Final Report

MM5/RAMS Fine Grid Meteorological Modeling for September 8-11, 1993 Ozone Episode

Work Assignment Number 31984-12
TNRCC Umbrella Contract Number 582-0-31984

Prepared for:

Texas Natural Resources Conservation Commission
12118 Park 35 Circle
Austin, Texas 78753

Prepared by:

ENVIRON International Corporation
101 Rowland Way, Suite 220
Novato, California 94945

Mission Research Corporation/*ASTER Division
PO Box 466
Fort Collins, Colorado 80522

31 August 2001

Table of Contents

Introduction

The Texas Natural Resource Conservation Commission (TNRCC) is developing an emissions control plan for the Houston/Galveston (H/G) area. Ozone modeling of the H/G area is being performed with the Comprehensive Air-quality Model with extensions (CAMx) and a photochemical modeling database developed by TNRCC. The meteorological inputs were generated using the SAIMM hydrostatic meteorological model which assimilated available meteorological observations. The SAIMM is rather outdated by today's standards. The original SAIMM wind fields did not agree well with observations, so the nudging coefficients were increased in the data assimilation until an "adequate" level of agreement was reached. The level of nudging that was used in the four dimension data assimilation (FDDA) was much stronger than typically used and may have interfered with the model's ability to represent the land/sea breezes and other meteorological features.

Examination of the final meteorological fields from SAIMM showed other undesirable characteristics. The surface wind fields demonstrated many anomalous divergent zones that could not be explained from a physical perspective. By reviewing the reports produced by SAI for that project, we were able to deduce that the divergent zones were produced by the combination of the data analysis scheme and the four-dimensional data assimilation scheme used in the runs.

Therefore, a previous project used the Regional Atmospheric Modeling System (RAMS) to replicate the 6-11 September 1993 episode in hopes of improving the wind field. This period was simulated with RAMS at a 4-km grid resolution. Several sensitivity experiments were performed that varied the strength of the four-dimensional data assimilation and the soil moisture initialization. The RAMS meteorological simulation that was chosen for air quality modeling exhibited very good temperature and wind verifications. However, there were still some discrepancies in the wind field that may have affected the photochemical model performance. Some of these discrepancies were attributed to the need for even higher model resolution especially along the Gulf coast and the Galveston Bay region.

The purpose of this work assignment is to produce new wind fields for the 6-11 September 1993 episode using RAMS at about a 1 km grid resolution and to compare these results with equivalent simulations from the Penn State/NCAR Mesoscale Model Version 5 (MM5).

The time schedule for this project was very short, about 6 weeks from the starting date to the submission of the draft report. As the simulations that were performed were rather large, the schedule drove the number and types of test and sensitivity simulations that could be performed. We will allude to this through the remainder of the report and have some suggestions at the end as to the types of sensitivity runs that would be helpful given additional time.

RAMS Description

RAMS, which was developed at Colorado State University and MRC, is a multipurpose, numerical prediction model that simulates atmospheric circulations ranging in scale from an entire hemisphere down to large eddy simulations (LES) of the planetary boundary layer. It is most frequently used to simulate atmospheric phenomena on the mesoscale (horizontal scales from 2 km to 2000 km) for applications ranging from operational weather forecasting to air quality regulatory applications to support of basic research. RAMS has often been successfully used with much higher resolutions to simulate boundary layer eddies (10-100 m grid spacing), individual building simulation (1 m grid spacing), and direct wind tunnel simulation (1 cm grid spacing). RAMS' predecessor codes were developed to perform research in modeling physiographically-driven weather systems and simulating convective clouds, mesoscale convective systems, cirrus clouds, and precipitating weather systems in general. RAMS' use has increased to more than 140 current RAMS installations in more than 40 different countries.

In the beginning, RAMS was run exclusively on the NCAR CRAY-1 machine. That machine's small central memory (1 Mword or 8 Mbytes) forced various design constructs that limited its application to what we would consider today to be small runs. When computers with significantly more memory became available we re-wrote the entire RAMS code to removed obsolete features. The first version of the "new" RAMS was released in 1988 as version 0a, and the first widely distributed version, version 2c, was released in 1991.

The RAMS developers were among the pioneers in modifying atmospheric models for distributed-memory parallel computer platforms. The development of the first parallel version of RAMS was begun at CSU in 1991. An essentially complete version was finished in 1994, support for MPI was implemented in 1995, and an installation of a prototype operational version of the parallel RAMS at Kennedy Space Center was accomplished in late 1995.

The current version of RAMS that is released to the general RAMS user community is version 4.4. This is the version that was used on these new high resolution simulations.

MM5 Description

The Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) is the latest in a series that developed from a mesoscale model used by Anthes at Penn State in the early 70's that was later documented by Anthes and Warner (1978). Since that time, it has undergone many changes designed to broaden its usage. These include (i) a multiple-nest capability, (ii) nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale, (iii) multitasking capability on shared- and distributed-memory machines, (iv) a four-dimensional data-assimilation. MM5 uses a terrain-following σ_p-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulations. Sigma surfaces near the ground closely follow the terrain, and the higher-level sigma surfaces tend to approximate isobaric surfaces.

MM5 has generally not been used for horizontal grid spacings as fine as 1 km. Until this project, we have not used the model ourselves at this high resolution and, in fact, have had reports from users that MM5 frequently crashes at these higher resolutions. It is hypothesized that the type of non-hydrostatic scheme that MM5 uses is responsible for this limitation. While we are confident that MM5 can run with a 4-km grid spacing, we were unsure that it would work at a 1 km spacing for these Houston/Galveston runs.

As it turned out, the high resolution runs did finish. However, as is shown in the qualitative results later, both the 4 and 1.33 km grids showed random convective cells that affected the integrity of the simulations.

We employed MM5 Version 3 Release 4 for these simulations.

RAMS Grid Structure

For the simulations of the 6-11 September 1993 period, the RAMS grids were configured identically to the previous project except an additional nested grid of 1.33 km horizontal spacing was added. We used a 16-km grid spacing over the regional-scale modeling domain area depicted in Figure 1. This enabled us to match very closely the grid spacing and location of the CAMx grid points for the regional photochemical simulation. This 16-km grid was surrounded by a 48 km spacing coarser grid covering much of the central U.S. and the Gulf of Mexico. Our experience has shown that the meteorological results are greatly enhanced if a significant portion of the synoptic scale is included in the simulation domain, rather than just forced in through the boundary conditions or the 4-dimensional data assimilation scheme.

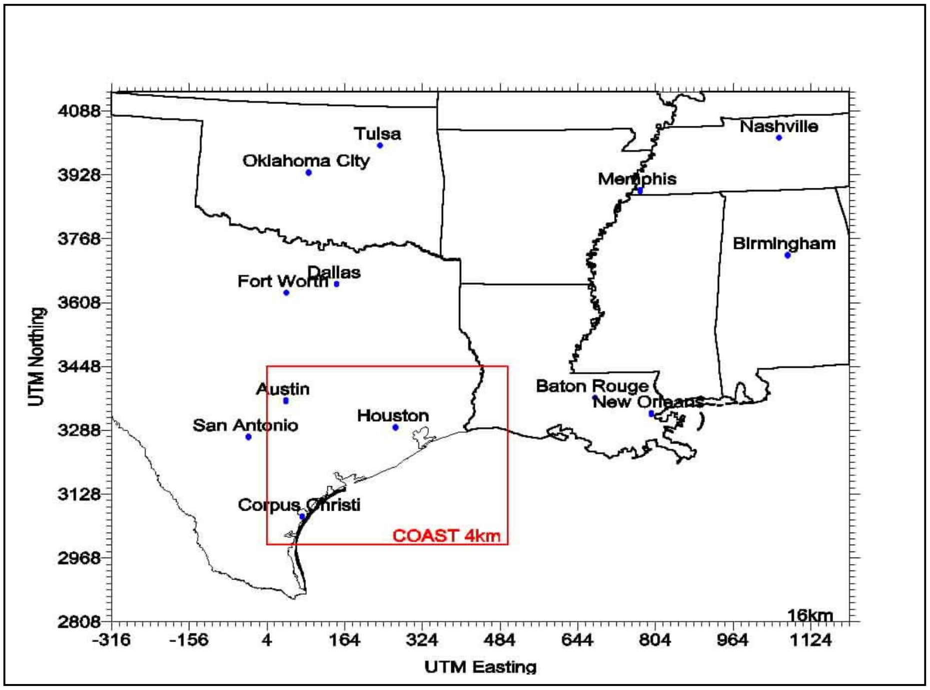


Figure 1 COAST domain locations

For the vertical structure, RAMS was configured to run all grids with 41 coordinate levels with the lowest wind and temperature level at about 10 m AGL, then smoothly stretching to a maximum of about 1000 m grid spacing. The top of the model was placed at about 20 km MSL to ensure that the various synoptic scale features such as the sub-tropical jet stream (which is located about tropopause level) are adequately resolved in the simulation domain. Although the upper level jets are not directly important in the low-level transport of ozone and its precursors, the jets do affect the low-level pressure patterns which control the low-level winds.

Table 1 summarizes the RAMS grid configuration. Care was taken to ensure that the RAMS grids was completely cover the corresponding CAMx grid and allow a buffer zone of at least three grid points around the horizontal boundaries.

Table 1 RAMS grid configuration for the new Houston/Galveston runs.

Grid	# of X points	# of Y Points	Vertical Levels	Δx (km)	Δy (km)	Δz (m) (Lowest)	Δt (s)
1	54	50	41	48	48	10	90
2	104	92	41	16	16	10	45
3	130	118	41	4	4	10	15
4	116	116	41	1.33	1.33	10	7.5

Figure 2 depicts the four RAMS grids.

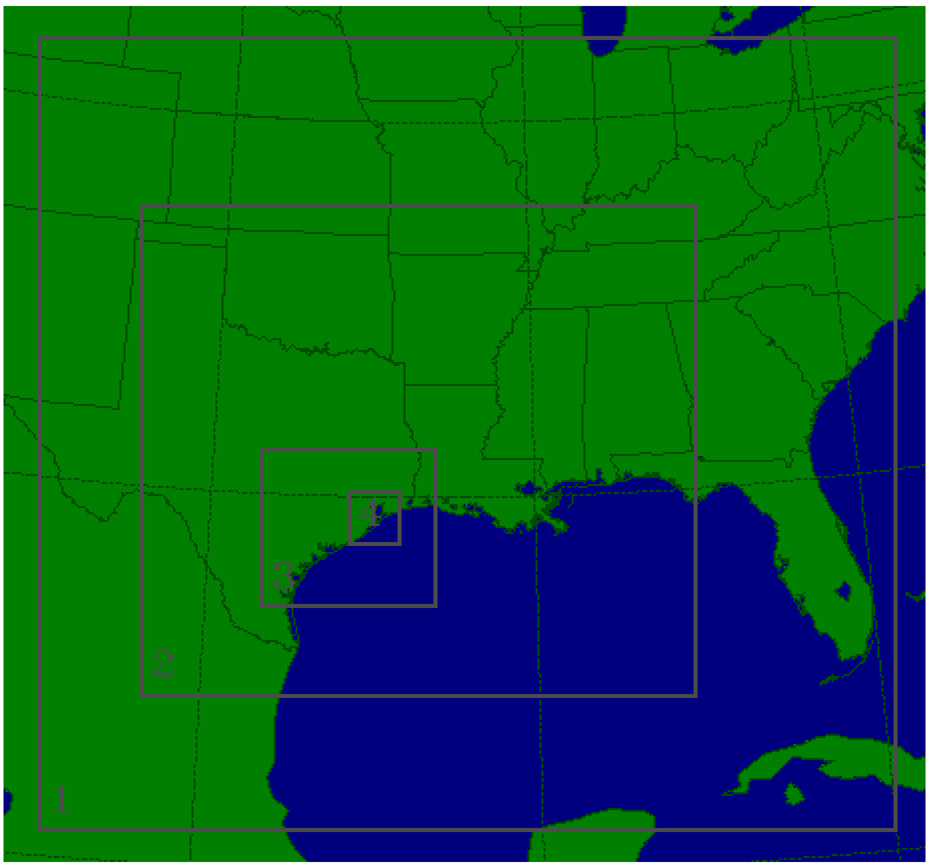


Figure 2 RAMS grid configuration for the 4-grid run.

Table 2 RAMS vertical grid levels.

RAMS Layer Interface Heights (m)	CAMx Layer Interface Heights (m)
19700.	
18700.	
17700.	
16700.	
15700.	
14700.	
13700.	
12700.	
11700.	
10700.	
9700.	
8700.	
7700.	
6730.	
5800.	
5020.	
4380.	.
3840.	
3400.	.
3030.	3030.
2715.	
2410.	
2120.	2120.
1850.	
1595.	
1380.	1380.
1200.	
1030.	
870.	
720.	720.
590.	
480.	
380.	380.
290.	
220.	220.
165.	
120.	
80.	80.
46.	
20.	20.

MM5 Grid Structure

For the simulations of the 6-11 September 1993 period, the MM5 model had a similar grid configuration to the RAMS grids. Because of the different projections (RAMS: rotated polar-stereographic; MM5: Lambert-Conformal) and the fact that MM5 is limited to a 3:1 grid nesting ratio, the domains were not be identical. We chose to have the 4 and

1.33 km grid to be as similar as possible between the two models. MM5 then had 12 and 36 km coarser grids. The following table summarizes the MM5 grid configuration.

