J9.5 MODELING THE STABLE BOUNDARY LAYER DEPTH FOR QUANTIFYING ITS UNCERTAINTY FOR DISPERSION

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## 1. INTRODUCTION

Accurately modeling the depth of the atmospheric boundary layer (ABL) is critical for atmospheric transport and dispersion (AT&D) modeling. The stable boundary layer is present about half the time; therefore it is necessary to model it appropriately. Dispersion is substantially different in the stable boundary layer than in the more frequently studied convective boundary layer. Plumes often disperse little and meander with the stable waves that are set up. These issues make it extremely difficult to accurately predict (or even ascertain) the depth of the stable boundary layer (Mahrt 1999, Vickers and Mahrt 2004). These issues also lead to different uncertainty characteristics for the stable boundary layer as well.

Uncertainty in predicting dispersion in the atmosphere is largely due to uncertainty in the meteorological fields, including the wind direction and speed, the depth of the boundary layer, and some measure of the atmospheric stability or size of the eddies (Lamb 1984, Lewellen and Sykes 1989, Peltier et al. 2010). Thus to assess the uncertainty of dispersion requires analysis of the uncertainty of these meteorological fields.

Here we concentrate on the impact of boundary layer depth on the uncertainty in downwind contaminant concentration. If one considers the top of the boundary layer to act as a lid to vertical dispersion (certainly a simplification, but one frequently employed in dispersion modeling), then sufficiently far downwind of the source, the concentration is roughly inversely proportional to the depth of the boundary layer by simple mass conservation arguments. This relationship implies that it is critical to correctly diagnose and predict the depth of the boundary layer in order to correctly forecast downwind contaminant concentration. Figure 1 shows an example dispersion calculation using the SCIPUFF transport and dispersion model (Sykes et al 2004) centered over Dugway Proving Grounds in Utah. The top figure shows the dispersed plume 43 min. after a modeled release of polypropylene as modeled for September 7, 2007 (during the FFT07 experiment) with the boundary layer depth input from the forcing mesoscale model (15 m as determined by Dugway's runs of the Weather Research Forecast (WRF) model. The bottom figure uses a boundary layer depth of 500 m. We see that the plume spreads substantially more and is transported further to the north and east. The situation is elucidated further by looking at the vertical extent of a southwest-northeast plane through the plume as shown in Figure 2. We see that the plume that is constrained to the lowest 15 m is not able to rise up toward the mountainous topography to the northeast. In contrast, the lower figure shows that with a boundary layer depth of 500 m, the plume is able to disperse vertically up the side and over the mountain, allowing further downwind transport.

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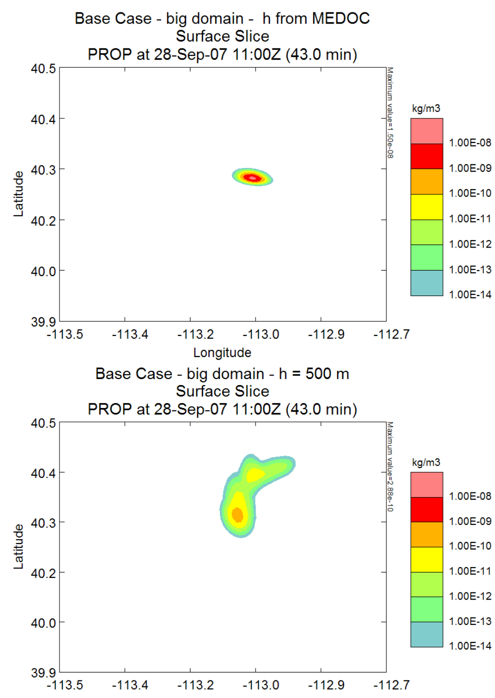


**Figure 1. SCIPUFF simulation of transport and dispersion of polypropylene on Sept. 7, 2007 at 1100 UTC for boundary layer depth determined by WRF at 15 m (top) and artificially set at 500 m (bottom).**

