EXECUTIVE SUMMARY

This final report describes work performed by Penn State for the EPA-funded Purchase Order EP08D000663 titled 'Stable Boundary Layers Representation in Meteorological Models in Extremely Cold Wintertime Conditions'. The purpose of the project was to develop, adapt, and test a methodology for stable boundary layer representation (initial onset, space/time evolution, dissipation) in three-dimensional numerical models, with a specific focus on the dark, extremely cold environments such as those in the winter in the Fairbanks, AK region. A particular concern is the frequent occurrence of very high fine particular matter (PM2.5) concentrations within the stable boundary layers that form in these conditions.

Ten tasks were defined in the Statement of Work (SOW) for this project. A summary of these tasks and a brief overview of the work completed can be found in the Appendix to this report. Two twenty-day episodes were selected from the 2007-2008 winter season to study periods of extremely cold temperatures and high PM2.5 concentrations and to evaluate model performance: one in near total darkness (14 Dec 2007 – 03 Jan 2008), and the other in partial sunlight (23 Jan 2008 – 12 Feb 2008). One baseline physics configuration and three physics sensitivity experiments were performed for each episode. The physics sensitivity experiments were used to assess the impact of different planetary boundary layer (PBL) parameterizations, land surface models, and atmospheric radiation schemes on the simulations. Each simulation used three nested grids: Grid 1 (12-km horizontal grid spacing) and Grid 2 (4-km) utilized the multiscale multigrid data assimilation strategy of Stauffer and Seaman (1994) in order to ensure the model and observations remain close over the extended duration of the simulations, and Grid 3 (1.3-km) did not use any direct data assimilation, and so was best-suited for quantifying the physics sensitivity. Grid 3, which is centered over the Fairbanks region, also possesses sufficient horizontal resolution to be used by the EPA as meteorological input to chemical and air transport and dispersion models. From the different physics packages one was to be recommended to the EPA for further mesoscale modeling of the region.

The major findings and impacts of this project are as follows:

- The use of the three-grid configuration with a multiscale, multigrid four-dimensional data assimilation (FDDA) strategy on the outer two grids and no direct FDDA on Grid 3 consistently produced qualitatively plausible atmospheric fields throughout the variety of meteorological conditions found in the episodes, despite the relatively sparse data density. Quantitatively, the multiscale, multigrid FDDA strategy led to improved root-mean-square-error (RMSE) scores for both wind and temperature on all grids. The FDDA on the outer domains had the desired effect of improving the simulations of Grid 3 without FDDA and used for physics sensitivity tests, by providing improved lateral boundary conditions.

- The best RMSE scores for the combination of both surface and sounding data required modification of the default FDDA procedure. These modifications included applying surface wind observational data to the third model vertical level instead of the lowest model level because wind observations are normally taken at a height of 10 m which is the height of the third level in the high vertical resolution configuration used here. The influence of surface observations was also restricted to approximately the lowest 100 m, instead of the top of the PBL, because the model-predicted PBL height in these simulations, based on the turbulent kinetic energy profile, was often found to be 1 km or higher. This correction applied the surface innovation (observation minus model value) in these predominantly stable boundary layers over a much shallower layer and produced improved statistical results in the lower troposphere.

- All model physics combinations tended to have a positive temperature bias on Grid 3, especially during the most extremely cold periods. All of the physics sensitivity tests tended to reduce the warm bias in comparison with the selected baseline physics package.

- Switching from the RRTM longwave / Dudhia shortwave radiation package to the RRTMG longwave and shortwave radiation package led to significantly reduced warm biases and better RMSE statistics. RRTMG was then used in all future physics sensitivity tests. The reduced warm bias seemed to be due to the longwave component, both because of direct examination of surface fluxes in the partial sunlight case, and due to the fact that the difference was more pronounced in the near total darkness episode.

- The simulation with the Rapid Update Cycle (RUC) land surface model, the Mellor-Yamada-Janjić (MYJ) PBL model, and the RRTMG radiation package was the coldest of the four physics suites tested, and had the lowest positive temperature bias and best statistics during those periods when the temperature was coldest. It was thus selected as the physics configuration of choice, since the coldest temperature conditions are those with the potential for the highest PM2.5 concentrations. However, there were periods in each episode, generally when the temperature was steadily decreasing in advance of an extremely cold period, during which the models had a cold bias. During these periods the RUC/MYJ/RRTMG configuration would usually be even colder and thus have worse magnitude temperature biases and RMSE scores. Thus, while this configuration was recommended, we also strongly recommended that the final fine-scale atmospheric data (i.e., from Grid 3) to be provided to EPA should come from an additional simulation in which FDDA is performed directly on Grid 3, in order to reduce some of this error.

- Wind component and wind speed statistics generally showed much less variability among the model physics sensitivity experiments than that seen for temperature. The MYJ/RUC/RRTMG (MRR) configuration usually produced slightly better wind statistics than the other configurations.

- Use of obs nudging for temperature and humidity (and not surface wind) on Grid 3 produced large improvements in the mass fields as expected, and also improvements in the wind fields above the surface. Results were very encouraging and suggested that a smaller (larger) time window should be used for the surface (above-surface) data assimilation. This capability present in the Penn State MM5 FDDA system has been added to the new-release version of WRF.

- In addition to this final report, deliverables to the EPA will include the full three-dimensional output at relatively fine temporal resolution (every 1 hour for Grid 1; every 12 minutes for Grids 2 and 3) for the final Grid 3 nudging simulation as well as all the baseline and physics sensitivity simulations. Model namelists, initialization files, and modifications to the model source code will also be provided.

- The development and refinement of WRF FDDA capabilities and supporting software, including the surface analysis nudging, observation nudging and the OBSGRID objective analysis and obs-nudging pre-processing code, occurred concurrently with this project. This separate development effort led by PI Dave Stauffer and funded by the Defense Threat Reduction Agency (DTRA) allowed us rapid access to the most recent and robust versions of the WRF FDDA code, and this greatly benefited this project.

- The results of the default FDDA procedures not performing well in this high vertical resolution modeling study of stable boundary layer environments motivated an additional FDDA code development effort to make the vertical influence functions of surface observations within the FDDA be a function of stability regime type, as well as to provide the user with greater flexibility in specifying the vertical influence functions. These modifications were not finalized in time to be used for this project but are scheduled to appear in the next official release of the WRF model.

- An extended abstract and oral presentation were made at the 13th Conference on Mesoscale Processes (Gaudet et al. 2009), and a manuscript based on the project is in preparation.

- Since the first draft of the final report, the Grid 3 FDDA design and simulations have been completed for both twenty-day episodes. The results showed that the use of obs nudging for temperature and humidity (but not surface wind) on Grid 3 produced large improvements in the mass fields (as expected), and also improvements in the wind fields above the surface. Results were very encouraging and suggested that a smaller (larger) time window should be used for the surface (above-surface) data assimilation. This capability present in the Penn State MM5 FDDA system has been added to the new-release version of WRF.