J7.2 MODELING THE ATMOSPHERIC BOUNDARY LAYER FOR WIND POWER

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1. INTRODUCTION

Understanding the details of locale-specific flow in the atmospheric boundary layer (ABL) is critical to both siting wind power plants and to making short term predictions of wind variability. However, since atmospheric motion is described by nonlinear dissipative dynamical systems it is sensitive to initial and boundary conditions. Therefore, most practical approaches to modeling involve both ensemble averaging in the model formulation and parameterizing subgrid scale processes with a stochastic formulation. This approach results in an average flow with a superimposed fluctuating flow. Modern time dependent Reynolds Averaged Navier Stokes (RANS) models operate this way. This approach produces an inherent mismatch between the wind field realization that occurs and the ensemble average calculation that is computed. This mismatch could lead to poor forecasts for situations where it is imperative to mimic the specific realization.

Our previous examples with simple models performed in the context of atmospheric transport and dispersion showed some success at using data assimilation to 1) identify the characteristics of the realization that is occurring and 2) use field observation data to back-calculate better flow modeling variables to match that realization (Haupt et al. 2009, Beyer-Lout 2007).

This current work seeks to predict details of fine-scale motion that includes the impact of local terrain, heating information, land use processes, and input from a mesoscale numerical weather prediction model. The challenge is to assimilate such information into a standard computational fluid dynamics (CFD) model. Such an effort requires new assimilation techniques that merge profiles at several locations as computed by the mesoscale model into the CFD simulation without double counting the subgrid scale motions and that is smooth enough to prevent spurious gravity wave generation.

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The new assimilation technique is tested in complex terrain near Rock Springs, PA with computed wind profiles input from fine resolution runs of the Weather Research Forecast (WRF) model run at Penn State. Section 2 describes the site. The mesoscale model as well as the CFD model are described in section 3. Section 4 also discusses the assimilation procedure. Section 5 gives some preliminary results while section 6 summarizes and discusses prospects for future work.

2. CASE DESCRIPTION

Our approach to testing our combined mesoscale and CFD modeling techniques is to construct case studies in an easily accessible site with meteorological monitoring on-site. The locale selected is thus the Rock Springs test site in central Pennsylvania nearby State College. The site is owned by The Pennsylvania State University and is instrumented with several meteorological towers that measure environmental fluxes in addition to wind and temperature variables at several different heights at several locations. The mountainous terrain is representative of locales that are frequently chosen to site wind power plants in central and western Pennsylvania. The terrain includes parallel mountain ridges that could be ideal for wind turbines. The ridges are separated by valleys well known for their agricultural value. In addition, our colleagues in the Meteorology Department at Penn State produce twice daily fine-resolution runs of WRF with nested domains of this region as discussed in section 3.1 below. The topography of this Central Pennsylvania region is depicted in Figure 1. The mountain ridges are oriented Southwest to Northeast and separated by broad valleys.

The initial case day chosen for initial analysis is a cold winter pattern on New Year's Eve Day of 2008 (model initialized at 0000UTC on December 31, 2008). The specific time for the CFD simulation is 2100UTC (1600 EST) on December 31. A cold front had just passed through the region leaving a pool of very cold Arctic air behind. Temperatures sunk to about -10°C and surface winds were moderate (around 10 m/s) from the northwest, which is roughly perpendicular to the line of the mountain ridges, making for an interesting flow pattern at Rock Springs.

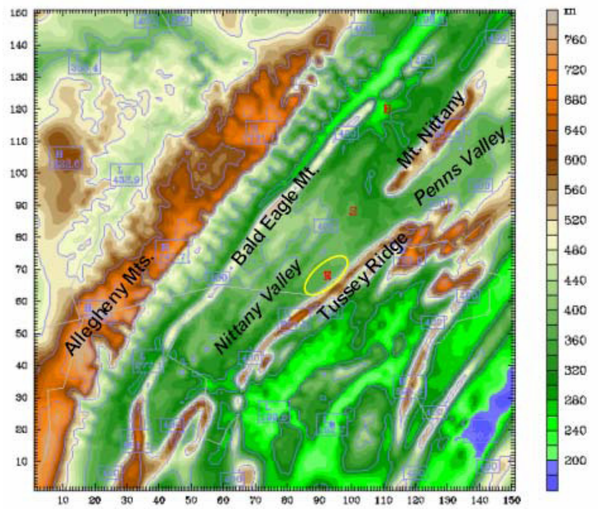


Figure 1. Topography of the region surrounding the Rock Springs site. The oval indicates the local observation network.

