

DRAFT FINAL REPORT FOR

Project: H23-2003-C2

MM5 Modeling for TexAQS 2000 with GOES Satellite Data Assimilation

Submitted to the

Houston Advanced Research Center (HARC)

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September 2004

1 Introduction

The following report summarizes the activities and results for project *H23-2003-C2*, the assimilation of Geostationary Operational Environmental Satellite (GOES) data in MM5 (Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model Version 5) at University of Alabama in Huntsville. While the utilization of GOES data has proven to be useful and demonstrates improvements in the performance of MM5, the report also points out the areas that need further attention. The study covers the period of August 23 through September 1, 2000, which coincides with Texas Air Quality Study 2000.

Some of the results from this project have been summarized in McNider et al. 2004, Biazar et al. 2004, Haines et al. 2004, and Han et al. 2004. The manuscripts will be attached as appendix to this report. In the following, after a short introduction we will proceed with a detailed description of the satellite assimilation technique used in this study. The description will detail the modifications we made to our techniques and also the addition of a new soil option in MM5 with improved numerical techniques. Then a short description of the satellite retrievals will be presented. Finally, the results from this study will be presented and will be followed by a discussion.

1.1 Scientific Background

There are two important but observationally uncertain parameters in the grid averaged surface energy budgets of mesoscale models – surface moisture availability and thermal heat capacity. Given the importance of surface heating in determination of boundary layer characteristics, the errors in the specification of these parameters have profound impact on the model predictions. We have been developing techniques (McNider et al. 1994, Lapenta et al. 1999) for assimilating Geostationary Operational Environmental Satellite (GOES) skin temperature tendencies during the mid-morning time frame to improve specification of surface moisture.

In the past surface moisture availability in models such as MM5 has been specified based on land use classification and climatological conditions or through land surface hydrology models. Use of the first technique leads to errors due to inaccuracies in relating land use types to moisture and due to deviations from climatological norms. The second technique – the use of a surface hydrological model while perhaps an improvement still requires specifications of difficult to quantify parameters such as root zone moisture, plant physiological characteristics such as root uptake, stomatal resistance, soil hydrologic conductivity, and antecedent precipitation.

Heat capacity of the surface in models such as MM5 has also been specified based on land use classification. While specification of heat capacity is relatively straight forward for single composition objects such as water, stone, concrete etc. The practical specification of heat capacity on a 4 km or 12 km grid where the surface is made up of everything from buildings, to streets, to grass, to trees to standing water is extremely

difficult. This is especially true in the highly heterogeneous urban and suburban environment.

In our techniques (discussed below) we have used satellite observations of surface skin temperature as an observational constraint to correct initial land use guesses of grid moisture availability and heat capacity. The satellite pixel radiative measurements also provide a natural averaging process needed for the grid average values in the model. In the past, satellite assimilation techniques for adjusting moisture availability have been tested in both case study modes (McNider et al. 1994, 1995) and operational modes (Lapenta et al 2000) and have shown to improve model performance. In this project, we have used satellite assimilation observational constraints, to greatly improve the characterization of the surface energy budget on fine spatial scales for the TEXAQS 2000.

1.2 Introduction to the Satellite Assimilation Technique

Early in the development of boundary layer mesoscale models (Deardorff 1978; Wetzel 1978; McCumber and Pielke 1981; Zhang and Anthes 1982) and later in global scale models (Dickinson 1984; Sellers et al. 1986) it was recognized that the correct specification and partitioning of surface fluxes were critical to the accurate characterization of boundary layer behavior. Additionally, spatial variations in surface fluxes and net radiation can lead to organized mesoscale circulations that often dominate the evolution of the regional atmospheric state affecting precipitation patterns and quantity (Koch et al. 1997; Lynn et al. 1998; Avissar and Pielke 1989; Rabin et al. 1990; Pielke et al. 1991). Additionally, the amount of radiation coming into the boundary layer and surface which is a function of cloud transmission and surface albedo is critical to boundary layer behavior and photochemical reactions.

In air quality simulations these boundary layer processes control mixing heights (impacting pollutant concentrations), temperatures (controlling thermal decomposition of PAN and other organic nitrates) and photolysis rates. Because of the importance of the surface energy budget and uncertainties in its implementation within models, we and other investigators have attempted to develop techniques to use satellite information to improve the fidelity of the land-surface models (Price 1982; Carlson et al. 1981; Wetzel et al. 1984; McNider et al. 1994; Gilles and Carlson 1995; McNider et al. 1995; Jiang and Islam 1999).

A prognostic equation for the surface skin temperature, based on the surface energy budget, can be written in the following form (Wetzel 1984; Pielke et al. 1991; Smirnova 1997),

$$C_b \left(\frac{dT_G}{dt} \right) = (R_N + H + G) + E \quad (1)$$

where dT_G/dt is the rate of change of the land surface temperature (LST), C_b the surface heat capacity, R_N is the net radiation (including incident shortwave, incoming

atmospheric longwave, and outgoing longwave), H is the sensible heat flux, G is the soil heat flux, and E is the latent heat flux.

