Final Report

RAMS METEOROLOGICAL MODELING FOR THE SEPTEMBER 6-11, 1993 HOUSTON OZONE EPISODE

Work Assignment No. 31984-05
TNRCC Umbrella Contract No. 582-0-31984

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February 16, 2001

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1. INTRODUCTION

The Texas Natural Resources Conservation Commission (TNRCC) is currently developing an emissions control plan for the Houston/Galveston (H/G) area that demonstrates compliance with the Federal 1-hour ozone standard by 2007. Ozone modeling of the H/G area is being performed using the Comprehensive Air-quality Model with extensions (CAMx) and a photochemical modeling input database developed by the TNRCC. The modeling database is comprised of gridded hourly meteorological fields (winds, temperatures, humidity, vertical mixing "diffusivities) and emission estimates on a system of nested grids. The grid system is shown in Figure 1-1, and includes a 16-km grid covering the COAST domain with a 4-km nested grid that covers the Houston/Galveston area. Note that the COAST domain is embedded in a larger 16-km resolution SUPER COAST domain depicted in Figure 1-2. However, in this study we limited the CAMx/RAMS simulations to the COAST domain (Figure 1-1) using boundary conditions from a SUPER COAST 16-km CAMx simulation.

The meteorological inputs were generated using the SAIMM hydrostatic meteorological model that assimilated available meteorological observations to "nudge" the predictions toward observations. The original SAIMM wind fields exhibited over predictions in speed, so the nudging coefficients were increased in the data assimilation until the wind speeds were sufficiently slow as to build up ozone predictions in the region toward measured levels. The SAIMM hydrostatic meteorological model, based upon the model of Pielke (1974), is old by today's standards. Furthermore, the level of nudging that was used in the final SAIMM four dimensional data assimilation (FDDA) was much stronger than is typically used and may have interfered with the model's ability to appropriately represent the land/sea breezes and other meteorological features.

In previous projects, examination of the meteorological fields from SAIMM showed other undesirable characteristics. Along with the higher wind speeds, 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 strong four-dimensional data assimilation scheme used in the runs.

Strong FDDA nudging to the observations will obviously make the wind field agree better with the observations, at the locations where there are observations. The verification statistics computed will potentially show better performance. However, if there are large differences in data density in the domain or data-void regions (such as over the Gulf), problems can arise. While these divergent zones affect the direction of the surface winds, another effect can be possibly more important: they will produce erroneous vertical motions which can significantly impact the vertical transport of ozone and precursors.

In the development of the H/G ozone control plan, there were a few grid cells in lower Harris County where future-year (2007) ozone concentrations appear to be insensitive to NOx controls. These few grid cells were driving the level of NOx control needed in the H/G region to extreme levels in order to attain the ozone standard. The SAIMM wind fields were suspect and sensitivity tests were conducted using idealized wind fields (Vukovich, Wheeler, and Arunachalam, 2000). However, the idealized wind field analysis was more research-oriented,

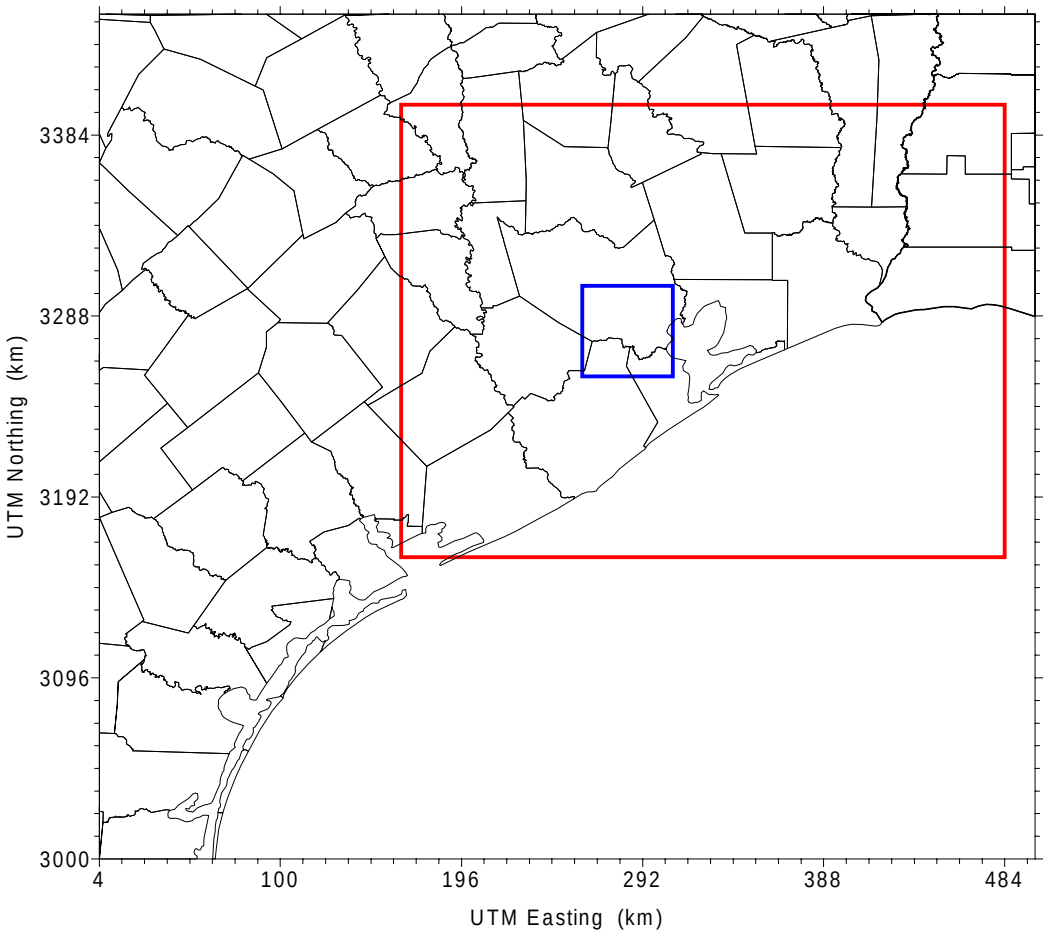
focusing on changes in model performance and not on sensitivity to NOx reductions. A version of Process Analysis was also applied to the H/G September 6-11, 1993 CAMx/SAIMM database (Yarwood, Morris, and Emery, 2000). The Process Analysis revealed no unusual processes or mass balance terms in the CAMx/SAIMM database, and identified the few stiff grid cells where ozone was insensitive to NOx controls as being VOC-limited. However, the reasons for this could not be determined.

Purpose

The most suspect component of the September 6-11, 1993 H/G photochemical modeling database is the wind field generated by the SAIMM. The purpose of the current study was to develop new wind fields for the episode using a current state-of-science meteorological model (RAMS), and perform CAMx meteorological diagnostic tests to investigate whether the SAIMM wind fields could be driving an incorrect control path for the H/G area.

The TNRCC provided the following data to support these activities:

- COAST domain meteorological data for the September 6-11, 1993 period
- All 1993 and 2007 Base Case CAMx inputs for the September 6-11, 1993 period on the 16-km Gulf Coast regional and 4-km COAST mesoscale domains
- September 6-11, 1993 model performance evaluation database (ozone observations and CAMx/SAIMM predictions at the ozone monitors and region-wide maxima).



16 km COAST domain: 31 x 28 16 km cells from (4, 3000) to (500, 3448)

4 km HGBPA domain: 80 x 64 4 km cells from (164, 3160) to (484, 3400)

Figure 1-1. SUPER COAST Houston/Galveston COAST domain 16/4-km grid configuration used in the CAMx/RAMS modeling of the September 6-11, 1993 period. Blue box in southern Harris County is location of stiff estimated ozone concentrations on September 8 in the CAMx/SAIMM database.

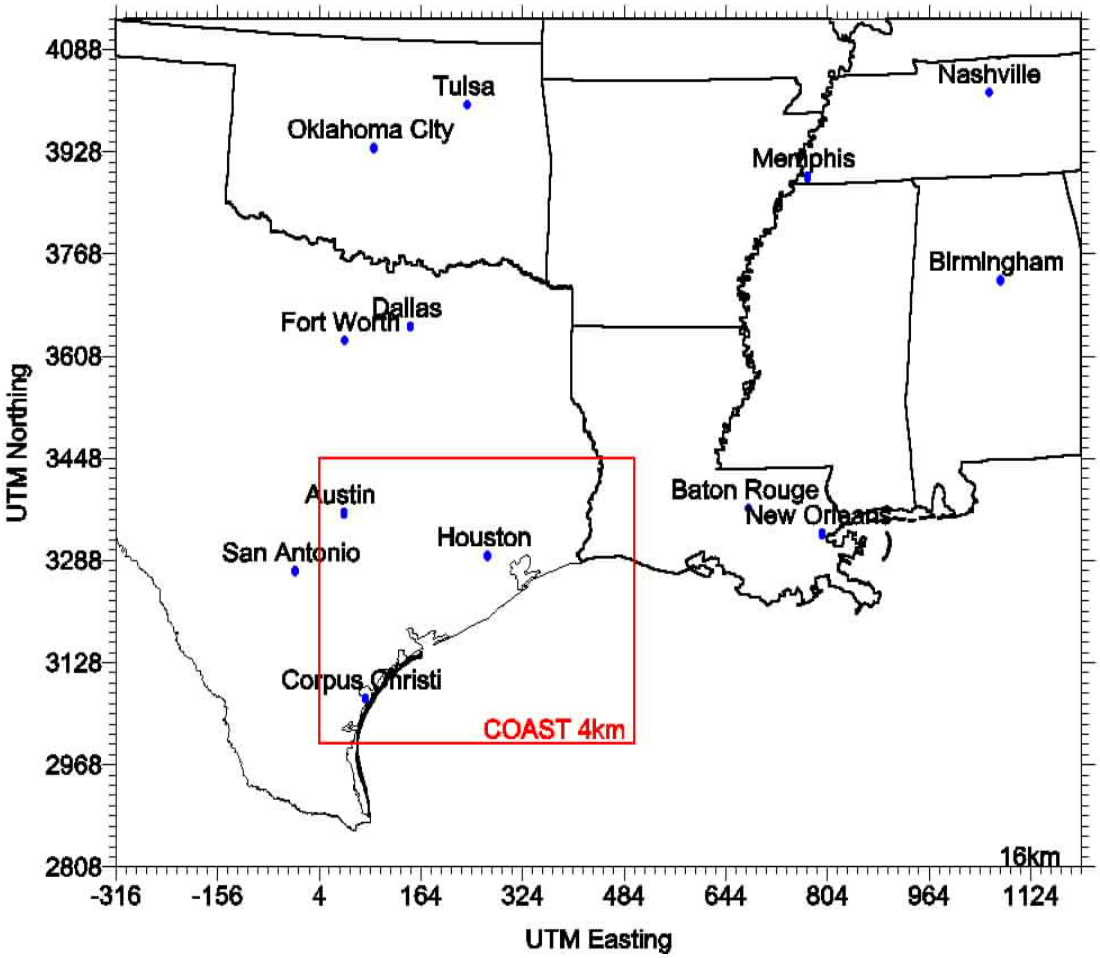


Figure 1-2. Gulf Coast 16-km regional-scale and COAST 4-km mesoscale domains used in the CAMx modeling of the September 6-11, 1993 period and the Houston area.

