Parameterization of Nonlocal Mixing in the Marine Boundary Layer: A Study Combining Measurements and Large-Eddy Simulation

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LONG-TERM GOAL

The long-range goal of this research is to improve understanding of small-scale mixing processes in the atmospheric boundary layer and to incorporate the effects of these processes in mesoscale models.

OBJECTIVES

The objectives of this project are to use a combination of observations, large-eddy simulation model results, and mesoscale model simulations to examine the formation and behavior of the marine boundary layer under low-wind conditions. Our focus is on understanding how stable boundary layers form when winds travel from warm water or land surfaces over colder water. Our main objective is to improve parameterizations of mixing processes for mesoscale models by investigating new approaches for modeling turbulent fluxes in stratified boundary layers.

APPROACH

The central hypothesis of this effort is that improvements in existing parameterizations of turbulent processes require a physical basis and that this basis may be gained through analysis of LES results and boundary layer observations. These model experiments will focus on four main topics driven in part by the CBLAST field experiments and by needed improvements in boundary layer parameterizations:

- Comparison of modeled turbulence with aircraft observations
- Comparison of the LES structure with standard parameterizations
- Analysis of decoupled boundary layer formation
- Testing of parameterization improvements in a mesoscale model for specific case studies

Models used in the study include the NRL Coupled Ocean Atmosphere Model Prediction System (COAMPS) and LES model described in Skyllingstad (2003).

WORK COMPLETED

Experiments focusing on the role of small-scale sea surface temperture (SST) variations were conducted with the goal of quantifying the effects of variable surface heat flux on the marine boundary layer (MBL). Results from these experiments were presented at the AMS Hurricane conference and a

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manuscript has been accepted for publication in Boundary Layer Meteorology (Skyllingstad et al. 2007).

RESULTS

Experiments were conducted using a large-eddy simulation model suggesting that relatively small variations in SST can have a significant impact on the vertical structure of the marine boundary layer over the investigated distances of 10-20 km. Two cases were examined, one for atmospheric flow over an SST transition from relatively warm to cold (WC) water, and the second for flow from cold to warm (CW) water. Results indicate that mixing is increased in the warm to cold case because of the initial deepening of the boundary layer over the warm water. In the cold to warm case, initial cooling generates a shallow internal boundary layer that initially limits mixing over the warm portion of the domain. The net effect is a deeper boundary layer in the warm to cold case, which causes stronger near surface winds and greater entrainment of the stable layer at the boundary layer top as shown by cross section plots in Figure 1 and 2.

Surface flux parameterizations, for example as based on Monin-Obukhov similarity theory, assume that forcing conditions are relatively homogeneous and evolve only slowly in time. Our experiments show that this assumption is not valid when SST varies rapidly over distances of a few kilometers. To help understand how surface flux variations affect the MBL, we examine the aggregate values for mean temperature and momentum as shown in Figure 3. These profiles compare the average boundary layer properties over the region of varying SST (zones 2 and 3), as well as the zone 1 profile predicted upstream from the SST fronts and a profile downstream from the frontal region from zone 4. If we assume that small-scale SST variations are averaged in operational mesoscale models, then the high and low SST used here would tend to offset, resulting in a uniform SST field and a neutral MBL structure similar to the average profile over zone 1.

Comparing the zone 4 profiles between case WC and CW in Figure 3 indicates that case WC forcing creates the most significant variation in the mean profiles after passing over the frontal zone. As noted above, the potential temperature for zone 2 in case WC is noticeably warmer than the zone 3 average from case CW. Consequently, the mixed layer in case WC is deeper resulting in a greater reduction in wind shear and stronger winds below 80 m over the frontal region. Downstream, the winds decrease near the surface because of the stable boundary layer that persists after leaving the cold water region. Turbulent fluxes of heat and momentum (not shown) are consistent with the deeper mixed layer, showing more vertical transport and stronger entrainment at the MBL top over the frontal region in case WC. The effects of the cold water in case WC generate a significant negative heat flux between 25-35 m in the zone 4 profile. In comparison, the zone 4 heat flux for case CW is similar to the zone 1 profile with relatively weak values.