In the actual application of such an energy budget in a regional model, either separate budgets must be developed for vegetative canopies (perhaps further decomposed into deep rooted and shallow rooted vegetation), bare soil and standing water (McCumber and Pielke 1981; Smirnova 1997). Or, a composite surface must be formed which reflects the aggregate effects of these distinct components (Wetzel et al. 1984). In this investigation we are taking the philosophy that the simpler composite approach is preferred.

This is based on three considerations:

1. For short-term weather predictions or after the fact air pollution case studies the critical partitioning of processes which allow long-term unadjusted runs that conserve water and energy are not needed. On the other hand GCM's must accurately keep track of water over many months or years of simulation; thus, it is imperative that they have detailed soil moisture models, hydrology and vegetative models.
2. The radiatively resolved pixels from satellite imaging sensors provide a natural integration consistent with a grid average composite.
3. It makes analytical manipulation and inversion of surface energy budget equations easier (see McNider et al. 1994) facilitating use of satellite data.

Previous investigators (see Carlson 1986 and Wetzel et al. 1984) have looked at a combination of a range of uncertainty in parameters affecting terms in the surface energy budget and sensitivity to this range of uncertainty. For the clear sky case, where net radiation can be adequately specified, Fig. 1 (taken from Carlson 1986) shows uncertainties in moisture availability and thermal inertia represent the largest potential errors in the behavior of the energy budget. For example, the likelihood of missing the wind speed by 10 m s^{-1} is much less than missing the specification of moisture availability and thermal inertia over the ranges shown in Fig. 1. Carlson et al. (1981) in an important early remote sensing study attempted to use two pieces of information (a polar orbiter daytime and nighttime IR measurement of temperature) to solve for moisture availability and thermal inertia. Wetzel et al. (1994) used the sensitivity to moisture availability to hypothesize that mid-morning LST tendencies could be used to infer moisture availability. We utilized a similar approach to formulate a satellite assimilation technique (McNider et al. 1994) that assigns all of the difference between a satellite (GOES) LST tendency and a model tendency to errors in the evaporative flux and subsequently inverted surface similarity relations to adjust moisture availability. This assimilation technique has been shown in case study tests and in a semi-operational environment to improve surface energy budget performance (Lapenta et al. 1999). Diak and Whipple (1995) also showed that LST tendencies from GOES could be used to estimate the partitioning of latent and sensible fluxes.

Just as Wetzel (1984) and Carlson (1986) in their sensitivity studies showed that moisture was most important in the mid-morning time frame, they also showed that LST tendencies were most sensitive to thermal inertia during the evening (Fig. 1). As part of this study, in a manner analogous to our utilization of GOES data to recover moisture

availability in the morning time frame, we have used GOES evening LST tendencies to adjust the bulk heat capacity in the surface energy budget.

Discussion & Recommendations

In this project we implemented satellite assimilation techniques in MM5 to recover grid-scale moisture availability and heat capacity for the TexAQS-2000 modeling period of August 23 through September 1, 2000. We modified our techniques and some of the numerics within MM5 to achieve optimum model performance. The results are promising and have shown improvements over the standard use of MM5.

By moisture availability adjustment we improved the model prediction of daytime temperatures. Both skin-temperature predictions and 2-m temperature predictions show better agreement with the observations. It also improved the prediction of BL heights. By adjusting the moisture availability alone, while the daytime temperature predictions were improved, the nighttime cooling of the surface was not adequate. Recovering the heat capacity from the afternoon skin-temperature observations seems to remedy this problem and our final results (adjusting both moisture availability and bulk heat capacity) exhibited good agreement with the observation. However, heat capacity adjustment considerably adds to the computational cost. During the time period when heat capacity is adjusted the atmospheric radiation calculation has to be performed more frequently. Also during this period many smaller soil time steps is needed to avoid numerical errors. In the final simulations, however, the BL height predictions seem to have suffered. In our final simulations the model over-predicted the BL heights in general.

The early satellite retrievals we used had lower albedo and higher insolation value for the cloudy regions. This problem was caused by the lack of correction for GOES sensor degradation in the retrievals. In our latest simulations we have used the reprocessed data which corrects for this. The correction is causing higher values for albedo products and lower values for the insolation over the cloudy regions. This could be one of the causes for faster drying of the surface, as in general less energy is reaching the surface over the entire region. Cloud contamination in the retrievals is also an issue that needs to be aware of. Therefore, on days where there are patchy sub-pixel scale clouds over the region this technique is not recommended.

While our technique is only applied to grids with clear sky, the use of it under complete clear sky is recommended. We also recommend the use of recycling with respect to the recovered heat capacities. Since the surface heat capacity does not exhibit large variations from day to day, the model can be initialized with the recovered values from a previous run. This will eliminate the high computational cost associated with the heat capacity retrieval. A recycling option has been added to MM5 for both moisture availability and heat capacity.

One area that needs more attention is the examination of the surface fluxes in these results. As a matter of fact by examining the fluxes we found out about the numerical

errors propagating through ground heat flux and causing the extreme nighttime warm bias in the early results. This led to introducing a new soil option with improved numerics in MM5. We are planning a re-examination of the partitioning of the flux terms within the surface energy budget.