2. METEOROLOGICAL MODELING WITH RAMS

RAMS DESCRIPTION

Mission Research Corporation (MRC) used the Regional Atmospheric Modeling System (RAMS) to simulate the meteorology for the South Texas region during the high ozone episode that occurred during the period of 6-11 September 1993.

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. 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 remove 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 4.3. This is the version that was used on the new Houston/Galveston (H/G) simulations.

RAMS CONFIGURATION

Grid Structure

For the simulations of the 6-11 September 1993 period, the RAMS grids were configured in the following manner. We used a 16-km grid spacing over the regional-scale CAMx modeling domain area depicted in Figure 1-1. 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 FDDA scheme. Finally, a 4-km mesoscale domain was placed inside the 16-km grid to cover the area of the 4-km CAMx COAST grid (Figure 1-1).

The following tables summarize the RAMS grid configuration. Care was taken to ensure that the RAMS grids completely covered the corresponding CAMx grid and allowed a buffer zone of three grid points around the horizontal boundaries. A depiction of the RAMS horizontal grids is shown in Figure 2-1.

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	30
3	130	118	41	4	4	10	15

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) were 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 2-1 shows the RAMS vertical levels for these simulations. The temperature and winds are defined at the layer midpoint heights while the vertical motion is defined at the interface heights. The levels that are depicted in bold font are the matching CAMx interface levels.

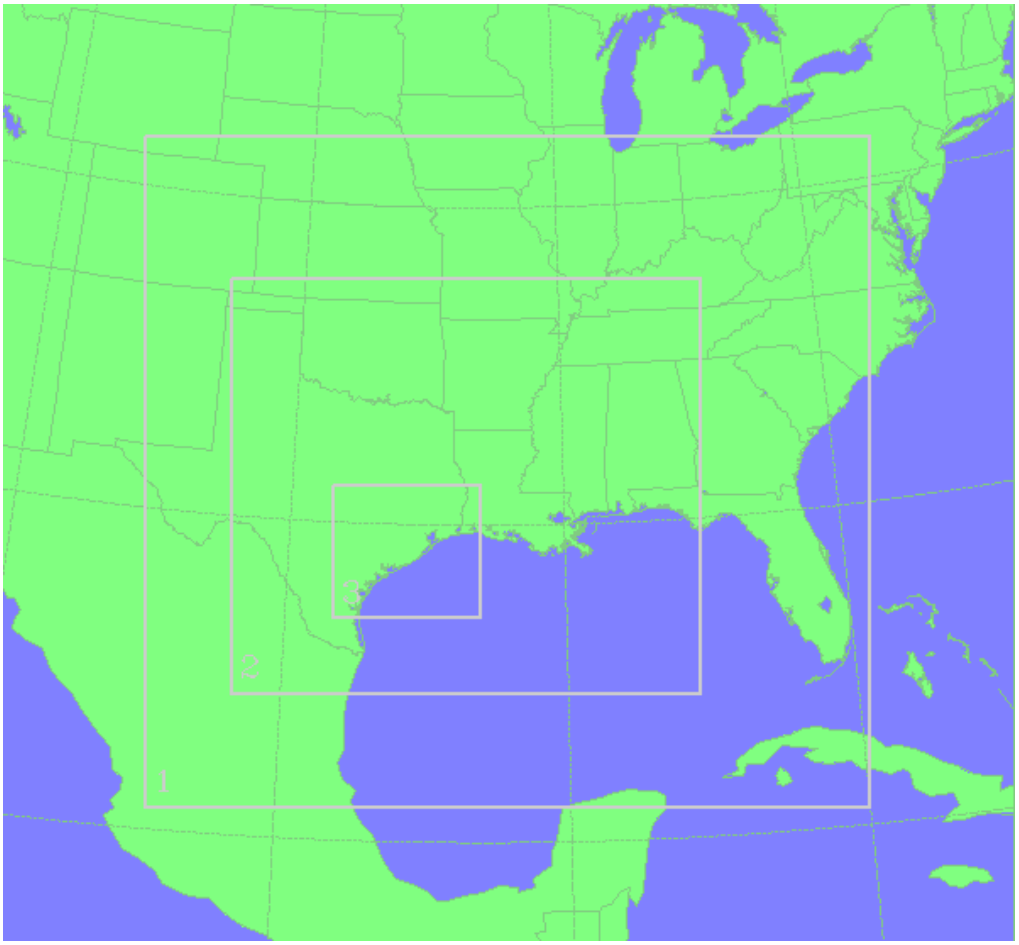


Figure 2-1. The RAMS nested grid structure used for modeling the H/G September 6-11, 1993 ozone episode. Grids 1-3 represent horizontal grid spacing of 48-, 16-, and 4-km, respectively.

Table 2-1. The RAMS vertical grid structure used for modeling the H/G September 6-11, 1993 ozone episode. All heights are given in m above sea level.

Interface Heights (m)	Layer Midpoint Heights (m)
19700	19200.0
18700	18200.0
17700	17200.0
16700	16200.0
15700	15200.0
14700	14200.0
13700	13200.0
12700	12200.0
11700	11200.0
10700	10200.0
9700	9200.0
8700	8198.1
7700	7210.6
6730	6252.3
5800	5391.8
5020	4685.3
4380	4097.4
3840	3609.6
3400	3207.3
3030	2868.7
2715	2560.9
2410	2262.8
2120	1982.8
1850	1718.9
1595	1482.8
1380	1287.4
1200	1113.7
1030	948.7
870	793.1
720	652.5
590	533.2
480	428.7
380	333.0
290	252.8
220	191.0
165	141.6
120	99.3
80	62.1
46	32.1
20	9.3
0	

Input Data Access and Preparation

The meteorological input data to RAMS 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 50 mb) on a 2.5 degree latitude-longitude grid. These data are archived every 6 hours and served 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 investigated and considered for inclusion in the data analyses. These observations included surface observations, wind profilers, and a rawinsonde. We included the surface observations from the COAST data in the data analysis. The profilers and rawinsonde were not used due to the fact that some of the profilers were not operating during the period and the remaining few points would not have made a significant difference to the simulation results.

After the data were accessed, all observations were subjected to stringent 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 compare a station’s value with that of its neighboring stations. The checks versus the first-guess fields 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.

After the input meteorological observational data had been 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. 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 already possessed archives of high-resolution topography and land use for the regional scale domain. These datasets are global and have about a 1 km resolution.

Model Physics Configuration

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

The four-dimensional data assimilation (FDDA) scheme that was used by 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 between an analysis nudging and an “observational” nudging scheme. Data analyses were generated every six hours to ensure that the RAMS simulations stayed consistent with the synoptic scale weather through the course of the 6 day runs.

Output Fields, Frequencies, Graphics

RAMS was set to output the simulation results every hour. A complete set of fields was output for all model grids, including u, v, w wind components, temperature pressure, cloud variables, precipitation, and eddy diffusion coefficients. MRC utilized the REVU package (RAMS Evaluation and Visualization Utilities) to generate any additional derived fields that are necessary.

Model Performance Evaluation

We also used the REVU system to produce a statistical verification of the simulation results. Statistical output can be provided for a number of times and levels for each simulation day, enabling both spatial and temporal verification.

Among the statistical parameters that can be calculated by REVU are:

- Root mean square error (RMSE)
- Mean absolute error
- Relative error
- Bias
- Root mean square vector error (RMSVE)
- Correlation coefficient

SIMULATIONS

Numerous simulations were carried out to determine the best combinations of some of the RAMS model parameters. Two of the main uncertainties in simulations of this type are the strength of the four-dimensional data assimilation (FDDA) nudging coefficients and the amount of soil moisture in the initial conditions. Experience has shown that the model results can be highly sensitive to these parameters. Table 2-2 summarizes the different simulations that were performed.

Table 2-2. Summary of RAMS simulations carried out for the study.

Simulation ID	Period	FDDA /Timescale (sec)	Observations	Soil Moisture
M3	9/6 00Z – 9/9 06Z	No/0.	NWS only	Drier
M4	9/6 00Z – 9/9 06Z	Yes/7200.	NWS only	Drier
S4	9/6 00Z – 9/9 06Z	Yes/10800.	NWS and some COAST surface	Medium
T4	9/6 00Z – 9/12 06Z	Yes/10800.	NWS and all COAST surface	Moister
T5	9/6 00Z – 9/12 06Z	Yes/10800.	NWS and all COAST surface	slightly > than S4
T6	9/9 00Z – 9/12 06Z	Yes/10800.	NWS and all COAST surface	slightly > than S4

Some comments on the above table:

- The FDDA timescale is related to the rate at which the model fields are nudged back toward the observations. The larger the value, the weaker the nudging is. As an example, a timescale of two hours (7200 sec) would mean that a grid point would be nudged about halfway to the observations in two hours, assuming the other model forcings were weak.

- Even though M3 did not use FDDA, the data analyses were still used to nudge the lateral boundary conditions of the coarsest grid.

- Since there are no routine measurements of soil moisture, the initialization of this quantity is done mostly by trial and error, based on the verifications of surface temperature and moisture.

- The NWS observations included all surface reports and rawinsondes that were available from the NCAR archives. The profilers and rawinsonde from the COAST datasets were not used due to the fact that some of the profilers were not operating during the period and the remaining few observation locations would not have made a significant difference to the simulation results.

VERIFICATION RESULTS

We will first start with a brief summary of the results of the six runs. Based on the average verification statistics over the highest resolution grid (domain 3) and the time series comparisons at individual stations, we can make the following general comments (Table 2-3).

Table 2-3. General results from the six RAMS applications to the COAST domain.

Simulation ID	Comments
M3	Exhibited higher errors than other runs due to lack of FDDA and too dry soil moisture.
M4	Lower errors than M3, but stronger FDDA smoothed some sea breeze features. Too dry soil moisture and lack of high-resolution COAST observations missed some subtleties of the wind features.
S4	Higher soil moisture and additional COAST observations produced good statistical agreements.
T4	Too high soil moisture washed out many sea breeze features and reduced daytime temperatures too much.
T5	Best simulation from a statistical standpoint. Small daytime warm bias and nighttime cool bias. Wind agreement good and bias small.
T6	Same configuration as T5, but "cold" start of last three days. Statistically very similar.

Simulation T5 was the best simulation from both a statistical and graphical standpoint. Following are graphs from run T5 for the six day period (computed every three hours) of two statistical quantities (Figure 2-2 and 2-6). The quantities are:

1) *mean absolute error* - average absolute differences between the model value and the observation value. A good indicator of accuracy, it is similar to Root Mean Square Error, but does not overly weigh outlying points.

2) *mean relative error* - average of the differences between the model value and the observation value. A good indicator of bias.

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

In addition, wind errors can also be viewed from the standpoint of a mean vector error. This metric simply takes the vector difference of the model wind and the observed wind. This approach accounts for both wind speed and wind direction errors. Figure 2-7 shows this metric for the six days in simulation T5.

