1. INTRODUCTION

Meteorological models can be large contributors to errors in atmospheric transport and dispersion (AT&D) predictions. Wind errors can be especially large in stable boundary layers (SBLs) with weakly forced near-surface flows. These are often the very cases likely to exhibit large direction fluctuations and poor dispersion of contaminants. Moreover, because turbulence is so weak in the shallow nocturnal SBL, compared to deep convectively unstable boundary layers, horizontal plume dispersion is often dominated by fluctuations at the small end of the mesoscale (mesogamma scale, ~2-20 km). Generally, the physics of these shallow mesogamma-scale fluctuations is poorly understood.

In stable conditions, the buoyancy production term of the turbulent kinetic energy (TKE) equation acts to suppress vertical motion, leaving horizontal mesoscale forces the chief source of plume dispersion. In such cases, plumes may remain highly concentrated over fairly long distances downwind from their source, while undergoing large local changes in direction due to mesoscale features at scales wider than the plume width. The resulting plume behavior is often referred to as meandering and has been observed in all sorts of locales worldwide. Stable meandering plumes may exhibit large periodic or irregular oscillations in direction, especially when the mean wind is light. In near-calm conditions the plume may even travel in a looping or nearly circular path. Analysis of field datasets led Hanna (1983) to conclude the two most probable factors contributing to stable plume meandering are near-surface density-driven currents over irregular terrain and transient internal gravity waves aloft moving through the environment.

Historically, numerical weather prediction (NWP) models have been ineffective at predicting real meandering flows in the SBL because (1) model resolution has been too coarse to resolve the relevant terrain irregularities and mesogamma scale motions that dominate fluctuating wind components in the SBL, and (2) turbulence parameterizations often are poorly designed and inadequately tested for stable conditions. In this study we attempt to explore the limits of SBL predictability and meandering plume behavior at very fine mesoscale resolutions. To meet this objective model evaluation must focus on the mesogamma scale and the local plume scale, neither of which is resolved by the standard synoptic meteorological observing network. Thus, model evaluation must span all scales from the synoptic scale to the plume scale. This is an ambitious effort requiring advanced numerical modeling tools and specially designed local observations to augment the standard meteorological database.

We hypothesize that an NWP model configured with sub-kilometer resolution, higher-order numerics and minimal diffusion may facilitate simulation of at least the statistics of mesogamma-scale wind variance in the SBL. In this study a nested-grid model is used to simulate real cases of weakly forced flows in the nocturnal SBL over central PA, including local wind fluctuations on time scales of 20-120 minutes that are associated with meandering behavior. Case evaluations are used to examine the chief dynamical processes leading to mesogamma-scale wind fluctuations and plume meandering. Time series decompositions and multi-case compositing are used to investigate the model’s predictive characteristics for the mean and fluctuating wind components in the SBL.

2. NUMERICAL MODEL AND EXPERIMENT DESIGN

The model chosen for this research is the Weather Research and Forecasting (WRF) system’s Advanced Research WRF (ARW) version 2.2.1 (Skamarock et al. 2005). To study the evolution of SBL flows, ARW is configured with four nested domains, each having a one-way interface with the next smaller grid. Table 1 gives the grid resolutions and number of horizontal points in each domain, while Figure 1 shows domain locations. All four domains have 43 layers in the vertical. The lowest 5 layers have depths of 2 m each, after which the layer thicknesses gradually increase with height up to the model top at 50 hPa. This configuration provides 10 layers in the lowest 50 m above ground level (AGL) (Figure 2). The very fine vertical resolution near the surface is designed to resolve SBL structure and processes. The finest domain covers ~67 X 67 km, has a horizontal resolution of 444 m and is centered over the Nittany Valley of central PA (Figure 3). This region is dominated by narrow quasi-parallel ridges oriented southwest-to-northeast, which flank broad valleys, with the Allegheny Mountains located in the northwest part of the domain.
This model configuration is designed specifically for investigating predominantly stable conditions. Vertical and horizontal scaling considerations are based on nocturnal SBLs typically having depths $h \sim 50$ m or less, roughly the thickness of the lowest one or two layers in most general-use mesoscale models. Thus, our finest horizontal grid scales to $\sim 10$ times the scale depth of the nocturnal SBL, $h$, while the vertical grid provides up to 10 layers within $h$. Consequently, an ensemble-mean turbulence scheme can be used here, similar to those used traditionally for convectively unstable planetary boundary layers (PBLs) in coarser-resolution mesoscale models. Here we choose the Mellor-Yamada-Janjic (MYJ) turbulence scheme (Janjic 2002), which is designed for both stable and unstable conditions. Other physics include the Dudhia radiation scheme and MM5 five-layer soil scheme for surface fluxes. However, we note this very fine grid would not be suitable for unstable conditions with a PBL depth $> 1$ km because the largest eddies would be resolvable and a Smagorinsky-type sub-grid filter scheme would be needed, transforming the model into a large eddy simulation (LES).