Table 3 MM5 grid configuration for the new Houston/Galveston runs.

Grid	# of X points	# of Y Points	Vertical Levels	Δx (km)	Δy (km)	Δz (m) (Lowest)	Δt (s)
1	72	66	41	36	36	10	90
2	139	124	41	12	12	10	45
3	139	118	41	4	4	10	15
4	127	118	41	1.33	1.33	10	7.5

The following figure depicts the MM5 horizontal grid structure.

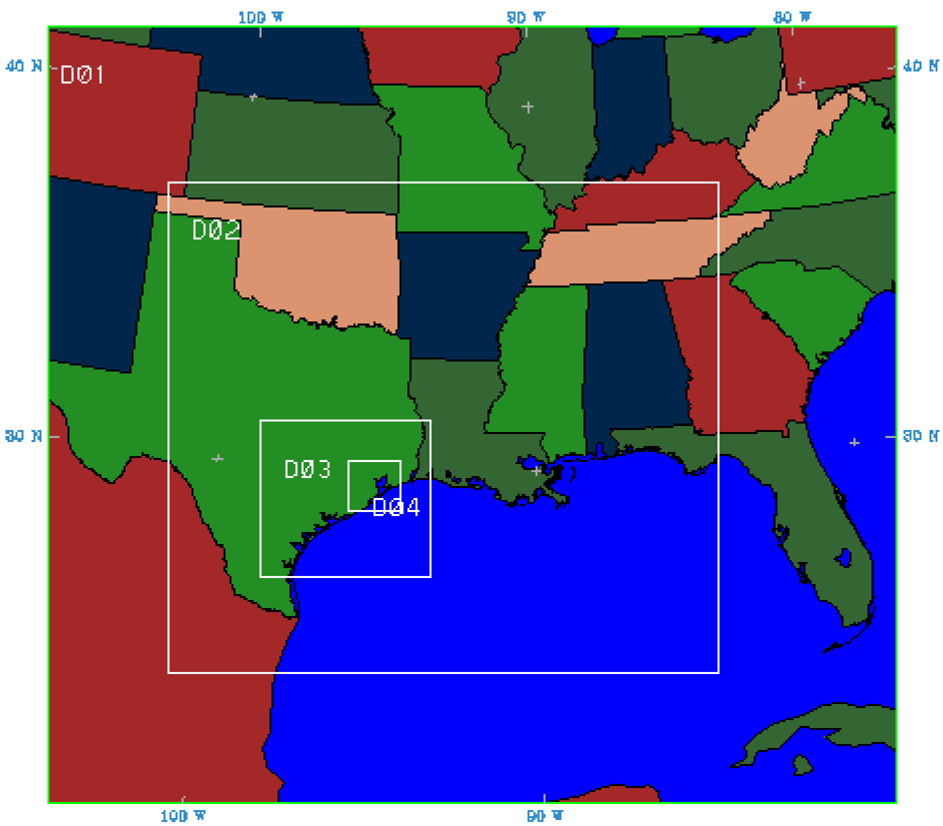


Figure 3 MM5 grid configuration for the 4-grid run.

In the vertical, MM5 was configured to match the RAMS vertical levels as closely as possible. This is somewhat more difficult to do, since MM5 is a terrain-following pressure coordinate, rather than terrain-following height like RAMS and CAMx. We chose to configure MM5 with the following σ_p levels: 41 sigma-p levels with top pressure of 10mb:

Table 4 MM5 vertical sigma-p layer interfaces.

1.000	0.998	0.995	0.990	0.985	0.980	0.975	0.965
0.955	0.940	0.925	0.910	0.895	0.875	0.855	0.835
0.810	0.785	0.755	0.725	0.695	0.660	0.625	0.590
0.540	0.485	0.425	0.360	0.300	0.250	0.200	0.160
0.125	0.100	0.075	0.050	0.035	0.025	0.015	0.010
0.000							

These sigma levels were determined by converting the RAMS height levels to equivalent pressure levels by assuming a hydrostatic base state of:

- surface pressure of 1000mb
- model top at 50mb
- surface temperature of 295K
- lapse rate of 50K/lnP (roughly 6.5K/km)

Using this base state, and the hydrostatic relation, one can cast the sigma-p equation:

$$\sigma_p = \frac{(p - p_{top})}{(p_{sfc} - p_{top})}$$

in terms of the base state and Cartesian height. The sigma-p levels used were computed from the RAMS sigma-z heights, rounded to 3 significant digits.

Input data access and preparation

For these simulations, we used the same input data as used on the previous RAMS simulation project. The meteorological input data to the meteorological models can be grouped into three categories:

Large scale gridded analyses: Global analyses of meteorology are available from the National Centers for Environmental Prediction (NCEP). We used the NCEP/NCAR Reanalysis data. The parameters of wind, temperature, and humidity are analyzed on pressure levels (20 levels extending from 1000 mb up to 10 mb) on a 2.5 degree latitude-longitude grid. These data are archived every 6 hours and serve as a first guess field for the data analysis. We accessed this data from the National Center for Atmospheric Research (NCAR).

Standard NWS observations: The rawinsondes and surface observations reported by the NWS and other national meteorological centers are also archived at NCAR. The rawinsondes are reported every 6 hours and the surface observations are archived every three hours. These data were accessed for the 6 day period.
Special observations from the COAST/GMAQS monitoring sites: Special observations taken in August/September 1993 from the GMAQS/COAST monitoring sites were included in the data analyses and FDDA. These observations included surface observations, wind profilers, and a rawinsonde. However, on the previous RAMS project, upon investigation it appeared that virtually all of the wind profilers and the rawinsonde were no longer available by the September episode. Therefore, we used only the available surface observations.

On the previous RAMS project, all NCAR and COAST observational data were processed with our quality control algorithms. MRC has developed a QC package which consists of three separate schemes: 1) internal consistency checks, 2) "buddy" checks, and 3) "first-guess field" checks.

The internal consistency checks consist of basic sanity and range checking of the observational data along with the physical constraints of hydrostatic balance. The buddy checks will compare a station's value with that of its neighboring stations. The checks versus the first-guess fields will compare an observation against the large-scale gridded pressure data analyses. At any of these three stages, observational data values can be flagged as missing, bad, suspect, or corrected.

1. RAMS

After the input meteorological observational data was quality-controlled, it was combined with the large-scale gridded analyses to produce a complete data analysis for RAMS initial conditions and the 4-dimensional data assimilation scheme. RAMS/ISAN (Isentropic Analysis package) was used for the analysis for the RAMS model. ISAN is a hybrid isentropic/terrain-following height coordinate scheme which uses a Barnes-type objective analysis algorithm.

Other types of input data which describe the surface characteristics are also necessary for the execution of RAMS. We possess archives of high-resolution topography and land use for the regional scale domain. These datasets are global and have about a 1 km resolution.

2. MM5

The terrain data used in MM5 originates from 30 second USGS data which has be averaged to several lower resolutions. The terrain height at a given grid point is interpolated from an appropriate resolution terrain data set. Vegetation/landuse data also originate from 30 second USGS data which has been reduced to several lower resolutions. The dominant landuse category is chosen for each model grid point.

Initial, boundary and nudging data are a combination of gridded analysis from the NCEP reanalysis project blended with surface and upper air observations. The reanalysis gridded fields are available at 2.5 degree horizontal resolution and time resolution of 6 hours. Upper air observations were obtained from the NCAR ADP archive which has a twelve hour time frequency. Surface observations were also obtained from the NCAR ADP archive and is available at 3 hourly intervals. The special COAST surface observations were also used at a 3 hourly frequency.

MM5 used its own data analysis package for its input data analysis, which consists of a multi-pass Cressman analysis. The observations are blended with the gridded data using a Cressman style objective analysis on pressure levels. A variety of quality control tests are performed to remove spikes from temperature and wind profiles and to remove superadiabatic layers in addition the observations are checked for consistency with the first guess gridded fields.

Model physics configuration

1. RAMS

RAMS was configured with the following physical and numerical options for the regional-scale runs:

- Mellor-Yamada type diffusion coefficients with prognostic turbulent kinetic energy
- Long and short wave radiative parameterizations
- Prognostic soil temperature and moisture model
- Prognostic vegetation parameterization
- Explicit and parameterized precipitation
- Four-dimensional data assimilation (analysis nudging)

The four-dimensional data assimilation (FDDA) scheme, which we used for RAMS for these simulations, has been termed in the meteorological literature as “analysis nudging”. Because the simulation domain is mostly over the relatively data-rich area of the central U.S. plains, there is little difference in the results of an analysis nudging or an “observational” nudging scheme. Data analyses were generated every six hours to ensure that the model simulations stay consistent with the synoptic scale weather through the course of the 6 day runs. The same strength of nudging (timescale = 10800. sec), that was determined to provide the best results from the previous project, was used for these simulations.

2. MM5

For the purposes of these simulations, we attempted to configure MM5 physics to approximate the RAMS configuration as closely as possible given the choice of MM5 schemes. This usually involved using the most complex MM5 scheme available for a particular process.

Two MM5 simulations were run, a three grid simulation initialized at 00Z 6 September 1993 and run till 06Z 12 September 1993 and a four grid simulation from 00Z 8 September 1993 through 06Z 12 September 1993. Unless specifically noted otherwise all of the following discussion applies to both scenarios.

The Grell scheme was used to parameterize cumulus convection. This is based on the rate of destabilization or quasi-equilibrium. It is a simple single cloud scheme with updraft and downdraft fluxes and compensating motion used to determine heating/moistening profile. Shear effects on precipitation efficiency are considered. The scheme was only applied on grid one since there are no available cumulus parameterization schemes available for grid resolutions on the order of 10km or less.

The PBL scheme is that of Gayno-Seaman which is based on Mellor-Yamada TKE prediction. It uses liquid-water potential temperature as a conserved variable allowing the PBL to operate more accurately in saturated conditions.

The 3 grid run parameterized microphysical processes using the Mixed-Phase Reisner scheme. This scheme has five predictive quantities, vapor, cloud water, cloud ice, rain, and snow. All interactions between the species are allowed except for riming. The 4 grid scenario used the Schulz microphysics. This is a simplified scheme (in terms of how species interactions are calculated) designed for running fast. It contains ice, graupel, and hail processes. The decision to use this scheme with the 4 grid scenario was made since it is highly efficient and would reduce overall model run-time. We also hoped that a change would affect some undesirable features of the simulation (as will be shown later).

The radiation scheme used was the Cloud-radiation scheme. It accounts for longwave and shortwave interactions with clear-air and clouds. In addition to producing atmospheric temperature tendencies it provides surface radiation fluxes. The soil model predicts temperature at five layers (1,2,4,8,16cm) using a vertical diffusion equation. It resolves vertical diurnal temperature variation in the soil allowing for a rapid response of surface temperature.

Analysis (Grid) nudging was used for four-dimensional data assimilation. Newtonian relaxation terms are added to the prognostic equations for wind, temperature, and water vapor. These terms relax the model value towards a given analysis. Nudging fields are available every 6 hours for upper air fields and 3 hourly for surface fields. Observation nudging was not tried, due again to the tight time schedule for these simulations and the extra time needed due to the complications of using the COAST observations in MM5.

Output fields and frequencies

As was done for previous projects, RAMS and MM5 were set to output the simulation results every hour. A complete set of fields were output for all model grids, including u, v, w wind components, temperature, pressure, cloud variables, precipitation, and eddy diffusion coefficients (or turbulent kinetic energy). These were converted to CAMx-ready fields with software developed by ENVIRON.

Model performance evaluation

We attempted to make the presentation of the models' statistical performance as consistent as possible between the two models. ENVIRON has developed software to compute statistics for MM5, while for RAMS, we generally use our own package (REVU) to produce a statistical verification of the simulation results. We investigated modifying one of these packages to input the other model fields. However, in the short time allotted for this project, this was not possible. We verified that each package computed the same statistics, then presented them in the same graphical format through the use of Microsoft Excel.

The statistics are computed using observations every 3 hours.

Simulations

Given the tight time schedule required for these simulation results, we did not have the opportunity to perform as many preliminary and sensitivity runs as we would have liked. For RAMS, the 4-grid RAMS run was completed for the entire 6-day period.

The following table summarizes the different simulations that were performed and will be compared in this report. RAMS-T5 was the simulation from the previous project with RAMS v4.3. All simulations used the standard NWS observations and all COAST surface observations in the data analyses for the FDDA.

Table 5 List of RAMS and MM5 simulations that were compared in this report.

Simulation ID	Period	Active grids
RAMS T5	9/6 00Z – 9/12 06Z	3 grids – 48, 12, 4 km
RAMS R4	9/6 00Z – 9/12 06Z	4 grids – 48, 12, 4, 1.33 km
MM5 G3	9/6 00Z – 9/12 06Z	3 grids – 36, 12, 4 km
MM5 G4	9/8 00Z – 9/12 06Z	4 grids – 36, 12, 4, 1.33 km

Aside from the grid configuration, the new RAMS-R4 simulation was configured the same as the previous RAMS-T5 simulation, except for the soil moisture initialization.

The statistics showed that RAMS-T5 had a small dry bias, so the new RAMS-R4 simulation was initialized with slightly more soil moisture.

Unfortunately, MM5 has executed slower than we anticipated, so we did not have time to test the sensitivity to different FDDA configurations or physics. If we do have time to run and additional day or two before 31 August, we will submit the statistical results as a supplemental report.