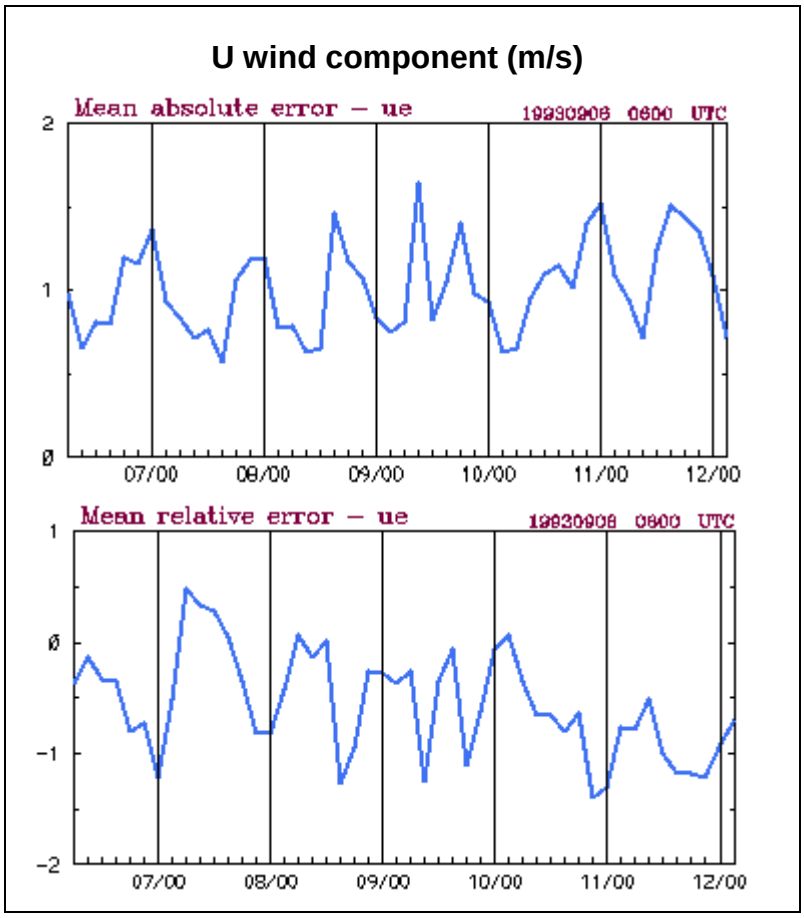


Figure 2-2. Absolute and relative error of the east-west (U) component in the 4-km RAMS grid for September 6-12, 1999.

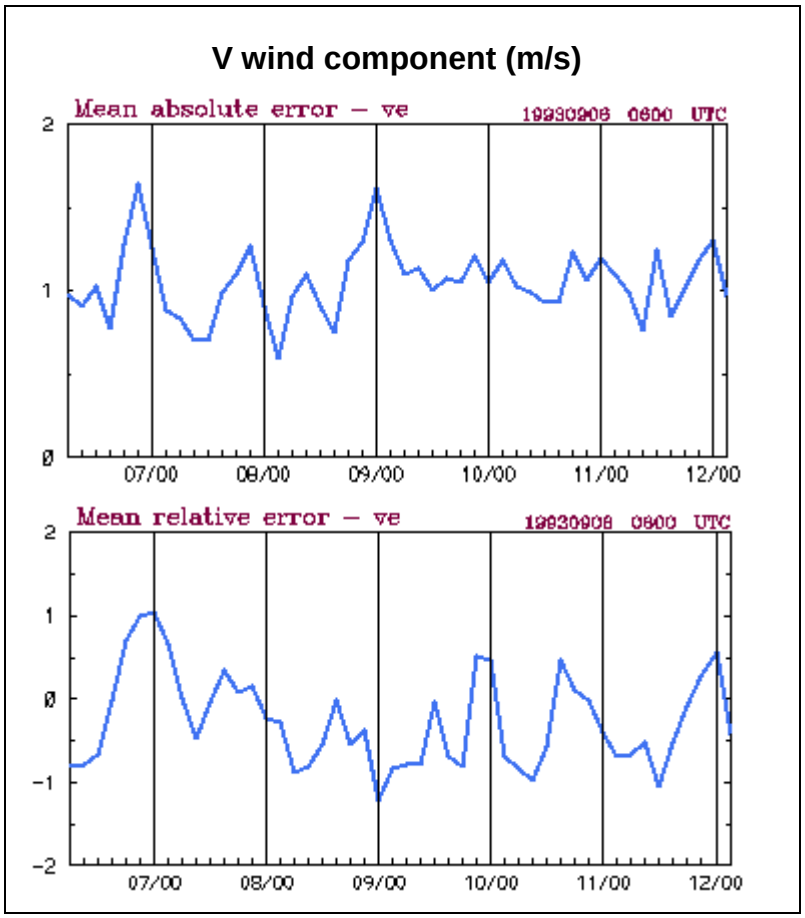


Figure 2-3. Absolute and relative error of the north-south (V) component in the 4-km RAMS grid for September 6-12, 1999.

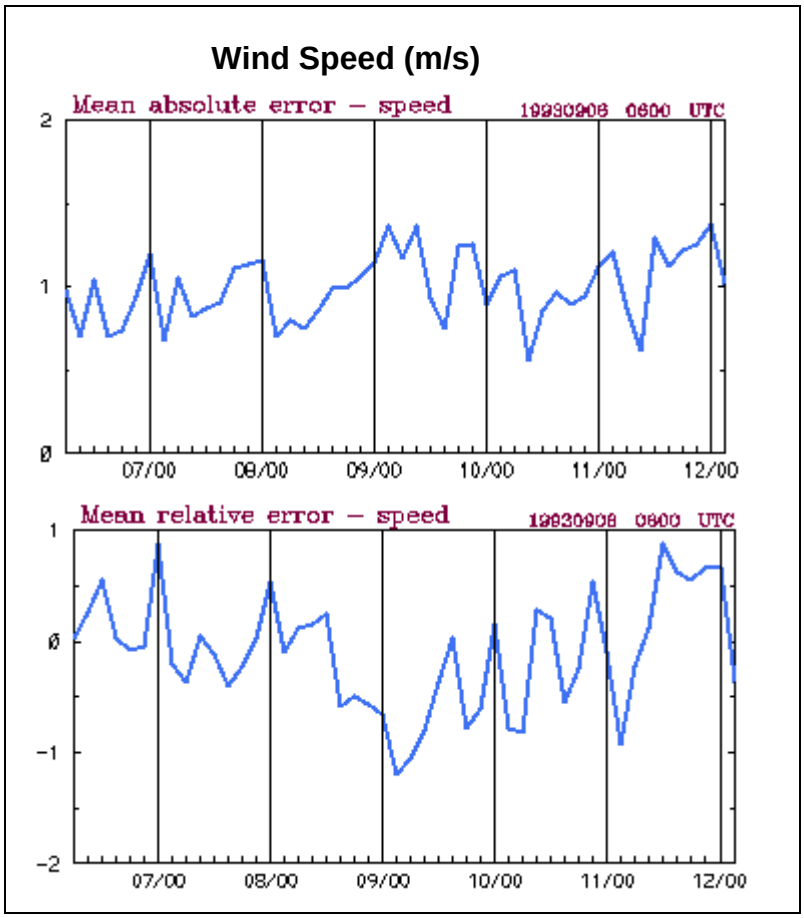


Figure 2-4. Absolute and relative error of the total wind speed in the 4-km RAMS grid for September 6-12, 1999.

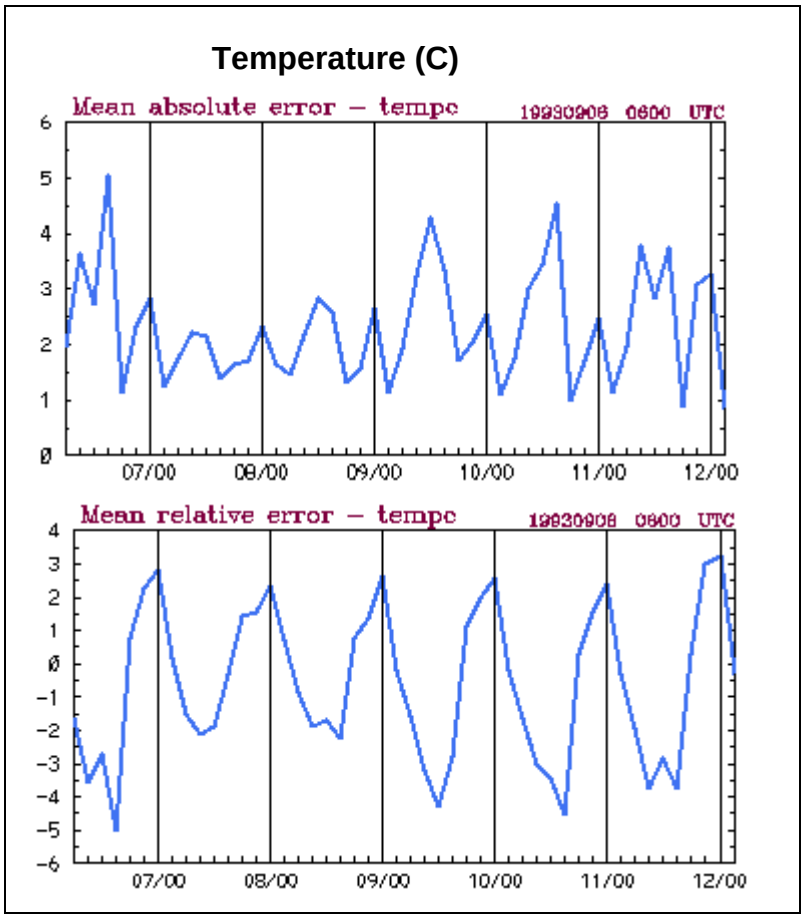


Figure 2-5. Absolute and relative error of the temperature in the 4-km RAMS grid for September 6-12, 1999.

