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

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Award #: N00014-01-1-0138

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 objective of this project is 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 main focus is on understanding how sea-surface temperature (SST) variablity affects surface fluxes and the marine boundary layer structure under low wind conditions. Our ultimate goal 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 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 et al. (2005).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE **Parameterization of Nonlocal Mixing in the Marine Boundary Layer:A Study Combining Measurements and Large-Eddy Simulation**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Oregon State University,College of Oceanic and Atmospheric Sciences,104 Ocean Admin. Bldg,Corvallis,OR,97331**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

Aircraft observations of the marine boundary layer taken during the CBLAST field experiment were examined by conducting a series of LES experiments focusing on SST variability over scales of 2-20 km. Two main cases were examined, contrasing the behavior of flow from warm to cold SST and cold to warm SST. Results indicate that the order of surface temperature forcing has a strong influence on the average surface flux and boundary layer structure downwind from the frontal region. Results from this work have been submitted to Boundary-Layer Meteorology.

RESULTS

Using a large-eddy simulation model and observations, we show that relatively small variations in SST can have a significant impact on the vertical structure of the marine boundary layer over distances of 10-20 km. Two cases are examined, one for flow from cold to warm water (C2W), and the second for flow from warm to cold water (W2C) (Figures 1 and 2). 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.

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. Changes in the flow upstream from the frontal region have a large impact on the momentum profile, but are not directly related to boundary layer changes forced by the SST variability. Although the pressure forcing is significant, it only averages about 20% of the flux divergence term, indicating that for fronts on 10-20 km scales most of the momentum response is produced by turbulent mixing and changes in the boundary layer depth rather than hydrostatic pressure.

Boundary layer changes produced by systematic SST variability are uniquely defined by the order of the surface forcing (cold to warm versus warm to cold) as shown in Figure 3. Here, we note that the average temperature and momentum profiles down stream from the frontal zone are considerably different, depending on the order of cold and warm SST. For example, for cold to warm, mixing over the warm water generates a more homogenized profile in comparison with the warm to cold case, where cooling leaves a low-level stable layer downstream from the frontal region.

We conclude that accurate parameterization is not feasible for SST variability on larger scales (5-20 km). At these range of scales, SST features must be resolved by the mesoscale model to accurately simulate the boundary layer structure. A single test using the model over a 2.4 km frontal region suggests that small-scale variations have very little impact on the overall boundary layer structure, and do not require full resolution. 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 2005).

