Simulating the Nocturnal Boundary Layer During Low-Level Jet Events

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Introduction

Simulating the correct evolution of the nocturnal boundary layer (NBL), also often referred to as the stable boundary layer, is a challenge for any numerical model, since the NBL is influenced by a variety of sub-grid scale phenomena (Lenschow et al. 1988). These phenomena include propagating gravity waves, stationary waves that are fixed with respect to the terrain, Kelvin-Helmholtz waves, and various drainage flows (Finnigan et al. 1984; Lenschow et al. 1988).

The best successes in simulating the NBL have occurred with large-eddy simulation (LES) models in which a stochastic approach has been used to model subgrid-scale turbulence (Mason and Thompson 1992; Mason 1994; Brown et al. 1994). This approach seems particularly reasonable for modeling the NBL, since Nappo (1991) has shown that breakdowns of stability are common in the stable boundary layer and that the heat fluxes during these breakdowns contribute significantly to the total heat flux during the night.

One of the important mesoscale features to simulate correctly over the United States is the low-level jet (LLJ), a wind speed maximum that occurs in the lowest few km of the atmosphere. The climatological frequency of LLJ development over the United States is documented by Bonner (1968) and shows that the Southern Great Plains Cloud and Atmospheric Radiation Testbed (CART) site of the Atmospheric Radiation Measurement (ARM) Program is located within the region of maximum LLJ occurrence.

While a number of investigators have examined simulations of strong LLJ events (typically with horizontal wind speed maxima in excess of 25 m s^{-1}), Stensrud and Pfeifer (1995) have shown that weaker LLJs occur on most days during the summertime. While these LLJs are more difficult to observe accurately, they can contribute to an increase of 25% in the average daily northward flux of water vapor. Rasmussen (1967) has shown that the low-level eddy flux of water vapor is strongest during the summer months and accounts for a large portion of the mean annual inflow into North America. Thus, it is appropriate to examine how well a numerical model can simulate these more typical LLJ events.

The numerical model chosen for use is the Pennsylvania State University/National Center for Atmospheric Research mesoscale model version 4 (MM4). The MM4 is a hydrostatic, sigma coordinate, nested grid model. It uses the Kain-Fritsch convective parameterization scheme for the nested grid, an Anthes-Kuo convective parameterization scheme for the coarse grid, a 1.5 order boundary layer closure scheme, a force-restore surface energy budget scheme, and explicit warm and cold cloud microphysics (see Stensrud and Fritsch 1994 for more information). To realistically produce the horizontal inhomogeneities in the surface energy budget, the weekly Crop Moisture Index (CMI) is compared with the Oklahoma Mesonet evapotranspiration measurements from four stations and the modeled heat flux values to tune the model values of moisture availability (M) to match the modeled evapotranspiration amounts to observations (Stensrud et al. 1996).

Model Results

The first 15 days of June 1994 have been simulated with the mesoscale model. Results indicate that, while the model simulates the strongest LLJ events fairly well, it often fails to reproduce the weaker LLJ events that occur more often and contribute a significant fraction of the total seasonal water vapor flux (Table 1). The height of the wind maximum of the LLJ obtained from the model simulations is compared with those obtained from the ARM 915-MHZ wind profiler data and the Weather Surveillance Radar - 1988 Doppler (WSR-88D) velocity-azimuth display (VAD) data at hourly intervals. It is found that the model has a mean absolute error (MAE) of 345 m in LLJ height over the entire 15-day period, that it underpredicts the maximum speed of the LLJ by 5.8 m s^{-1}, and that it has a MAE of wind direction at the time of the maximum LLJ speed of 36 degrees.

Table 1. Probability of detection (POD), critical success index (CSI), and Heidke skill score (HSS) of simulated LLJs between (a) 10 - 15 m s^{-1} and (b) 15 to 20 m s^{-1} as calculated by comparing hourly WSR-88D VAD winds and MM4 data from Fort Worth, Texas, from 1 to 15 June 1994. Number of hourly data that match the wind speed criterion are also listed.

Speed	Events	POD	CSI	HSS
10-15	122	0.646	0.562	0.423
15-20	62	0.667	0.534	0.580

Since the model produces such a significant error in LLJ height (close to half the average height of the LLJ during this time period), while the model almost always produces the LLJ too low in comparison with observations, it may be that the parameterization of the NBL is not reproducing the correct depth of the boundary layer at night. Since LES model simulations have indicated that a stochastic approach is necessary to produce the correct evolution of the NBL, a very simple stochastic mixing model, termed the intermittent mixing model, is developed and tested to see if such an approach could lead to improved predictions of the LLJ.

Intermittent Mixing Model

Mason and Thompson (1992) argue that using a fully deterministic model to simulate the stable boundary layer is incorrect because the presence of stochastic fluctuations in the subgrid parameterization are necessary to achieve a correct simulation of regions that are statically stable. They devised a stochastic scheme to represent the subgrid stress variations in a LES model and found improvements in their simulations of a stable boundary layer. Unfortunately, the approach used is based upon a fully second-order closure scheme for the boundary layer, which is too computationally expensive for use in a mesoscale model where 1.5-order closure schemes are more common. Thus, the intermittent mixing model (IMM) is developed, based upon a fully stochastic approach to modeling the NBL. While this approach is undoubtably oversimplified, the results are indicative of the need for stochastic techniques to simulate the NBL in mesoscale models as well.