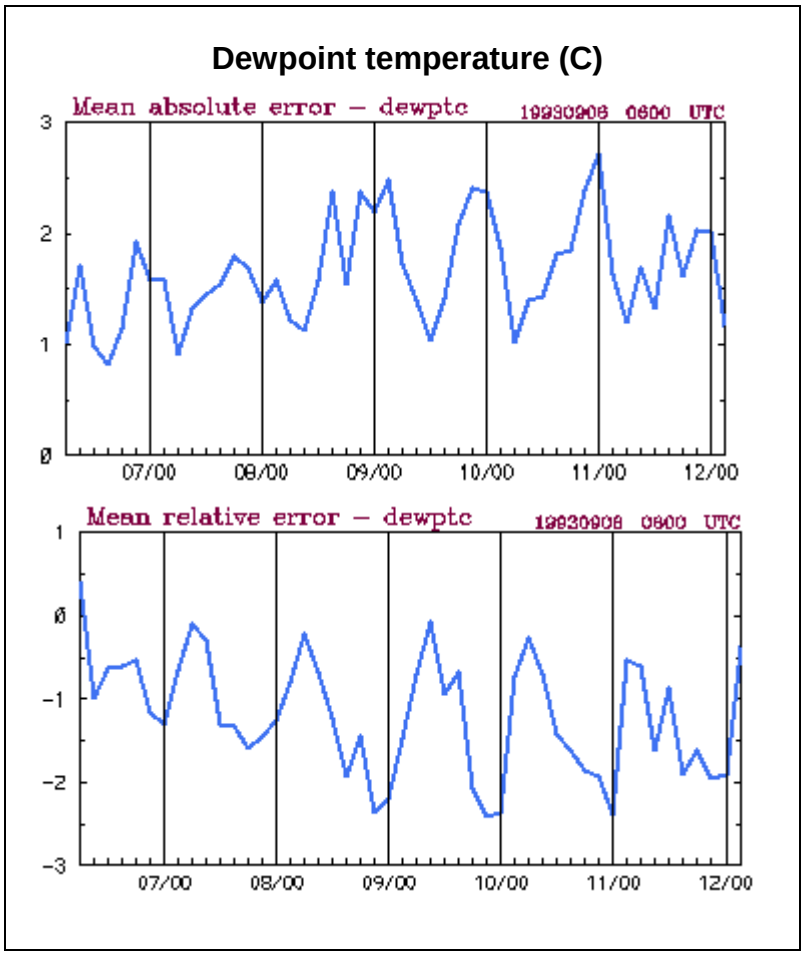


Figure 2-6. Absolute and relative error of the dewpoint temperature in the 4-km RAMS grid for September 6-12, 1999.

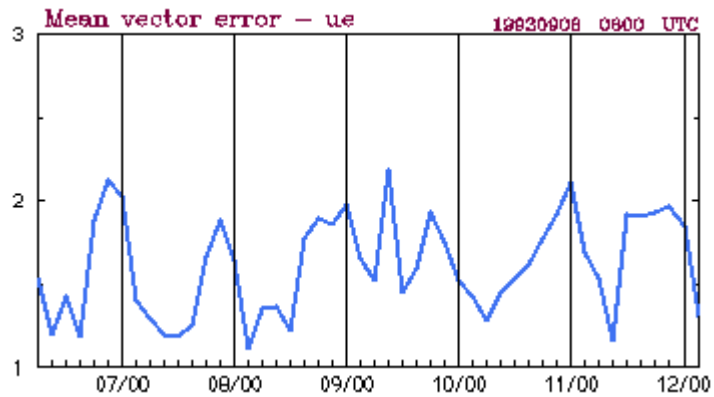


Figure 2-7. Absolute and relative error of the east-west (U) component in the 4-km RAMS grid for September 6-12, 1999.

DISCUSSION

From a statistical standpoint, simulation "T5" is one of the better that we have performed with RAMS for photochemical modeling purposes. Wind speed mean absolute errors were about 1 m/s and the bias was very small. With the mean vector errors between 1 and 2 m/s, the wind fields were very well simulated.

There are some biases that can be noted in the temperature statistics. There was generally a high bias (about 3°C) in the daytime high temperatures and a low bias at night. These biases can be explained somewhat by the fact that there was also a small dewpoint bias (1-2°C mean relative error). This indicates that perhaps the soil moisture was still a bit lower than actual which created too much heat transfer to the atmosphere during the day and allowed too much radiative cooling during the night. However, much of this cold bias was due to the differences at just a few of the stations. For example, looking at the temperature time series for station HSMA, (Figure 2-8) the low predicted nighttime temperatures can be seen. For this station, one could hypothesize several reasons for the cold temperatures, including the aforementioned slightly low dewpoints, neglect of haze in RAMS, or incorrect accounting for urban effects (such as the increased heat capacity of buildings and concrete). However, other stations from the COAST database showed rather remarkably high predicted nighttime temperatures. Site surveys of the locations of these observation stations would be warranted to try to deduce the actual causes. However, because of the excellent agreement of the wind fields, we do not feel that these biases affected the overall integrity of the simulation.

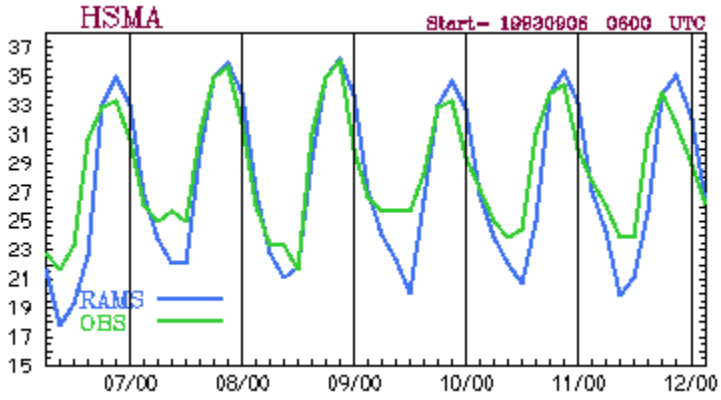


Figure 2-8. Observed and predicted (T5) temperature at the site HSMA September 6-12, 1999.

3. BASE CASE CAMx PERFORMANCE

CAMx Version 2.03 was run for the September 6-8, 1993 period using the RAMS S4 and T4 meteorology, and for the entire September 6-11, 1993 period using the RAMS T5 meteorology. Appendix A provides plots of time series at 37 sites in the 4-km H/G domain, and spatial maps of daily maximum ozone for the entire CAMx/RAMS_T5 simulation. In this section we describe CAMx performance with the RAMS meteorological inputs relative to performance with the SAIMM fields. All CAMx 1993 Base Case simulations reported here were run on ENVIRON computers using the following Base Case emission files obtained from TNRCC/MCNC:

- uamv_el_ei.9309{*date*}.93.base.regular
- uamv_lo_ei.9309{*date*}.coast_16km.93.base.regular
- uamv_lo_ei.9309{*date*}.hgbpa_04km.93.base.regular

Figure 3-1 below summarizes the CAMx/RAMS_T5 and the original CAMx/SAIMM ozone performance statistics for September 6-11, 1993, based on observation-prediction pairings at 37 sites within the 4-km H/G domain. Table 3-1 gives these numbers for the September 8th day, and also includes the CAMx/RAMS_T4 and CAMx/RAMS_S4 results.

EPA has performance goals for three statistical performance measures as follows:

- Unpaired Peak Accuracy $< \pm 20$ percent
- Normalized Bias $< \pm 15$ percent
- Normalized Gross Error $< 35\%$

On September 8 (Table 3-1), the unpaired peak prediction accuracy relative to the peak observed ozone concentration (214 ppb) is –10, -19, -10, and –21 percent for the CAMx SAIMM, RAMS_T5, RAMS_T4, and RAMS_S4 simulations, respectively. All four model simulations meet the performance goals with the CAMx/RAMS simulations exhibiting lower bias (-1 to +3 percent) than the CAMx/SAIMM (13 percent) simulation and similar gross error (25-30 percent). The only partial exception to this is the RAMS_S4 run, which exhibits an unpaired peak prediction accuracy just over the EPA guidance criteria.

Table 3-1. Summary CAMx ozone statistical performance measures on September 8, 1993.

Performance Measure	SAIMM	RAMS_T5	RAMS_T4	RAMS_S4
Peak Observed Ozone (ppb)	214.0	214.0	214.0	214.0
Peak Predicted Ozone (ppb)	193.1	172.6	192.1	170.0
Unpaired Peak Accuracy (%)	-9.8	-19.4	-10.2	-20.6
Average Accuracy of the Peak (%)	15.6	3.7	13.4	2.9
Normalized Bias (%)	13.1	-3.1	2.1	-1.1
Normalized Gross Error (%)	25.4	24.7	29.7	25.3

Considering the September 8-11 simulation period (Figure 3-1), both the CAMx SAIMM and RAMS_T5 base case simulations meet EPA's performance goals. While the CAMx/SAIMM simulation exhibits generally better performance for peak ozone (paired and unpaired), the CAMx/RAMS_T5 simulation exhibits better paired peak performance on the 8th and 9th, better bias statistics overall, and just slightly worse gross error.

Based on statistical performance measures alone, the CAMx/RAMS base case simulation model performance appears to be slightly degraded from the CAMx/SAIMM base case simulation. This is especially true for the unpaired peak performance measure on September 8th, 10th and 11th. However, the extreme over prediction in southern Harris County exhibited by the CAMx/SAIMM simulations on September 8 has been improved as shown by the time series plots at the Croquet monitor for the CAMx/SAIMM and CAMx/RAMS_T5 simulations (Figure 3-2). Furthermore, the average paired peak accuracy for September 8 is dramatically improved with CAMx/RAMS_T5 (Figure 3-1).

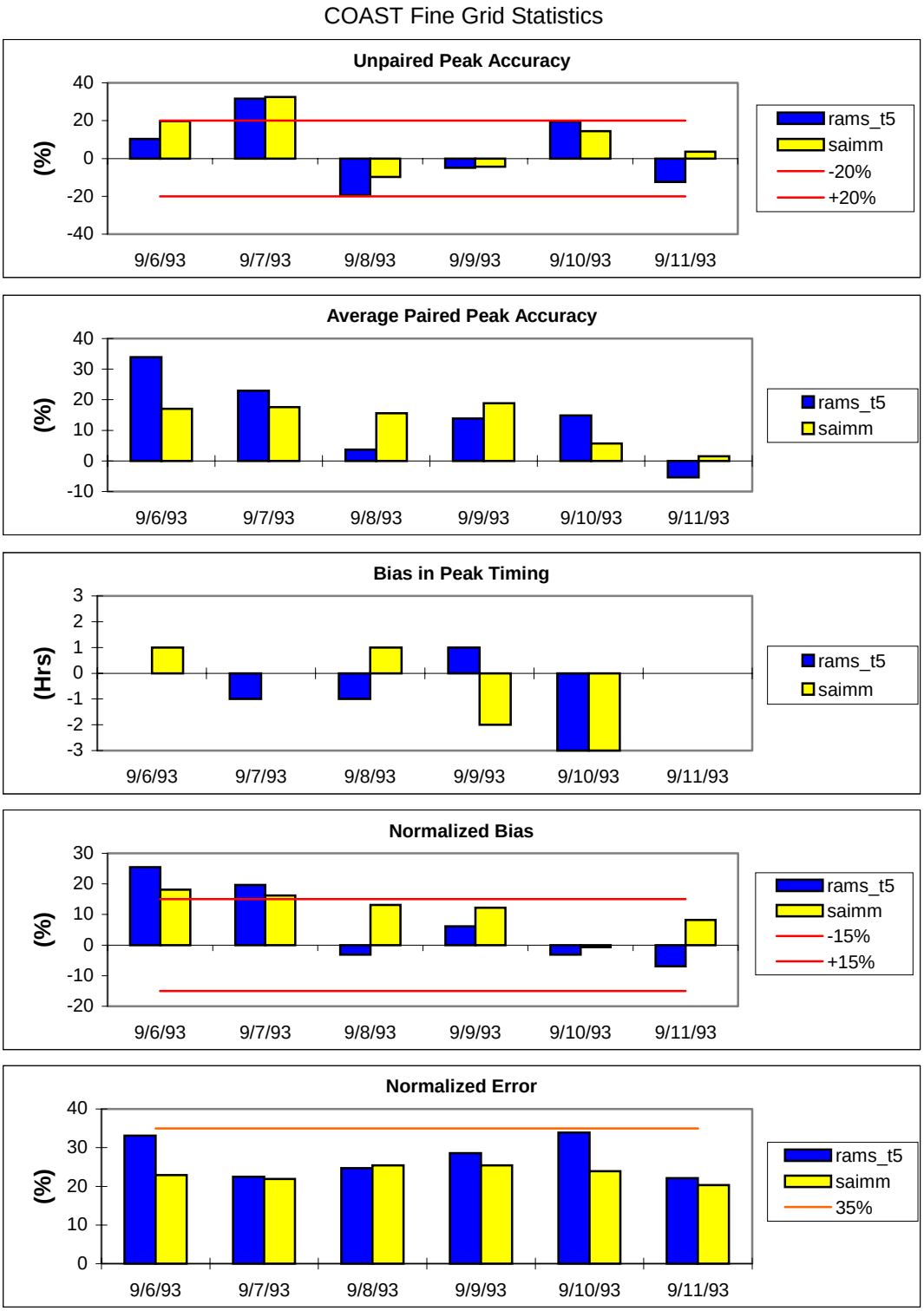


Figure 3-1. Comparison of key performance statistics over each day of the September 6-11, 1993 H/G episode for the CAMx/SAIMM and CAMx/RAMS_T5 runs. EPA acceptance criteria is also shown.

