18.1 MODELING EXTREMELY COLD STABLE BOUNDARY LAYERS OVER INTERIOR ALASKA USING A WRF FDDA SYSTEM

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1. INTRODUCTION

Fine particulate matter (PM2.5, referring to particles with diameters less than 2.5 microns) has been implicated in a variety of health issues, including respiratory disease. It is important to be able to determine the primary sources responsible for exceedance events when they occur, as well as to predict the potential impact of source emission changes.

Though Fairbanks, Alaska, would seem to be in a relatively pristine environment, during the winter season the absence of solar heating, the strong longwave radiative cooling, and the absence of moderating marine influences lead to extremely cold temperatures. Associated with these cold temperatures are stable boundary layers (SBLs) that can be as shallow as tens of meters (Vickers and Mahrt 2004), and are capped by some of the strongest inversions observed, with temperature jumps of up to 20 degrees C (Benson 1970). During these conditions emissions from vehicular traffic, power plants, and home heating (mostly consisting of diesel and wood fuels) are trapped in a shallow layer near the ground, leading to high particulate concentrations and contributing to the occurrence of ice fog. Exacerbating the problem is the fact that in SBLs the winds and turbulence are generally quite weak and sensitive to a variety of phenomena such as drainage flows and gravity waves. The evolution of these SBLs thus becomes a complex function of synoptic weather patterns, topography, turbulence, surface energy budgets, and precipitation.

This study is part of a multidisciplinary effort to better understand all the factors leading to high PM2.5 concentrations in the Fairbanks North Star Borough area. One of our goals is to provide a mesoscale numerical model configuration that can adequately represent the meteorology of the SBLs in the region. This meteorology can then be combined with emissions data and air quality models to provide better forecasts and analyses of PM2.5 concentrations. Even with state-of-the-art mesoscale models, however, some form of Four Dimensional Data Assimilation (FDDA) is generally needed to maintain model accuracy throughout a study period (e.g., Deng and Stauffer 2006, Tanrikulu et al. 2000). In other words, observations are ingested by an FDDA-assisted meteorological model to produce a dynamically consistent analysis (dynamic analysis) of the observed state throughout a model simulation. Another aspect of our study is to perform sensitivity tests with different combinations of mesoscale model physics parameterizations (including planetary boundary layer (PBL) schemes, land surface model schemes, radiation schemes, and microphysics schemes) and determine those that lead to the best predictions of meteorological conditions.

However, we must balance the need for generating atmospheric analyses that are as close as possible to the observed meteorological conditions with the need of performing physics sensitivity studies using as little externally imposed forcing (for example, by the FDDA) as possible. In this manuscript we will describe how we solve this potential dilemma by using a multigrid multiscale FDDA strategy, as proposed by Stauffer and Seaman (1994). This study is one of the first where the multiscale FDDA strategy has been adapted to the Weather Research and Forecasting (WRF) mesoscale model, a new state-of-the-science mesoscale model.

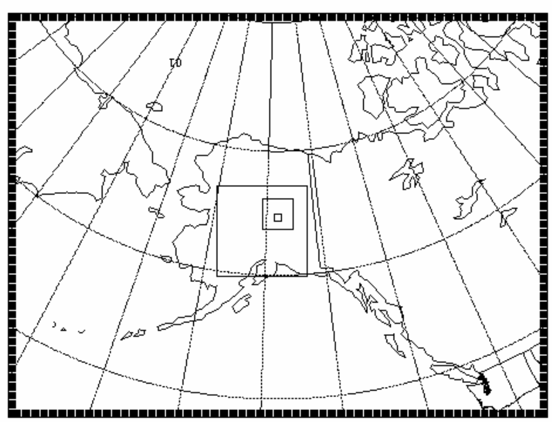

Figure 1. Nested grid configuration of WRF, showing the 12-km Grid 1, the 4-km Grid 2, and the 1.333-km Grid 3 referred to in the text, and the proposed 0,444-km Grid 4.

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2. NUMERICAL MODEL AND EXPERIMENT DESIGN

The simulations performed for this project applied the Weather Research and Forecasting (WRF) system's Advanced Research WRF (ARW) (Skamarock et al. 2008). The major baseline and sensitivity tests make use of the recently released version 3.1 of WRF-ARW. Figure 1 shows the three one-way nested grids used in all simulations, with 12-km, 4-km, and 1.333-km horizontal grid spacing, respectively (Table 1). In future work, the sensitivity to adding a fourth domain of 0.444 km horizontal grid spacing will be examined. All grids use 39 vertical levels, of which the lowest of the 38 half-layers is 2 m above the surface. The vertical resolution near the surface was chosen to be sufficient to resolve SBLs on the order of tens of meters deep.