Statistical Results

We will first present the statistical verifications for the simulations. We will focus on the following statistical quantities are:

- *mean absolute error (MAE)-* average of the absolute values of the differences between the model value and the observation value. Good indicator of accuracy. Similar to Root Mean Square Error, but does not overly weigh outlying points.

$$MAE = \frac{\sum_{1}^{N} \left| \Phi_O - \Phi_P \right|}{N}$$

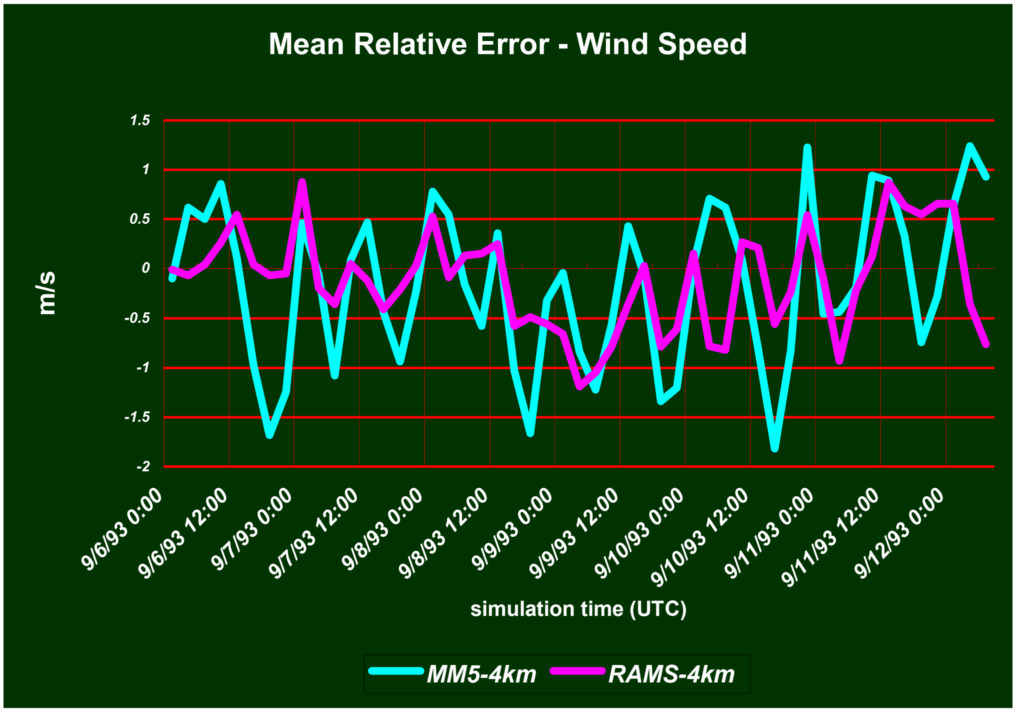
- *mean relative error(MRE)* - average of the differences between the model value and the observation value. Good indicator of bias.

$$MRE = \frac{\sum_{1}^{N} \left(\Phi_O - \Phi_P \right)}{N}$$

All observations within the grid 3 region were used for the following statistics, except for those that were flagged by the quality control procedure. But even though the procedure was used, there still were several questionable values that were allowed to remain. The majority of these were from the COAST observations.

1. Verification statistics – RAMS / MM5 at 4 km

The following graphs present the mean errors for the RAMS T5 and the MM5 G3 simulations. The variables of wind speed, temperature, and water vapor mixing ratio are compared.



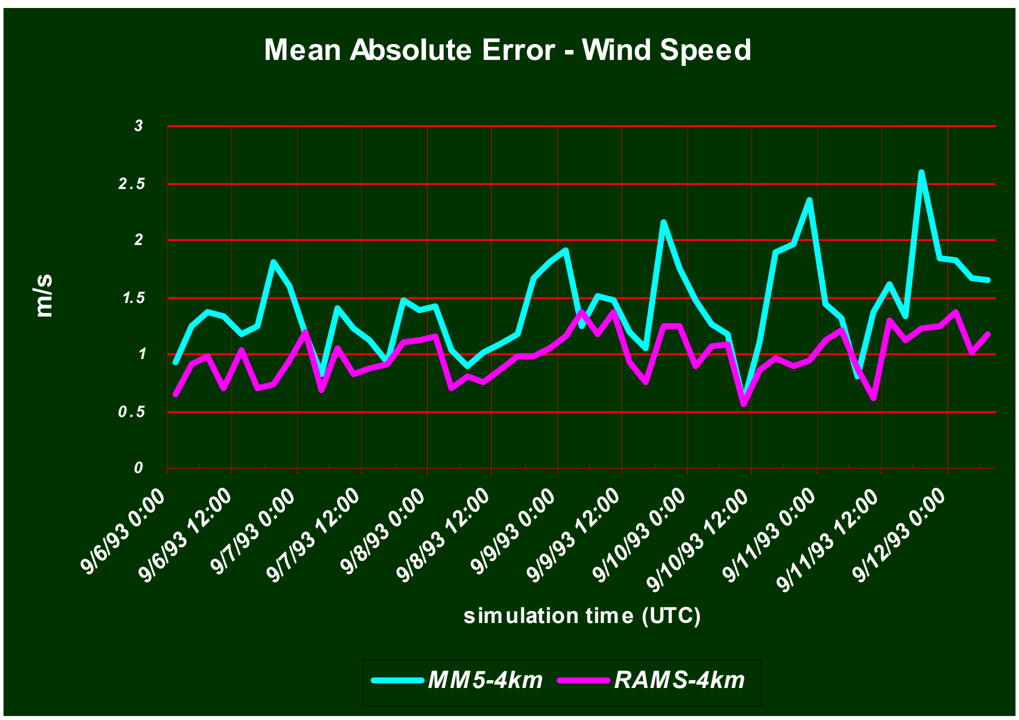
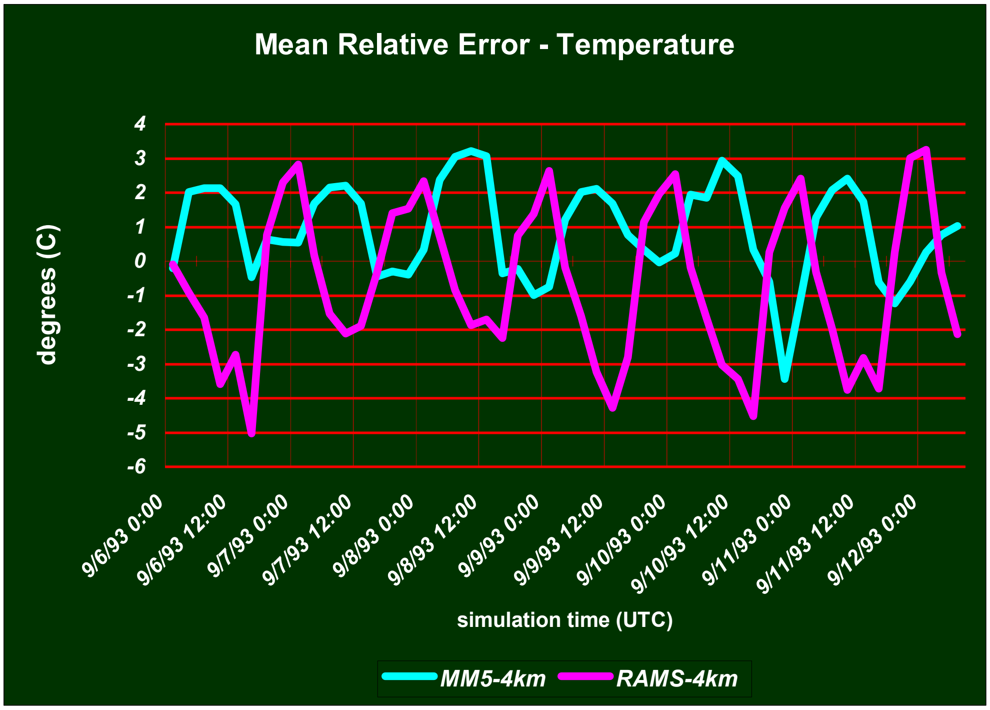


Figure 4 MM5 G3 and RAMS T5 mean wind speed errors using observations from the 4 km grid domain



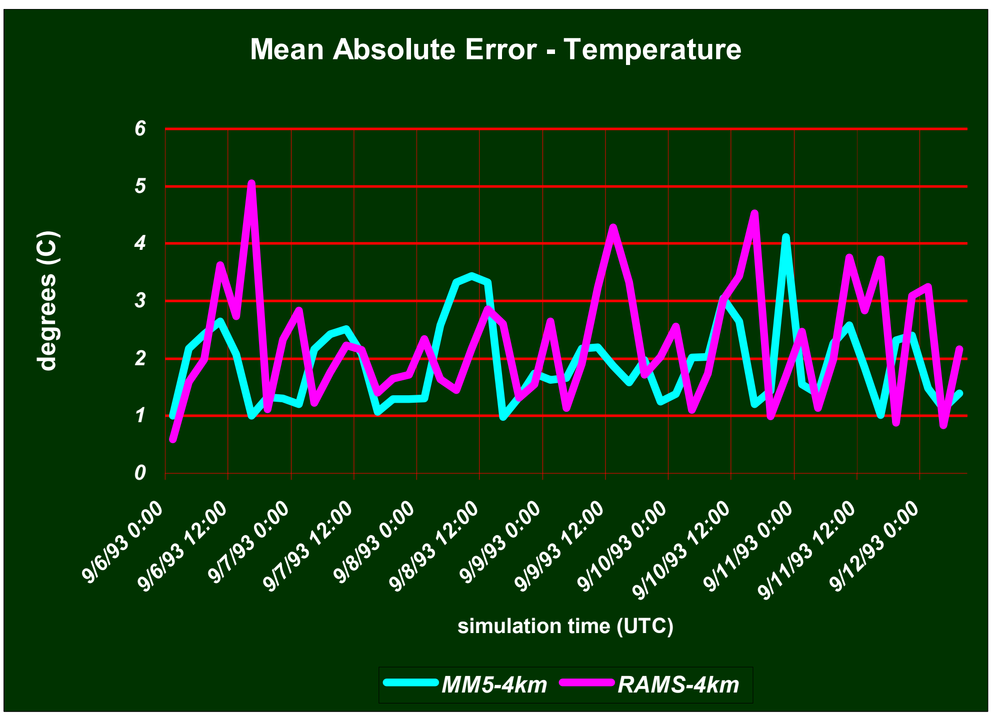
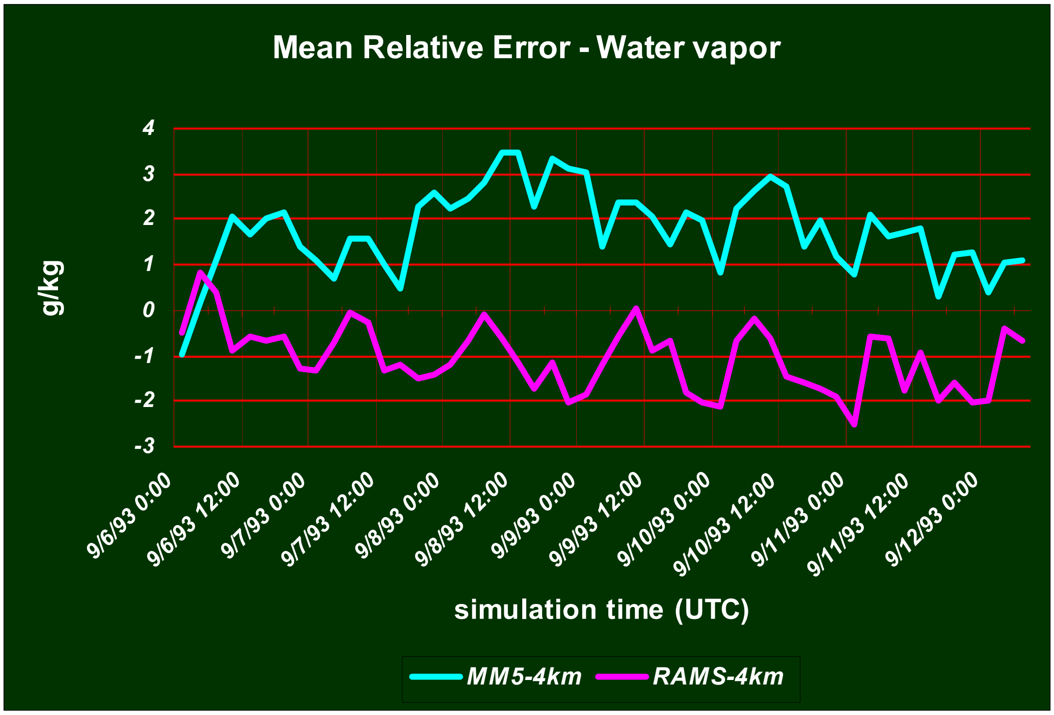


Figure 5 MM5 G3 and RAMS T5 mean temperature errors using observations from the 4 km grid domain



