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A preliminary study of assimilating numerical weather prediction data into computational fluid dynamics models for wind prediction

Frank J. Zajaczkowski, Sue Ellen Haupt*, Kerrie J. Schmehl

Applied Research Laboratory, P.O. Box 30, the Pennsylvania State University, State College, PA, 16804, USA

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ABSTRACT

The goal of this effort is to combine the strengths of Numerical Weather Prediction (NWP) with Computational Fluid Dynamics (CFD) to produce locale-specific flow patterns that could be used for micrositing wind power plants. We do this in two ways: (1) we use the mesoscale model data as inflow for the CFD model and (2) we assimilate vertical profiles of mesoscale model output into the CFD model as a body force. We study the impact of this technique with a case study in the rolling topography of central Pennsylvania. We compare wind profiles between the mesoscale model alone, the CFD model alone, and the fully assimilated mesoscale/CFD solution. In addition, we examine the impact of the mesoscale assimilation into the CFD model on the fine-scale flow structure. This preliminary approach of combining techniques in NWP and CFD through data assimilation provides a unique assessment of the utility of specific locations for wind power production as well as for improving simulations for other purposes.

1. Introduction

Understanding the details of locale-specific flow in the Atmospheric Boundary Layer (ABL) is critical for making short term predictions of wind variability, such as is necessary for applications, including wind power plants or other industrial or defense needs that require details of a wind prediction. Computational Fluid Dynamics (CFD) is capable of modeling the details of flow around specific geographic and man-made features. On the other hand, Numerical Weather Prediction (NWP) models incorporate information representing the outer scale geophysical variability through evolving boundary conditions and by assimilating observations of the current state of the atmosphere to predict flow characteristics. In addition, NWP models account for the effects of radiation, moist convection physics, land surface parameterizations, atmospheric boundary layer physics closures, and other physics packages. Mesoscale NWP with data assimilation has been used extensively to study meteorological flow features and to forecast the weather. Turbulence features finer than about 1 km, however, are not well captured by the turbulence physics of such models. CFD models, however, have proven useful at capturing the details of smaller scales in the flow around features such as buildings and fine-scale topography. Since the needs for wind energy typically range on spatial scales between 100 m and 1 km where the flow is difficult to resolve (Department of Energy, 2008), there is a need for better modeling of the scales between the application of these two types of models. Ideally we wish to combine the advantages of both types of models. Ehrhard et al. (2000) used a mesoscale model to provide lateral boundary conditions for their microscale wind field model, MIMO. In addition they imposed the mesoscale flow on the microscale model by interpolating a steady state solution onto the fine grid and adjusting the interpolated flow with known similarity functions. Yamada (2004) combined the fine-scale modeling approach with the mesoscale smoothly by defining the turbulent fluxes in terms of a turbulence length scale that must be determined implicitly. Li et al., (2007) coupled the mesoscale model, RAMS, with the CFD model, FLUENT, "offline" by providing FLUENT with RAMS boundary and initial conditions at specified time intervals. Various other approaches nest the CFD models in an NWP model (Schneiderbauer and Pirker, 2010, Kinbara et al., 2010; Mirocha et al., 2010; Li et al., 2010; Liu et al., 2010; Lundquist et al., 2010, among others). A goal of such approaches is to dynamically pass information in both directions. That approach, however, suffers from two primary difficulties: 1. Since both models use a subgrid model to parameterize the unresolved turbulent cascade to smaller scales, the dissipation could be "double counted,"[1] and 2. The turbulence parameterization must

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* Corresponding author. Current address. National Center for Atmospheric Research, Research Applications Laboratory, 3450 Mitchell LaneBoulder, CO 80301, USA. Tel.: +01 303 497 2763; fax: +01 303 497 8386.

E-mail addresses: fxz101@psu.edu (F.J. Zajaczkowski), haupts2@asme.org (S.E. Haupt), kjl203@psu.edu (K.J. Schmehl).

[1] Note that this "double counting" does not occur if the coarse and fine models only trade information at boundaries or if a single static interpolation from one grid to another is used.

