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

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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. Studies of the atmospheric boundary layer using large-eddy simulation (LES) have demonstrated the value of these models in describing basic turbulent processes in the atmospheric boundary layer. We are now at a point where LES can be applied to a broader range of problems that include decoupled flow in stable boundary layers and cases with strong baroclinic shear coupled with convection. This proposal describes a study to examine the role of turbulent mixing in defining boundary layer structure during conditions with weak winds and stratification and cases with strong vertical momentum flux. LES experiments will be used in combination with measurements taken during the Coupled Boundary Layers Air Sea (CBLAST) field programs to test existing non-local mixing schemes and examine alternatives when these schemes fail. Boundary layer parameterizations developed in this study will provide the connection between surface flux algorithms developed as part of CBLAST, with operational mesoscale models such as the COAMPS forecast model. Our goal is to increase the accuracy of coastal mesoscale prediction by adding physically-based approximations to one-dimensional mixing parameterizations.

OBJECTIVES

Research will focus on two main areas that are poorly represented in boundary layer parameterizations:

- **Non-local Momentum transport.**
- **Stable Boundary Layers.**

The main objective of this research is to use LES and observations to improve representations of non-local transport in existing ABL parameterizations. The CBLAST program provides a unique opportunity to combine observations and modeling to better understand the dynamics of transport and mixing in the marine boundary layer. LES modeling has a role in this program by providing a tool for examining small-scale mixing processes that must be parameterized in mesoscale model applications. Combining observed boundary layer parameters with LES results will provide the basis for improving

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14. ABSTRACT

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. Studies of the atmospheric boundary layer using large-eddy simulation (LES) have demonstrated the value of these models in describing basic turbulent processes in the atmospheric boundary layer. We are now at a point where LES can be applied to a broader range of problems that include decoupled flow in stable boundary layers and cases with strong baroclinic shear coupled with convection. This proposal describes a study to examine the role of turbulent mixing in defining boundary layer structure during conditions with weak winds and stratification and cases with strong vertical momentum flux. LES experiments will be used in combination with measurements taken during the Coupled Boundary Layers Air Sea (CBLAST) field programs to test existing non-local mixing schemes and examine alternatives when these schemes fail. Boundary layer parameterizations developed in this study will provide the connection between surface flux algorithms developed as part of CBLAST, with operational mesoscale models such as the COAMPS forecast model. Our goal is to increase the accuracy of coastal mesoscale prediction by adding physically-based approximations to one-dimensional mixing parameterizations.

15. SUBJECT TERMS

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existing parameterizations and investigating new approaches for modeling turbulent fluxes in stratified boundary layers. A second priority of this project is the inclusion and testing of non-local mixing parameterizations in a mesoscale model. Observations from the CBLAST field programs (primarily the low wind site) will be used to verify if the modified parameterizations improve model forecasts. To summarize, we plan to address the following science questions:

- **What are the turbulent processes that are active in the stable boundary layer over the ocean?**
- **How does large-scale forcing affect turbulence production in the upper portion of the SBL?**
- **What effect do swell and wind waves have in controlling the ABL momentum flux?**
- **Can we account for stable boundary layer processes, such as bursting, through non-local fluxes in ABL parameterizations?**

APPROACH

The central hypothesis of the proposed effort is that improvements in existing parameterizations of turbulent processes require a physical basis and that this basis may be gained through analyses 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 the modeled turbulence fluxes with observations from aircraft.**
- **Comparison of the LES boundary layer structure with the Frech and Mahrt (1995) boundary layer model.**
- **Analysis of the non-local transports in the LES and formulation of new mixing algorithms for detached boundary layers and baroclinic shear cases.**
- **Testing of parameterizations in a mesoscale model for time periods overlapping specific CBLAST field study periods.**

LES Model

We apply the LES model described in Skyllingstad et al. (1999) and Denbo and Skyllingstad (1996). This model is based on the time dependent three-dimensional Navier Stokes equations with subgrid turbulence closure provided by the filtered structure function (FSF) approach of Ducros et al. (1996). The model horizontal boundaries are periodic, and a radiation condition is imposed at the upper boundary.