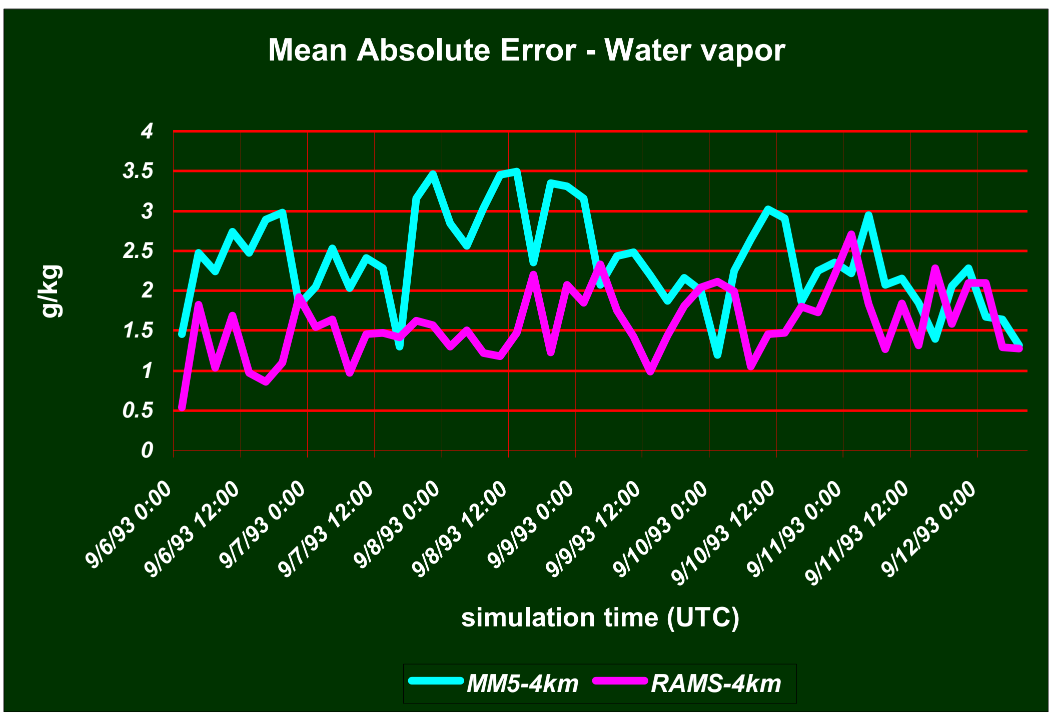


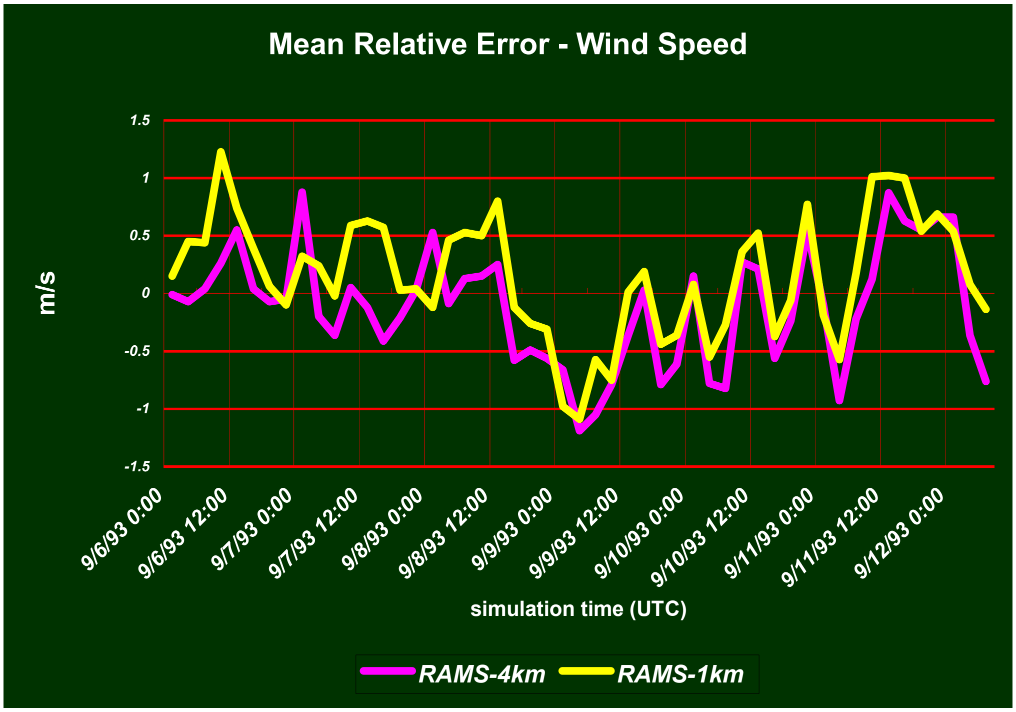
Figure 6 MM5 G3 and RAMS T5 mean water vapor errors using observations from the 4 km grid domain

For these simulations, statistically RAMS shows a slightly better performance in the wind speed. RAMS had an average absolute error of about 1 m/s for the wind speed over the entire 6day period, while MM5 was slightly larger at about 1.5 m/s. MM5 showed more of a bias toward too low wind speeds, especially in the early-mid afternoon hours. The temperature statistics are similar, although MM5 did not show the tendency to not have the nighttime cold temperature bias that RAMS exhibited. For the water vapor, the RAMS-T5 statistics were again slightly better than MM5-G3. The RAMS-T5 simulation tended to have a slightly low water vapor bias, while MM5-G3 had a high bias

Given the fact that FDDA is applied, it is not surprising that the statistics were similar between the two model simulations.

2. RAMS at 4 km compared to 1.33 km

The following graphs present the mean errors for the RAMS T5 and the RAMS R4 simulations. The variables of wind speed, temperature, and water vapor mixing ratio are again compared. These statistics use all observations that are located on the 4 km, grid 3 domain area.



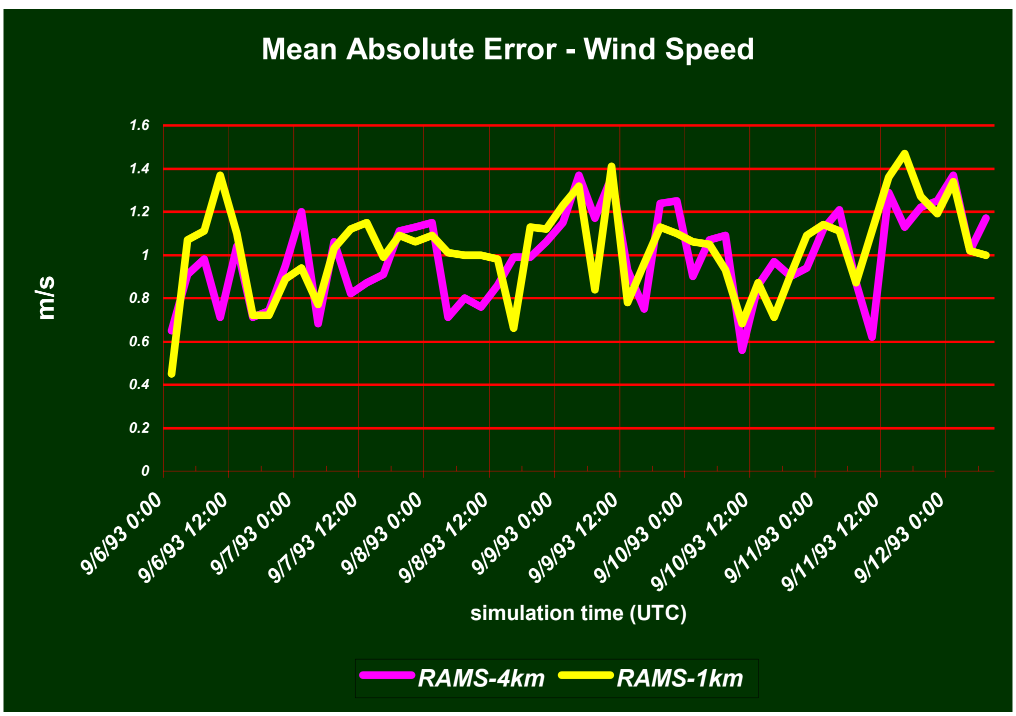
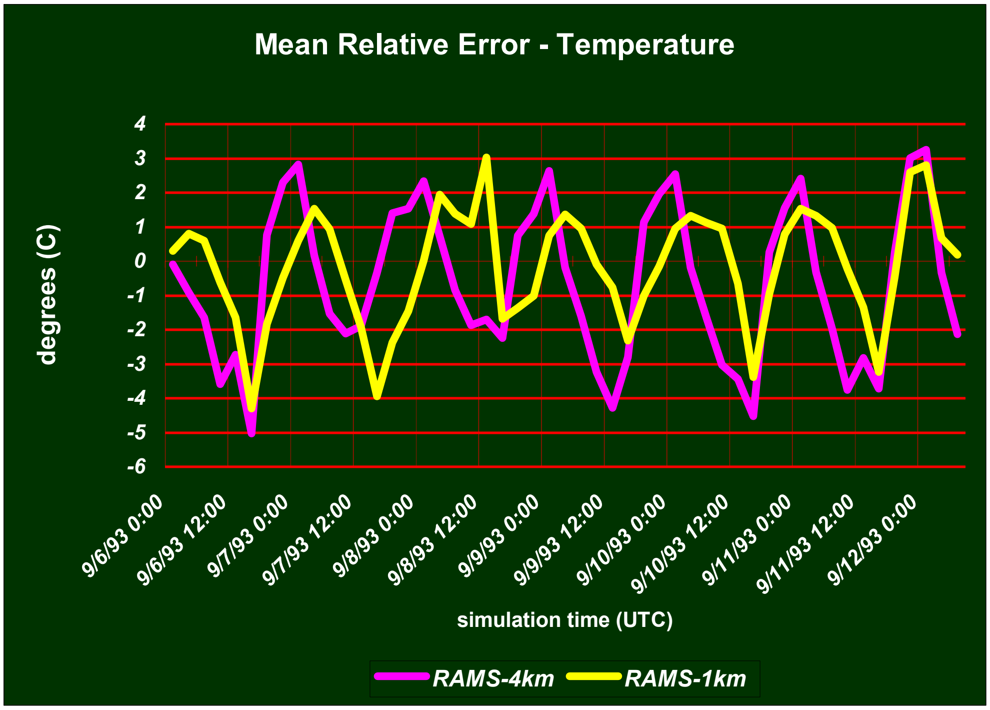


Figure 7 RAMS T5 and RAMS R4 mean wind speed errors using observations from the 4 km grid domain



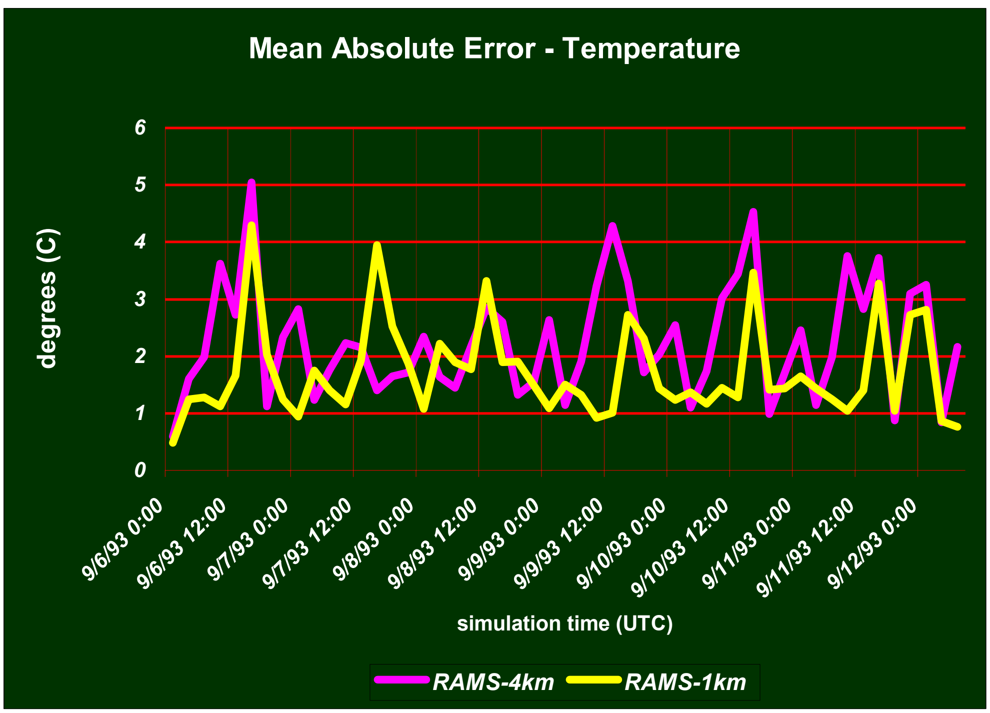
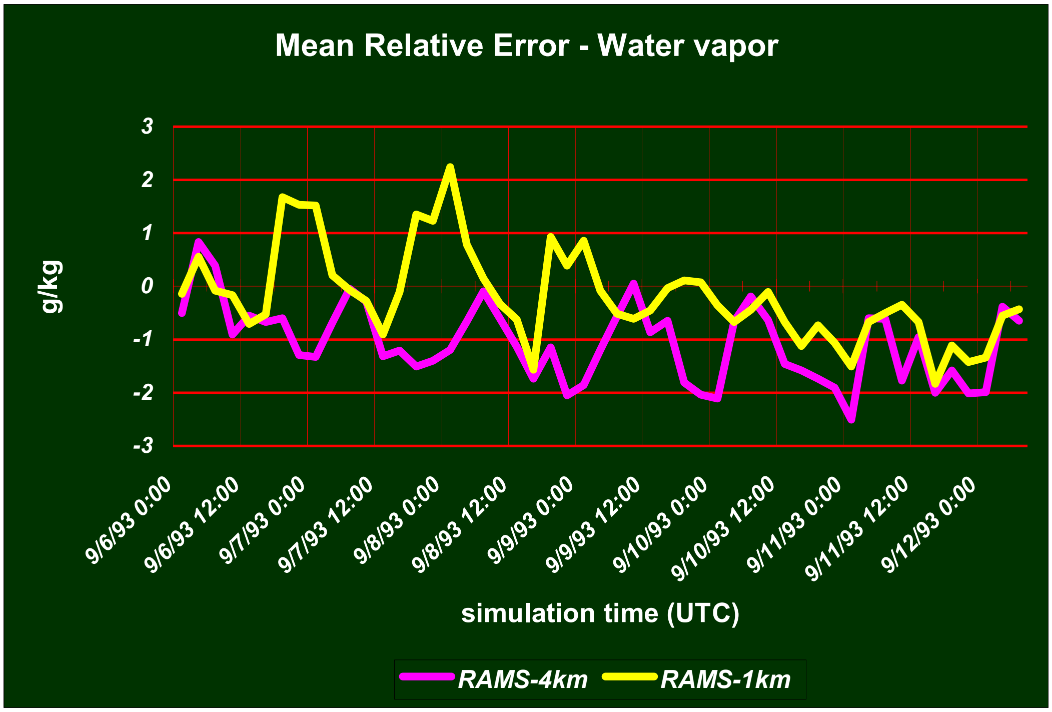