Domain No.	Horiz. Res. (km)	Time Step (s)	No. of Points
1	12.000	24	401 x 301
2	4.000	8	202 x 202
3	1.333	4	202 x 202

Table 1. Resolution, time step and size of nested-grid WRF domains. All domains have 39 layers in vertical.

As the basis for model evaluation we are examining two twenty-day episodes during the 2007-2008 winter season, one characterized by partial sunlight, the other by near-complete darkness. The episodes selected (Dec. 14 – Jan 3; Jan 23 – Feb 12) encompass the two times within this winter season of extended cold temperatures and high PM2.5 concentrations for Fairbanks. Most of the simulations during the initial testing phase were performed over a three-day test period corresponding to the start of the partial sunlight episode, 0000 UTC 23 Jan 2009 – 0000 UTC 26 Jan 2009. This period is initially characterized by relatively warm temperatures around Fairbanks, but temperatures drop below -25 C during the second half of the three-day period (see Fig. 2).

Fairbanks is located near the Tanana River Valley in central Alaska, to the north of the Alaska Range (Fig. 3). The elevation of the city is approximately 130 m MSL, but the city itself is located in a bowl-shaped region, surrounded by hills to the north and northwest that can reach above 500 m. The effect of this topography is to restrict airflow and the dispersion of pollutants, increasing their potential concentrations.

Simulations are initialized using the 0.5-degree Global Forecast System (GFS) 0-hour forecasts, and run in dynamic-analysis mode using the FDDA method described in the next section. Each experimental period is broken down into an initial five-day simulation segment and subsequent five and one-half day simulation segments that overlap for one-half day. In this manner a relatively seamless dynamic analysis is produced for each 20-day episode.

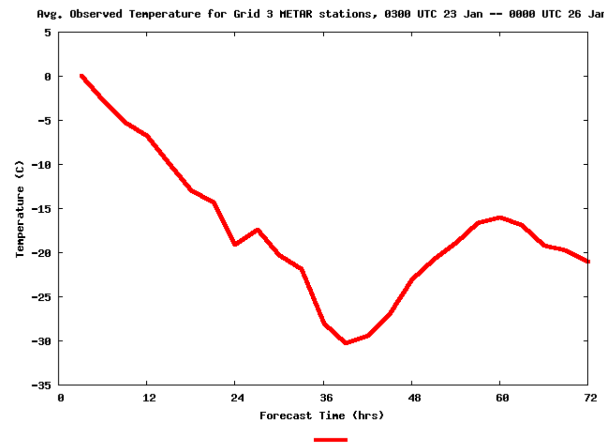

Figure 2. Average observed surface METAR temperature for stations located within the 1.333-km Grid 3 of the WRF configuration for the test period 0000 UTC 23 Jan 2008 – 0000 UTC 26 Jan 2008, in degrees Celsius.

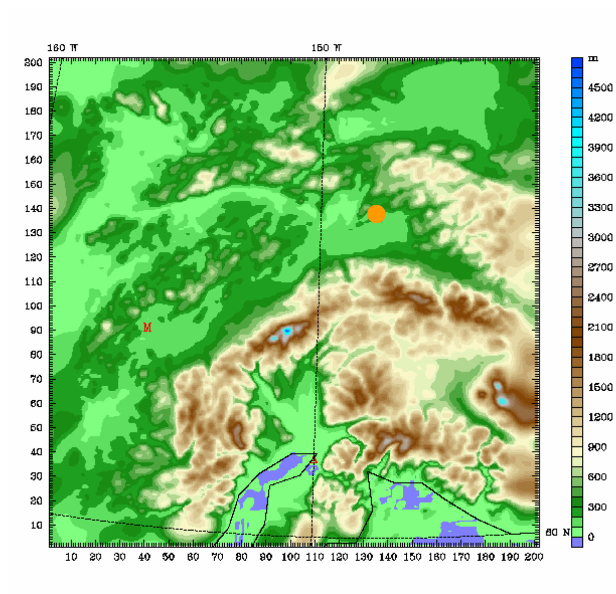

Figure 3. Model topography within the 4-km Grid 2 of the WRF configuration. Fairbanks is denoted by the orange dot to the northeast of the center of the domain. The horizontal extent of the domain is approximately 800 km.