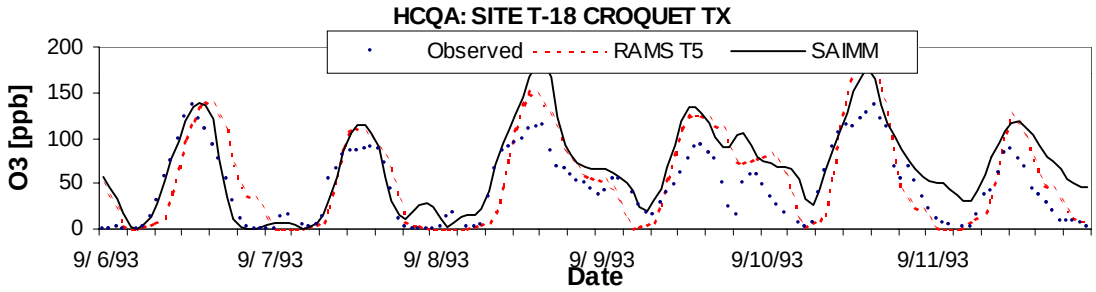


Figure 3-2. Time series of observed and predicted ozone at the Croquet monitoring site in southern Harris County, for the CAMx/SAIMM and CAMx/RAMS_T5 simulations.

4. ANALYSIS OF FUTURE YEAR BASE AND CONTROL RESPONSES

CAMx was run for the entire September 6-11, 1993 period using the RAMS T5 and SAIMM meteorology and the 2007 Base Case future year emission inventory inputs that were provided by TNRCC/MCNC. The 2007 Base Case files used were:

- egtsc.allpts.199309{*date*}.07basD.bin
- low_ei.16km.199309{*date*}.07basD.bin
- low_ei.4km.199309{*date*}.07basD.bin

Then CAMx was run for four emission reduction scenarios using both sets of meteorological inputs so that the impacts of the alternative meteorology on these reduction scenarios could be ascertained. The following reductions were modeled that varied the level of VOC/NOx emission reductions:

CNTL1: 30% anthropogenic NOx reduction (0/30)
CNTL2: 30% anthropogenic VOC reduction (30/0)
CNTL3: 30% anthropogenic NOx and VOC reduction (30/30)
CNTL4: 75% anthropogenic NOx reduction and 30% anthropogenic VOC reduction (30/75)

Note that CNTL4 is the closest approximation to the emission reductions modeled for the Houston SIP. The VOC/NOx emission reduction sensitivity tests consisted of across-the-board VOC and/or NOx anthropogenic emission reductions for the entire COAST domain (Figure 1-1).

2007 BASE CASE

Table 4-1 below shows the daily maximum ozone predicted in the 4-km H/G domain from each day of the episode, and for both the CAMx/RAMS_T5 and CAMx/SAIMM runs. Note that these results emulate the differences in Base Case performance described in Section 3. Specifically, the CAMx/RAMS_T5 simulation exhibits lower daily peak ozone than the CAMx/SAIMM simulation on the 8th and 11th, comparable peak ozone on the 9th, and higher daily peak ozone on the 10th. This suggests that the most limiting day to achieve the 1-hour standard with emission reductions may shift from September 8 to September 10 in the CAMx/RAMS_T5 simulation. Recall that Base Case performance on the 10th was the worst for CAMx/RAMS, with over predictions in unpaired and paired peak performance, and large gross error. Thus, relatively poor model performance for this day leads us to question the daily peak ozone in the 2007 Base Case.

Table 4-1. Daily maximum ozone (ppb) predicted within the H/G area in the 2007 Base Case simulations for the September 1993 episode.

Date	CAMx/SAIMM	CAMx/RAMS_T5
September 8	172.9	156.7
September 9	163.6	163.9
September 10	162.9	171.2
September 11	172.5	144.9

Plots of predicted daily maximum ozone fields in the 4-km H/G domain on September 8 and 10 are provided in Figures 4-1 through 4-4. On September 8 (Figures 4-1 and 4-2 for the two simulations), the CAMx/SAIMM fields exhibit a large ozone cloud southwest of Houston whereas the CAMx/RAMS_T5 fields have shifted this plume southward and the peak is ~15 ppb lower. On September 10 (Figures 4-3 and 4-4) the maximum Houston ozone plume is in a similar area but it is much more expansive in the CAMx/RAMS_T5 simulation and extends westward, whereas in the CAMx/SAIMM simulation the cloud is more compact as on September 8.

Appendices B and C provide spatial maps of daily maximum ozone for the CAMx/RAMS_T5 and CAMx/SAIMM 2007 Base Case runs, respectively, for each day of the episode.

2007 REDUCTION SCENARIOS

Table 4-2 presents the daily peak ozone in the 4-km H/G domain for all the emission reduction sensitivity scenarios modeled, and for both the CAMx/SAIMM and CAMx/RAMS_T5 simulations. In both cases, heavy reductions in NOx as in CNTL4 are necessary to reach 120 ppb. Similar relative reductions in the daily peaks are seen for all of the scenarios. However, the days that exhibit the largest under predictions in the CAMx/RAMS_T5 simulations (September 8 and 11) tend to show the smallest relative change in the peaks (particularly for the CNTL4 case).

Note that on September 8 for the CNTL4 scenario (30/75 VOC/NOx control) the CAMx/RAMS_T5 case has a higher peak ozone (120.9 ppb) than achieved using the SAIMM fields (118.7 ppb) even though the 2007 baseline peak is 15 ppb lower when using RAMS. This would suggest that the RAMS fields have resulted in this day being even “stiffer” in order to achieve the standard. A similar argument might be made for September 10, since it also has a higher daily peak under CNTL4 for the CAMx/RAMS_T5 simulation. However, this day was an over prediction day in the 2007 baseline, and the relative reduction of the peak is quite similar to the CAMx/SAIMM simulation.

Table 4-2. Predicted daily maximum ozone in the H/G area for four VOC/NOx emission reduction scenarios, and the percent reduction of the peak from the 2007 Base Case.

	CNTL1 (0/30)		CNTL2 (30/0)		CNTL3 (30/30)		CNTL4 (30/75)	
Date	**Ppb**	**%**	**Ppb**	**%**	**ppb**	**%**	**ppb**	**%**
			CAMx/SAIMM					
September 8	164.5	4.9	166.0	4.0	161.3	6.7	118.7	31.3
September 9	157.6	3.7	156.0	4.6	154.0	5.9	114.0	30.3
September 10	153.9	5.5	158.2	2.9	150.9	7.4	111.6	31.5
September 11	163.2	5.4	163.8	5.0	158.4	8.2	113.1	34.4
			CAMx/RAMS_T5					
September 8	153.2	2.3	151.4	3.4	149.1	4.9	120.9	22.4
September 9	154.8	5.5	158.6	3.3	150.7	8.1	113.7	30.6
September 10	160.0	6.5	166.8	2.5	156.6	8.5	119.6	30.1
September 11	136.8	5.6	140.3	3.1	133.2	8.1	111.8	22.8

Figures 4-5 through 4-8 display the predicted daily maximum ozone fields in the 4-km H/G domain on September 8 and 10 for the CNTL4 scenario using the two sets of meteorological inputs. On the 8th, the daily peak ozone sets up in a similar area just south of Houston in both CAMx/RAMS_T5 and CAMx/SAIMM simulations. The RAMS fields have resulted in "pulling" the location of the ozone peak toward Houston as the CNTL4 reductions are applied (compare Figure 4-6 to Figure 4-2), which is not necessarily seen with the SAIMM fields. This appears to be the situation with September 10 as well (compare Figure 4-8 with Figure 4-4). We expect this to be a result of a lack of stagnation in the area south and west of Houston that is so prevalent in the SAIMM wind fields.

A lack of stagnation may be a reason why the CAMx/RAMS_T5 simulation for CNTL4 on September 8 is stiffer than CAMx/SAIMM. Consider the following conceptual model. The precursor emission reductions may be shortening the time scale for ozone formation downwind of Houston while reducing the overall ozone yield. In a non-stagnant wind field this would tend to lower the downstream peak while moving it closer to the source area. The shortening of the time scale may be competing against the effects of emission reductions, especially if ozone is being formed from more fresh emissions near the source area (rather than aged/diluted emissions downstream). In the case of CAMx/SAIMM, only one effect is operating on the ozone plume due to stagnation, which is local ozone formation from the direct fresh emissions from the urban source area.

Appendices D through K provide plots of predicted daily maximum ozone in the 4-km H/G domain for each day of the episode, for each of the four emission reduction scenarios, and for both CAMx/RAMS_T5 and CAMx/SAIMM simulations. Also shown in these appendices are plots of the difference fields between each control scenario and the respective 2007 Base Case fields.