Experiments will cover a range of conditions as observed at the low wind CBLAST site. Cases will also be performed for the hurricane and high wind field studies, however, verification of the boundary layer structure in these cases will be more difficult given the observational restrictions. Initial profiles of temperature, winds, and geostrophic pressure gradient will be taken from mesoscale simulations using the COAMPS model to ensure that all forcing fields are adequately prescribed. The focus of the low wind experiments will be on stable boundary layers and situations were wave momentum is being transferred from the wave field to the surface layer. Experiments will be performed using both observed ABL structure (profiles taken from aircraft, nearby radiosonde, or mesoscale model gridded data) and idealized flow conditions.

At the low wind site off of Martha's Vineyard it is anticipated that SBL cases will occur during the field study when relatively warm continental air flows over the colder ocean. For these cases, we will initialize the model as though it is over land and then impose a lower boundary heat flux calculated using the ocean surface temperature and a bulk formulation (this will be modified as the wave boundary layer research efforts devise improved surface flux algorithms). This is equivalent to following a volume of air as it travels from land over a fetch equal to the model run duration divided by the surface wind speed.

If we are reasonably confident in the LES results, then we can use the simulated turbulence datasets to examine features that control the transport of momentum and scalars. For example, non-local terms in parameterizations are designed to account for large eddy transport that covers some portion of the boundary layer depth. Using the LES fields, we can track parcel motions through the flow and directly calculate the functional forms of the non-local transport. A similar exercise can be performed using lidar data, but without knowing the scalar fields or full three-dimensional structure of the turbulent eddies. In cases with decoupled turbulence above the stable surface boundary layer, we can again diagnose the non-local transport produced by episodic mixing events, or bursts, by tracking parcels and calculating the eddy flux variables. Potential parameterization enhancements that will be examined include adding a non-local term for decoupled turbulent layers. For example, one possible approach for parameterizing these cases might use a modified version of the Troen and Mahrt (1985) method. The scheme would first estimate the top of the SBL by searching upward for a Richardson number below a critical value of roughly 1. Following the Troen and Mahrt approach, a bulk Richardson number would be applied to determine the thickness of the decoupled layer, but with a base value taken from the top of the SBL. Profiles for K_f and non-local transport will be set using the standard shape functions, but with scaling provided by the difference between the local wind and the geostrophic wind. Adjustable parameters would be set according to results from the LES cases and observations.

WORK COMPLETED

Efforts in FY2002 focused on the simulation of boundary layer flow from a heated land surface to a colder ocean surface. These conditions are typically encountered along the eastern seaboard and were observed during the 2001 preliminary CBLAST Martha's Vineyard aircraft experiments. Results from the 2001 Martha's Vineyard campaign are still being analyzed. As a proxy, similar flow scenarios observed during the Coastal Duck experiment reported in Vickers et al. (2001) were used to design LES experiments described here. In this report, we address the first objective listed above by examining some of the turbulence processes that are generated in a stable, weak wind boundary layer generated by offshore flow. These experiments will be used as a basis for parameterization testing and development in ongoing performance of this research project.

Duck N.C. observations

Aircraft data taken from the Shoaling Waves Experiment (SHOWEX) show that flow from warm, relatively rough land over cold, smooth water generates a distinctive pattern of low level winds and turbulence. Over the land, the boundary layer has significant shear forced by convective motions that transport momentum from aloft to the the surface. Turbulence is strong because of the combined effects of convective heating and the rough surface. When the boundary layer moves over the water, surface cooling and the reduction in roughness cuase a gradual decay in boundary layer turbulence and a rapid increase in the low level winds. Roughly 5 km offshore, the boundary layer exhibits only limited shear between 15 m and the boundary layer height, suggesting that near surface stratification and decreased roughness has decoupled the surface from the original boundary layer.