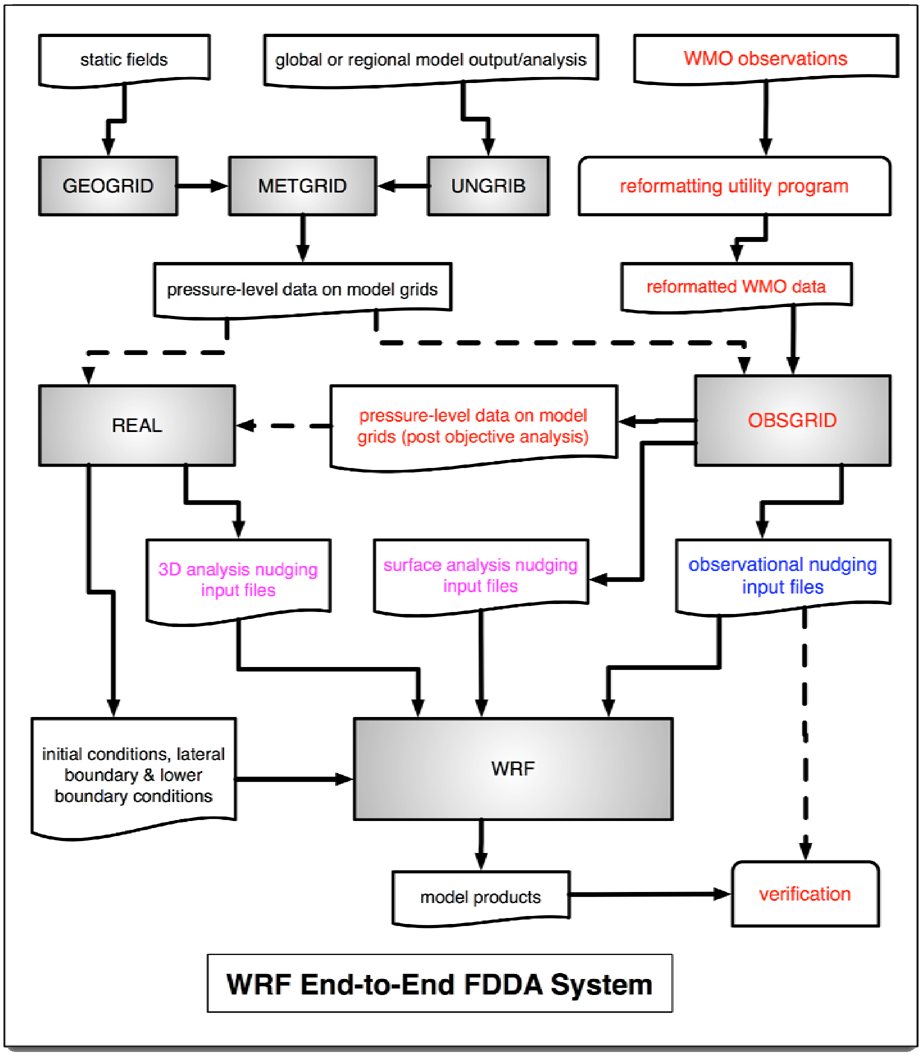

Figure 4. Diagram of the WRF End-to-End FDDA system used for this study (from Deng et al. 2009). Items in red represent new features and capabilities.

The baseline simulation uses the Noah land surface model (Chen and Dudhia 2001), which in addition to possessing a four-layer soil moisture and temperature model, can predict snow water content and snow depth, as well as the variations of parameters such as soil thermal diffusivity with snow content. The PBL scheme used was the Mellor-Yamada-Janjic turbulence scheme (Janjic 2002), which predicts vertical turbulent diffusion based on a predictive equation for turbulent kinetic energy (TKE). However, for our baseline simulations, we reduced the minimum threshold TKE from 0.1 m^2 s^{-2} to 0.01 m^2 s^{-2} (Stauffer et al. 2009). No convective scheme is used on all grids finer than 12–km resolution. The Morrison microphysics (Morrison et al. 2005) that is used on all grids was selected based on its previous application to high-latitude simulations; the scheme predicts the mixing ratios of cloud ice, cloud water, graupel, rain, and snow, as well the concentrations of cloud ice, graupel, rain, and snow. The baseline simulation also uses the Dudhia shortwave / RRTM longwave radiation schemes (Skamarock et al 2008).