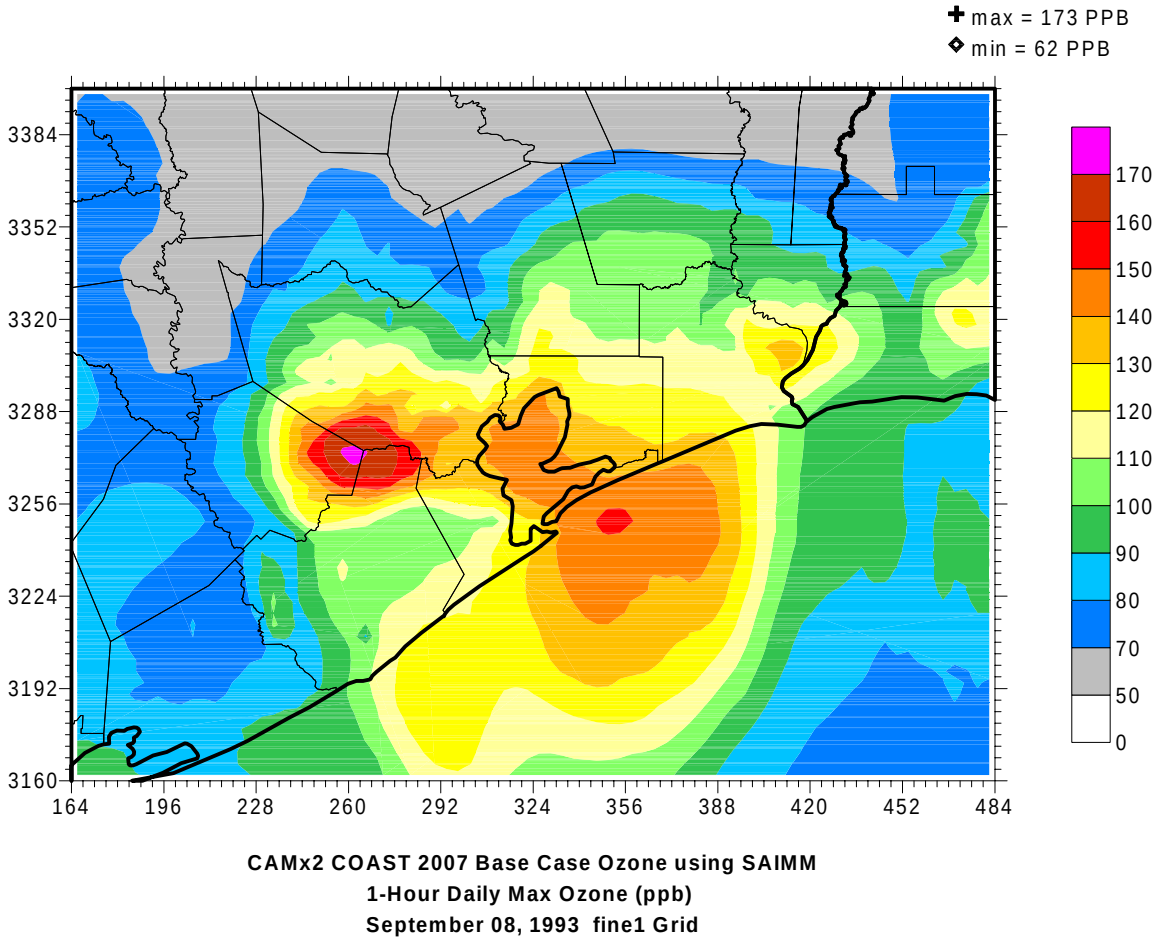


Figure 4-1. Predicted daily maximum ozone (ppb) in the 4-km H/G domain on September 8, 1993 for the CAMx/SAIMM 2007 Base Case.

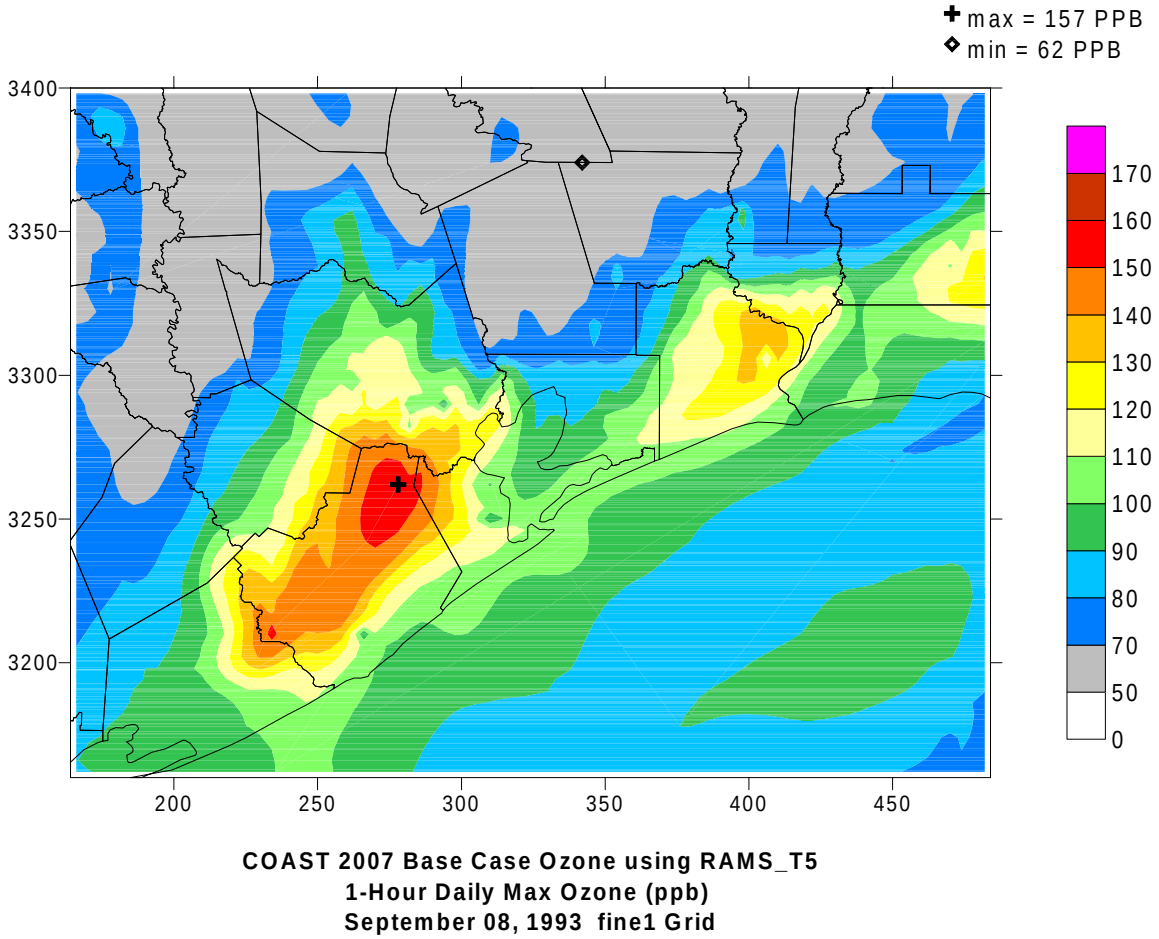


Figure 4-2. Predicted daily maximum ozone (ppb) in the 4-km H/G domain on September 8, 1993 for the CAMx/RAMS_T5 2007 Base Case.

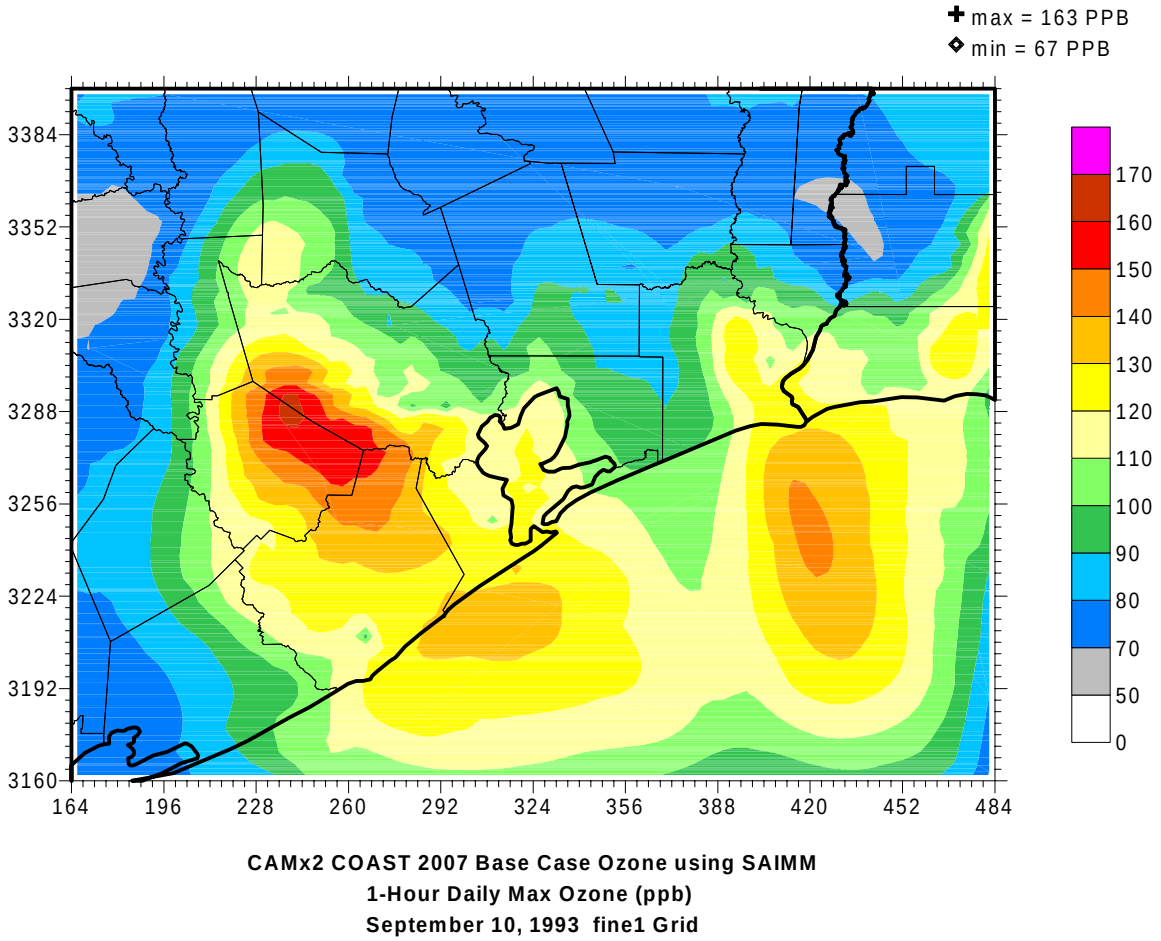


Figure 4-3. Predicted daily maximum ozone (ppb) in the 4-km H/G domain on September 10, 1993 for the CAMx/SAIMM 2007 Base Case.

