P6.4 TAKING A CLOSER LOOK AT THE TURBULENCE IN A HIGHER-ORDER CLOSURE MESOSCALE MODEL

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1. INTRODUCTION

Many mesoscale models today use some kind 2nd-order closure modeling of turbulence. While the closure is derived from theory, the closure constants are usually derived from a combination of laboratory and field measurements. When deriving the theory many simplifying assumptions are made, and for the closure constants horizontally homogeneous and stationary conditions are assumed. The results in the mesoscale model are usually evaluated in terms of the effect on the resolved scale variables. However, the effect of the lack of homogeneity and stationarity in real conditions is usually never evaluated in any detail - everyone is happy a long as it works.

In this study, the modeled turbulence in a highly heterogeneous coastal flow is investigated. As a basis for the study observations off the coast of northern California from the Coastal Waves '96 field program (Rogers et al. 1998) are used, in order to ensure a realistic behavior of the model flow. A description of the study area is found in the companion presentation 15.6 (Söderberg et al. 2002); more results from the joint observational and modeling study can also be found here. The aim of the study is not necessarily a perfect correspondence between simulations and observations; we are more interested in examining the physical properties and processes within the flow.

2. MODEL DESCRIPTION AND SETUP

A three-dimensional, hydrostatic, nonlinear, primitive equations numerical model with a higher-order turbulence closure is employed. The advection scheme is of 3rd-order both in time and space (Enger and Grisogono 1998); turbulent diffusion is treated semi-implicitly. A terrain-influenced transformation of the vertical coordinate system is applied (Pielke 1984, pp. 118-125). The turbulence closure is a modified level-2.5 closure (Mellor and Yamada 1982), including a correction for non-realizable 2nd-order moments, inherent in this type of closure, and an improved formulation for the pressure redistribution terms in the TKE equation, the "wall correction" (Andrén 1990). The model, sometimes referred to as the MIUU-model, is well-documented in the literature and has been tested against measurements and analytical solutions (e.g. Enger et al. 1993; Grisogono 1995). In particular it has been used in studies of orographic and coastal flows (Enger and Grisogono 1998; Tjernström and Grisogono 2000). One of the model's principle features is the treatment of turbulence.

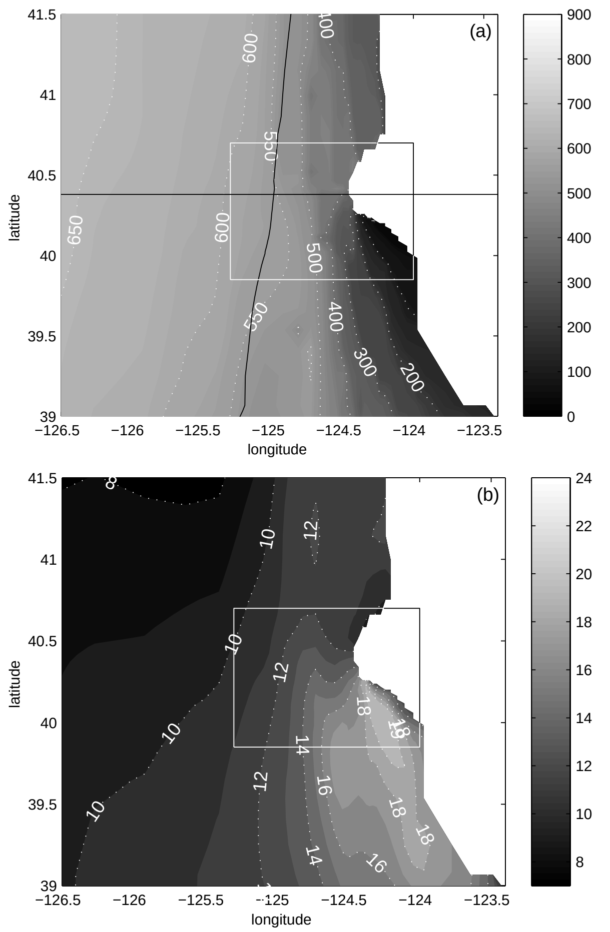

Figure 1. Modeled (a) BL depth, and (b) near-surface wind field. In (a) the solid black lines define four regions with distinct dynamics; the north-south line marks the Fr=0.8 contour. In each map the area covered by observations is also indicated.

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In order to achieve high resolution in the model center and keep the lateral boundaries far from the area of interest, a horizontally expanding grid is used; the maximum horizontal resolution is 2x2 km^2 in the center of the model domain. The vertical grid expands log-linearly with height, from a resolution of ~6 m at the surface to ~150 m at the model top. The model run was optimized for observed conditions upstream of Cape Mendocino. A well-mixed MBL capped by a strong inversion was given to the model at initial time; the low-level background flow was set northerly. Observed SST, with the lowest SST in the lee of Cape Mendocino, was used and held constant in time.