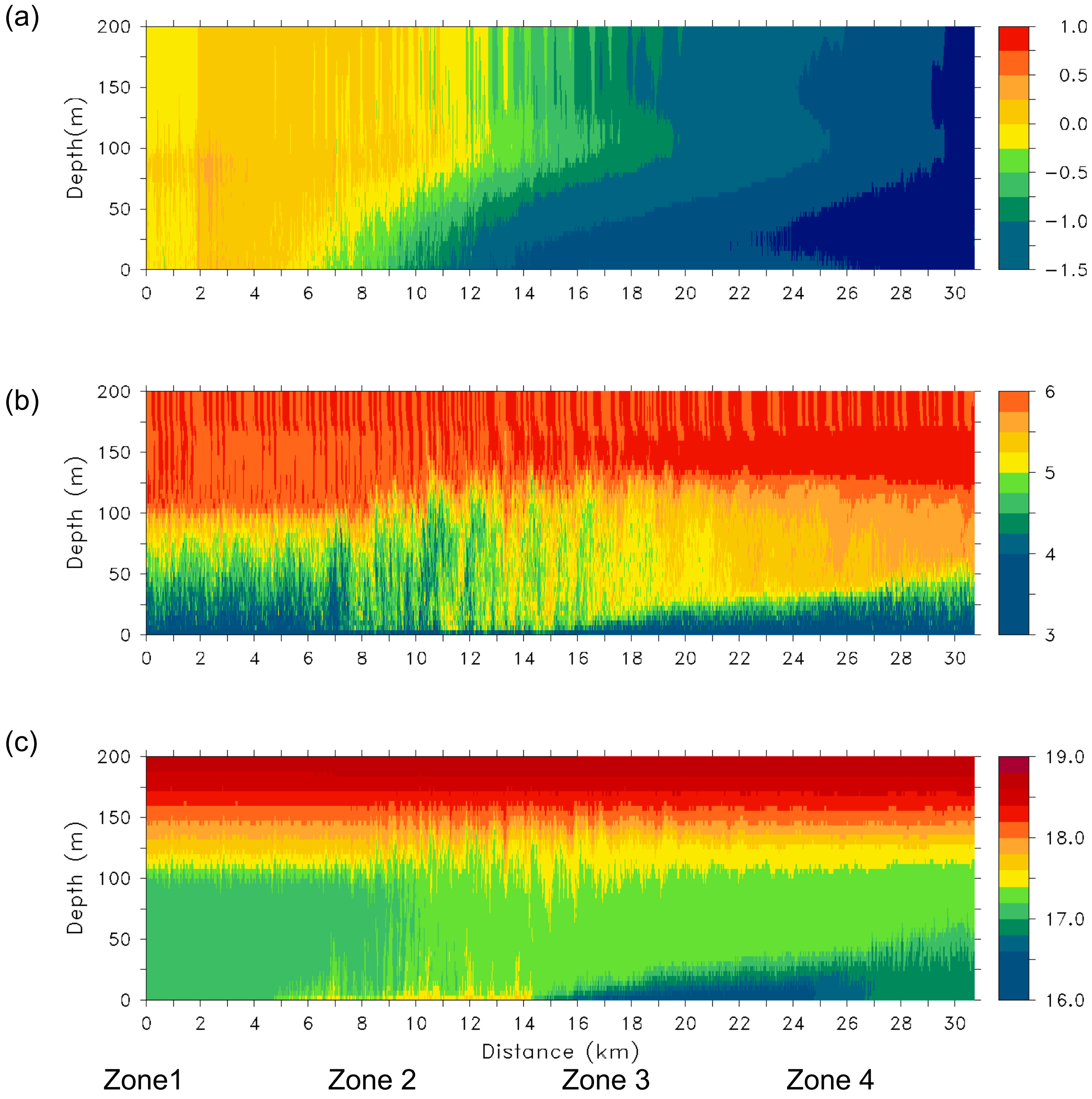

Figure 1. Cross section plots in the vertical and horizontal direction at y = 126 m for Case W2C showing (a) perturbation pressure (Pa), (b) horizontal velocity (m s^{-1}), and (c) potential temperature (^{o}C) after 80 min. Surface temperature in this case is 290 ^{o}C in Zone 1, 292 ^{o}C in Zone 2, 288 ^{o}C in Zone 3, and 290 ^{o}C in Zone 4.