Sub-kilometer WRF forecasts are run daily for 12 h during the nocturnal period, beginning at 0000 UTC. With a time step on the innermost domain of 2.5 s, the 12-h forecasts are completed in $\sim 6$ h using four nodes of a Linux cluster at Penn State University (PSU), each node having four 3-GHz CPUs. Output files on the entire 1.333- and 0.444-km domains are saved at 12-minute intervals and over the local observing network at 10-s intervals to support analysis of mesogamma-scale fluctuations in the model.
Wind speed and direction at Rock Spring are measured using Vaisala WS425 two-dimensional sonic anemometers. These instruments have a very low starting threshold (~0.10 ms\(^{-1}\)) and 1 Hz sampling rate. In late summer 2007 the first five sonic anemometers were deployed in a preliminary “scoping” network on 10-m towers at elevations of 3 and 10 m AGL, along with 10 Campbell thermistors to measure temperature. The raw data are collected in real time and averaged to one-minute intervals for distribution and archival. Seven additional sonics and five more thermistors were deployed in early 2008. Three of the new sonics and thermistors were deployed on a 50-m tower in late May.

4. MODEL RESULTS AND EVALUATION

4.1 Vertical Structure of the SBL

Dataset analyses by Vickers and Mahrt (2004) have shown that buoyancy flux in the radiation-driven SBL often decreases more or less linearly with height from a large negative value at the surface to a small value at the top of the layer (Figure 4). Above the SBL the flux profile often maintains a near-zero constant even if there is turbulence aloft. They concluded SBL depth can be diagnosed in many cases as the level where the absolute value of the flux stops decreasing, which can be very useful when turbulence exists through a deep layer further aloft, for example in the base of a low-level jet (LLJ). However, there can be many exceptions where other processes can disrupt this “ideal” profile.

Figure 5 shows the low-level buoyancy flux profile predicted by ARW at Rock Spring, PA, on the night of 10 Sept. 2007. The model-predicted buoyancy flux profile is very similar to the observed “ideal” case of Vickers and Mahrt, even though there is slight negative flux above the diagnosed SBL top. In this case the small flux aloft is probably related to weak vertical mixing in and below a residual daytime mixed layer between ~250-1500 m AGL (also see Seaman et al. 2008). Future evaluations using data from the 50-m tower at Rock Spring should allow direct verification of model-predicted buoyancy flux profiles and SBL depths.

Given the apparent effectiveness of the MYJ PBL scheme and the high-resolution WRF configuration for predicting realistic SBL structure, a prototype diagnostic algorithm has been developed to analyze SBL depth routinely. Figure 6 demonstrates this diagnostic nocturnal SBL depth, along with potential temperature and turbulent kinetic energy (TKE), in a vertical cross section through a portion of the Nittany Valley near Rock Spring at 0800 UTC, 14 November 2007. In this autumn case, the SBL depth is only ~15-30 m. While TKE is minimal near the surface, there is considerable TKE aloft where the wind shear in the LLJ produces modest instability. In other cases (not shown) downward turbulence transport from aloft causes intermittent episodes of greater TKE near the surface. In those cases the concept of a definable shallow SBL may be replaced by a continuously turbulent zone extending temporarily from the surface to several hundred meters AGL. When the shear aloft subsequently decreases sufficiently, the elevated TKE weakens or dissipates, allowing the shallow radiation-driven SBL to become re-established. Thus, the model appears capable of simulating commonly observed nocturnal turbulence behavior.

4.2 Internal Gravity Waves and Surface Density Flow

Shallow density-driven currents are common over irregular terrain on clear nights due to radiative cooling. In mountainous regions these density currents are referred to as mountain breezes, but they are ubiquitous over small hills and gentle slopes as well, especially when the mean wind is weak. Internal gravity waves can be induced in the stable free atmosphere by a variety of imbalances in the dynamic forcing. Perhaps the most common gravity-wave-inducing mechanism involves lifting of a stably stratified current over a ridge or mountain range.
In PA internal gravity waves are common downwind of the Allegheny Mountains, which run through the western part of the 1.333- and 0.444-km domains (see Fig. 3). Seaman et al. (2008) showed an example of trapped internal gravity waves simulated by the WRF-ARW in the lee of the Alleghenies for the case of 18 August 2007. The wavelength at 850 hPa was 14 km in that case with a northerly flow at ~15 ms$^{-1}$. As expected the wave train was resolved well on the 1.333-km grid, but was severely aliased on the coarser 4-km domain (not shown). Seaman et al. also showed these waves were able to propagate smoothly from the WRF-ARW 1.333-km domain into the 0.444-km domain, while preserving their wavelength and amplitude quite well, and avoiding significant distortions or refraction when passing through the grid interface.