3. MULTISCALE FDDA STRATEGY

In this study we used a multiscale FDDA strategy (Stauffer and Seaman 1994) as implemented in the WRF end-to-end FDDA system (Deng et al. 2009) on the outer two domains to provide improved lateral boundary conditions for the finer WRF domain(s) in order to investigate the sensitivity of the model solutions to various model physics . The type of FDDA used is Newtonian relaxation, or ‘nudging’. On the coarsest grid, a combination of nudging towards gridded analyses (‘analysis nudging’) and nudging towards specific observations in the vicinity of their valid time and location ('observation nudging') was used. On Grid 2, only observation nudging to the asynoptic one-hourly data was applied, while on Grid 3 no FDDA was applied.

The analysis nudging relaxes model fields towards 3D gridded analyses generated every 6 hours; these 3D analyses use the GFS fields as an initial background, but supplemented by the introduction of observations through an objective analysis procedure. The observation nudging procedure is the only FDDA method applied on Grid 2. Grid 3 is not affected directly by FDDA, but it is indirectly affected through its lateral boundaries with Grid 2. Thus the 1.333-km Grid 3 benefits from improved accuracy in its lateral boundary conditions due to FDDA, and the intentional absence of imposed nudging tendencies on Grid 3 allows it to be a good testbed of model sensitivity to different physics schemes.

In order to apply the multiscale FDDA procedure to WRF-ARW, two new features were developed for version 3 and/or 3.1. One is the OBSGRID package, developed by NCAR with guidance from Penn State University as part of Penn State's WRF FDDA development effort for the Defense Threat Reduction Agency (DTRA) in which an end-to-end FDDA system for WRF has been designed for public release (Fig. 4). It takes as input the gridded atmospheric / static fields created by the METGRID package of the WRF Preprocessing System (WPS) and files of observations in the MM5 'little_r' format. OBSGRID uses the METGRID output as a background for an objective analysis of those observations that pass various quality-control (QC) steps. The output objective analyses can then be used by the REAL package of WRF-ARW to generate the files used in 3D analysis nudging. Both the settings of quality control checks and the frequency of objective analysis may be specified by the user. Furthermore, OBSGRID generates text output of quality-controlled observations for both observation nudging within WRF-ARW, as well as for statistical verification.

The second new feature is surface analysis nudging, whose addition to the WRF-ARW code was also described in Deng et al. 2009. In this method higher temporal resolution surface analyses, compared to that of the 3D analyses, may be applied within the model's PBL or lower atmospheric layers. OBSGRID has also been adapted to perform QC and output the surface-analysis nudging files; for our simulations we use a three-hour frequency for the gridded surface analyses.

Parameters used to control the FDDA details such as the strength and type of nudging are found within the namelist used in the WRF-ARW simulation. The user may control the strength of the nudging coefficient by variable type and the horizontal radii of influence. Vertical weighting for surface-based observations are by default prescribed functions of model level that extend up to the predicted PBL height.

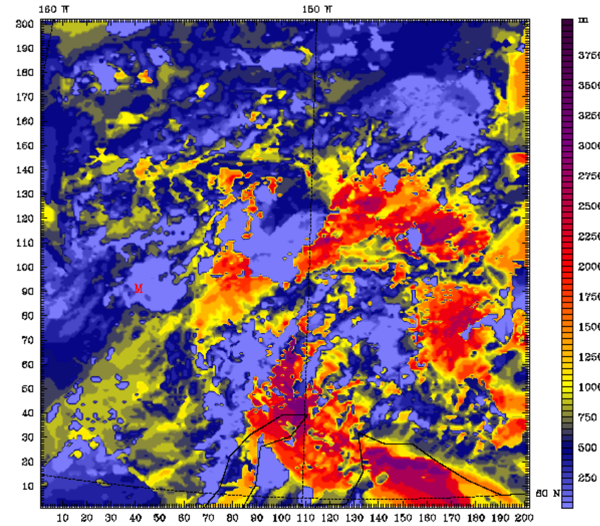

Figure 5. WRF-predicted PBL height at 1200 UTC 25 Jan 2008 (60-hour simulation time) within the 4-km Grid 2. Simulation does not include FDDA.