Figure 8 RAMS T5 and RAMS R4 mean temperature errors using observations from the 4 km grid domain



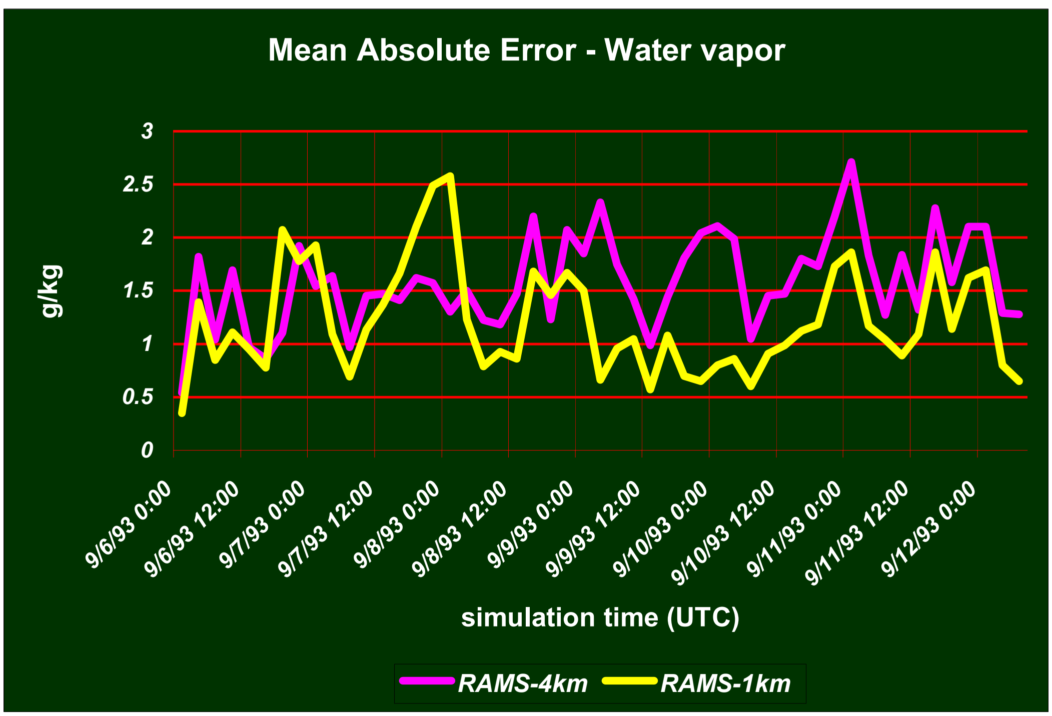
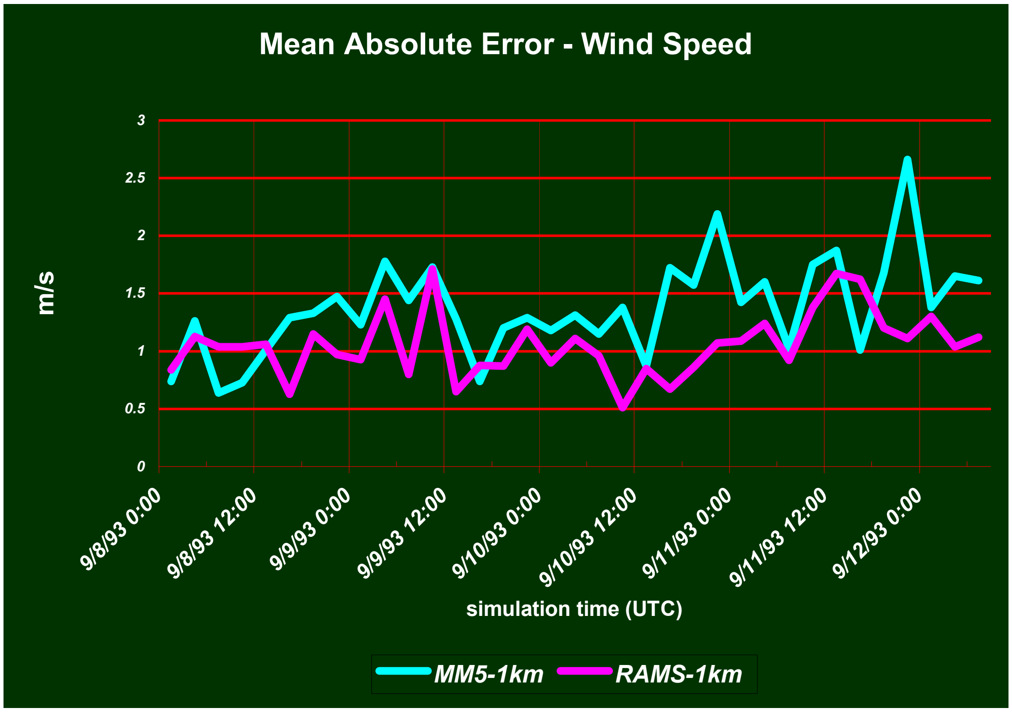


Figure 9 RAMS T5 and RAMS R4 mean water vapor errors using observations from the 4 km grid domain

Statistically, the T5 and R4 runs are similar, but some improvements are seen. The wind speed errors remained small in the R4 run, while the temperature errors were reduced, especially in the 8-10 September period. The nighttime cold bias of the T5 run was especially reduced during those nights. The water vapor verifications were also improved, due mostly to the increase in the initial values of soil moisture. There was also no average bias for the first 5 days of the simulation, while a small dry bias again appeared during the last day.

3. MM5 and RAMS compared at 1.33 km

The 4-grid MM5 configuration did execute through the 4 days from 8 September 0000 UTC to 12 September 0600 UTC. The following graphs depict the mean errors comparing the RAMS R4 and the MM5 G4 simulations. Only the observation sites that were located on the 1.33 km, grid 4 region are included in these statistics.



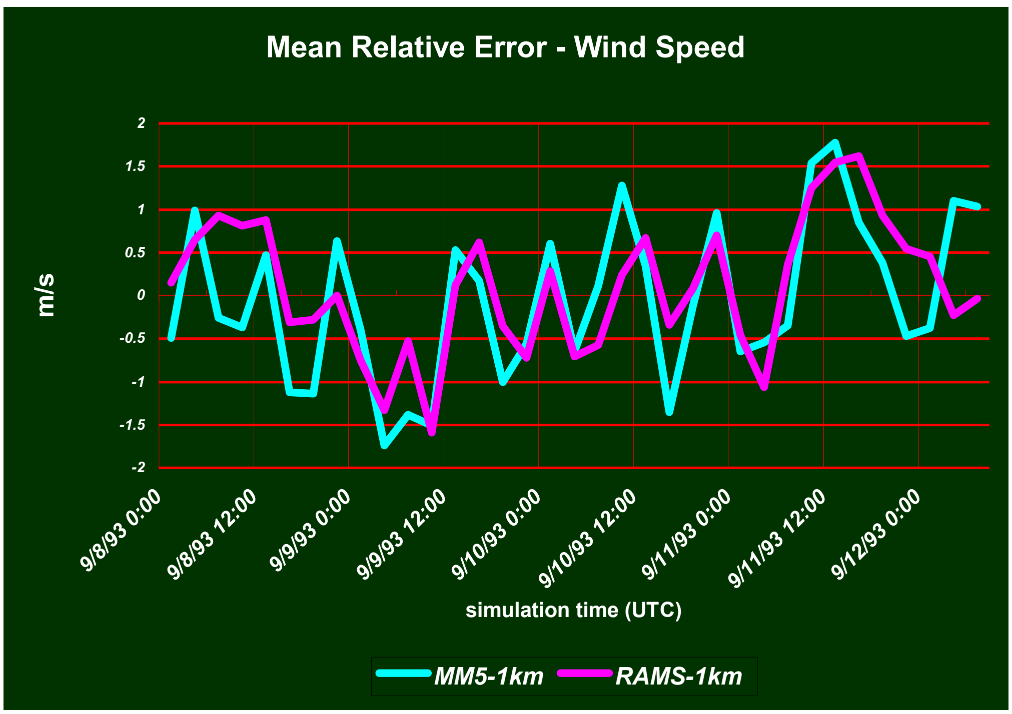
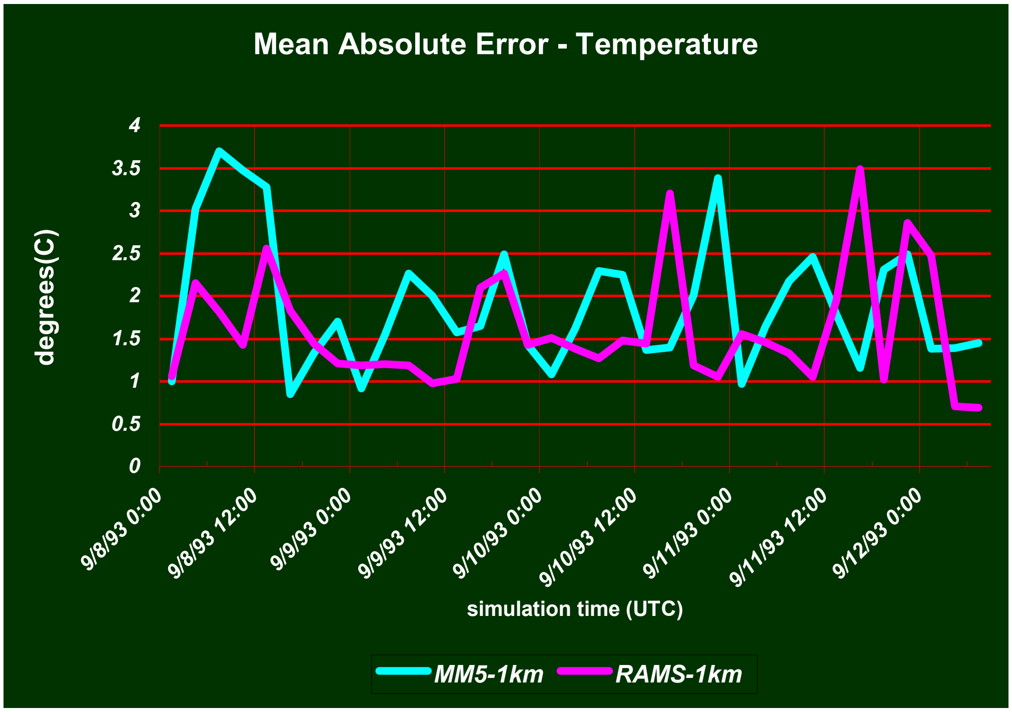


Figure 10 MM5 G4 and RAMS R4 mean wind speed errors using observations from the 1.33 km grid domain