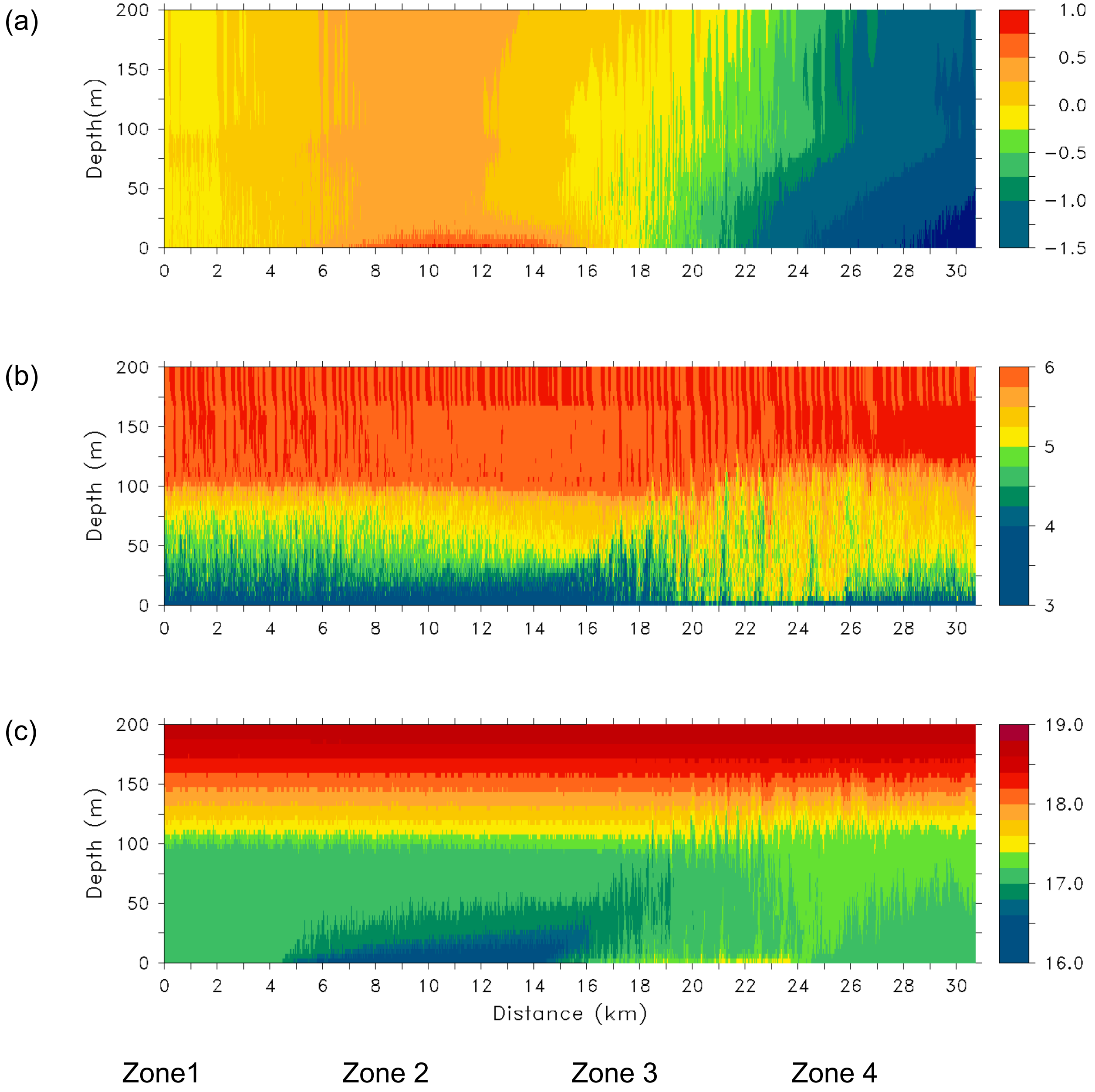

Figure 2. Same as Figure 1, except for Case C2W. Surface temperature in this case is 288 °C Zone 2 and 292 °C in Zone 3.