3. THE MODELING PROCESS

3.1 The WRF Model Setup

Fine-scale Numerical Weather Prediction (NWP) is used here to provide initial and boundary conditions for the CFD calculations. The mesoscale model runs are accomplished using version 2.2.1 of the Advanced Research WRF (ARW) model (Skamarock et al. 2005). The model uses a third order scheme for vertical convection, fifth order finite differencing for the horizontal advection scheme, and third order Runge Kutta time integration. These schemes optimize the accuracy of small scale waves (Wicker and Skamarock 2002), which are important for correctly modeling fine-scale flow in complex terrain.

The five nested grid WRF-ARW configuration used here has resolutions of 36 km, 12 km, 4 km, 1.33 km, and 444 m (see Figure 2). The finest grid is centered over Rock Springs, PA. The one-way nest interfaces from the coarser to the finer grids. There are 43 vertical layers for the finest horizontal mesh. The finest spacing is concentrated near the surface with five layers representing the lowest 10 m as shown in Figure 3. This fine spacing is appropriate for the neutrally stable conditions observed on that day. This configuration is initialized twice daily by the Stauffer research team at Penn State (http://www.meteo.psu.edu/~wrfrt/). Four Dimensional Data Assimilation (FDDA) incorporates observations into the outer grids (see Stauffer et al. 2008).

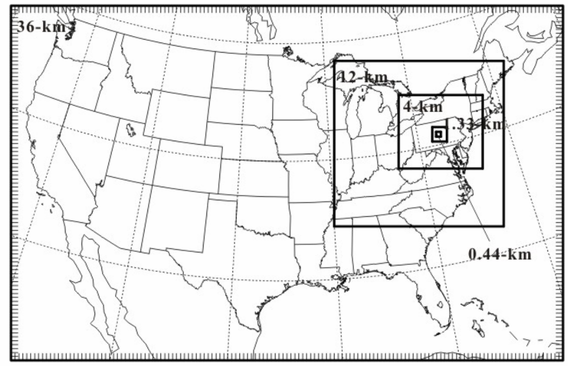


Figure 2. Nested grid configuration for model runs of the WRF-ARW model for studying atmospheric boundary layers in central PA.

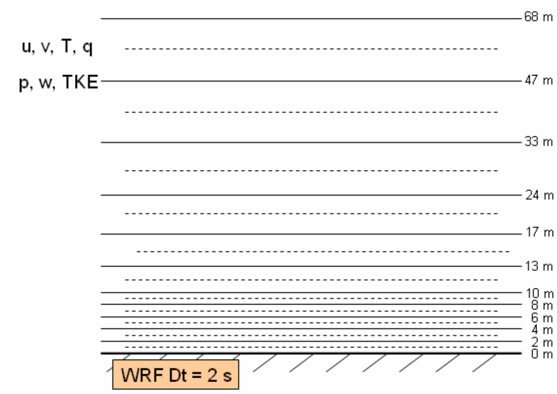


Figure 3. Vertical grid configuration for the lowest 70 m above ground level for the finest nest of the WRF-ARW runs.

3.2 Application of the Acusolve CFD Model

The goal of this effort is to assimilate the finest grid information from WRF-ARW into a high fidelity CFD simulation. This process is accomplished in two ways. First, the wind profiles computed by WRF are used as the inflow conditions for the CFD model. Second, profiles of the temporally and spatially varying flow field can be assimilated to the CFD model at the correct time intervals at each of the WRF grid points.

The CFD simulations are accomplished using the commercial flow solver, AcuSolve (http://www.acusim.com/) from ACUSIM, Inc. AcuSolve uses a Galerkin/least squares finite-element flow method that is second-order accurate in space and time (Lyons et al. 2009). The code is capable of using a broad array of boundary conditions and includes data monitoring and data extraction tools. It is robust and accurate for application of both its RANS and Large Eddy Simulation (LES) modes. Specifically for this project, we plan to implement a blending of these two methods, Detached Eddy Simulation (DES). AcuSolve can be used for modeling fine-scale details of flow around objects, including horseshoe vortices and separation and reattachment (Wilson et al. 2009) as well as the lee effects from upstream buildings (Long et al. 2009).

