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Eulerian dispersion modeling with WRF-LES of plume impingement in neutrally and stably stratified turbulent boundary layers

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HIGHLIGHTS

- We simulate realistic turbulent flow over Cinder Cone Butte using the WRF-LES model.
- Both neutral and stably stratified turbulent boundary layers were simulated.
- An SF_6 scalar plume was also modeled and compared to concentration measurements.
- Simulated concentration RMSE was recorded between 1.2 and 2.0.
- Model limitations were associated with boundary condition uncertainty.

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ABSTRACT

The vast range of space-time scales associated with turbulent flow adjacent to rugged terrain is especially problematic to predictive dispersion modeling in atmospheric boundary layers (ABLs) partly due to the presence of non-linear flow features (e.g., recirculation zones, diffusion enhancement, etc.). It has been suggested that in such ABLs, explicitly modeling large turbulent eddies, through large-eddy simulation (LES), may help to curtail predicted concentration errors. In this work, passive scalars were introduced into the Weather Research and Forecasting (WRF) LES model for the purpose of simulating scalar plume interaction with an isolated terrain feature. Using measurements from the Cinder Cone Butte (CCB) field campaign, we evaluate the ability of WRF-LES to realistically simulate the impingement of Sulfur Hexafluoride (SF_6) plumes onto CCB in both neutrally and stably stratified environments. Simulations reveal relatively accurate scalar trajectories with respect to thermal stability, including complex patterns such as plume splitting below the hill dividing streamline. Statistical accuracy varied with case study, but for the neutral case we recorded greater than 50% of predicted 1 h averaged surface concentrations within a factor of 2 of the observations. This metric, along with several others, indicates a performance accuracy similar to, or slightly better than, alternative Reynolds Averaged Navier–Stokes models. For the stably stratified case, the spatial distribution of surface concentrations was captured well; however, a positive concentration bias was observed which degraded quantitative accuracy scores. The variable accuracy of the WRF-LES model with respect to thermal stability is similar to what has been observed in regulatory analytical models (i.e., concentration under predictions in neutral environments and concentration over predictions in stable environments). Possible sources of error and uncertainty included the omission of mesoscale wind meandering (i.e., realistic boundary conditions) and sub-grid turbulence parameterization.

1. Introduction

The predictive modeling of scalar transport and dispersion is significantly more difficult in regions of sloping terrain compared to regions of flat homogeneous terrain. This increased difficulty is primarily attributed to two additional elements of complexity introduced by the presence of variable topography. One source of uncertainty is associated with the unique turbulent diffusion features commonly induced by sloped terrain, for example, in hill recirculation zones (Hunt et al., 1978). In some cases, these features can enhance localized scalar deposition through trapping, or alternatively promote mixing, thereby modifying the spatial

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dimensions and core concentration of a scalar plume with respect to transport distance (Hanna et al., 1982; Liu et al., 2001). Another added element of uncertainty is potential flow redirection by the terrain (Snyder et al., 1985). For a point source scalar, and associated downstream plume, this redirection can vastly alter the trajectory of the plume under variable winds (e.g., plume impingement, pooling in basins, channeling through valleys, etc.) (Banta et al., 1990, Ch. 6). The level of uncertainty contributed by these two elements is dependent upon a number of critical factors such as terrain slope, source location with respect to obstacle locations, and ambient thermal stability among others (Cermak, 1984; Ryan and Lamb, 1984).

Despite the above challenges, regulatory dispersion modeling systems (e.g., COMPLEX1, CTDM, and AERMOD) have experienced great improvements in accuracy over the past few decades with regards to dispersion in complex terrain. Furthermore, the value of such analytical models has also been compounded by their relatively low computational cost and execution time. However, the empirical relationships used in the analytical models have been shown to demonstrate certain weaknesses when dealing with heterogeneous terrain such as 1-h to 3-h concentration errors of a factor of 2 or 3 (Lott, 1986). Moreover, concentration biases have been found to have several sensitivities. For example, tendencies to over (under) predict mean areal concentrations under neutral (stable) stratification were attributes of the early Complex Terrain Dispersion Model (CTDM) while the position of scalar sources with respect to the dividing streamline was also associated with biases in CTDM (Strimaitis et al., 1988). These issues motivate the evaluation of a new and improved generation of physically-based models which are also capable of capitalizing on the recent growth in computational power. One such class of models is large-eddy simulation (LES) models, which have the ability to realistically simulate turbulent atmospheric boundary layer (ABL) flow down to spatial resolutions on the order of 10 m or less (Moeng and Wyngaard, 1989; Andren, 1995).

