamental properties of the turbulence structure of the boundary layer, the spatial variability of the radar propagation environment, and the vertical distribution of aerosol.

Coastal Waves 96 (CW96) took place off the coast of Northern California and Oregon during June and early July 1996. A total of eleven research flights were conducted by the National Center for Atmospheric Research C-130. The flights made extensive measurements centred on the regions of high spatial variability found around prominent coastal headlands. Analysis focused on the interaction of the mesoscale flow with coastal topography and the response of the boundary layer to this forcing.

In January 2000 this program was extended with a change of focus. New activities were to be centered on the two 10-m diameter buoys that formed the SIO Marine Observatory. Funding was provided to equip the buoys with turbulence instrumentation to measure air-sea fluxes and evaluate the performance of surface-flux parameterizations. Following David Rogers' decision in the summer of 2000 to leave SIO, ONR cancelled the grant with effect from September 2000 before measurements of turbulence properties had commenced. A modification to the program was granted to Ian Brooks to allow operations of the buoy activities to be wound-down in an orderly fashion, the meteorological data collected over the previous three years to be organized and archived so that it could continue to be available to the academic community, and turbulence logging software to be completed so that the instrumentation could be utilized on other projects. Copies of the archived data have been provided to users at within SIO and at SPAWAR San Diego and their subcontractors. The entire data set has been transferred to the archive maintained by the Integrative Oceanography Division at SIO (formerly the Center for Coastal Studies). The turbulence instrumentation and logging software have since been used with great success on the arctic ice sheet by one of our long-term collaborators Prof. Michael Tjernström of Stockholm University, Sweden.

3. Scientific Results

a) SHAREM-115

The boundary layer over the Persian Gulf was found to exhibit unusual surface flux conditions – hot, dry air is advected from the surrounding desert land mass over the cooler waters of the Gulf. Heat loss to the surface stabilizes the lower boundary layer leading to the formation of a stable internal boundary layer just 100-300 m deep. While the surface heat flux in the region of aircraft observations (~500 km downwind of the coast) was -15 W m^{-2} the surface moisture flux was observed to be +300 W m^{-2} at the upwind end of the observation area, falling to 250 W m^{-2} at the downwind end. This exceptionally large latent heat flux overcame the downward heat flux to drive weak convection in the lowest 30% of the boundary layer. Local similarity theory was applied to turbulence measurements; results were in reasonable agreement with previous studies. An important result regarding the definition of the local scaling variables was highlighted as a result of the extreme latent heat flux. Many standard texts (including Stull's 'Introduction to Boundary-layer Meteorology' and Garratt's 'The Atmospheric Boundary Layer') and articles in the literature define the scaling quantities as:

$$u_L(z) = [\overline{w'u'}^2 + \overline{w'v'}^2]^{1/4}$$

$$\theta_L(z) = -\overline{w'\theta'}/u_L$$

$$L_L(z) = -u_L^3 / \left[\kappa\beta\overline{w'\theta'}\right]$$

$$= u_L^2 / \left[\kappa\beta\theta_L(z)\right]$$

where both the temperature scale and the length scale are defined in terms of either the sensible heat flux or, where humidity is significant, in terms of the the virtual potential temperature flux. This allows the substitution of the temperature scale into the definition of the length scale as above. Our results demonstrate that this is formally invalid, the length scale must be defined in terms of the virtual potential temperature flux, so as to include the contribution of humidity to buoyancy, but the temperature scale must be defined in terms of the sensible heat flux so as not to be contaminated by the humidity flux contribution to the virtual potential temperature flux.