The domain modeled for Rock Springs has dimensions of 2.6 km × 2.0 km in the horizontal and is 1 km deep. The grid is composed of hexahedral elements and constructed using Gridgen, from Pointwise, Inc. Figure 4a shows the inner 444 m WRF domain with the inner AcuSolve domain marked. Figure 4b is a blowup of the terrain for the CFD mesh. The velocity profile plane that serves as the inflow boundary for the AcuSolve model is evident in that figure.

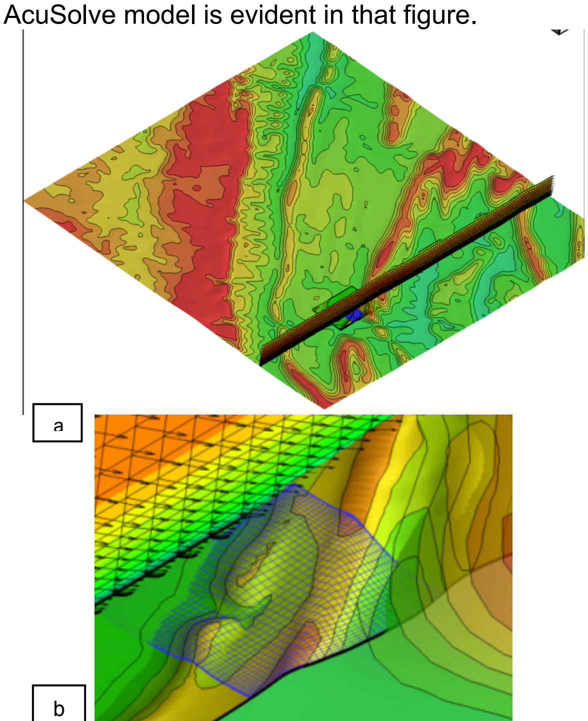


Figure 4. a) WRF 444 m domain with box over the Rock Springs Acusolve site b) blow-up displaying the Acusolve domain and the WRF determined inflow plane.

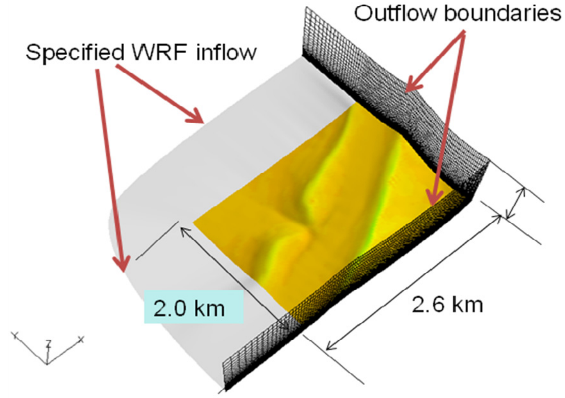


Figure 5. Boundary conditions for the computational domain.

The model applies no slip boundary conditions at the surface, inflow conditions from the WRF 444 m grid on the north and west sides, and outflow conditions on the east, south, and top boundaries. In order to avoid pressure field anomalies at the inflow, the domain has been modified to include a constant elevation “fetch” areas on the north and west sides of the domain as displayed in Figure 5.

3.3 Analysis of Grid Resolution

Several different grid resolutions are assessed to determine the necessary mesh to adequately model the fine-scale features. Figure 6 displays the coarse, medium, and fine grids, which include 155,000, 441,000 and 1.3 million points respectively. AcuSolve was run for each of these meshes and the velocity profiles are compared at the three locations indicated in Figure 6. Figure 7 shows the results for location 1, which is in the saddle between the mountain ridges, plotting the u, v, and w components of the velocity. At this particular site, the profiles gradually converged to a consistent profile, indicating that the fine mesh is adequate to assess our assimilation methodologies. The results for the two other sites marked in Figure 6 confirmed this conclusion.

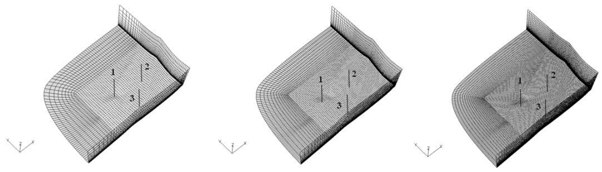


Figure 6. Numerical grid study meshes, from left to right: coarse, medium and fine. Velocity comparison locations are shown.

