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STAFF EVALUATION OF A DRAFT FINAL REPORT

TITLE:	Improving the Accuracy of Mixing Depth Predictions from the Mesoscale Meteorological Model MM5
CONTRACTOR:	MCNC
PRINCIPAL INVESTIGATOR:	Kiran Alapaty
AMOUNT:	$92,481
DURATION:	31 Months

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I. SUMMARY

Accurate meteorological information is needed to support air quality modeling, which is used to predict future air quality, determine the effects from control of emissions, and formulate the State implementation plans for attaining federal standards for ozone and particulate matter. Ambient pollutant concentrations are sensitive to the mixing depth -- the depth in the atmosphere through which pollutants emitted near the surface are mixed and diluted. Therefore, this depth must be correctly characterized for reliable air quality modeling results. Meteorological models that both simulate the thermodynamics of the atmosphere and utilize meteorological observations can better characterize the spatial and temporal variability of mixing depth, winds, and other variables needed in the air quality model, compared to what could be done using diagnostic modeling of the observations.

The objective of this study was to improve the accuracy of the mixing depth estimates generated by the meteorological, state-of-the-science model widely known as MM5 and used by the ARB. It simulates the physical processes and assimilates information from meteorological measurements. MM5 was demonstrated, in developing the State

Implementation Plan for Ozone, to reproduce the significant flow features in areas of complex terrain with finer detail than would be expected from the spacing of the available observations. However, MM5 overestimated the mixing depth when used with limited observations. The contractors have investigated the numerical and physical processes in the model that affect estimation of mixing depth. They have tested and described improvements in the formulation of MM5, the handling of input data, and practices regarding model application. Application of these findings will increase the accuracy of mixing depth estimates used in the air quality models

II. TECHNICAL SUMMARY

Objective

The objective of this work was to improve the meteorological modeling capability of MM5 for accurately estimating mixing depths in California.

Background

In order to determine how to most cost-effectively meet health-based air quality standards, it is essential to understand and accurately predict the changes in ozone concentrations that will occur in response to changes in emission rates of ozone precursors. That response is simulated by air quality models that represent the combined effects of emissions, meteorological mixing and transport, chemical reactions, and removal processes for specific locations and times. This project was initiated because the air quality models require accurate meteorological data, in addition to other types of input data. Along with the wind speed, the mixing depth determines the volume into which emissions are diluted. Generally, the mixing depth is equivalent to what meteorologists call the "planetary boundary layer" (PBL), or "atmospheric boundary layer" (ABL). The PBL is that layer of the atmosphere where turbulent mixing causes the vertical transport of momentum, sensible and latent heat, and trace gases. Both the results and the source of turbulent mixing can be observed in the vertical gradients of momentum, temperature, and humidity.

The mixing depth and other meteorological information is supplied by running prognostic meteorological models (e.g., MM5) with assimilation of meteorological observations. Prognostic models mathematically represent the thermodynamic relationships between the meteorological variables to predict the evolution of the meteorological fields in response to physical forcings, such as daily heating and cooling of the surface and changes in large-scale pressure patterns. When guided by data assimilation, prognostic models provide more physically realistic fields than would be available from simple diagnostic models, which interpolate between observations using only the simplest constraints provided by physical principles, such as conservation of mass.

In California, land-sea and mountain-valley dynamics provide a rigorous test for meteorological models and difficulties supplying adequate meteorological data for input to air quality models. In central California, the mixing depth generally increases from north to south and from west to east. With the onshore northwest winds that are typical during the summer ozone season, the daytime mixing is relatively shallow at the coast. The depth increases with distance from the coast, as marine air is warmed by land surfaces and flows toward the great inland valleys, defined by the coast range and the Sierra Nevada. Within the San Joaquin Valley, the marine influence is limited mainly to the northern portion and the mixing depth is greater to the south. Along the Pacific coast the mixing depth generally decreases with latitude because the sea surface temperature decreases with latitude.

Two main questions were posed in this study. What physical processes cause mixing depths in California to differ from those in other parts of the country? What must be included in the formulation of MM5 and in the methods of application to be able to accurately represent the influential physical processes and correctly predict mixed layer depths? These questions arise from the following observations. The contrast in afternoon air temperature between the coast and the inland valleys is commonly 40° to 50°F, and afternoon temperatures often exceed 100°F in the valleys. In other areas, these conditions would commonly provide much higher mixing depths than are seen in California during ozone episodes.

To counter the growth of model errors over time, MM5 is generally applied with continuous assimilation of observed winds, temperature, and humidity. With this technique, known as four-dimensional data assimilation (FDDA), both the model predictions and the observations contribute to the solution. Generally, the observations available for assimilation are the relatively sparse National Weather Service soundings. When additional observations are needed for air quality modeling, special monitoring programs must be conducted. Observations are assimilated only above the mixed layer depth. Assimilation of observations near the surface has generally not been used because it caused inconsistencies between modeled temperatures at the surface and in the lowest layer of the atmosphere.