Figure 7 depicts the vertical structure of propagating internal gravity waves predicted on the night of 14 August 2007, when the mean southerly winds aloft were more gentle (~5 ms$^{-1}$). The waves are evident in the figure as perturbations in the potential temperature and vector wind fields ~200-400 m above the valley floor, but they also extend downward to the near-surface layers where their amplitude is damped. Close to the ground, cool density-driven currents are shown propagating downhill both to the southwest (left) and northeast (right). Thus, the WRF-ARW is simultaneously generating perturbed flow through the two physical processes proposed by Hanna (1983) to induce low-level wind fluctuations that, in light-wind conditions, can result in stable plume meandering. However, without remote sensing instrumentation to observe the flow aloft over central PA, it is difficult to verify specific features of the model prediction above the SBL at this time.

### 4.3 Mesoalpha-Scale Statistical Evaluation

Before evaluating local solutions for the SBL on the model’s inner domains, WRF-ARW’s accuracy for predicting the synoptic and mesoalpha scales must be established. Mesoalpha-scale domain-wide statistical evaluation was performed using the Model Evaluation Toolkit (MET) code provided by the WRF Development Testbed Center (DTC) in Boulder, CO. MET has been scripted to run nightly following each model forecast cycle to validate the forecasts on the two outer domains against standard surface METAR and radiosonde data. Here we present a month-long composite of root mean square errors (RMSE) and bias errors in the 12-h ARW predictions (1200 UTC) versus pressure on the 12-km and 4-km domains for April 2008 (Figure 8). Recalling that the 12-km domain covers the full CONUS, we note these errors generally are lower than winter season-averaged forecast errors reported for a 5-km CONUS domain by Koch and Gall (2005) and comparable to average errors during the spring season found for a similar 13-km domain by Nance et al. (2007).

### 4.4 Local Fluctuations and Meandering Winds

For the final step of this preliminary model evaluation, winds predicted by WRF-ARW at the Rock Spring, PA, are verified against data from the local field network. Since plume transport and dispersion is the cumulative result of integrated wind and turbulence acting on air parcels, it is important to examine the high-frequency fluctuating component of the predicted low-level state variables in addition to their lower-frequency mesoscale behavior.
We begin by comparing the observed and model-predicted wind speed and direction for a typical case at Tower Site 1 (Figures 9 and 10). This site is located ~0.75 km from the base of Tussey Ridge (~2.5 km southwest of “R” in Fig. 3). Figure 9 shows 12-h time series of one-minute averaged observed and predicted speeds at 3 m and 10 m AGL for the night of 7 October 2007. Both of the time series contain a range of frequencies, but all the fluctuations are too slow to be associated with the weak turbulence in the shallow SBL. To isolate the more-predictable low-frequency component, Gaudet (2008) applied a 2-h running mean filter to the model’s time series, yielding the smoother curve shown here in red. The figure shows the dominant non-turbulent fluctuations in the model have periods of ~0.3-2.0 h, as in the observations, while higher-frequency variability is poorly captured by ARW. Similar to the obs, the largest-amplitude fluctuations occur near the initial time and again in the final hours of the 12-h forecast. We hypothesize that these large lower-frequency fluctuations are associated primarily with the passage of mid-level internal gravity waves propagating through the model atmosphere, which modulate the near-surface drainage winds, as shown in Figure 7.