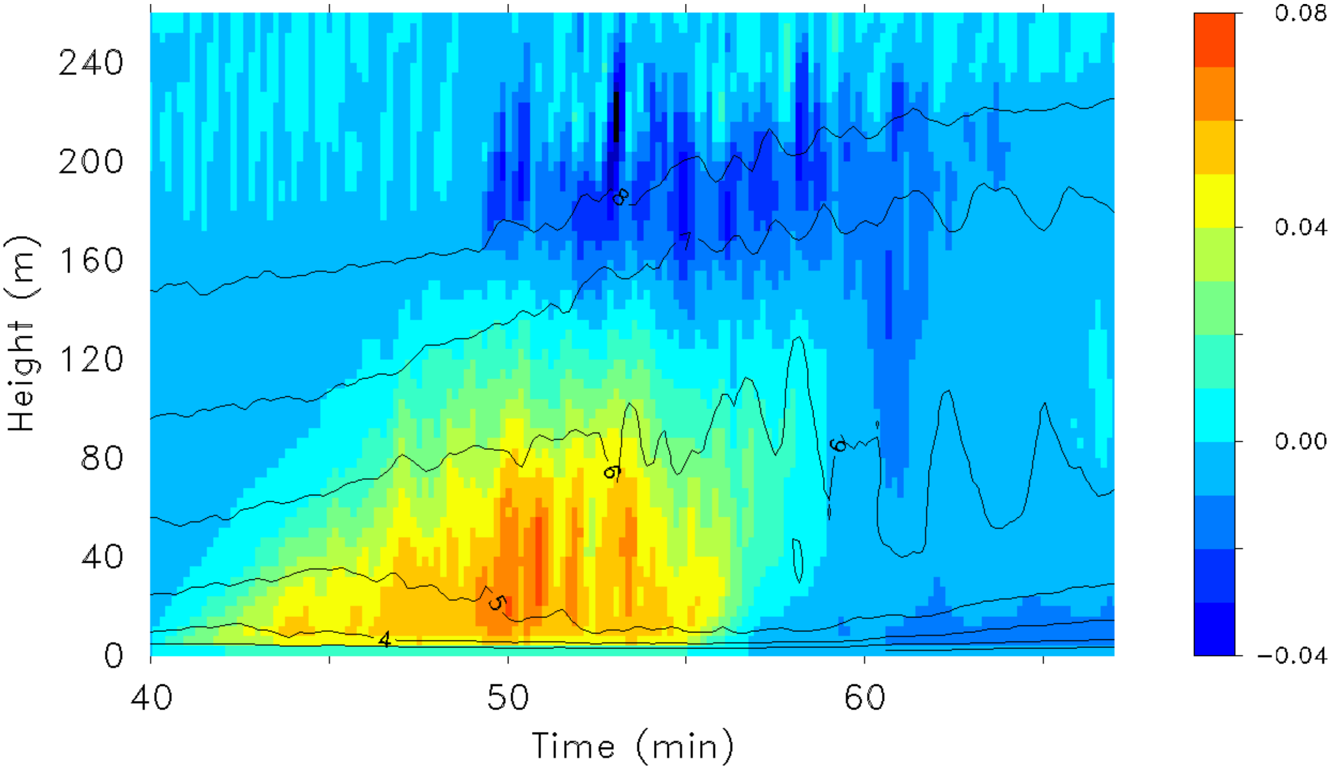

Figure 1. Horizontally averaged turbulent heat flux ($^{o}C\ m\ s^{-1}$) and horizontal velocity plotted as a function of depth and time. Heating starts at ~40 minutes and changes to cooling at ~55 minutes, representing the transition from heated land to cooler water.

LES Simulations

Two different approaches were taken in applying LES to the coastal transition problem. The first approach (refered to as the Lagrangian Domain) treats the LES model domain as a Lagragian volume and simulates the transition from land to water by changing the surface boundary conditions from a heated, rough surface representative of land, to a cooled, smooth surface consistent with the coastal ocean. The second approach (refered to as the Fixed Domain) attempts to simulate a narrow channel extending from the land surface to the ocean so that the change in surface parameters is contained within a fixed model domain. The advantages of the first approach is that it allows for much higher resolution because the domain only has to encompass scales important for resolving the boundary layer eddies. However, larger scale circulations generated by the abrupt change in surface properties at the coast line cannot be simulated with this approach and require a domain that covers a much larger cross coast line distance as is simulated in the second approach.