MM5 was applied for simulation of the meteorological conditions during the San Joaquin Valley ozone episode of August 3-6, 1990. During this period, the actual PBL depth in the San Joaquin valley was about 600 to 1,200 meters (m). When two different treatments of the PBL processes were used in MM5, without the use of special observations of upper air winds, temperature, and humidity and surface winds, the PBL depth was overestimated by 400 to 500 m. Both versions were also applied using the special observations; FDDA of the special observations provided realistic estimates of PBL depth.

Despite the tendency toward overestimation of PBL depth, MM5 is a state-of-the-science non-hydrostatic model that has been demonstrated capable of reproducing important flow features in central California when using FDDA of observations. However, there is concern regarding the ability of MM5 to simulate the PBL processes correctly in this region and accurately predict mixed layers, specifically during episodes of high ozone concentration, without relying on assimilation of extensive observations to force the solution.

Project Summary

The contractors investigated potential sources of inaccuracy in mixed-layer depths over central California, when simulated by a standard formulation of the meteorological model MM5, using data assimilation. They identified the potentially important processes and then tested and recommended changes to improve model performance. Using standard and alternative model formulations, they compared observations and simulations, to test the adequacy of MM5 in representing both surface and large-scale atmospheric processes. They also identified the factors, model formulations, and modeling practices essential for adequately representing the most influential physical processes for determining the growth of the daytime PBL over this region.

First, the contractor studied the representation of surface processes, using a 1-D PBL model to identify factors influencing performance. They developed and tested two new methodologies to improve predictions of PBL depth. One improvement is a new technique for assimilating observations of the surface layer into the model, while maintaining consistent thermodynamic relationships and modeled mixed-layer structures. The other improvement allows, within the land surface parameterization, explicit representation of the latent heat flux from vegetation, thereby improving the estimates of total latent heat flux and the partition of available energy between latent and sensible heat. These two new methods will require further testing in a 3-D mesoscale model.

Next, using the MM5 with a nested-grid configuration, the contractor studied the effects of large-scale atmospheric processes on PBL growth. They performed several sensitivity studies to understand process interactions and identify the significant and insignificant aspects of model configurations. These studies focused on the effects of (1) large-scale dynamics and thermodynamics, (2) vertical resolution, (3) initializing the marine atmospheric boundary layer, (4) mesoscale circulations in the Sacramento Valley, (5) different PBL turbulence parameterizations, and (6) including a four-dimensional data assimilation strategy.

They found that increasing model vertical resolution from 32 to 62 layers did not lead to a significant increase in the proficiency of the model estimations. Inclusion of a large outer domain, covering the East Pacific Ridge, helped to yield better model solutions in the inner domains. Removal of analysis nudging in coarser domains in the lowest 1.5 kilometers also helped the model solutions in the innermost domain in which no nudging was performed. Boundary layer initialization over the marine environment did not significantly improve the model solutions. Finally, application of a physically robust PBL scheme resulted in further improvements in the model predictions, compared to a simple boundary layer scheme. Thus, an enhanced model configuration was identified that provided improved mixed-layer predictions over central California and confirmed a vertical resolution of 32 layers was adequate.

III. STAFF COMMENTS

The purpose of this project was to improve the meteorological modeling capability and accuracy of MM5 for estimating mixing depths in California. This would provide needed data for regulatory air quality modeling and assist decision-makers in understanding how ambient ozone concentrations will change in response to changes in emissions of ozone precursors.

Comments are provided by staff of the Research Division. Additional comments may be provided by staff of the Planning Technical Support Division’s air quality modeling sections prior to the meeting.

The contractors provided a well-organized and effective work plan and executed that plan faithfully. They responded effectively to difficulties and discovered and corrected some existing errors in model code. In some cases, their work efforts went beyond the strict scope of the task definitions in order to meet all of the objectives of the study.

Other comments are mostly minor and mainly editorial in nature; however, some general comments and questions are offered.

- An abstract and Executive Summary should be added.

- In addition to the definitions included in the text, the report should include a glossary of mathematical symbols for ease of reference.
- Meteorological terms should be defined.
- In the first paragraph of the introduction, the final sentence might be interpreted to mean that mesoscale meteorological models are capable of providing adequate input data to air chemistry models without any observational data for assimilation. If that is the intended statement, it should be clarified and supported with references or examples.
- Editorial changes are requested to improve readability of sections 3.1 and 3.2. Needs include transition and introductory paragraphs for some subsections and perhaps some reorganization. ARB staff will work with the author to make these changes. The organization of section 3.3 is clear and logical and would provide a good model for section 3.1. In section 3.3, the initial focus is on the physical processes influencing the depth of the PBL. Consideration of the model formulation and application (e.g., resolution, domain) necessary to simulate those processes naturally follows. The initial discussion of the large-scale processes orients the reader and provides the introduction for hypotheses. Description of the methods (simulations) used to test the hypotheses also follows naturally. In section 3.1, the specific physical processes considered, and the hypotheses regarding their importance to determination of the PBL depth, should be discussed prior to describing the modeling effort and results.

IV. STAFF RECOMMENDATIONS

Staff recommends the Research Screening Committee accepts this draft final report, subject to inclusion of appropriate revisions and additions in response to the staff comments, and any changes and additions specified by the Committee.