4. RESULTS

Figure 1 shows the modeled BL depth and 30-m wind field. The collapse of the BL in the lee of Cape Mendocino and accelerated flow within the expansion fan agrees well with observations (see Söderberg et al. 2002). The mean structure and the dynamics have been investigated in a number of studies, e.g., Edwards et al. (2001) who compared the results from a shallow-water model with observations of the June 7 case studied here. However, the observed complexity of the flow cannot be explained only in terms of a shallow-water model. As an example it has been shown that a lee-wave triggered by the cape contributes to the BL collapse in the lee of the cape (e.g., Burk and Thompson 1996; Söderberg and Tjernström 2001).

The highly 3-dimensional structure of the flow is illustrated in Figure 2 by back-trajectories calculated from the model. From here it is evident that airparcels that end up at 30 m above the surface (solid lines) have a different history than those that end up at the modeled inversion base (dotted lines). Of note is that the low-level air within the expansion fan originates in the northwestern part of the model domain while the air at the inversion base originates much closer to the coast.

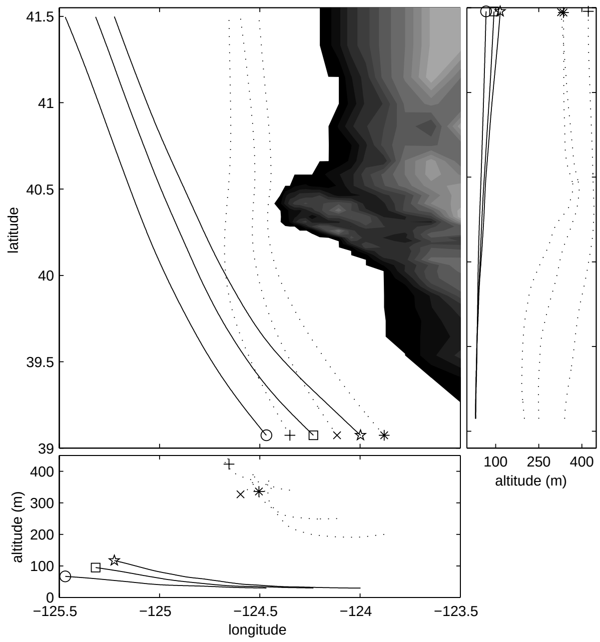

Figure 2. Back-trajectories calculated from the model. The solid lines indicate airparcels that end up at 30 m above the surface; dotted lines indicate airparcels that end up at the inversion base.

Turbulence data from the model is divided into four dynamically different regions: upstream and downstream of the cape, and near-coast and offshore. The north/south division is taken at the cape, while the offshore/nearshore division is taken along the Fr=0.8 isoline, where Fr is the shallow-water Froude number (see Figure 1a). Figure 3a shows modeled momentum flux for the nearshore downstream area (essentially the expansion fan). The altitude is normalized by the modeled BL depth z_i while the profiles are normalized by the modeled u_*^2. Most of the profiles are spread around the normalized profile for stable stratification (thick solid line) suggested by Lenschow et al. (1988). Individual lines, however, are either more convex or concave. Note also the relatively large upward momentum flux above the modeled BL top; this feature appears only on the near-coast side of the jet. The model results suggest that this region becomes turbulent due to a secondary circulation around the jet at the inversion, which advects warm air from over land out above the jet. This leads to reduced static stability and Richardson number, to a point where the wind-shear above the jet is able to sustain turbulence. Normalized velocity variance profiles for the offshore upstream section, where the conditions are the most homogeneous, are shown in Figure 3b. The profiles are similar to what is expected in a well-mixed near-neutral layer (Brost et al. 1982). A local increase in the velocity variances is found just below the inversion, which most likely is associated with the jet-like wind structure found near the inversion base, even this far offshore. Figure 3c shows velocity variances for the downstream nearcoast area (the expansion fan). It is obvious that this BL is far from the generic homogenous steady state on which most model closures are based.