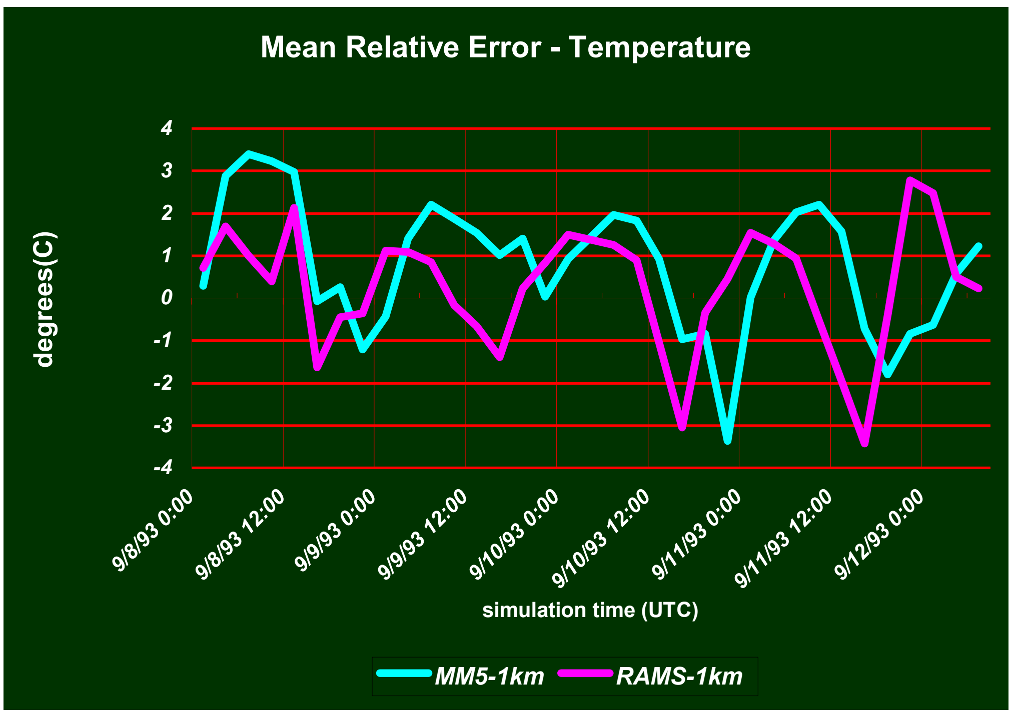
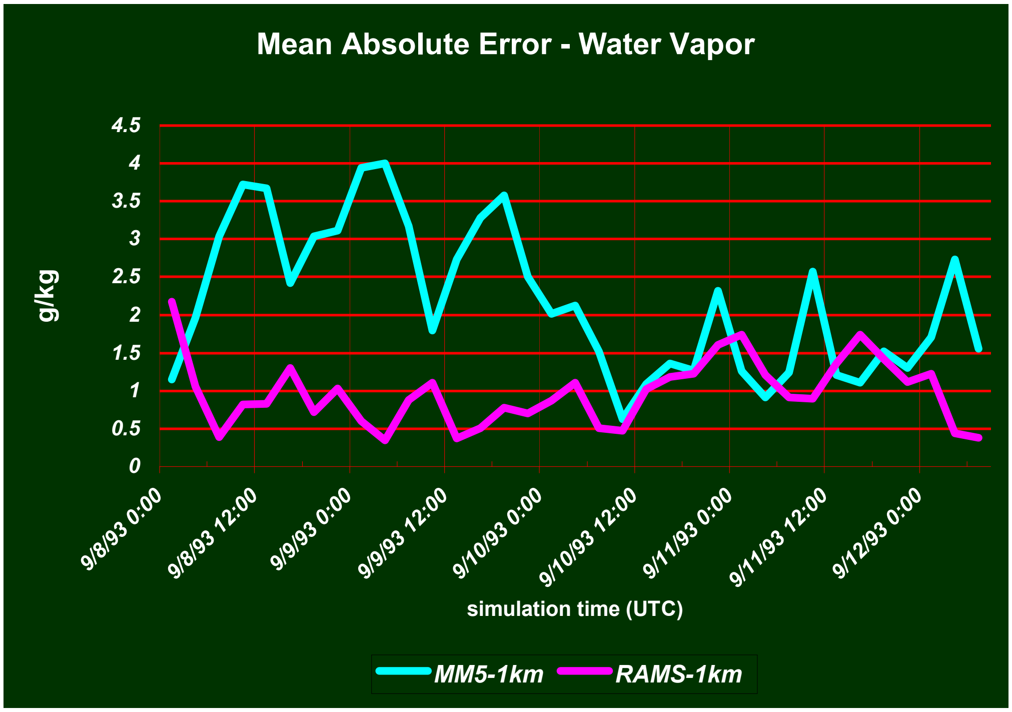


Figure 11 MM5 G4 and RAMS R4 mean temperature errors using observations from the 1.33 km grid domain



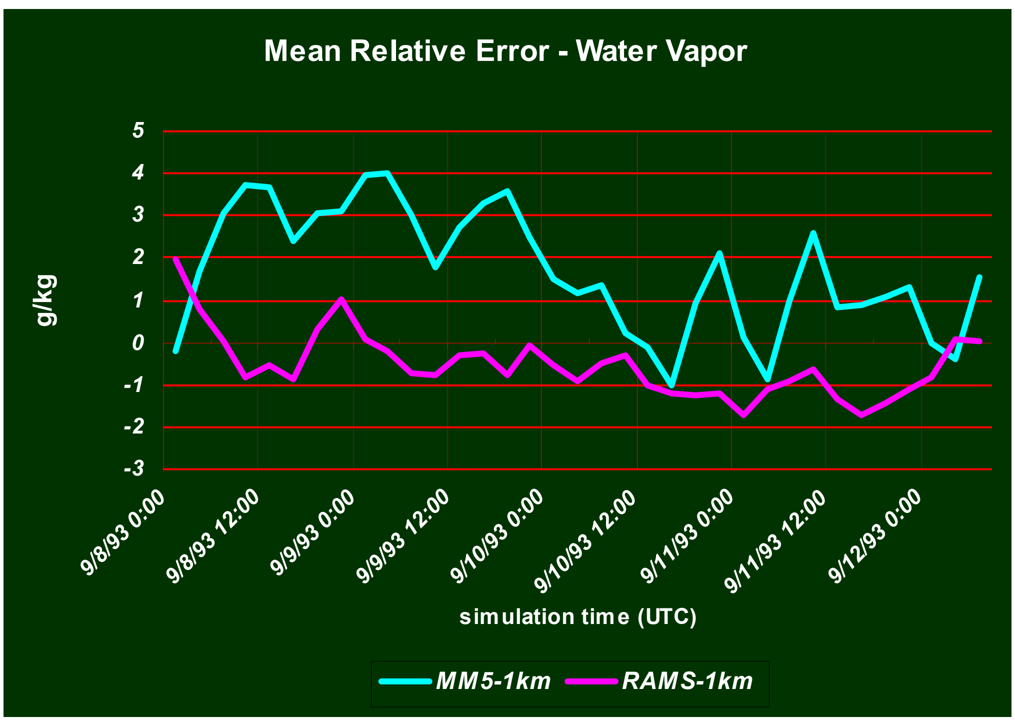


Figure 12 MM5 G4 and RAMS R4 mean water vapor errors using observations from the 1.33 km grid domain

Qualitative results

There are a large number of possible fields that can be viewed to qualitatively compare the 4 runs in question. We will present here only a few comparison plots of surface wind fields comparing the relevant runs. The RAMS R4 and the MM5 G3 and G4 runs will be converted to CAMx format and delivered to TNRCC as part of this project. These files can be visualized with the PAVE software to view the meteorological fields for any of the times for these simulations.

1. *RAMS / MM5 at 4km*

While the statistical performance between RAMS-T5 and MM5-G3 were similar, there were many subtle (and not so subtle) differences in the fields. For many of the times during the run, the surface wind fields looked rather similar. Take for example, 8 September, 1800 UTC (1200 CST), focusing on the portion of the domain over Galveston Bay.

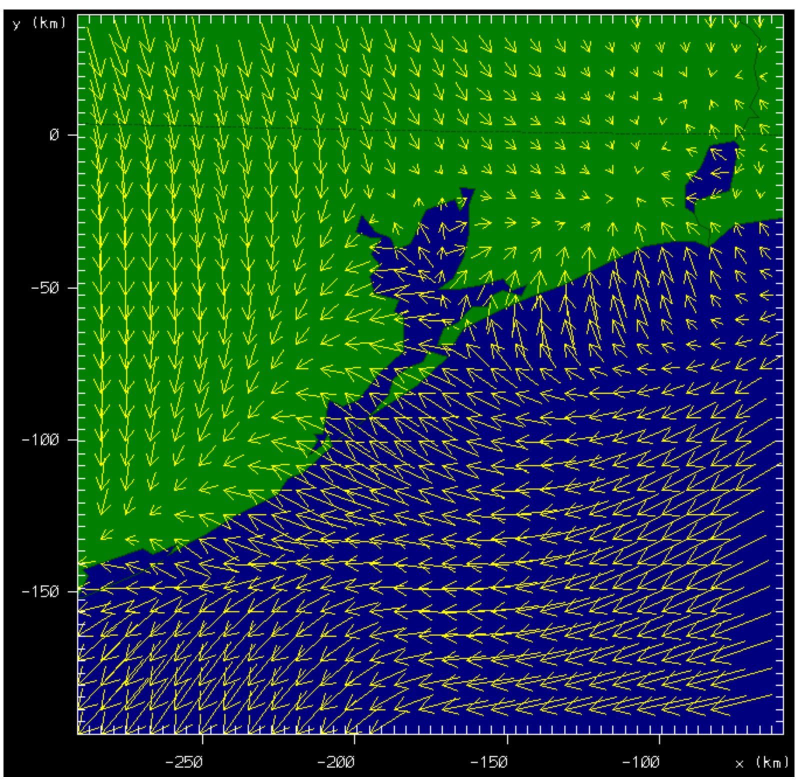


Figure 13 RAMS T5 surface wind field, 9/8, 1800 UTC. Vectors are plotted every other grid point.

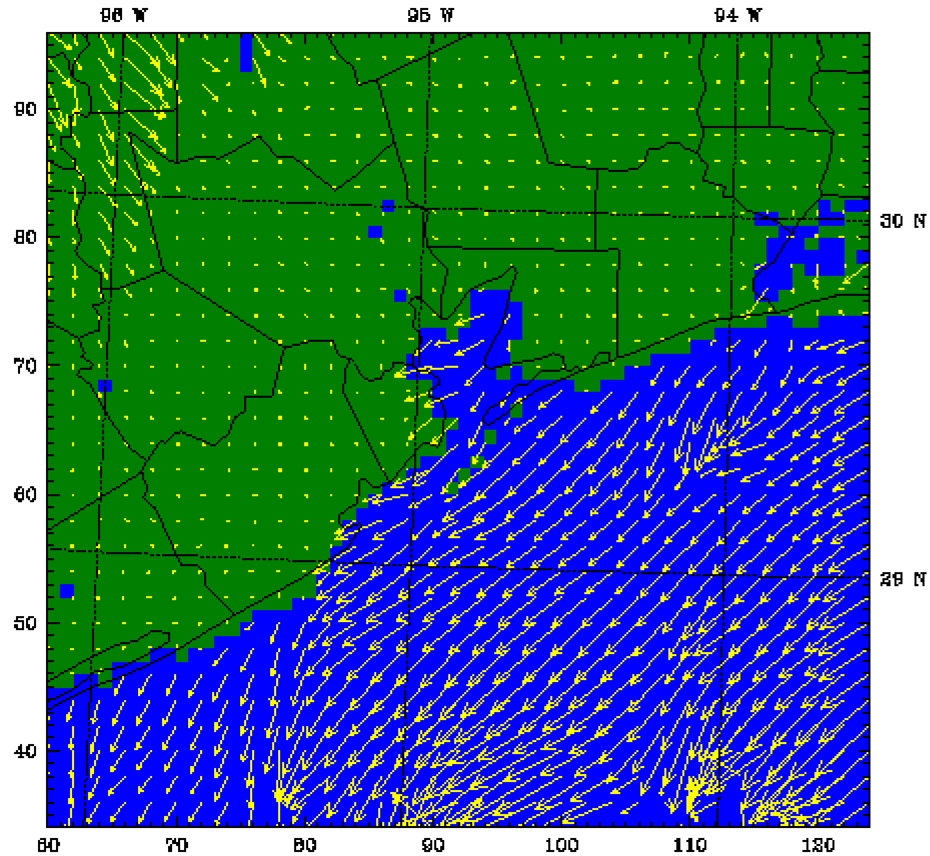


Figure 14 MM5 G3 surface wind field, 9/8, 1800 UTC. Vectors are plotted every other grid point.

In general, the wind direction was similar between the runs are similar, especially over the Gulf and to the north and northwest of Houston. But closer examination right along the coast shows that MM5 (Figure 14) did not generate the degree of wind turning due to the sea breeze formation that RAMS (Figure 13) did. The observations at this time (Figure 15) did show a significant cross-coast component to the flow.

Another “typical” MM5 feature that these simulations portrayed was the underprediction of wind speed over land during the day. Numerous other MM5 users have reported the same feature. This can be seen in both the statistics and the vector plots above.

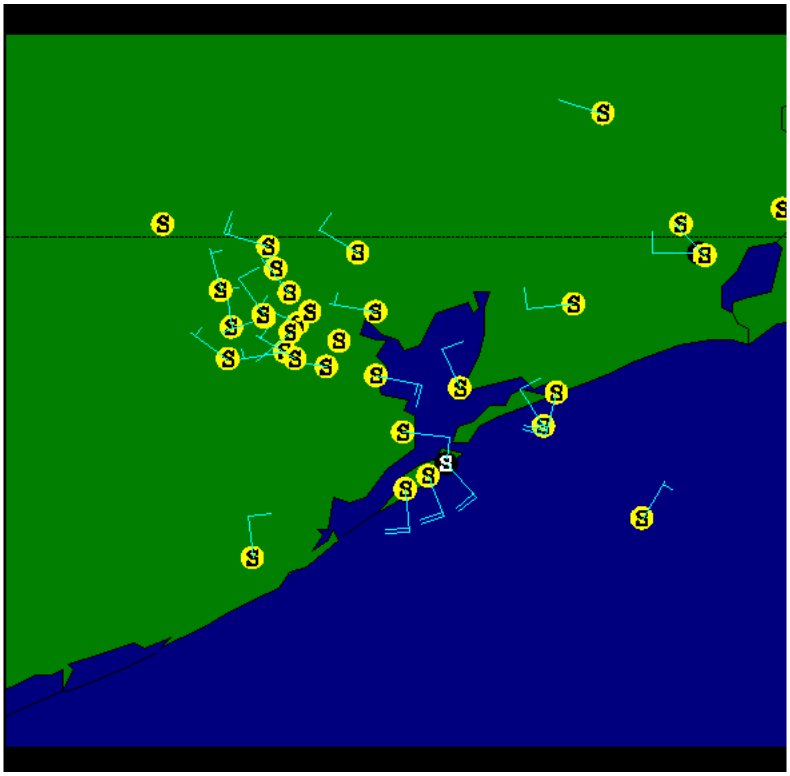


Figure 15 Observed surface wind field, 9/8, 1800 UTC.