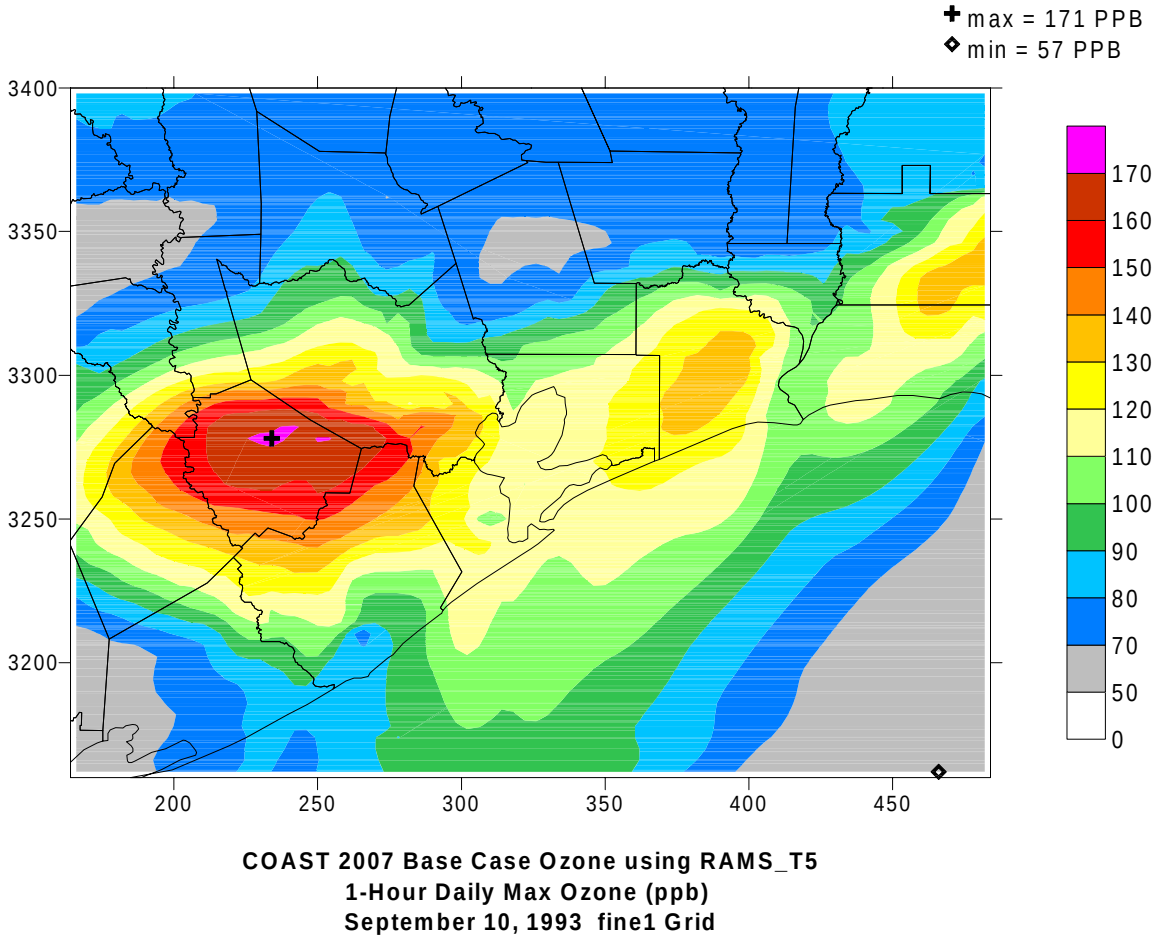


Figure 4-4. Predicted daily maximum ozone (ppb) in the 4-km H/G domain on September 10, 1993 for the CAMx/RAMS_T5 2007 Base Case.

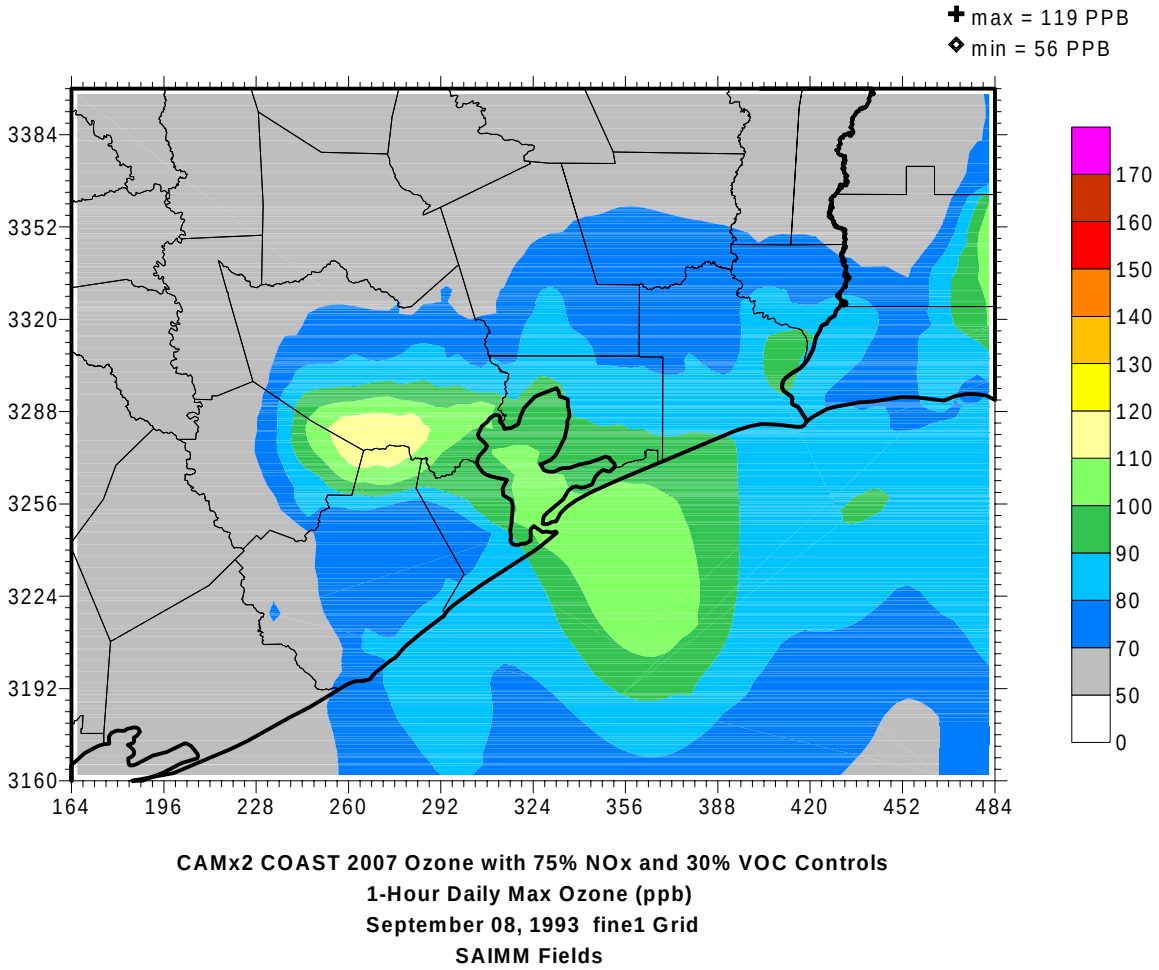


Figure 4-5. Predicted daily maximum ozone (ppb) in the 4-km H/G domain on September 8, 1993 for the CAMx/SAIMM 2007 CNTL4 (75/30) Case.

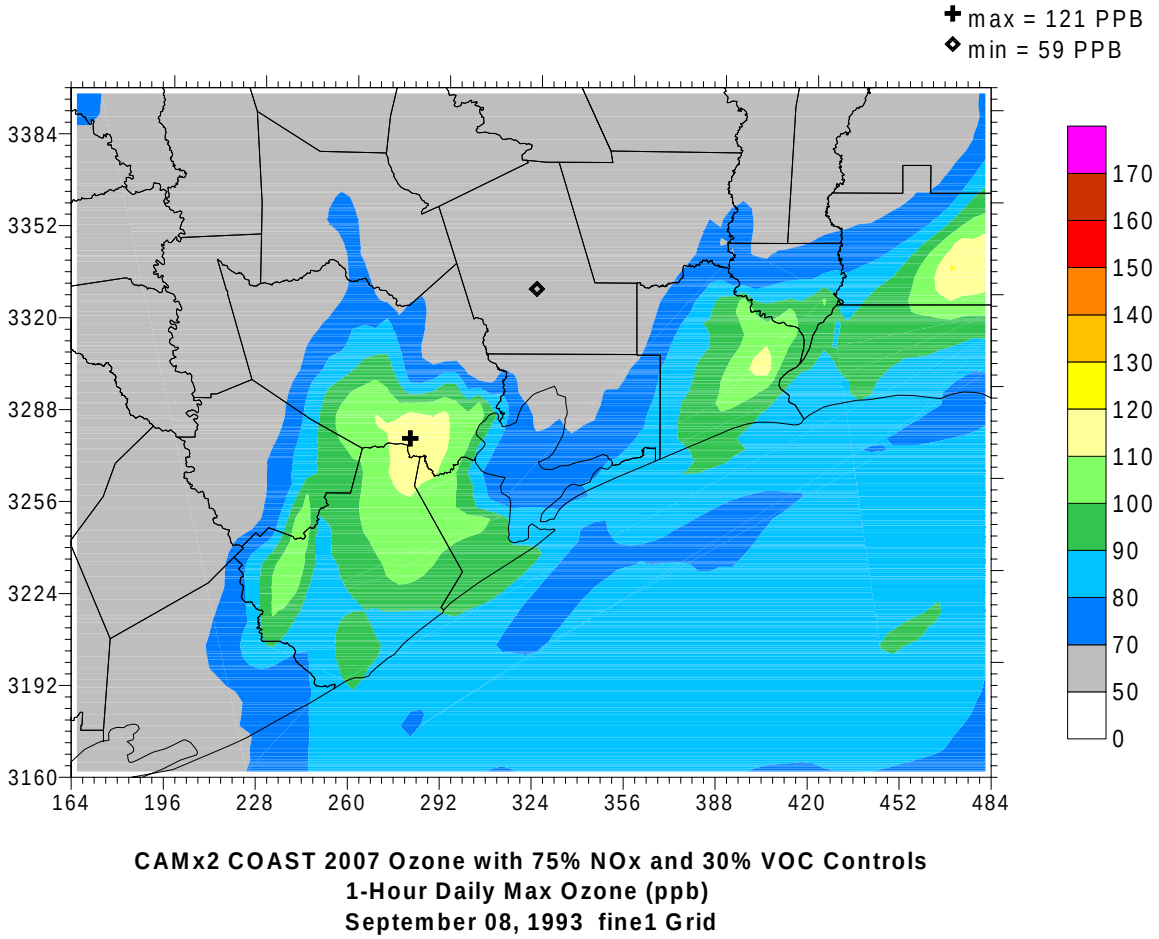


Figure 4-6. Predicted daily maximum ozone (ppb) in the 4-km H/G domain on September 8, 1993 for the CAMx/RAMS_T5 2007 CNTL4 (75/30) Case.