As shown by this relatively simple set of experiments, developing a parameterization that accounts for small-scale SST variability poses a big challenge. Our results suggest that subgrid-scale variations in SST can generate significant variations in the boundary layer structure that are strongly correlated to the degree of surface warming versus cooling and the order in which surface fluxes vary in the downwind direction. When warming is upstream from cooling, the SST variation has a bigger impact because of boundary layer deepening from convective overturns. Cooling upstream from warming generates an internal cold boundary layer that constrains the effects of downstream warming.

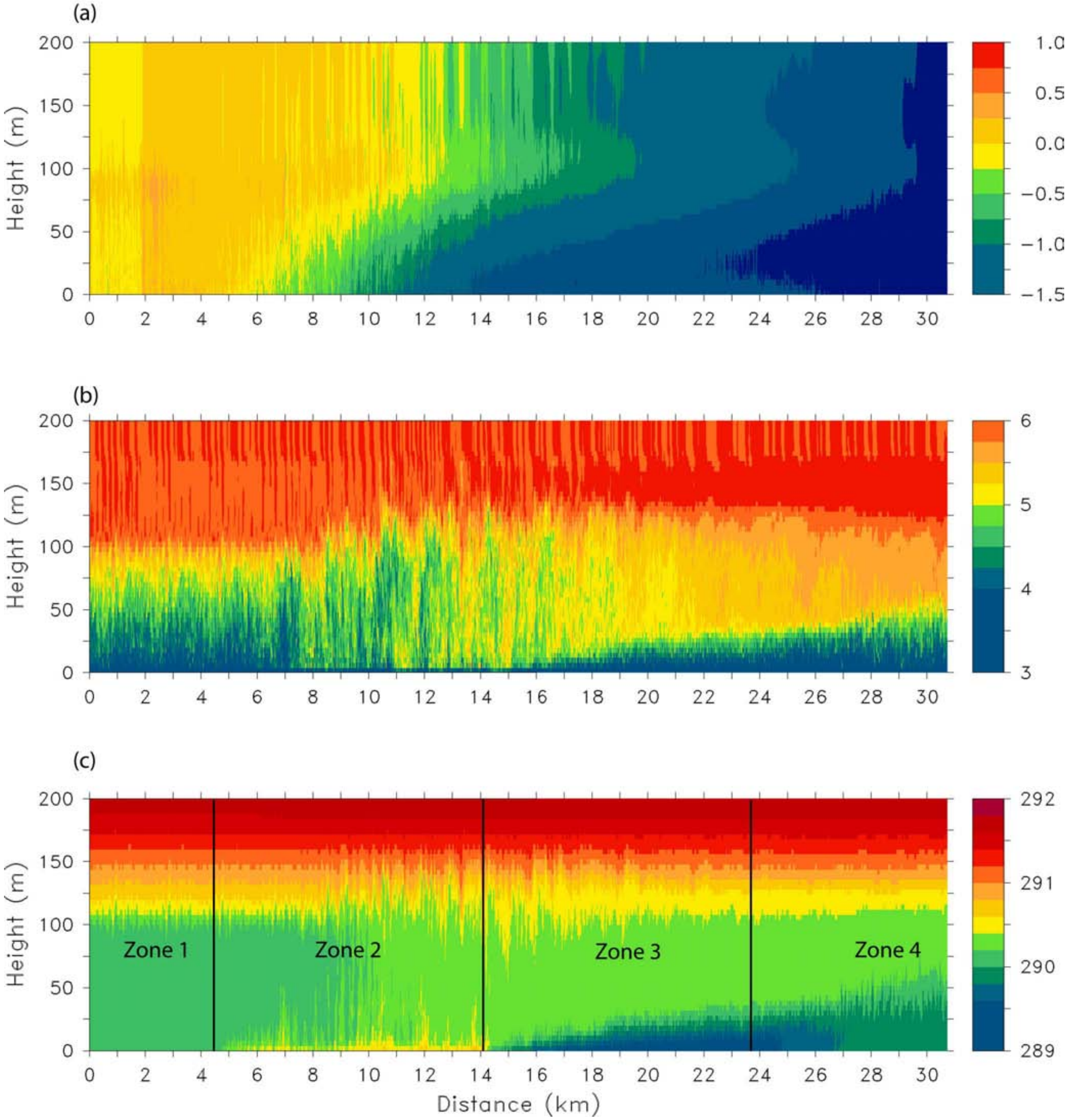

Figure 1. Cross section plots in the vertical and horizontal direction at y = 126 m for the warm to cold case showing (a) perturbation pressure (Pa), (b) horizontal velocity (m s^{-1}), and (c) potential temperature (K) after 80 min. Sea surface temperature in this case is 290 K in Zone 1, 292 K in Zone 2, 288 K in Zone 3, and 290 K in Zone 4.