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span the "terra incognita," defined as the range between the validity of the mesoscale models and Large Eddy Simulation (LES) models (Wyngaard, 2004). Our approach avoids these issues by instead assimilating the output of a mesoscale NWP model into a CFD model. Our goal is to provide a preliminary study of this approach applied in rolling terrain to determine whether it can be used to capture the fine-scale structure of the ABL. Although the mesoscale models and CFD models resolve different scales, we hope to use the larger scale model to influence the finer scale model to find a mass consistent state that satisfies both the outer scale boundary conditions and finer scale forcing by features (such as terrain) that are not resolved in the mesoscale model.

We use the output of the Weather Research and Forecasting (WRF) NWP model with Four-Dimensional Data Assimilation (FDDA) to initialize and assimilate data into CFD simulations with much finer grid resolution. Assimilating the NWP model data is critical to obtaining the spatially varying outer scale patterns. The CFD model is then able to accurately model flow around fine-scale topographic features. The assimilation process has led to large improvements in weather forecasting (Kalnay, 2003).

The technique is demonstrated with case studies in the rolling topography of central Pennsylvania. This site is convenient for several reasons. First, there is meteorological monitoring equipment on-site that can provide observations for test cases. Secondly, it is typical of locales where utilities choose to site wind power plants in the Appalachian Mountains. Wind turbines dot the ridges of central Pennsylvania and are beginning to provide significant power to the region. Thus, it is an ideal locale to study the flow in complex terrain. Finally, a concurrent Penn State project includes producing twice daily fine-resolution runs of WRF with nested domains.

The case day chosen for testing is a cold blustery winter day. The mesoscale model is run and the resulting u, v, and w wind fields from the finest grid are assimilated into the CFD model. We compare the wind profiles of the mesoscale model alone, the CFD model with a constant inflow, the CFD solution with the WRF data inflow, and the fully assimilated mesoscale/CFD solution.

Section 2 describes the site and details of our modeling process. Section 3 describes the assimilation procedure and Section 4 presents results from the case study. Conclusions and prospects are presented in Section 5. This feasibility study of using this approach of combining state-of-the-art techniques in NWP, CFD, and data assimilation provides a unique assessment of the utility of specific locations for wind power production as well as numerous other potential applications.

2. Modeling procedure

Any engineering simulation of fluid flow requires careful assessment of the geometry and flow initial conditions, building a computational mesh that is optimized to the specific features, and careful selection of modeling parameters. These features of our simulation are described herein.

2.1. Site description

Our approach to testing our combined mesoscale and CFD modeling techniques is to construct a case study in an easily accessible site with meteorological monitoring on-site. The locale selected is thus the Rock Springs test site in central Pennsylvania near 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 parallel mountain ridges are separated by valleys well known for their agricultural value. In addition, colleagues in the Meteorology Department at Penn State produce twice daily fine-resolution runs of WRF with nested domains of this region as described in Section 2.2 below. The mountain ridges are oriented southwest to northeast and separated by broad valleys.

2.2. Case description

The case day chosen for initial analysis is a cold winter pattern on New Year's Eve Day of 2008 (model initialized at 0000 UTC on December 31, 2008). The specific time harvested for the CFD simulation is 2100 UTC (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 $-10\,^{\circ}\mathrm{C}$ 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.

2.3. WRF model setup

Fine-scale NWP runs provide the initial and boundary conditions for the CFD modeling. 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, 1998), which are important for correctly modeling fine-scale flow in complex terrain.

The five nested grid WRF-ARW configuration used here has grid resolutions of 36, 12, 4, 1.33, and 444 m as depicted in Fig. 1a. 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 as indicated in Fig. 1b. The five layers nearest the surface comprise the lowest 10 m. This fine spacing is appropriate for the neutrally stable conditions modeled here. This configuration is initialized twice daily using outer boundary conditions from the Global Forecast Model (GFS) by the Stauffer research team at Penn State (http://www.meteo.psu.edu/~wrfrt/). Four Dimensional Data Assimilation incorporates observations into the outer grids (see Stauffer et al., 2008).

2.4. AcuSolve CFD model

The CFD simulations are accomplished using the commercial flow solver, AcuSolve (http://www.acusim.com/) from ACUSIM, Inc. (ACUSIM Software, 2008). 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 Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulation modes. It also allows us to implement a blending of these two methods to produce a Detached Eddy Simulation (DES). AcuSolve can be used for modeling fine-scale details of flow around objects, including horseshoe vortices and separation and reattachment (Haupt et al., in press) as well as the Lee effects from upstream buildings (Long et al., 2009).