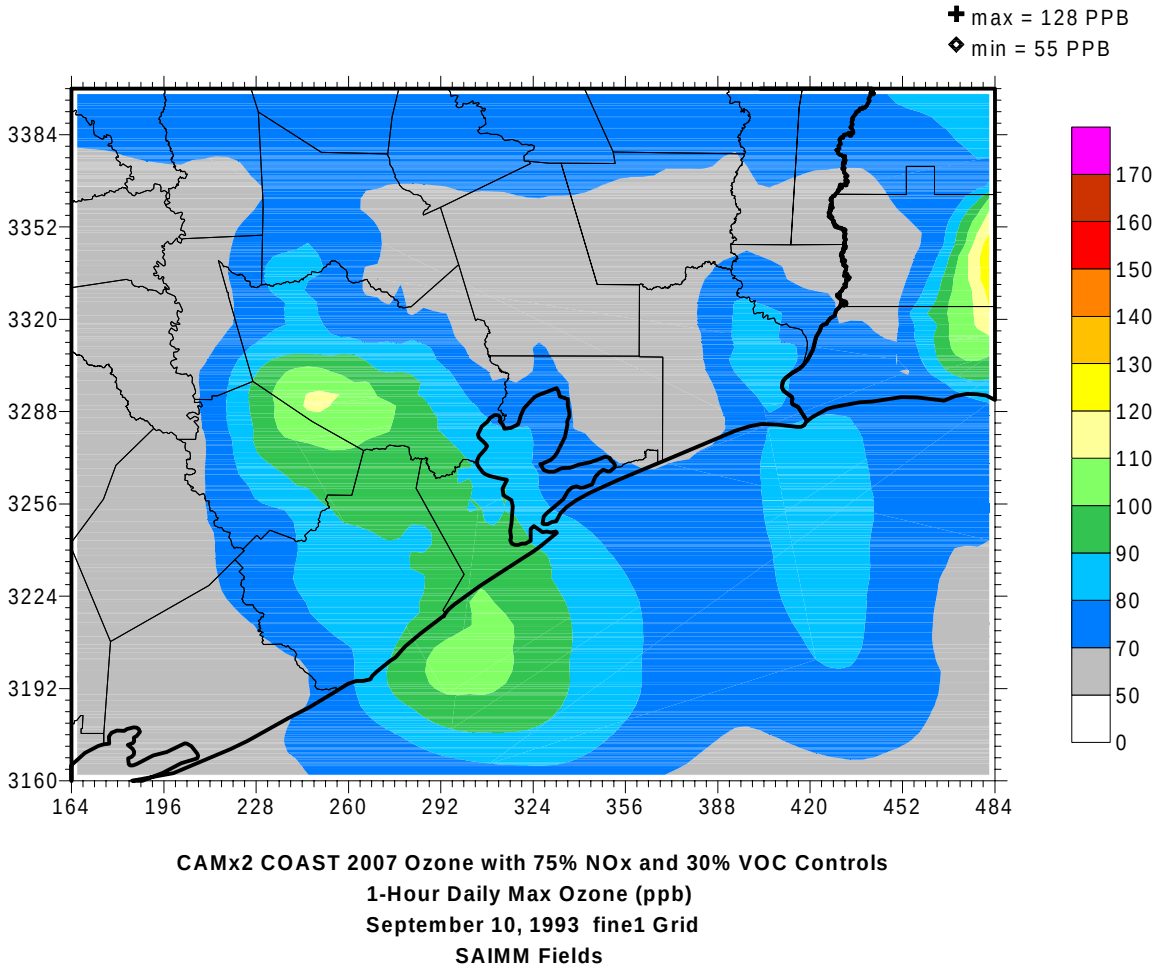


Figure 4-7. Predicted daily maximum ozone (ppb) in the 4-km H/G domain on September 10, 1993 for the CAMx/SAIMM 2007 CNTL4 (75/30) Case.

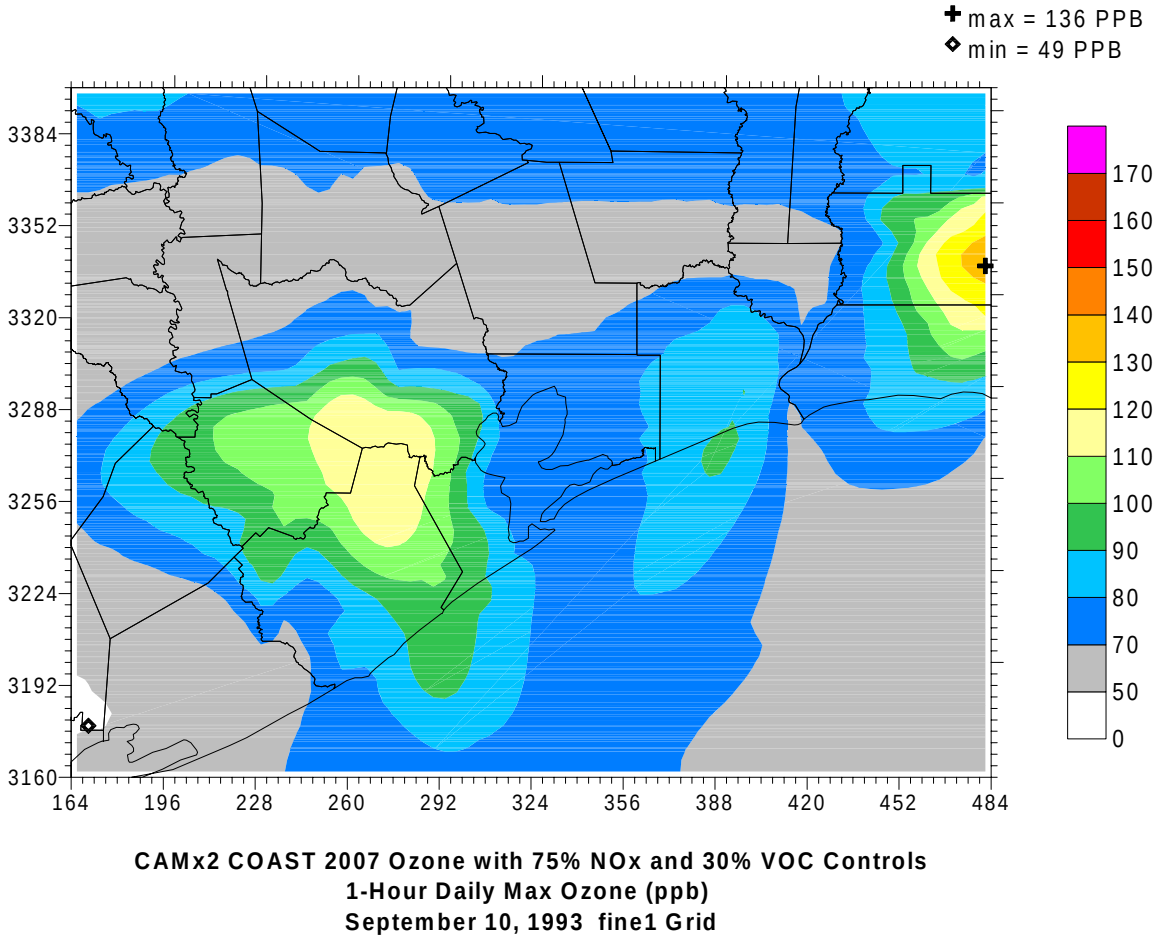


Figure 4-8. Predicted daily maximum ozone (ppb) in the 4-km H/G domain on September 10, 1993 for the CAMx/RAMS_T5 2007 CNTL4 (75/30) Case.

5. SUMMARY AND CONCLUSIONS

The objective of this study was to develop improved meteorological inputs for the Houston/Galveston area and the September 6-11, 1993 ozone episode and determine whether the 2007 ozone estimates using the improved meteorological fields were more sensitive to emission reductions than using the old SAIMM meteorological fields.

Meteorological Modeling

New meteorological fields were generated using the RAMS prognostic meteorological model. Several meteorological model sensitivity simulations were performed that varied the level of four dimensional data assimilation (FDDA) and the level of initial soil moisture. Changes in the meteorological model inputs for these sensitivity simulations were guided by attempts to improve the performance of the meteorological model, not the performance of the air quality model. The RAMS_T5 meteorological model simulation exhibited model performance for winds and temperatures that was quite good and better than most RAMS simulations performed for air quality modeling. Thus, it was selected for use in the photochemical modeling.

Base Case Model Performance

The RAMS_T5 meteorological output data were processed using the RAMSCAMx processor to generate CAMx meteorological inputs for the September 6-11, 1993 episode and the H/G 16/4-km grid (Figure 1-1). CAMx was exercised for a 1993 base case, a 2007 base case, and several 2007 VOC/NOx emission reduction scenarios. The performance of the CAMx/RAMS_T5 and CAMx/SAIMM for predicting the observed ozone concentrations revealed that, in general, CAMx/SAIMM exhibited better performance in predicting the unpaired peak observed ozone concentrations, whereas CAMx/RAMS_T5 exhibited lower bias in predicting average daily maximum and hourly ozone concentrations across the network. Both the CAMx/RAMS_T5 and CAMx/SAIMM met EPA's ozone model performance goals.

Future-Year Control Scenarios

The effects of VOC/NOx across the board emission reductions in 2007 of 0/30, 30/0, 30/30, and 30/75 percent (%VOC/%NOx) were analyzed using the CAMx/RAMS_T5 and CAMx/SAIMM databases for the September 6-11, 1993 H/G episode. Previously, the CAMx/SAIMM database ozone estimates had exhibited a stiffness to NOx emission reductions that was especially apparent on September 8th. The CAMx/RAMS_T5 database exhibited a similar stiffness and, if anything, exhibited slightly more stiffness on September 8th than the CAMx/SAIMM database. However, this may be due to the fact that the CAMx/RAMS_T5 2007 base case is starting with a lower peak ozone concentration on September 8th than the CAMx/SAIMM 2007 base case.

Conclusions

New meteorological inputs were developed for the September 6-11, 1993 Houston/Galveston ozone episode using the RAMS prognostic meteorological model (RAMS_T5). Several RAMS sensitivity runs were performed varying the level of FDDA and initial soil moisture within their ranges of uncertainty to improve the meteorological model performance. Physically realistic wind fields were developed in an objective fashion based on improvements to the meteorological model simulation. This is in contrast to the SAIMM simulations that used extremely strong nudging of the winds that produced unphysical features.

The CAMx/RAMS_T5 and CAMx/SAIMM 1993 base case simulations both exhibited ozone model performance that met EPA's performance goals. The CAMx/RAMS_T5 and CAMx/SAIMM both exhibited similar stiffness of the peak ozone concentrations responsiveness to NOx controls. Thus, it appears that the stiffness of the CAMx/SAIMM peak ozone concentrations are likely not due to the unphysical characteristics of the SAIMM wind fields but rather are likely due to the emissions inventory and resultant atmospheric chemistry. Thus, use of the CAMx/RAMS_T5 database would likely not appreciably change the findings of the Houston SIP modeling that was based on the CAMx/SAIMM database.

The CAMx/RAMS_T5 database was developed in just two months with a limited amount of model sensitivity runs. Further analysis of RAMS model sensitivity simulations altering model inputs (e.g., soil moisture) within their range of uncertainty could be performed to improve the simulation. However, even without these additional simulations we believe that the existing RAMS_T5 meteorological fields represent significant improvements over the SAIMM fields because they were prepared in a more objective fashion and exhibit more physically realistic features.

REFERENCES

Yarwood, G., R.E. Morris and C.A. Emery. 2000. "Diagnostic Analysis of the COAST Domain Modeling of September 6-11, 1993 Including CAMx Process Analysis." Prepared for The Houston Regional Monitoring Program. May.