The feature of MM5 underestimating the sea breeze flow was common throughout the 6 day run. Without additional sensitivity runs, it is unclear what aspect of the model configuration could be changed to improve these features.

Another feature of the MM5 simulation that was more disconcerting than the sea breeze wind direction was its propensity to develop small thunderstorms on the 4 km grid. For example, the surface wind field on 9 September, 1200 UTC (Figure 16) shows the thunderstorm outflows over the Gulf and another cell over the coast. The RAMS wind field at the same time (Figure 17) do not show these developments. It is unclear from the information that we have whether there were convective cells in the region at this time, but the downdraft outflow from these cells seem to be overpredicted. Other times are actually worse, for example, Figure 18 shows the outflow from numerous individual cells, while the observed winds (Figure 19) showed no evidence of outflows. Again, without doing additional sensitivity runs, it is difficult to say what improvements can be made to the runs with other available parameterizations.

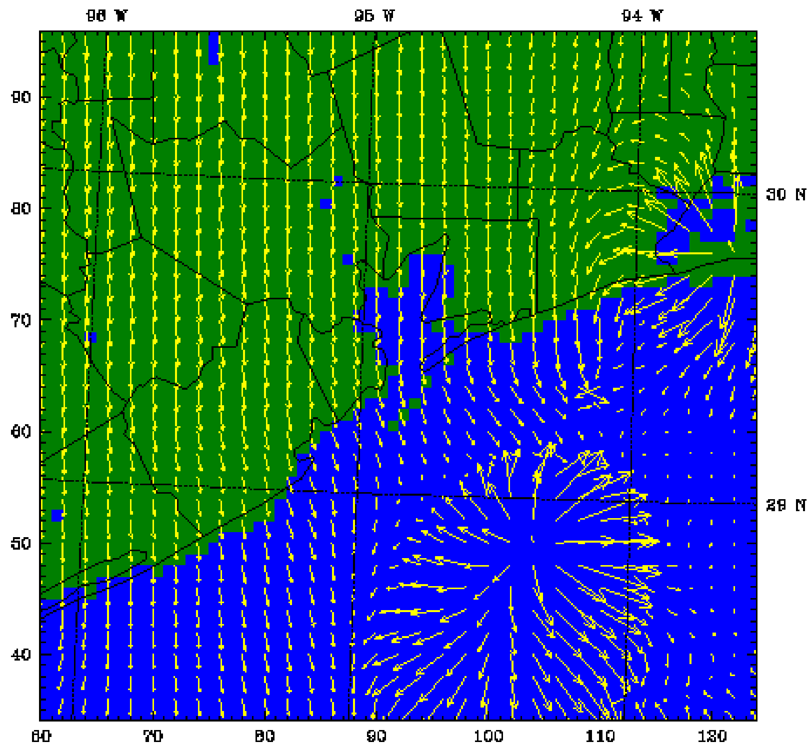


Figure 16 MM5 G3 surface wind field, 9/9, 1200 UTC. Vectors are plotted every other grid point.

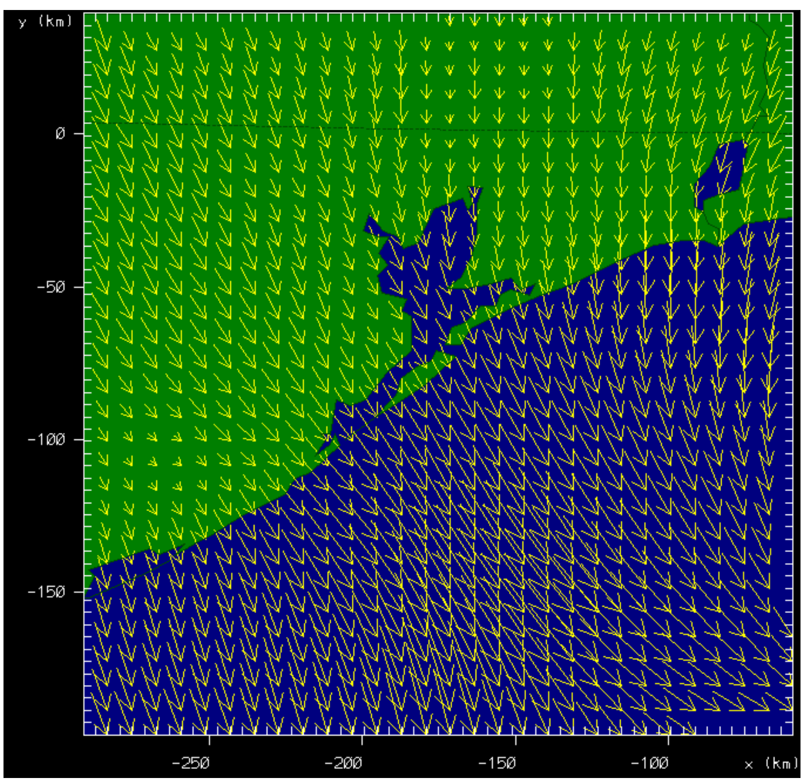


Figure 17 RAMS T5 surface wind field, 9/9, 1200 UTC. Vectors are plotted every other grid point.

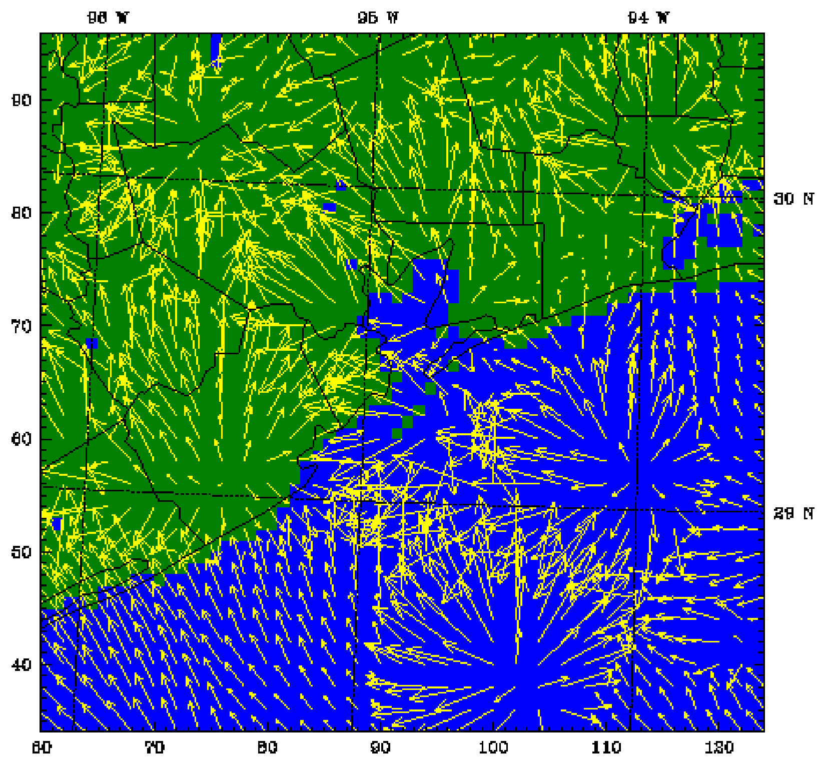


Figure 18 MM5 G3 surface wind field, 9/10, 2100 UTC. Vectors are plotted every other grid point.

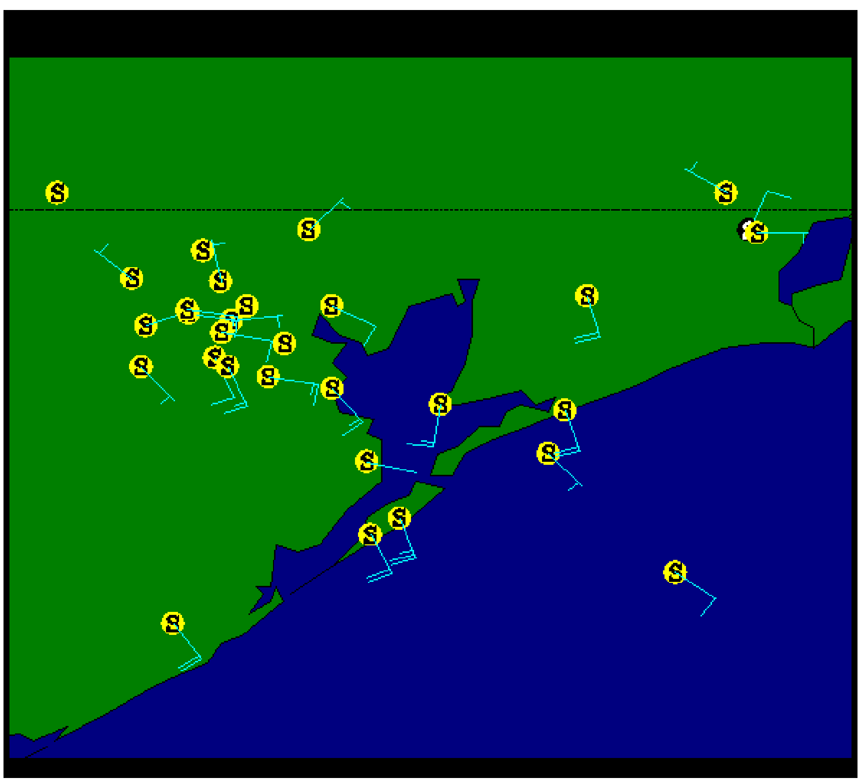


Figure 19 Observed surface wind field, 9/10, 2100 UTC.

2. *RAMS at 4 and 1.33 km*

As mentioned, the statistical performance between RAMS T5 and R4 were very similar. A qualitative comparison showed the expected results: as the resolution increases, the physiographic features are more clearly distinguished, and the meteorology is better able to respond to them. Smaller scale features are produced and many features are more clearly defined.

Let's look at one particular time as an example. On 8 September at 2100 UTC (1500 CST), the observed winds (Figure 20) showed a well-developed sea breeze circulation. The winds were almost perpendicular to the coast to the southwest of the bay and veering more toward the south to the east of the bay. The winds over most of Houston were weakly from the northeast, which placed the sea breeze front just to the south of the metropolitan area. The RAMS T5 simulation (Figure 21, note winds are plotted here every grid point) did a relatively good job at simulating these features. Now let's compared the same wind field from the 1.33 km grid in the RAMS-R4 simulation (Figure 22, note vectors are plotted every other point). The additional amount of detail is striking. Note how clearly the higher wind speeds over the bay are simulated (due to lower surface roughness) and the sharp reduction of the speed as the flow impacts on the land to the north. The flows over the Gulf are no longer smooth and uniform, as gravity waves from larger scale features can now be resolved. One of the other features that was commonly seen in the results at this resolution was the impact of the Houston urban area, with its increased roughness and higher temperatures.

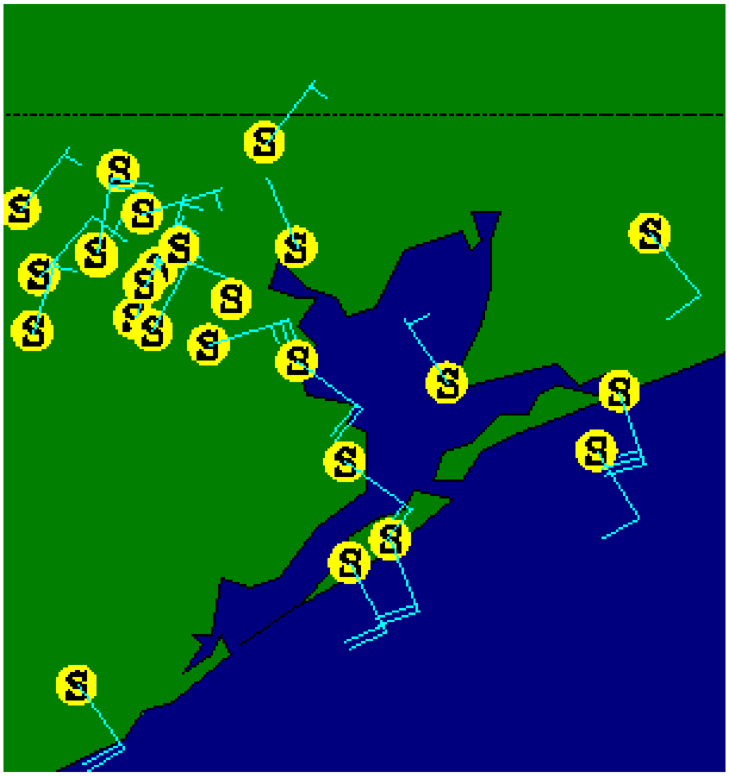


Figure 20 Observed surface wind field, 9/8, 2100 UTC.