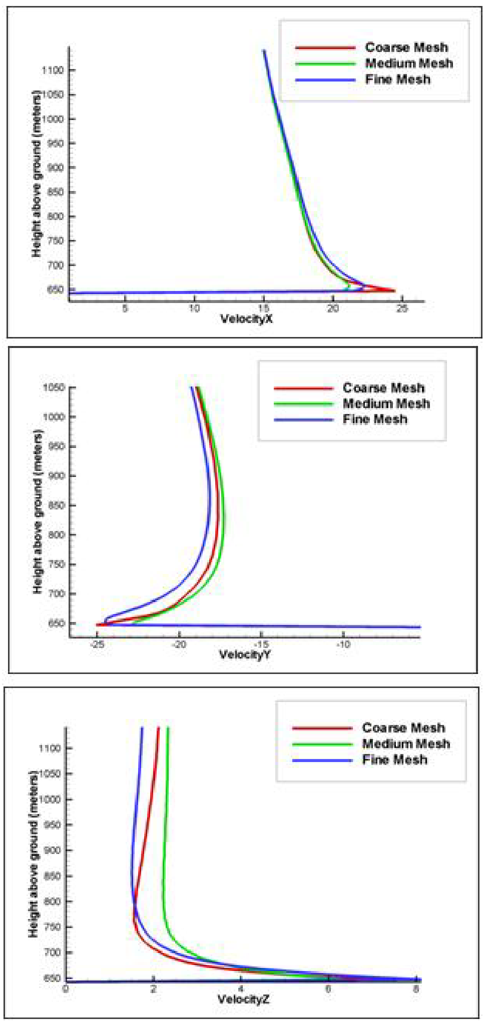


Figure 7. Numerical grid study results. Velocities shown are u, v and w (top, middle, bottom) at location 1 for the three mesh resolutions (coarse-red, medium-green, fine-blue).

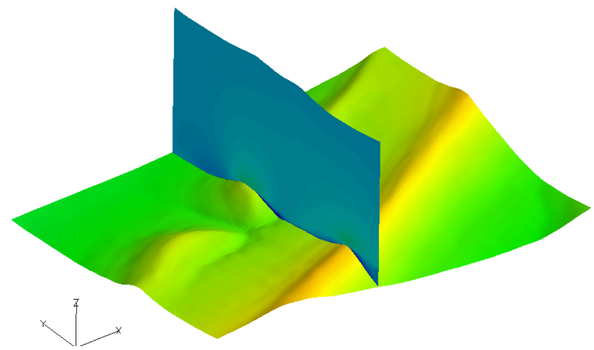
4. ASSIMILATION

We incorporate the WRF mesoscale model data into the AcuSolve CFD simulation in two ways. First, we apply inflow conditions determined by WRF. Second, we directly assimilate at interior points by adding a body force model to AcuSolve. Both approaches are described and demonstrated below.

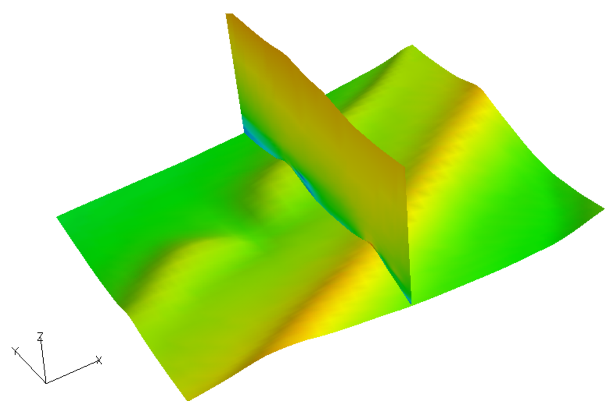
4.1 Inflow Modeling

Inflow conditions are compared using two different methods. In the control experiment, a constant inflow of 10 m/s is used everywhere. In the second experiment, we input a spatially varying inflow, both vertically and horizontally, from the WRF 444 m grid as shown in Figures 4 and 5.

Figure 8 shows the impact of including a velocity profile as computed by WRF as an inflow condition to Acusolve. Figure 8a indicated that if no inflow condition is provided (that is, a constant inflow is used), AcuSolve is not able to spin up a realistic velocity profile, even after a substantial integration time on a sufficiently fine grid. In contrast, when initialized with the velocity profile computed by the fine mesh of WRF (Figure 8b), the resulting velocity profile is realistic.



a.



b.