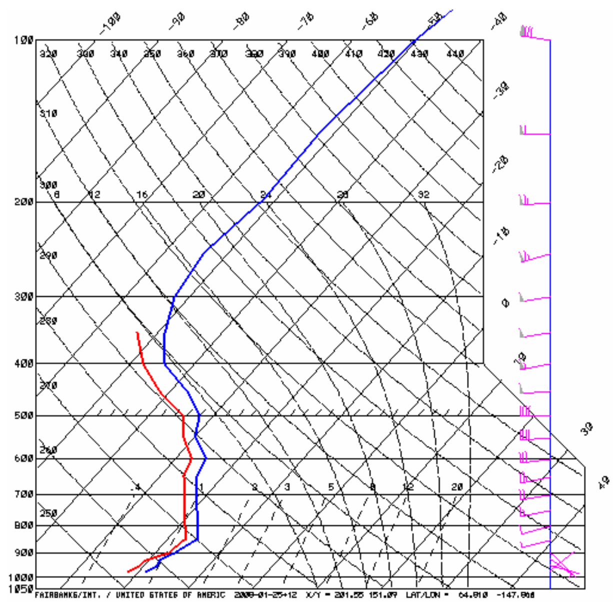

Figure 6. Observed sounding at Fairbanks, 1200 UTC 25 Jan 2008. Temperature is shown in blue; dew point is shown in red.

4. APPLICATION OF WRF FDDA TO ALASKA CASE

It was necessary to modify the default WRF FDDA in a number of ways in order to adapt it to the unique conditions of the Alaska simulations. First, in more typical meteorological simulations, it is assumed that the height at which surface observations are measured is less than the height of the lowest half-model layer, and usually some correction is applied to relate the lowest model level value to the observations. However, in this case the lowest model half layer is 2 m above the surface (and top of lowest full level at 4 m), which is actually less than the height at which surface wind components are measured (10 m). Hence rather than compute the innovations used in nudging by differencing observations with values at the lowest model half layer (possibly with a similarity-based correction), we directly difference wind observations with model wind values at the third half layer, which is very close to 10 m above the surface. Mass variables such as temperature are measured at 2 m and so can be directly differenced with values at the lowest-model half layer without any similarity adjustment.

The need for a second modification became apparent as we were doing preliminary FDDA simulations during the test simulation period from 0000 UTC 23 Jan 2008 – 0000 UTC 26 Jan 2008. The model PBL scheme showed a tendency to predict horizontal patches of PBL heights of a kilometer or more (Fig. 5), despite the fact that the time periods were the early morning hours in the high-latitude winter season. Examination of the patches showed that they tended to be associated with elevated regions of wind shear near ice-saturated regions, where the PBL scheme would generate layers of TKE. One consequence of the large values of PBL height is that the model's default surface analysis nudging and obs nudging schemes spread the influence of surface observations to large heights. However, both modeled and observed soundings at this time were quite stable (Fig. 6), and it seemed unrealistic that there would be strong correlations in the model errors computed at the surface and those at 1-1.5 km under these conditions. Indeed, we discovered that the presence of surface analysis nudging for these simulations tended to make model-predicted root-mean-square (RMS) errors worse, particularly when the verification dataset was low-level (> 750 hPa) rawinsonde data, which we hypothesized was due to the influence of surface METAR observations being spread too far above the surface in the vertical.

Therefore, we instituted a case-specific modification of the surface analysis nudging and obs nudging vertical weighting functions for the Alaska simulations. First, we redefined the vertical weighting functions to restrict the influence of surface observations to the lowest 10 m for winds and 2 m for temperature and mixing ratio, regardless of the predicted PBL height. While this improved the rawinsonde-based RMS errors, the surface METAR-based RMS errors simultaneously became worse. Cross sections of the temperature field between the two simulations confirmed that the modification had the desired effect on the model PBL structure – removing the influence of surface observations during a period during which the model had a warm bias made the model PBL even warmer (because when the influence of nudging is present, the effect of observations colder than the model is to decrease the model temperature). However, this warming effect extended all the way to the model surface, which was not desirable because it made surface temperature forecasts with a warm bias worse. This suggested that surface temperature observation innovations were not being nudged over a deep enough layer, causing them to be mixed out in the model PBL.

Ultimately we made use of a compromise method, where the influence of surface observations on nudging would be restricted by the vertical weighting function to heights of less than 225 m above the surface, regardless of the predicted PBL height. Using this revised vertical weighting function recovered most of the accuracy for predicting surface METAR observations while retaining good accuracy for predicting low-level rawinsonde observations. This vertical weighting function was used for both surface analysis nudging and the obs nudging of surface observations.