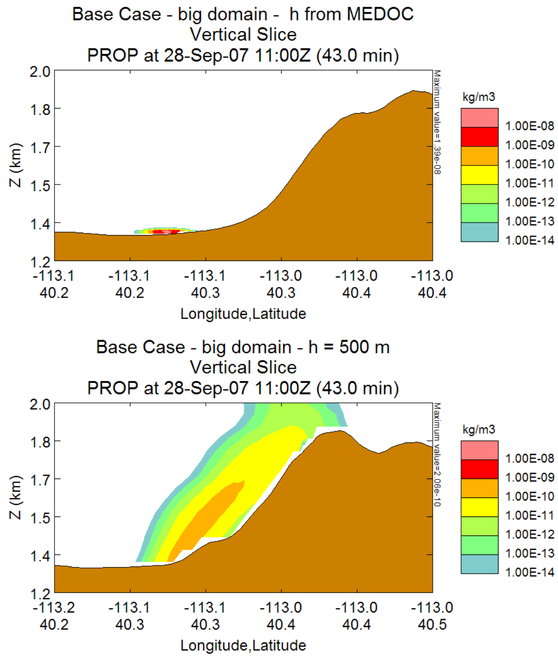


**Figure 2. Vertical cross-sections through the SCIPUFF modeled plumes of Figure 1.**

Unfortunately, it is difficult to accurately predict, or even define, the depth of the stable boundary. As opposed to the easily defined boundary between the boundary layer and the less well mixed layer above for the convective case, the top of the stable boundary layer is often poorly defined. For the convective case, one can look for minima in the turbulent kinetic energy (TKE) field or the lowest inversion base. For the stable case, however, there is seldom a well-defined boundary. The top of the layer is determined by complicated, turbulence extinguishing effects of the stable stratification. To complicate matters, mesoscale models that frequently drive the atmospheric transport and dispersion models are unlikely to predict the depth of the boundary layer. In addition, nocturnal effects such as propagation of very stable gravity waves or long-lived solitary waves cause temporal fluctuations in the boundary that defines the top of the boundary layer (Sun et al. 2003).

Here, we examine current methods for determining the depth of the stable ABL, particularly a recent formulation by Zilitinkevich (2007), which has shown skill in estimating stable and neutral ABL depths when compared to large eddy simulations. We assess the sensitivity of ABL depth for the FFT07 field experiment during nighttime hours as well as for other available observations. Specifically, computation of the ABL depth during the nighttime hours is compared for various methodologies, including SCIPUFF simple diurnal calculations, WRF predictions, and the Zilitinkevich formulation. We consider new SBL parameterizations that could prove more accurate for AT&D. In addition, we consider the impact of the uncertainty of the calculation of the SBL depth on dispersion uncertainty. This study reveals the importance of further evaluation of theoretical advances in SBL depth formulations and the need for field studies to verify them.

Section 2 describes Zilitinkevich model. The application of this model to the FFT07 data are described in section 3. Section 4 discusses the implications of these results and what is necessary to improve on the state-of-the-art.

## 2. MODELS FOR THE STABLE BOUNDARY LAYER DEPTH

Vickers and Mahrt (2004) have compared various types of models for computing boundary layer depth, $h_E$ , given surface level turbulence data. The work by Zilitinkevich et al. (2007) is a representative model that is a composite of three models: for truly neutral conditions (where surface buoyancy flux, $B_s$ = 0 and the inversion strength aloft, measured by the Brunt-Vaisala frequency, *N = 0*), conventionally neutral conditions ( $B_s$ = 0 and *N > 0*), and nocturnal stable conditions ( $B_s$ < 0 and *N = 0*). The Zilitinkevich et al. (2007) formulation for boundary layer depth is written as

$$\frac{1}{\mathbf{h_E}^2} = \frac{\mathbf{f}^2}{(\mathbf{C_{TN}u_*})^2} + \frac{\mathbf{N}|\mathbf{f}|}{(\mathbf{C_{CN}u_*})^2} + \frac{|\mathbf{fB_s}|}{(\mathbf{C_{NS}u_*}^2)^2} \quad (1)$$

where f is the Coriolis parameter, $u_*$ is the friction velocity, and $C_{TN}$, $C_{CN}$, and $C_{NS}$ are empirically derived constants for the truly neutral, conventionally neutral, and nocturnal stable conditions as denoted by the three terms on the right-hand side of (1) respectively. Zilitinkevich et al. (2007) accomplished 160 large eddy simulation (LES) runs with different combinations of N, wind speed and direction, f, and surface roughness to compute these empirical constants. For each run they determined the boundary layer depth as the elevation at which $|\tau_\mathbf{w}|_{\mathbf{z=h}} = 0.05\mathbf{u_*}^2$. They fit a line through a plot of the log of the diagnosed depth versus the predicted depth and found a best fit when $C_R = 0.6$, $C_{CN} = 1.36$, and $C_{NS} = 0.51$ . This is the formulation used here to estimate the stable depth of the ABL for the data from Dugway during Trial 71 of FFT07.