The IMM is constructed to operate only in regions where the bulk Richardson number is positive, i.e., in regions that are statically stable. A simple K-theory approach is used as the basis for this technique, where the background value of K is set to 1 m^2 s^{-1}. The value of K is allowed to reach up to 45 m^2 s^{-1}, but is chosen randomly at each time step. The number of times that K is allowed to be above the background value is dependent upon the shear value across the layer. The larger the shear, the more frequently K is allowed to exceed the background value. A typical time series of K at a given model point (Figure 1) shows the stochastic nature of this parameterization. Admittedly, turbulence is not this intermittent and future refinements should include a time scale for the turbulence as suggested by Nappo (1991).

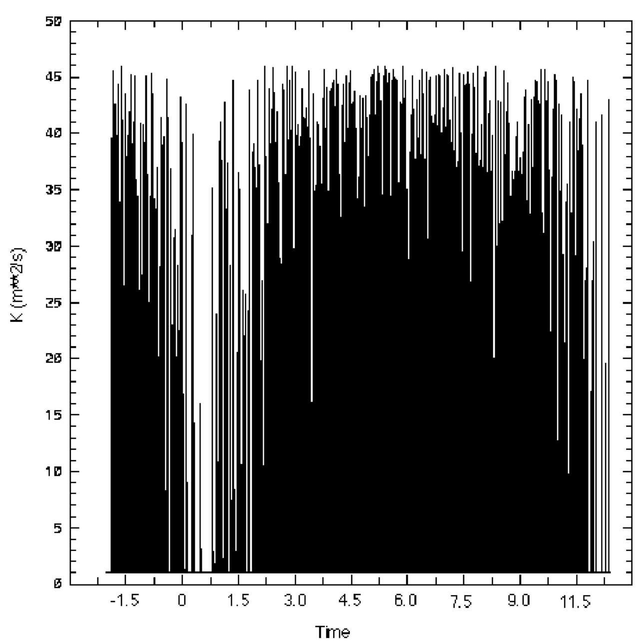

Figure 1. Values of K versus time for one-dimensional IMM at second level above ground.

The IMM is tested in a simple one-dimensional PBL model against the Blackadar scheme (Zhang and Anthes 1982) for 20 days using sonde data from the ARM central facility. Results indicate that the IMM is a significant improvement over the Blackadar scheme for predicting the height of the NBL (Table 2). In particular, the Blackadar scheme consistently underestimates the depth of the NBL, whereas the IMM has a very small bias in NBL depth and has less variation in depth as well when compared with observations. These results suggested that the IMM should be further tested in the PSU-NCAR MM4 to ascertain if it is at all capable of improving the LLJ simulations. Therefore, the IMM is ported to the MM4 and used to predict the temperature and specific humidity fields, although not initially the momentum fields. Eight days during June 1994 are simulated and results compared to the initial results from MM4 that used a 1.5-order closure scheme.

Results from the MM4 simulations using the IMM indicate that the height of the maximum wind speed of LLJs is improved by 100 m when using the IMM (Table 3), the errors in wind direction are comparable to those found with the standard version of MM4, and the errors in wind speed are almost 1 m s^{-1} greater when using the IMM than when using the original MM4 1.5-order closure scheme. Thus, while the IMM produces a better simulation of the LLJ height, it is slightly worse in simulating the LLJ wind speed.

Table 2. Mean absolute error (MAE), bias, and standard deviation of errors in NBL height (m) at 1200 UTC as simulated by the Blackadar and IMM approaches initialized using data from 0000 UTC. Wind profiles during the night specified analytically, but constrained using the observed values. A LLJ is assumed to occur during the night for each event.

Scheme	MAE	Bias	Std. Dev.
Black	152.05	-152.05	195.71
IMM	82.4	5.2	135.61

Table 3. Mean absolute errors in the height (m) of the LLJ wind speed maximum (Dheight), the LLJ maximum wind speed (Dspeed, ms^{-1}), and the direction of the LLJ (Dtheta, degrees) from the MM4 using the 1.5-order closure scheme and the IMM.

Model	Dheight	Dspeed	Dtheta
1.5 order	345	5.8	35.8
IMM	243	6.6	38.8

Owing to the large gradients in specific humidity with height, it is not clear which LLJ evolution would be more accurate at simulating the northward flux of water vapor.

These initial results using the IMM are encouraging in that the development of the NBL appears to be more realistic, which strongly suggests that stochastic approaches to simulating the NBL are needed for mesoscale models as well as for LES models. However, the results also indicate that more study and refinements are needed to better define the time-scales of the turbulent eddies and the frequency of their creation. The IMM assumes that the stronger the shear in a layer, the more frequent the production of turbulence. It may also be that other factors control the production of turbulence as well that need to be included in this simple parameterization scheme.

Discussion

A simple stochastic model for simulating the NBL in a meso-scale model has been developed and tested using both one-dimensional and three-dimensional models of the atmosphere. Initial results indicate that this intermittent mixing model produces more reasonable simulations of the depth of the NBL than does the 1.5-order closure scheme found in MM4. While it is clear that more refinements to this stochastic boundary layer model are necessary, the results strongly suggest that a stochastic approach is the correct one for simulating NBLs in mesoscale models.

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