For a more general solution to using surface data for FDDA within WRF, Penn State University and NCAR have developed an FDDA design plan that will allow the user the freedom to specify vertical weighting functions of different shapes for different stability regimes and atmospheric variables, and as a function of PBL depth if appropriate.

5. INITIAL BASELINE RESULTS

We performed qualitative and quantitative verification of the baseline model forecasts for the three-day test period using observations (METAR, rawinsonde, and other synoptic and local station reports) that had passed through the OBSGRID QC procedure and verification software originally developed by NCAR. The verification of sounding observations was performed at the standard pressure levels of the background GFS analysis, which are defined every 25 hPa near the surface. The verification of surface observations was performed by comparing observations directly with the model layers corresponding to the observational height (2 m for temperature and mixing ratio; 10 m for wind components) using the software provided by NCAR, along with additional verification software developed at Penn State.

The use of the multiscale FDDA procedure clearly produces substantial improvements in the accuracy of the test period forecasts. Figures 7 and 8 compare the predictions of Grids 1, 2, and 3 with the eight surface METAR observations for stations that are located within Grid 3. The baseline simulation without any FDDA (lightest shading) contains much higher RMS errors for all meteorological variables and all grids than the runs with FDDA (darker shades; the darkest shade is the method discussed at the end of Section 4, and is denoted by 'FDDA 3' in the plots). As might be expected, Grid 1 temperature errors (Fig. 7) are reduced the most with the presence of analysis nudging (both 3D and surface) and obs nudging; the improvement is somewhat less on Grid 2 with only obs nudging. The improvement is least on Grid 3, but this is noteworthy because nudging is not directly applied to Grid 3, so all of this improvement (about 0.8 C in RMS error) is due to the use of improved lateral boundary conditions from the dynamic analysis of the coarser grids. For wind component statistics the improvement in RMS errors on Grid 3 is actually comparable to the improvement in Grid 2 errors (Fig. 8). This provides confirmation that the multiscale FDDA procedure can be used on the outer domains successfully to produce improved simulations on the finer grid(s) for the physics sensitivity tests.

A time series plot of surface METAR temperature bias errors (Fig. 9) shows that all baseline grids and FDDA procedures tend to underestimate the magnitude of the observed temperature tendencies; in other words, the models have a cold bias when the temperatures are warmer in the first half of the test period, and a warm bias during the colder second half of the test period. The use of FDDA often (but not always) reduces the magnitude of temperature biases of either sign.

A time series of model-predicted PBL height at the location of the Fairbanks station (Fig. 10) shows that the use of FDDA by itself is sufficient to reduce some of the higher PBL height predictions mentioned above, although during the warmer half of the period the use of FDDA makes little difference in predicted PBL height. Although PBL height can be difficult to verify observationally, the FDDA-predicted values of a few hundred meters certainly seem more reasonable than the non-FDDA values of one kilometer or more, especially given the cold conditions at the time.

Qualitatively, during the colder half of the three-day test period it can be seen that a simulation with FDDA does a much better job at capturing the cold temperatures developing in the Arctic air mass in the Yukon River valley in the northern part of Grid 2 (compare Figs. 11 and 12), which ultimately migrates to Fairbanks and initiates the most intense cold spell of the season. The FDDA run also does a better job at predicting the temperatures and wind flow in the southwestern part of Grid 2 and in the Prince William Sound area.

6. PRELIMINARY PHYSICS SENSITIVITY TESTS

Figure 13 shows an example of a physics sensitivity test performed on the baseline simulation, but with no FDDA applied on any domain. This particular test confirms that the combination of RRTMG shortwave and longwave radiation schemes (newly available in WRF version 3.1) improves surface METAR temperature statistics for the three-day test period by approximately a half-degree C on the 1.333-km Grid 3. We intend to use the RRTMG radiation suite in subsequent sensitivity testing using the multiscale FDDA strategy outlined above on the coarser two domains, and applied to the full 20-day episodes.