Next, Figure 10 shows a similar comparison of 12-minute averaged nocturnal wind directions observed and forecasted for the 7 October case at Site 1 near the base of Tussey Ridge. The observed winds have a mean direction of ~210 degrees through most of the night, with large fluctuations of about +/- 100 degrees. However, WRF-ARW predicted a mean nocturnal wind direction of ~250 degrees, representing an error in mean direction of ~40 degrees at this site. Visual inspection of model-predicted horizontal flow near Rock Spring (not shown) indicates the local winds turn sharply over a distance of 1-2 km in the vicinity of this site due to the influence of a nearby row of low hills. Even though the model has captured the dominant direction (southwest) in the Nittany Valley, local distortion of the winds close to these hills leads to large direction errors at this site. Meanwhile, Figure 10 shows that direction fluctuations in WRF-ARW for this night also are about +/-100 degrees, on the same scale as those observed, but only during periodic bursts. We note that very few previous numerical investigations have been able to generate fluctuations of predicted speed and direction on time scales shorter than an hour in a manner having any apparent relationship to observations. We believe these non-turbulent mesoscale fluctuations are critical to understanding and predicting realistic plume behavior in stable light-wind conditions, including plume meandering.
Based on the evaluations shown in Figures 9 and 10, a running-mean temporal filter was applied to all cases having strong nocturnal radiation-driven SBLs during Oct-Nov 2007. This procedure separated the low-frequency deterministic component of the model solutions from the higher-frequency components found to be mostly non-deterministic in terms of their poor correlation with observed fluctuations of the same scale (Gaudet 2008). Figure 11 shows a time series of the filtered deterministic mesoscale component predicted by the model for 3 November 2007 versus the observed time series to which the same filter was applied. Although there is some positive speed bias (~1 ms\(^{-1}\) during the evening, decreasing to ~0.2 ms\(^{-1}\) by morning), the evolution of the wind through the night is very similar. By composing these filtered time series over the 16 autumn cases found to have well-developed nocturnal SBLs, it is apparent that WRF-ARW predicts the very weak wind speeds at 9 m AGL quite well on the 0.444-km domain, but the 1.333-km grid has a much larger positive speed bias (Figure 12). It is hypothesized that the model’s failure to simulate gradually decreasing speeds through the night may be due to certain characteristics of the MYJ PBL scheme.

![Figure 11. Filtered deterministic component of speed (ms\(^{-1}\)) at 9 m AGL for Site 1, 3 Nov. 2007 on the 0.444-km domain. Shown are WRF-ARW (red) and observed wind (black).](image)

Although the higher-frequency fluctuations removed from the model-predicted time series in Figures 11 and 12 have low correlation coefficients when compared to the observed fluctuations (not shown), they are found to have similar spectra for time scales of ~20-120 minutes (Gaudet et al. 2008). At these time scales, they can contribute significantly to stable plume meandering in the SBL. Insight into the impact these high-frequency wind fluctuations may have on transport in the SBL can be appreciated by examining parcel trajectories for some individual cases (Figures 13 and 14). Figure 13 presents 3-h trajectories for nine parcels released in one grid cell at Rock Spring, PA, from a height of 3 m AGL at 0000 UTC, 3 May 2008. Without sub-grid dispersion the cluster of parcels moves toward the northeast carried by the mean southwesterly winds (~1 ms\(^{-1}\)) in the SBL. This direction is consistent with the most frequent directions observed in the valley (Seaman et al. 2008). However, due to the periodic fluctuations in wind direction, many of the parcels move in a sinusoidal manner characteristic of a classic meandering plume. As expected in real cases, this behavior is not universal. Some of the parcels released within the same grid cell exhibit weaker oscillatory behavior as they travel toward the northeast. Figure 14 reveals similar near-surface trajectories on another night that travel in a nearly circular looping pattern for two hours before some begin to move up the valley. On other nights (not shown), parcel trajectories sometimes reverse direction as they respond to large shifts of the near-surface ABL wind direction that may occur when channeled winds in Nittany Valley interact with mesoscale features farther aloft. Gaudet et al. (2008) explore the statistical behavior of these fluctuations in the form of spectra based on the predicted and observed wind time series.

![Figure 12. Filtered deterministic component of speed (ms\(^{-1}\)) in nocturnal SBL at 9 m AGL, composited over 16 autumn cases. Shown are observed speed (red) versus model speed on 0.444-km domain (blue) and 1.33-km domain (green).](image)

5. SUMMARY

In this study, an instrumented field network and a specially configured version of WRF-ARW have been used to study predictability of SBL structure and behavior. Using very fine grid resolution and the MYJ PBL scheme, it has been shown that the modeling system can predict important aspects of the nocturnal SBL, including realistic buoyancy flux profiles, and the wind speed and direction fluctuations associated with stable plume meandering.

Future analysis of field data from a 50-m tower will evaluate predictions of SBL vertical structure. PSU also is exploring options to acquire remote sensing instruments to observe internal gravity waves aloft. Additional work will extend the model evaluations to include testing of the Quasi-Normal Scale Elimination (QNSE) PBL scheme of Galperin et al. (2007).
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6. REFERENCES