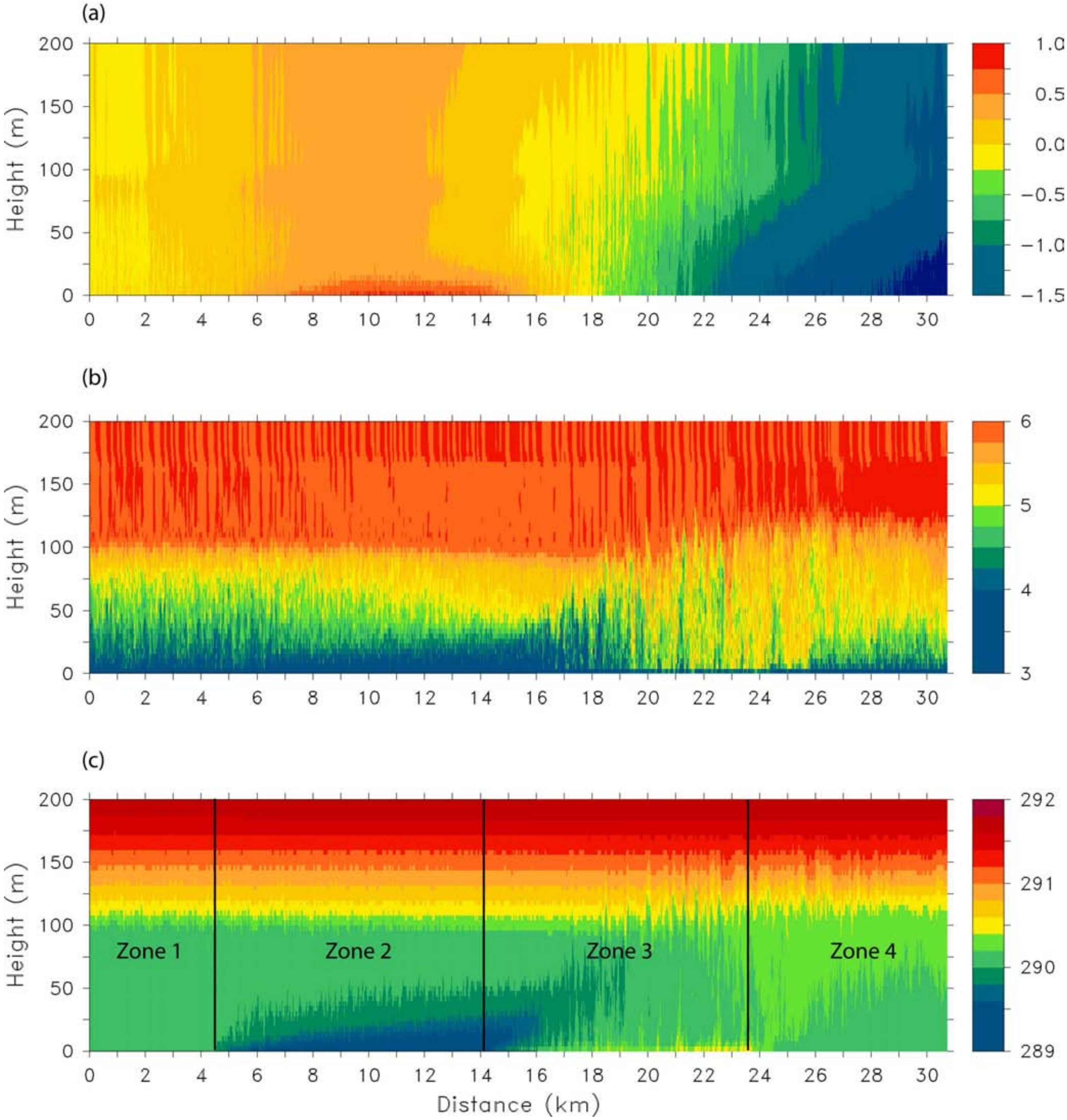

Figure 2. Same as Figure 1, except for cold to warm case. Sea surface temperature in this case is 288 K under Zone 2 and 292 K under Zone 3.