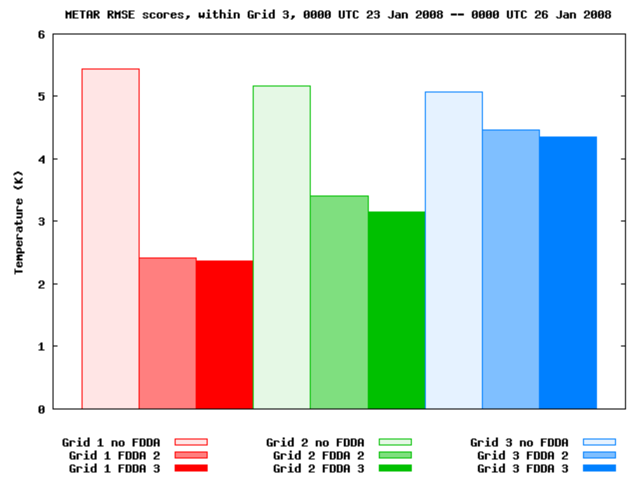

Figure 7. Surface METAR RMS errors for temperature compiled for those stations located within Grid 3 for simulations from 0000 UTC 23 Jan 2008 – 0000 UTC 26 Jan 2008. Verification statistics are computed every 3 hours during the period. FDDA 2 and FDDA 3 refer to modified FDDA schemes with vertical weighting functions restricted to model half layers below 89 m and below 225 m, respectively.

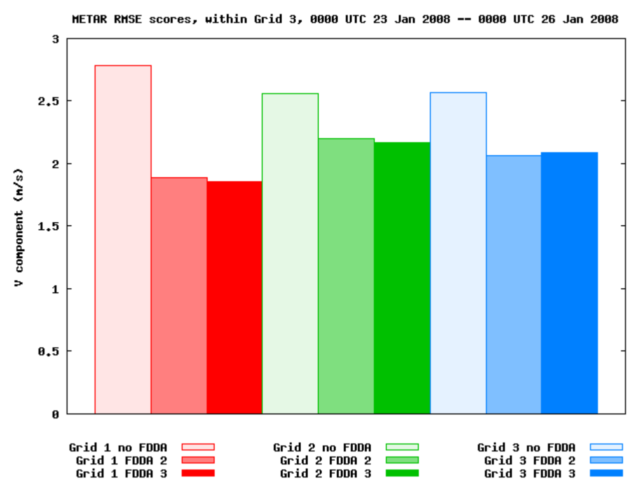

Figure 8. Same as Fig. 7, but for the v-component of wind velocity.

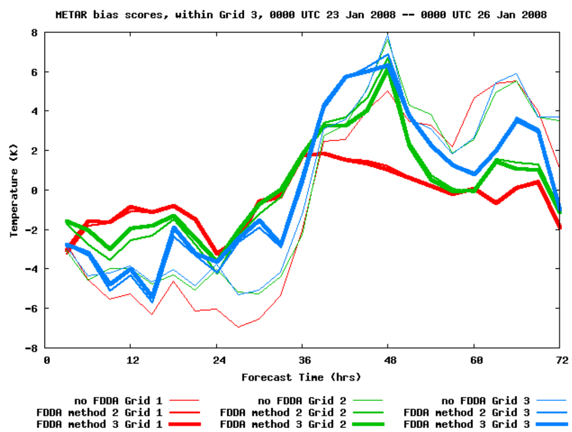

Figure 9. Time series of model-predicted temperature bias compiled for those METAR stations located within the 1.333-km Grid 3, for 0000 UTC 23 Jan 2008 – 0000 UTC 26 Jan 2008.

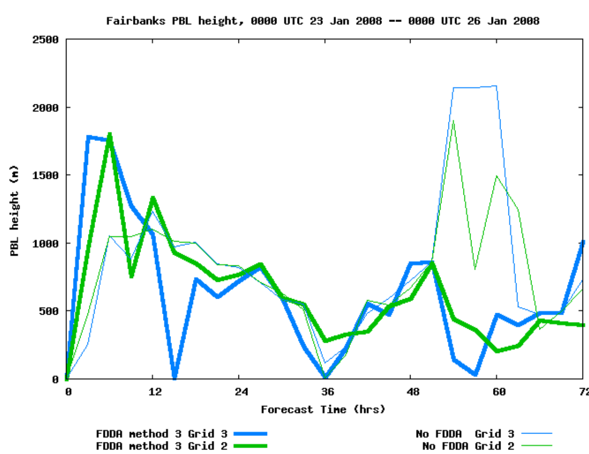

Figure 10. Time series of model-predicted PBL height for Fairbanks from 0000 UTC 23 Jan 2008 – 0000 UTC 26 Jan 2008.