An analysis of the radar propagation environment demonstrated that there is considerable spatial variability in both the trapping layer associated with the boundary-layer inversion, and the surface evaporation duct. Observations of spatially varying modified refractive index were used with a range dependent propagation model (TEMPER-3b) to assess the error resulting from neglecting the spatial variability – this error was found to be as large as 50-60dB over extensive regions; this is approximately 10 times the acceptable error for operational purposes.

b) Coastal Waves 96

A major finding of the CW96 analysis was the extent to which the marine layer was supercritical. summer marine boundary layer along Southern Oregon and to past Point Conception California and beyond 124 W is supercritical or near supercritical a majority of the time. For every major cape and many minor capes, there is a supercritical expansion fan on the southern side where the marine layer flow accelerates and thins. On the upwind side of every major cape is a compression bulge where the marine layer thickens and slows. Much of the modification of BL structure in the flow around a headland can be explained in terms of a simple shallow water model; the success of this approach depends on the existence of a strong inversion, as the inversion weakens so the effectiveness of the shallow water model decreases. In many cases the inversion depth was observed to be a significant fraction of that of the boundary layer, a complete treatment of the boundary layer flow requires that this inversion structure be taken into account, requiring the use of much more complex models.

The coastal atmosphere was frequently stably stratified. Over 50% of the CW96 aircraft observations indicate stable conditions. Variations in stability are most strongly linked to variations in the sea surface temperature with the strongest stability coincident with the coldest sea surface temperatures. Internal boundary layers occurred frequently.

Parameterized surface fluxes of wind stress, heat and moisture were found to differ significantly from the measured fluxes in stable regions. It is likely that this is due in large part to the invalidity of the assumption of homogeneity that underlies the parameterization within this spatially variable environment. Of particular note is the serious over-estimation of the magnitude of the latent heat flux under conditions for which it is directed downward to the surface (ie water vapor is condensing out at the sea surface). This result supports other recent observations by James Edson at WHOI, and suggests a particular problem exists in the surface flux parameterization for these conditions.

The sea surface temperature (SST) pattern is determined by the wind stress and wind stress curl. The wind stress drives the mixing, but the curl becomes a significant factor in the spatial variability away from the direct influence of the coastal barrier. Near shore there is nearly uniform cold water associated with upwelling adjacent to a fixed barrier. Here, variations in the stress do not appear to be important; providing there is a constant wind stress, upwelling occurs. Further offshore the SST field shows regions of warm water and regions of cold water in patches about 20 km in diameter. There is little correspondence between the SST pattern and the wind stress; however, the wind stress curl shows a remarkably similar pattern: regions of positive curl correspond with cold water and regions of negative curl correspond with warm water. Positive curl implies divergence in the ocean mixed layer and a shallowing of the pycnocline. Negative curl implies convergence in the ocean mixed layer and a deepening of the pycnocline. If the mixed layer is shallow, the wind stress will drive entrainment of colder water into the mixed layer at a faster rate than in a deeper mixed layer. The wind stress curl can account for this pattern.

The radar propagation environment shows considerable spatial variability due in large part to the significant changes in boundary-layer depth associated with the interaction of the mean flow with coastal topography. The surface evaporation duct has also been shown to exhibit significant spatial variability associated with the high SST gradients around coastal headlands.

4. Publications

a) Journal Articles

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b) Conference Abstracts

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Brooks, I. M. and D. P. Rogers. "Observations of the turbulence structure of a well-developed internal boundary layer over the Persian Gulf". *Proceedings of 13th Symposium on Boundary Layers and Turbulence*, 367-370, Dallas, January 10-15, 1999.

Brooks, I. M., D. P. Rogers, and L. Regier. 2000: The Scripps Institution of Oceanography Marine Observatory: a platform for real-time measurements of the coastal ocean and atmosphere. *4th Symposium on Integrated Observing Systems*, Long Beach, January 9-14, 134-137.

Dorman, C.E., B. Grisogono, D.P. Rogers, "Long Gravity Waves in California's Summer Marine Boundary Layer". American Meteorological Society, 12 Symposium on Boundary Layers and Turbulence. July 28-August 1, 1997, Vancouver, BC, Canada, 342-343, 1997.

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