## 3. MODEL APPLICATION

Equation (1) was applied to hourly averaged data from the north tower at Dugway Proving Grounds for the night of September 28, 2007, when there were also actual measurements of the boundary layer depth from a Frequency Modulated Continuous Wave (FMCW) radar. Specifically, we used $\overline{w'T'}$, temperature at 8 m, $u_*$, and $dT/dz$ taken over 2 m to 32 m. Figure 3 displays a scatterplot of the results of (1) compared to the FMCW measurements for the five different hours with available measurements. We see that (1) drastically underpredicts the boundary layer depth.

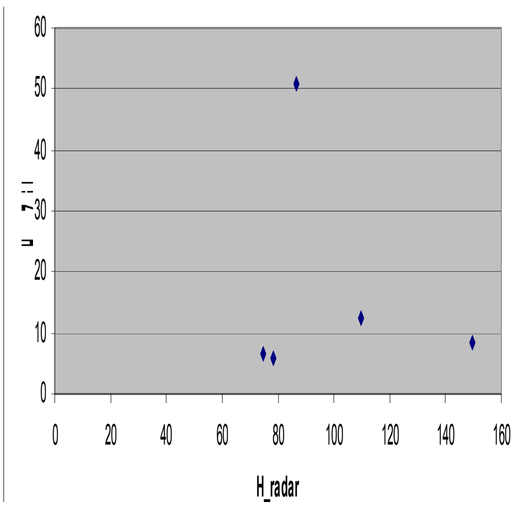


**Figure 3. Scatterplot comparing the boundary layer depth computed from (1) with the radar data for hourly average depths on Sept. 28, 2007 at Dugway Proving Grounds.**

To further analyze the results, we break down the calculation in (1) by terms and assess the depth computed for each of the terms. Table 1 lists the results with each row representing a calculation for each of the five hours with corresponding radar observed boundary layer depth. We see that the depth computed by the truly neutral term is the highest and that by the nocturnally stable term is consistently the lowest, in fact being quite low for most of the night but beginning to break up as the inversion weakened in the final hour of the computation. Since (1) assesses the depth by summing the inverses of the squares, the lowest depth is the one that controls the final estimate (h_Zil). That value is consistently lower than the depth that is measured by the FMCW radar.

**Table 1. Boundary layer depth (*h*) as computed by each term of (1) and measured by the radar**

| h_radar | h_TN | h_CN | h_NS | h_Zil |
|---|---|---|---|---|
| 149.7 | 343 | 34.4 | 8.7 | 8.5 |
| 109.75 | 416 | 48.1 | 13 | 12.5 |
| 78.3 | 228 | 28 | 5.9 | 5.7 |
| 74.8 | 259 | 25.5 | 6.9 | 6.7 |
| 86.4 | 500 | 74 | 70.8 | 50.9 |

## 4. DISCUSSION

Although accurate atmospheric transport and dispersion modeling requires a good estimate of the boundary layer depth, the actual depth is often not known, particularly during stable nocturnal periods, which comprise a large fraction of the total time. We have applied a recently developed formula (Zilitinkevich et al. 2007) to data from Dugway Proving Grounds during the FFT07 experiment (specifically Trial 71 on September 28, 2007). We found that the computed boundary layer depths did not agree well with those measured.

More theoretical and modeling studies are necessary to further refine estimates of boundary layer depth for transport and dispersion. There are many influences to the depth, including gravity waves, cold air drainage, and presence of a low level jet. The boundary layer depth varies temporally and spatially. Traveling waves can make a large impact on the depth. And finally, it is often difficult to discern the most appropriate depth even when there are measurements.

Uncertainty in atmospheric transport and dispersion due to uncertainties in the nocturnal stable boundary layer depth are likely to be rather large. Quantifying those uncertainties remains a major challenge.

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