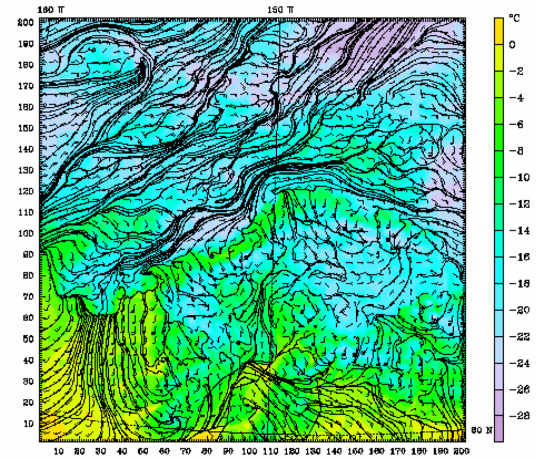

Figure 11. Model temperature at 2 m and streamlines at 10 m for the 4-km Grid 2 at 0600 UTC 25 Jan 2008 (54 hour simulation time) for simulation without FDDA.

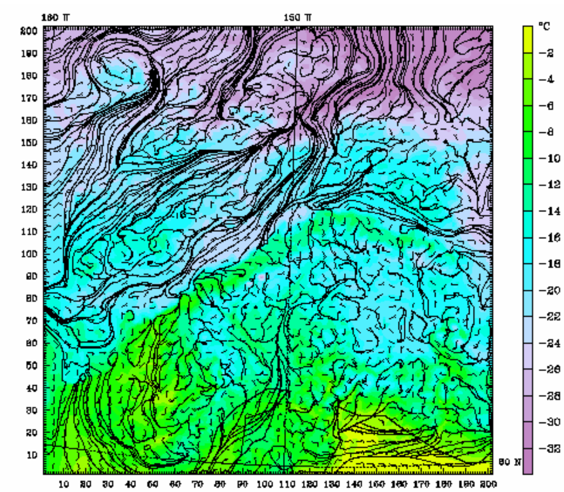

Figure 12. Same as Fig. 11, but for simulation using FDDA.

7. SUMMARY AND FUTURE WORK

We have demonstrated the capabilities of the new WRF end-to-end FDDA system for this Alaska PM2.5 study. We have also shown how the use of a multiscale FDDA system can lead to improved meteorological fields at approximately 1-km resolution that can be used for both physics sensitivity studies and as input to air quality models. However, some adaptations to the default WRF FDDA procedures had to be made to account for the extremely high near-ground vertical resolution of the Alaska WRF domains, and the predominantly stable nature of the model boundary layers.

The baseline and physics sensitivity simulations for the entire duration of each high-concentration episode are currently in progress. Plans for sensitivity tests include using the RRTMG longwave and shortwave radiation packages, Quasi-Normal Scale Elimination (QNSE) PBL scheme (Galperin et al. 2007), and the RUC land surface model. We would also like to examine the potential improvement by adding a 0.444-km nested grid domain.

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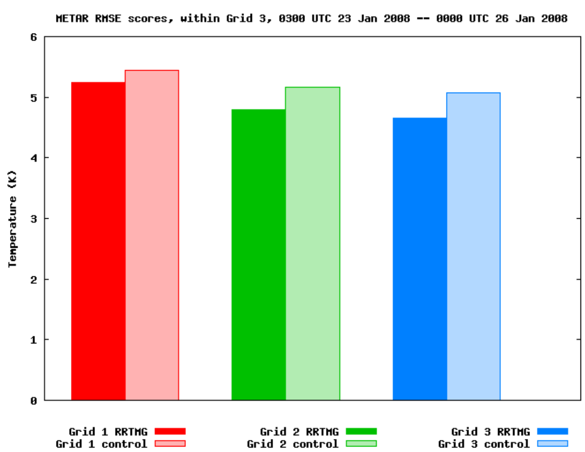

Figure 13. Surface METAR RMS errors for temperature compiled for those stations located within Grid 3 for simulations from 0000 UTC 23 Jan 2008 – 0000 UTC 26 Jan 2008. Verification statistics are computed every 3 hours during the period. RRTMG refers to a simulation using the RRTMG shortwave and longwave radiation package; control refers to a simulation using the RRTM longwave and Dudhia shortwave radiation package. Neither simulation uses FDDA on any grid.

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