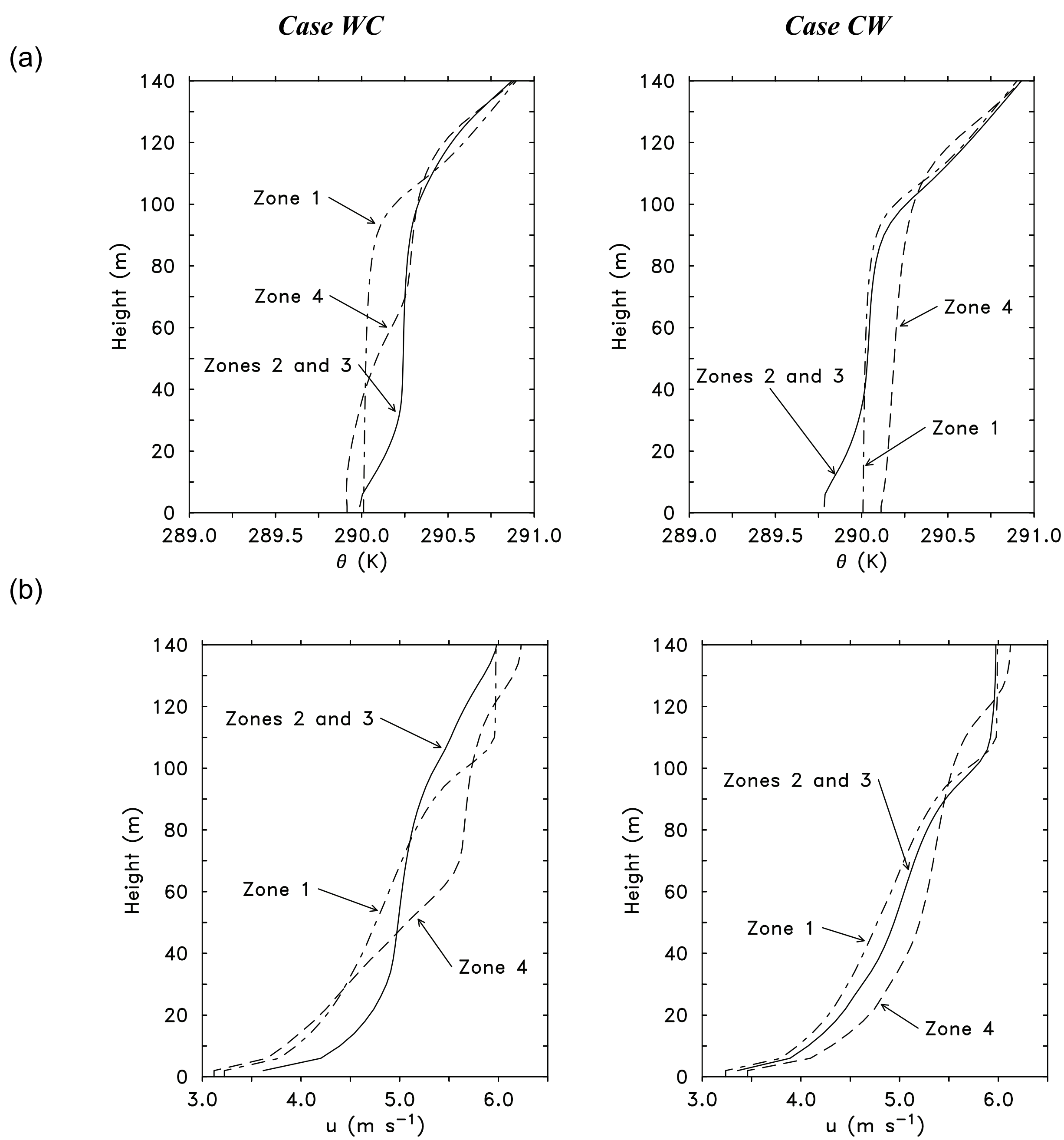

Figure 3. Vertical profiles of horizontally averaged (a) potential temperature and (b) horizontal velocity taken from case WC (left) and CW (right) at 80 minutes from zones representing the frontal transition (Zones 2 and 3), upstream conditions (Zone 1), and downstream conditions (Zone 4).

Increasing model resolution will reduce this parameterization problem. At what point do SST variations become small enough to use an average value? As a final test, we conducted an experiment with a warm to cold transition reduced in scale so that zone 2 and 3 encompassed just 2.4 km. Average profiles taken from this case over the warm and cold water and just downstream from the frontal region (not shown) suggest that small amplitude SST variations have a minimal effect on the mean properties of the MBL. Nevertheless, the heat flux variations produced by the front (not shown) are still different from the constant SST example.

Surface fluxes are also affected by the history of the flow as it passes over the warm and cold water. For example, upward fluxes are larger over the warm water in the cold to warm case because the upstream cooling generates a greater T – SST gradient over the warm water. Similar effects are noted in the wind stress, but with smaller differences between the two SST scenarios.

Analysis of the momentum budget for both scenarios shows that the most significant term affecting horizontal momentum over the frontal zone is the turbulent vertical flux divergence. Although the thermally-forced pressure forcing is significant, it only averages about 20% of the flux divergence term, indicating that for fronts on 10-20 km scales with light winds (6 m s^{-1}) most of the momentum response is produced by turbulent mixing and changes in the boundary layer depth rather than hydrostatic pressure. Our results agree with scaling arguments presented in Samelson et al. (2006) indicating that boundary layer depth controls the downstream strength of near-surface winds in warm to cold transitions, whereas advection and vertical transport are more dominant in cold to warm scenarios.