Figure 8. Comparison of velocity profiles perpendicular to the terrain for a) constant inflow velocity and b) inflow velocity specified from WRF 444 m input.

4.2 Internal Assimilation

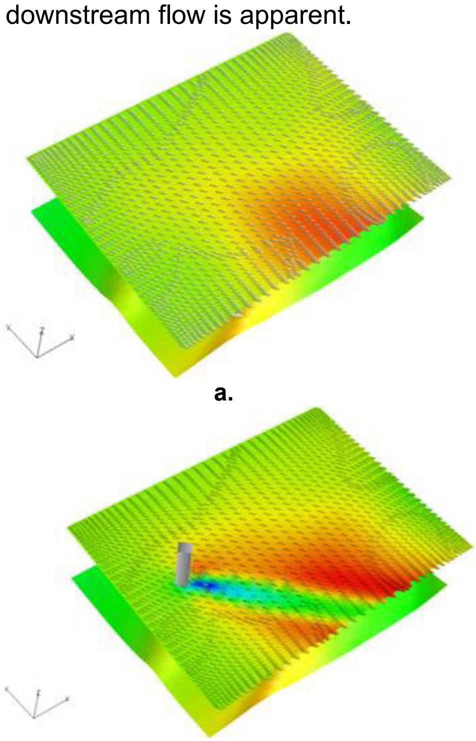
We apply a Newtonian Relaxation data assimilation technique to incorporate the WRF data profiles into the CFD simulations. Such assimilation techniques are not common practice in CFD. The Acusolve code is modified to incorporate a body force that acts to “nudge” the modeled solutions toward an observation, in much the same way as is often done in NWP. For example, the body force appears in the *u* momentum equation as an additional forcing on the right hand side:

$$\rho \frac{\partial u}{\partial t} + \rho u \bullet \Delta u + \Delta p = \Delta \bullet \tau + \rho b \quad . \tag{1}$$

Here *u* represents the *x*-velocity component, ρ is the density of the fluid, *P* is the pressure, τ is the surface and viscous stresses, and *b* is the incorporated body force:

$$b(x,y,z,t) = \frac{1}{\Delta t}(u_O - u_S) \quad . \tag{2}$$

This body force depends on the innovation, that is, the difference between the observed velocity, u_o, and that simulated, u_s, modulated by the time step Δt. Figure 9 shows the impact of assimilation data from a notional meteorological tower within the CFD domain. The flow field without any assimilation appears in Figure 9a while 9b compares the same solution with assimilation via data from the tower. The impact of the assimilation on the downstream flow is apparent.



a.

b.

Figure 9. Flow field modified by the use of a notional body force. The top figure shows the flow field with no body force and the bottom one shows the corrected flow field.

5. MODEL IMPLEMENTATIONS

Several different variations in the modeling approach are assessed here. We specifically study the impact on the simulation results of including surface heating or cooling conditions and a surface canopy model.

5.2 Surface Cooling

To correctly model atmospheric conditions, it is important to include the impact of surface heating. For the case study here on a very cool winter snow covered day, the surface cools the atmosphere. For this synthetic analysis, we set the inflow temperature profile at a constant -1°C. We compared the flow field for a ground temperature of the same (-1°C) as the inflow with that when the ground temperature is assigned a value of -13°C. We compared for the resulting wind profiles for the same site as was shown in Figure 6. The variation in velocity components for location 1 are plotted in Figure 10. The u component weakens somewhat with a cooler surface temperature. The v-component, nearly perpendicular to the mountains, varies the most for this location in the saddle between ridges, the surface acceleration being weaker for the cooler surface. The vertical component weakens a bit when surface cooling is implemented. The other sites showed similar results.