Currently, the extension of LES to scalar dispersion and transport modeling has shown promise in both homogeneous (Weil et al., 2004; Nottrott et al., 2014) and heterogeneous terrain situations (Michioka and Chow, 2008; Kirkil et al., 2012). Over sloping surfaces especially, where spatio-temporally varying turbulence regimes are expected, the use of LES versus simpler dispersion models offers the advantage of potentially capturing a vast spectrum of non-linear microscale flow features (Wood, 2000). These include lee recirculation and terrain induced turbulence enhancement, which are known to impact time averaged scalar distributions (Dawson et al., 1991). Given these capabilities, many researchers are exploring use of LES in addressing some historically difficult, yet high priority, problems such as scalar transportation in urban settings (Nakayama and Nagai, 2011; Lundquist et al., 2012)

While the allure of LES-based approaches to dispersion modeling is clear, they are nonetheless handicapped by several outstanding problems, some of which have long plagued other dispersion modeling approaches. Most notably, the accuracy of LES models, like all computational fluid dynamics models, are absolutely reliant upon accurate input forcing conditions e.g., wind speed, wind direction, thermal stability (Talbot et al., 2012). For dispersion timescales, these input conditions may vary highly with time making it difficult to prescribe realistic forcing conditions using coarse temporal resolution input data e.g., hourly averaged wind and temperature profiles (Hanna, 1983). This issue may be even more problematic when simulating flow near hills and other bluff-bodies (Parente et al., 2011; Balogh et al., 2012). Therefore, errors introduced by a lack of knowledge of boundary conditions can degrade the accuracy of LES-based dispersion simulations. This concept has been supported by high fidelity laboratory tank experiments and numerical simulations which have demonstrated that the inability to capture meandering wind direction can easily lead to predicted concentration overestimates of factors of four to ten along the plume centerline (Snyder, 1985; Kristensen et al., 1981; Etling, 1990). At the same time, concentration underestimates can also be produced at locations off of the plume centerline.

In this paper, we implement passive tracers into the Weather Research and Forecasting – Large Eddy Simulation (WRF-LES) model in order to simulate two realistic field experiments from the Cinder Cone Butte (CCB) dispersion field study (Lavery et al., 1982; Strimaitis et al., 1983). The WRF-LES model was selected for this study for multiple reasons but primarily because it is freely accessible and therefore used by more than 20,000 users worldwide (Weather Research and Forecasting Model Homepage, Accessed: 2014). This popularity stems also from the fact that the mesoscale WRF model has demonstrated skill in short to medium range weather forecasting and because of its extensive data assimilation capabilities (Kumar et al., 2013). In addition, the robustness of the WRF model has been tested for conditions ranging from turbulence-scale (Moeng et al., 2007) to global climate-scale (Lo et al., 2008). Despite challenges linked to multiscale coupling, initial attempts to generate coupled mesoscale and microscale atmospheric simulations are encouraging (Zajaczkowski et al., 2011; Mirocha et al., 2014). For dispersion modeling in the planetary boundary layer, this presents great opportunity since variability in large scale flows influences microscale flow features. In this study, we evaluate the ability of the non-coupled (i.e., only microscale) WRF-LES model to simulate accurate scalar transport and dispersion over complex terrain. This work represents an exploratory effort to assess the potential strengths, weaknesses, and overall value of WRF-LES for modeling plume impingement onto an isolated hill in the presence of neutral and stable stratification. This work is valuable as it presents the first documented effort, to the knowledge of the authors, to apply WRF-LES to stable boundary layer flows and to the problem of turbulent transport and dispersion in an area influenced by complex terrain features.

2. Field experiments and simulation details

In this section, we detail the CCB field study and discuss the specific hours which our results focus on. Additionally, we introduce the WRF-LES modeling system and describe the model configuration and simulation specifics.

The Cinder Cone Butte field campaign took place in 1980 and was designed to study the complex problem of plume impingement onto a bluff body (e.g., a hill) under various stability regimes. The CCB field study was part of a much larger initiative carried out by the Environmental Protection Agency (EPA) designed to develop and improve numerical models (e.g., Complex Terrain Dispersion Model, or CTDM) suitable for estimating concentration distributions in regions of complex terrain. This effort included field studies (e.g., Cinder Cone Butte, Hogback Ridge), laboratory experiments, and theoretical studies.

All CCB experiments were undertaken during various nighttime hours in order to represent multiple stability classes. Each experiment involved the continuous release of passive tracer gases, primarily Sulfur-Hexaflouride (SF_6), from a mobile crane upstream of the butte. In parallel surface concentration measurements were recorded at various locations on and near the butte. CCB itself is a cone-shaped, nearly symmetrical hill near Mountain Home, ID bounded by relatively flat, homogeneous terrain in all directions (i.e., ~10 km radius). It is roughly 1 km in diameter and rises approximately 100 m above its surroundings with a surface roughness length of ~0.1 m (Fig. 1).