Initial conditions for both experimental approaches consist of a boundary layer temperature structure having a constant value of 280 at the surface up to 300 m, capped by a temperature inversion with stratification of 2/1000 m. In the preliminary Lagrangian case, both initial and geostrophic winds were set to a value of 9 m s^{-1} , and allowed to adjust over a 2 hour spin up period. In the fixed domain case, the model was set up with a sponge region where temperature and winds were relaxed to assumed profiles representative of a heated land surface (basically a log wind profile through the boundary layer). Preliminary runs for the fixed domain case were performed with an initial geostrophic wind of 12 m s-1

A sample of results from the Lagrangian case are presented in figure 1 showing a time-height cross section of turbulent heat flux and horizontal velocity from the start of surface heating (representing the land surface), through the onset of surface cooling (representing the ocean surface) at 50 minutes. Heating over the land surface causes rapid transport of momentum as well as heat resulting in a reduction in wind shear in the middle of the boundary layer and stronger shear near the surface. When cooling is imposed, downward momentum transport toward the ground decreases causing an acceleration below ~50 m as the boundary layer decouples from the surface. Also noticeable are oscillations in the velocity fields over the cooling region suggesting the formation of internal waves as turbulent eddies generated by convection are dissipated.

A similar boundary layer behavior is produced in the Fixed domain case as presented in figure 2. Here, horizontal velocity is reduced over land near the surface because of high surface roughness and vertical transport of momentum by convective eddies. As the air mass moves over water, lower roughness and decaying convection combine to force an acceleration of the flow in the lower part of the boundary layer. Turbulence parameters from both simulations show good agreement with aircraft observations reported in Vickers et al. (2001).

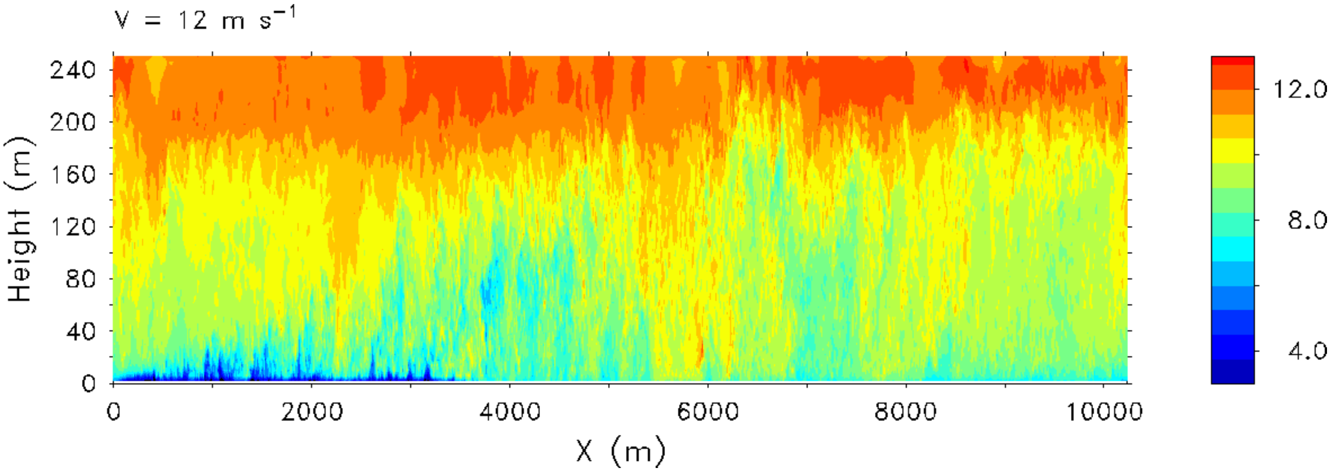

Figure 2. Cross section of horizontal velocity as a function of height above ground and horizontal distance. Changes in surface heat flux and roughness simulating the transition from land to water are imposed at x = ~3500 m. Cooling over the ocean inhibits convective mixing, resulting in an acceleration of the winds between 10-40 m height.

RELATED PROJECTS

This work complements efforts in our core ONR research project comparing COAMPS results with satellite derived wind fields and mesoscale simulation of offshore flow (Samelson and Skyllingstad). The LES results provide a realistic turbulence simulations for testing higher order closure techniques implemented in the mesoscale simulations.

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