5.3 Surface Canopy Model

We additionally analyze the impact of implementing a basic surface canopy model based on adding a porosity body force. Acusolve implements the Darcy_Forchheimer porosity model by adding another body force to the momentum equation (2) as

$$\frac{\rho}{\phi} \frac{\partial u}{\partial t} + \rho u \bullet \Delta u + \Delta p + Rf = \Delta \bullet \tau + \rho b \tag{3}$$

where *R* is a tensor that rotate the forcing function, *f*, which is modeled as

$$f = \left(\frac{C_{Darcy}\mu}{k_i} + \frac{C_{Forch}\rho}{\sqrt{k_i}} |u| \right) u_i \tag{4}$$

where C_{Darcy} and C_{Forch} are the linear and quadratic coefficients of the porosity model, μ is the molecular viscosity, k_i is the permeability in the principal direction *i*, and u_i denotes the i^{th} velocity component. Here we used $C_{Darcy} = 0$, $C_{Forch} = 0.1$, and $k_i = 0.7$ for each *i*.

Figure 11 indicates the impact of including such a model. The top panel is the control run without the surface porosity model. The streamtraces run smoothly over the terrain. When the porosity model is implemented in the grey patch indicated in the bottom panel, the downstream traces show a large deviation near the ground. The along-wind velocity profiles have been altered so that the flow increases more gradually over the modeled canopy and the flow is quite obviously more complex and realistic.

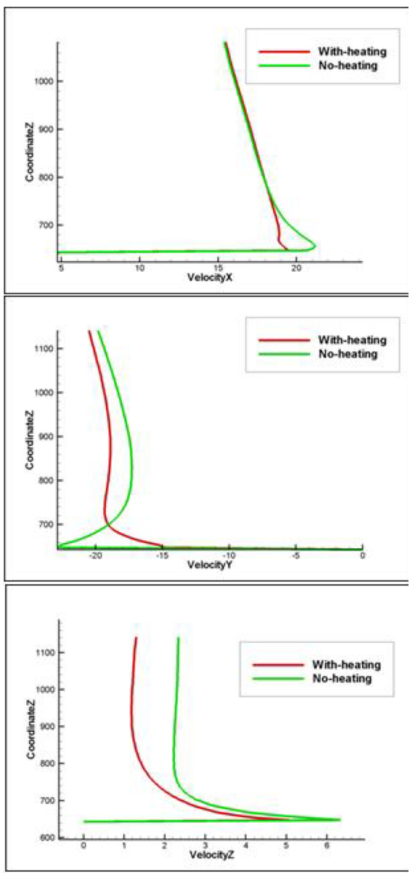
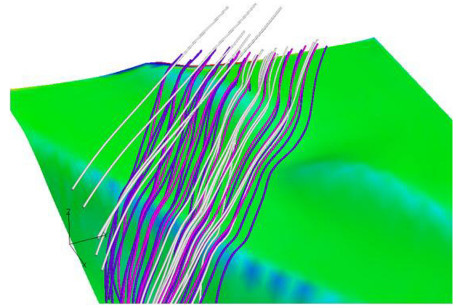


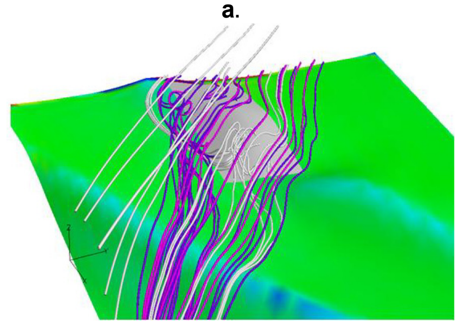
Figure 10. Impact of surface cooling on the velocity components (u-top, v-middle, w-bottom).

5. CONCLUSIONS AND PROSPECTS

This project has demonstrated the first steps toward assimilating mesoscale model data into a CFD simulation. The assimilation uses both an inflow condition and a body force to incorporate interior wind profiles. Note that temporally varying conditions could also be used for dynamic assimilation. This work has also confirmed the importance of implementing surface cooling and canopy models.



a.



b.

Figure 11. The impact of including a canopy porosity model. a– no canopy, b – grey patch indicates canopy region.

By using the spatially varying inflow and assimilating wind profiles from a fine-scale WRF run as forcing conditions for Acusolve, we can approximately replicate a realization for a particular time. Note that the WRF run used four dimensional data assimilation to produce a flow field consistent with simultaneous observations. The Acusolve computed wind field showed more variability in the flow field that did the constant velocity control run.

This work is a step toward fully assimilating both fine scale WRF data and local meteorological observations into a CFD model. By doing such an assimilation, we expect to approach simulating a specific observed realization of fine scale atmospheric flow that indicates specific flow features and differential winds.

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