It was noted that the curvature of the normalized momentum flux profiles in Figure 3a were either convex or concave. The model reveals that the scatter around the analytical expression is a result of the complex response to many factors, such as changes in the surface turbulence forcing or BL depth. The response to these factors is illustrated in Figure 4, where normalized momentum-flux profiles and wind-speed profiles along the eastern-most 30-m trajectory in Figure 2 are plotted against normalized altitude. The profiles are divided into four sectors from the northernmost point of the trajectory; the upwind profile in each sector is denoted by a heavy solid line, heavy dashed line is the downwind profile, and the dotted lines are all profiles in between. In the first sector (0-95 km) the wind speed increases while z_i and u_* only changes marginally; thus the momentum flux profiles only changes slightly. In the next

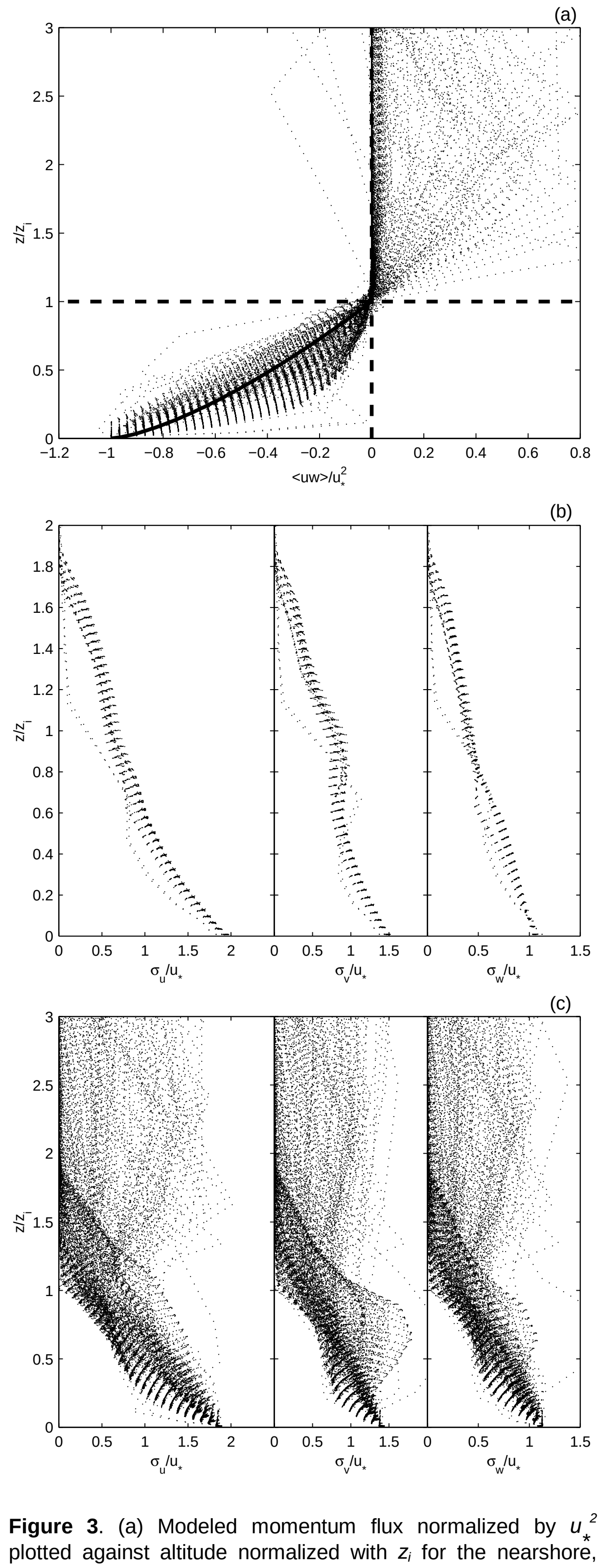

Figure 3. (a) Modeled momentum flux normalized by u_*^2 plotted against altitude normalized with z_i for the nearshore, downstream area; solid line is the profile suggested by Lenschow et al. (1988) for stable stratification. (b) Normalized profiles of standard deviations for the offshore upstream area. (c) As (b) but for the expansion fan area.

sector (95-160 km), however, changes in the curvature of the momentum flux profile are more pronounced. The wind speed continues to increase but also u_* increases while z_i starts to decrease and as a result the momentum flux profile becomes more and more concave along the trajectory. In the third sector (160-295 km) the BL depth decreases rapidly and the wind speed attains its largest magnitude along the trajectory; the combined effect leads to that the wind shear also has its maximum in this sector. This increases the mixing in the BL and thus acts towards a more linear shaped momentum flux profile. Farther downstream in the fourth sector (295-355 km), where the wind speed decreases rapidly, the momentum flux profile becomes convex for a short distance before returning to linear. This shows that the model closure is able to generate a realistically behaving non-homogeneous BL turbulence structure, although not strictly proving it to be correct.