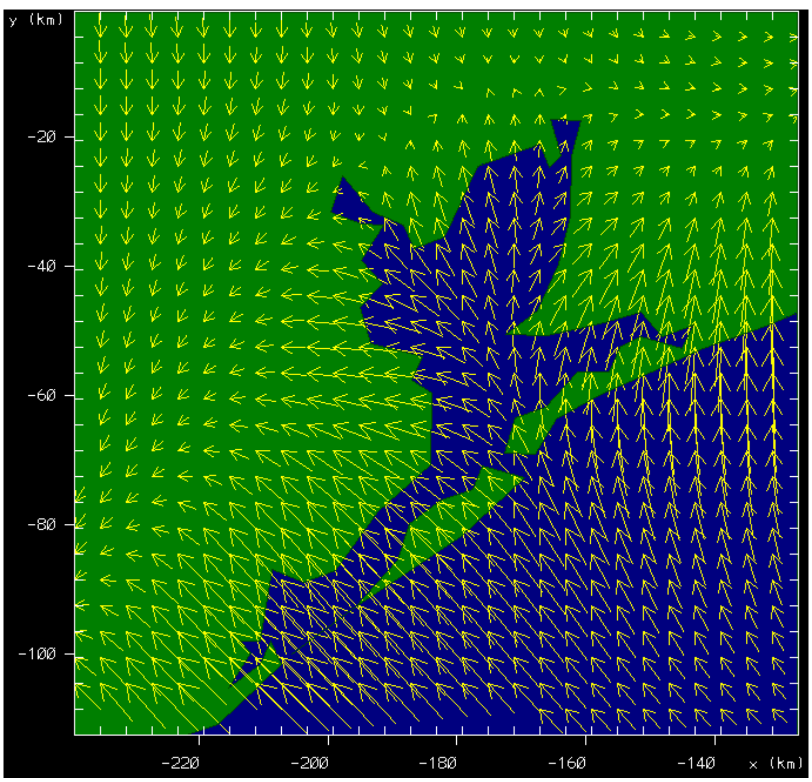


Figure 21 RAMS-T5 surface wind field, 9/8, 2100 UTC. Vectors are plotted every grid point.

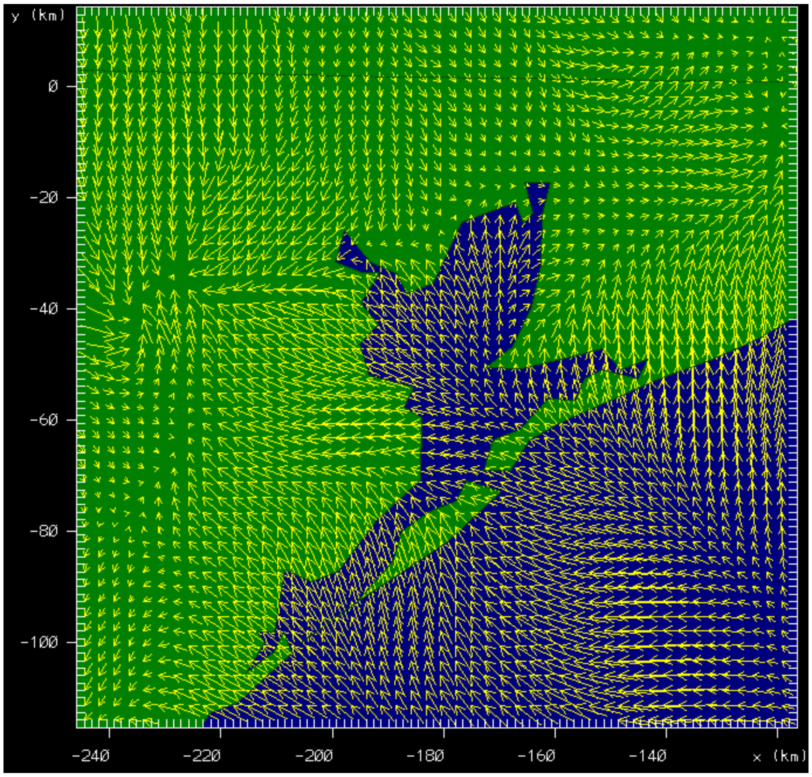


Figure 22 RAMS-T5 surface wind field, 9/8, 2100 UTC. Vectors are plotted every other grid point.

3. MM5 at 1.33 km

We were pleasantly surprised that MM5 executed through the 4.25 days of high-resolution simulation and, as mentioned, performed adequately from a statistical point of view. However, the higher-resolution grid did not solve the main problems that the 4 km simulation displayed. The sea breeze cross-coast wind component was still underpredicted most of the time, as shown in Figure 23. This can also be compared to the MM5 G3 field (Figure 14) and the RAMS T5 field(Figure 13).

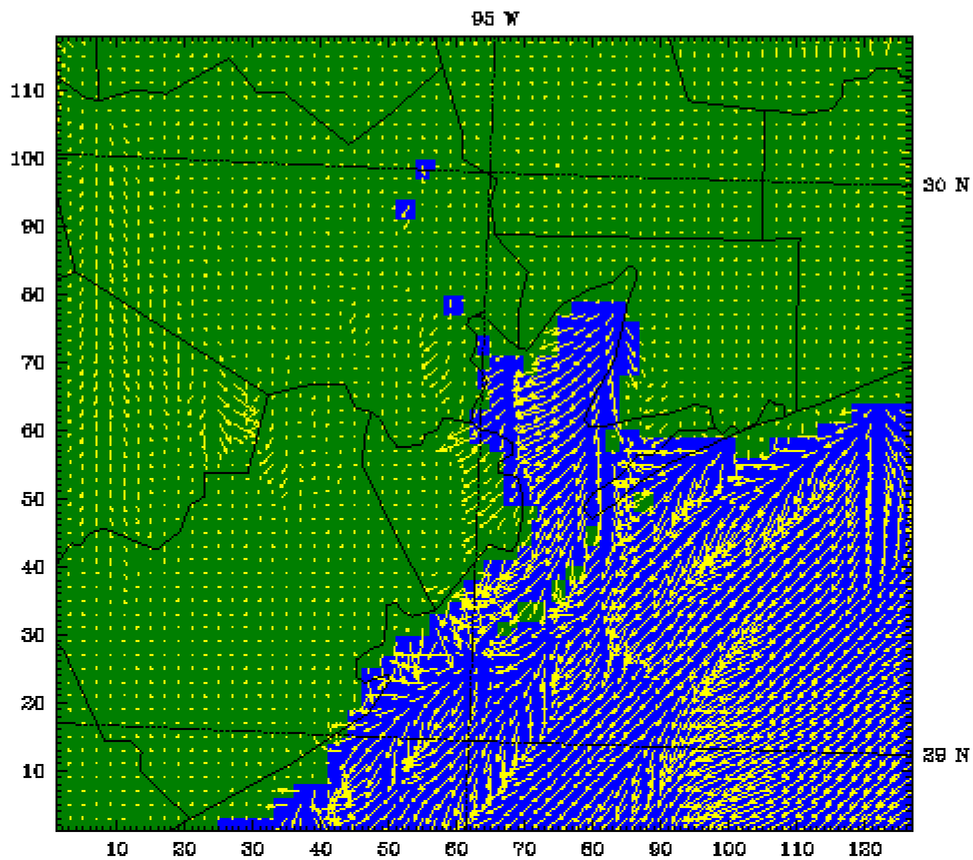


Figure 23 MM5 G4 surface wind field, 9/8, 1800 UTC. Vectors are plotted every other grid point.

The MM5 G4 simulation also retained the feature of generating numerous explicit convective cells, probably to a worse degree that the G3 simulation. Figure 24 shows the surface wind field and the outflow produced by the storms at 2100 UTC on 9/10. This can be compared to the G3 simulation in Figure 18.

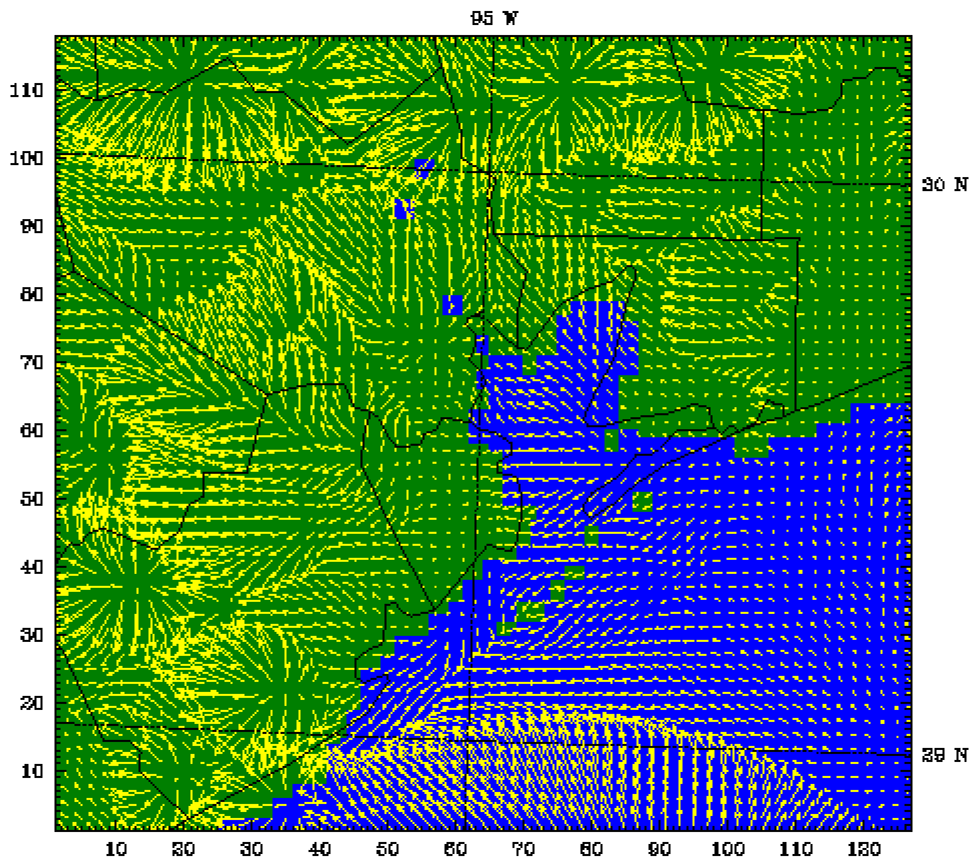


Figure 24 MM5 G4 surface wind field, 9/10, 2100 UTC. Vectors are plotted every other grid point.

Summary

From a statistical standpoint, this simulation continues to be one of the better that we have performed with MM5 and RAMS for photochemical modeling purposes. MM5 G3 and G4 and RAMS T5 and R4 all statistically showed good results. However, part of this good statistical performance was due to relative uniformity of temperature and low wind speeds throughout the period. The qualitative comparisons between RAMS and MM5 at 4 km showed agreement much of the time, although MM5 seemed to develop weaker sea breezes and overprediction of outflows from convective cells.

The high-resolution RAMS R4 simulation, with a fine grid of 1.33 km, showed similar verification statistics to the coarser resolution RAMS T5. As expected, the R4 simulation developed smaller scale features and better defined sea/bay breeze structures.

The high-resolution MM5 G4 simulation had the same issues as the coarser G3 simulation. The sea breeze turning of the flow from the Gulf perpendicular to the coast was not handled well and the extraneous convective cells still appeared. It was hoped that using a different explicit microphysics scheme would have eliminated these cells, but it appears that either they were caused by the PBL scheme or they were an inherent behavior of MM5.

The tight schedule for this project impacted the time available for numerous possibilities of sensitivity runs and investigations of scientifically-interesting issues that could affect the accuracy of the meteorological and photochemical modeling. Following are some suggestions for such investigations:

- Identify causes of MM5 behavior – Various sensitivity tests would be helpful to identify which model components were responsible for the weak sea breeze flows and the extraneous convective cells.

- FDDA – Four-dimensional data assimilation continues to be used for these types of meteorological simulations. Some sensitivity investigations have been performed in the past regarding strength of nudging, types of nudging (analysis, observational, etc.), etc. However, this past work has focused on lower resolution runs, not the high-resolution runs such as performed here. And as the future progresses, the use of these higher resolution runs will expand, since these resolutions are necessary to resolve meteorological circulations that are relevant for photochemical modeling purposes. To our knowledge, the behavior of FDDA nudging has been used, but not been investigated, on grid spacings approaching 1km.

- Simulation “production cycle” – The typical configuration for these type of multi-day episodic simulations has been to make a continuous, or nearly so, run through the whole period, using FDDA to keep the simulated meteorological fields in line with the observed meteorology. However, this requires a relatively high level of FDDA which can smooth the impact of using the higher resolutions grids. Other types of production cycles are possible and could lead to lower amounts of FDDA and retention of higher resolution meteorological information. For example, a possible structure could be similar to an operational forecast cycle, where individual 24-hour simulations could be done, with more FDDA nudging used at the transition times to minimize the effect of the transition.

- More detailed investigations of meteorological features – With a week-long simulation of a coastline area such as Houston/Galveston, numerous meteorological circulations, including sea/bay breezes, land breezes, gust front interactions, etc. are present every day of the simulations. These small-scale features do affect the transport of ozone and precursors. However, limited detailed investigations of these features are usually performed in the context of these simulations, and then usually only when the photochemical model is performing poorly.