IMPACT/APPLICATIONS

Boundary layer changes produced by SST fronts are uniquely defined by the order of the surface forcing (cold to warm versus warm to cold) and would be even more complicated by random SST variations. We therefore hypothesize that accurate parameterization is not feasible for SST variability on larger scales. For smaller scales, a single test using the model over a 2.4 km frontal region suggests that small amplitude variations may have negligible impact on the overall boundary layer structure. Nevertheless, they do affect the net surface flux, which may be significant in regions with large SST variance. Many of the effects of small-scale SST variability may be already built into flux parameterizations, which are based on large empirical data sets and use average correlations of flux and ΔT data (e.g. Vickers and Mahrt 2006).

TRANSITIONS

The results from this work may have important consequences for mesocale modeling in the coastal zone where SST can vary on small scales. Results from this work will be communicated to Navy researchers (S. Wang, J. Pullen) who are actively involved in mesoscale modeling activities.

RELATED PROJECTS

This work complements efforts to model the coupled ocean atmosphere system (ONR project, Skyllingstad and Samelson). Both of these projects utilize coastal atmospheric models that will benefit from improved understanding of the marine boundary layer.

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PUBLICATIONS

Skyllingstad, E.D., L. Mahrt, D.Vickers, and R. M. Samelson, 2007. Effects of mesoscale sea-surface temperature fronts on the marine boundary layer, Boundary-Layer Meteorol., In press.