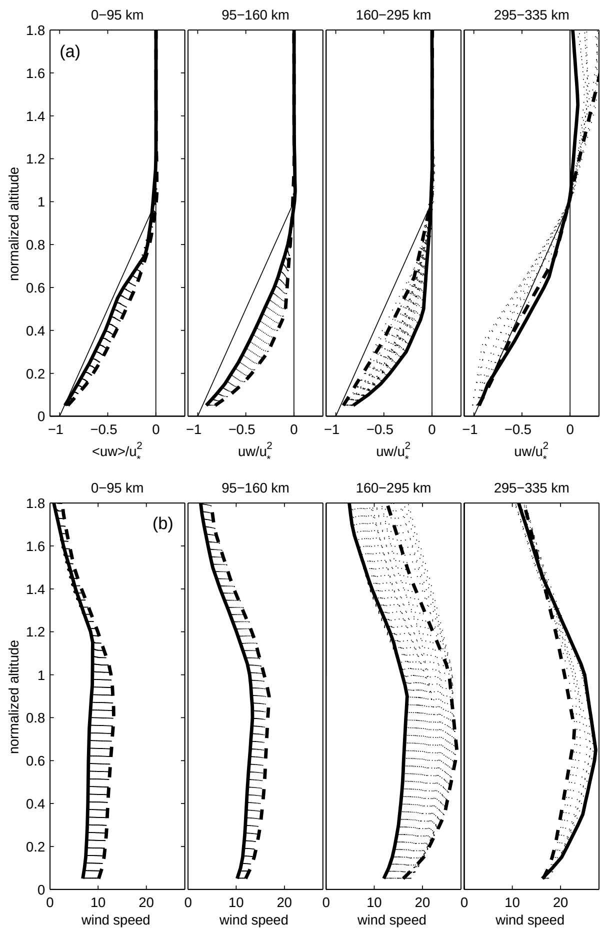

Figure 4. Normalized (a) momentum flux and (b) wind-speed profiles along the eastern-most 30-m trajectory in Figure 2 divided into four sectors where a distinct change in the profile shape can be recognized. Thick solid lines indicate the upwind profile in each sector, thick dashed lines the downwind profile, and dotted lines all profiles in between. In (a) the ideal linear stress profile expected for well mixed, neutral conditions is included for reference (thin solid).

5. DISCUSSION

Modeled turbulence in a highly heterogeneous coastal flow has been investigated using a numerical model with a higher order turbulence closure. To ensure a realistic behavior of the model results observations from the Coastal Waves ’96 field program (Rogers et al. 1998) have been used as a basis for the study. The model run was validated for observed conditions upstream of Cape Mendocino. The observed mean state of the BL was reproduced well by the model in most respects, both upstream and downstream of the cape (see Söderberg et al. 2002).

Observations and model results show that the perturbed BL within the expansion fan definitely can not be considered homogeneous. This raises the question if a numerical model with a turbulence closure based on prognostic TKE, such as the present model, can be used in a study like this in spite of the underlying assumption of homogeneity and steady state employed in the closure formulation. Will the modeled turbulence reflect the “true state” of the turbulence structure in the BL in any sense at all, since the characteristics of the modeled turbulence to some extent are predetermined by the model closure? If turbulence in a particular atmospheric state is poorly understood on a more basic level, we cannot expect simulations with an ensemble-average closure model to shed new light on the situation. Nevertheless, if modeled turbulence agrees well with that from observations it lends credibility to the model for further studies of similar boundary layers and widens the ensemble where the model may be applied, while model results analyzed over a wider ensemble of conditions can at the same time be used to generalize observational results. In Söderberg et al. (2002) it is shown that observed and modeled BL velocity variances, scaled with local similarity scales, agreed surprisingly well; the same scaling applies to both observed and modeled turbulence. Thus, the model is not only able to reproduce the BL dynamics but also able to capture other physical properties and processes within the flow. These encouraging results allow us to continue the investigation.

Finally, another important aspect when modeling turbulence is related to the boundary conditions applied in the model. Surface layer parameters are in most models, including this one, calculated from the mean fields using some form of Monin-Obukhov similarity theory. These are then used as boundary conditions for e.g. the prognostic TKE-equation. This once again implies an assumption of stationarity and horizontal homogeneity as in the turbulence closure. Thus, in a model as the present the prognostic TKE is continuously forced toward a steady-state boundary condition. Indeed, when comparing observed and modeled surface layer turbulence this is where the discrepancies are the largest. In order to improve the performance of numerical models simulating heterogeneous environments, implications of boundary formulations based on Monin-Obukhov similarity theory needs to be further examined.

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