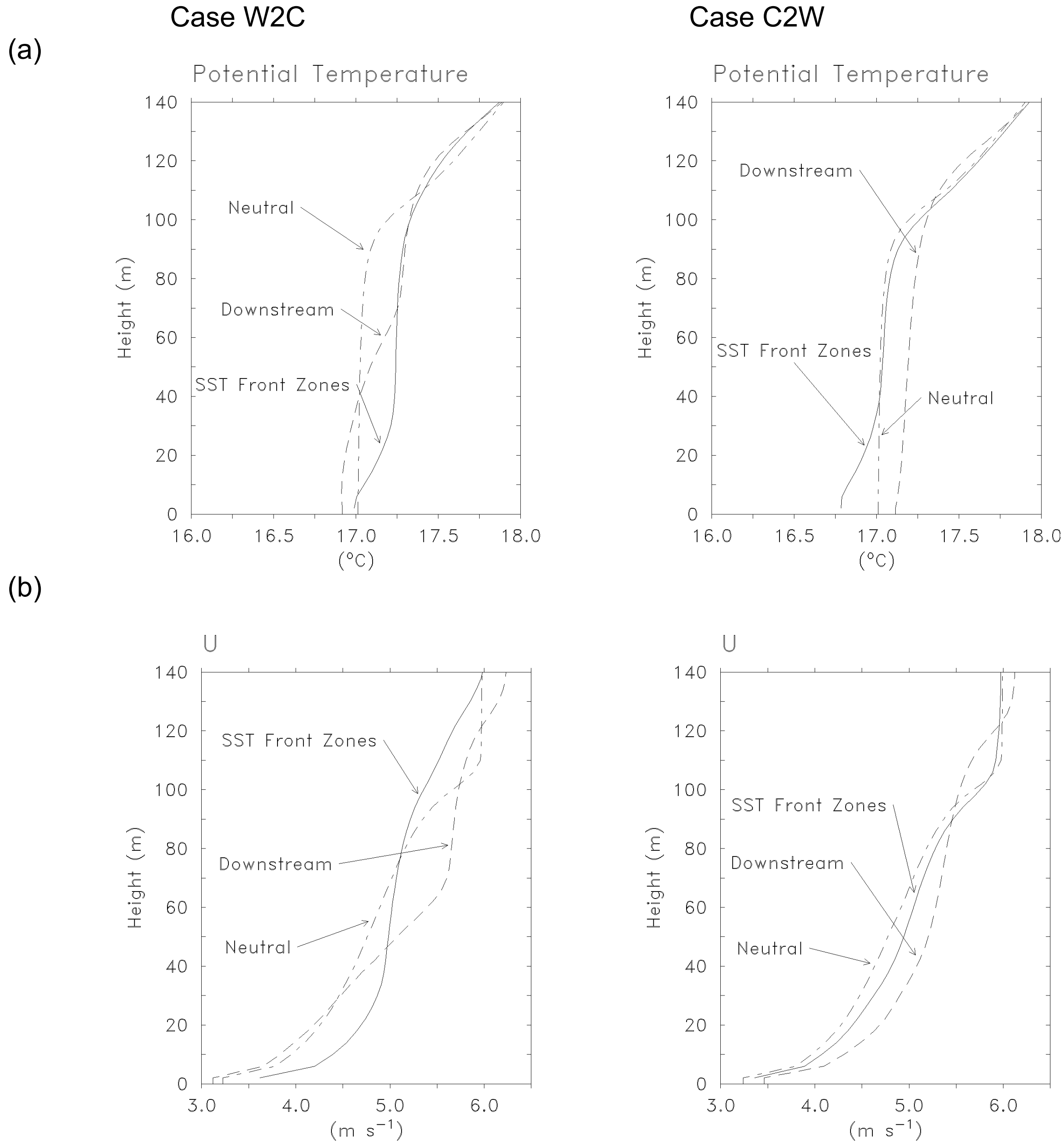

Figure 3. Vertical profiles of horizontally averaged (a) potential temperature and (b) horizontal velocity taken from case W2C and C2W at 80 minutes. Averages are calculated over zones 2 and 3 for the SST Front Zones, over zone 1 for the Neutral profile, and between y = 30.08 and 30.72 km for the Downstream profiles.

IMPACT/APPLICATIONS

An important question facing mesoscale modeling concerns the scales of SST features and how much resolution is required to adequately account for these scales. Our results indicate that for significant SST fronts (2-4 ^{o}C) on scales of 10-20 km, models will need to resolve the horizontal features with good fidelity for moderate to low winds. With coarse resolution, significant changes in the boundary layer structure produced by unresolved SST features could lead to erroneous forecasts, for example, by missing a fog event or abrupt wind increase. Future work will focus on the sensitivity of the marine boundary layer to SST variability for a range of wind speeds and initial boundary layer depth.

TRANSITIONS

Techniques for estimating wind speeds from SST variations will be made available to NRL contacts (S. Wang, J. Pullen, J. Doyle).

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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