MM5 Simulations for TexAQS 2000 Episode

Task 3: Sensitivities to modifications of the MRF PBL scheme

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1 Introduction

ATMET has performed numerous sensitivity simulations with MM5 for both the 1993 and 2000 episodes for the Houston-Galveston region (ATMET, 2002a; ATMET, 2003a; ATMET, 2003b). A major component of these simulations has been the testing of the various PBL schemes that are implemented in MM5. The results of these simulations consistently showed that, of all the PBL schemes, the MRF scheme usually provided the best results, at least when it comes to surface verification.

However, as many other MM5 users have noted also, the MRF scheme consistently overestimates the height of the PBL, which is crucial for good air quality simulations. All experiments conducted have shown this tendency to overestimate the depth of the boundary layer especially during the daytime hours. This overestimation manifests itself in numerous ways, even from a meteorological viewpoint. For example, in ATMET 2003b, the too rapidly-growing daytime PBL played a role in a significant low bias of dew point temperature at the surface on many days.

The MM5 MRF PBL scheme is designed after a procedure described by Hong and Pan (1996), which followed very closely on earlier work of Troen and Mahrt (1986). Hong and Pan first implemented this scheme in the NCEP MRF model, which is the main global forecast model run at NCEP to produce the AVN forecasts (the name of the model and forecasts have recently been changed to the GFS, Global Forecasting System). The scheme was developed with the MRF model in mind, relatively coarse horizontal resolution, vertical resolution coarser than is usually used today in mesoscale models, and a requirement that very little computer resources be used. The scheme was later implemented in MM5 by Dudhia and Hong.

There are several aspects to the scheme (stable vs. unstable boundary layers, diffusion above and below the boundary layer height). For this task, we focused on the regime of that seems to cause the most problems, diffusion within the unstable boundary layer.

In ATMET (2003b), we reviewed the formulation of the MRF scheme and identified several features in the implementation that could lead to this overprediction. The MRF scheme is based on the use of a profile function for the vertical exchange coefficient. Sub-grid diffusion schemes based on the O'Brien profile function date back to at least the early 1970's. While termed a "non-local" scheme by Hong and Pan, this scheme still produces an eddy exchange coefficient where the mixing is done locally (i.e., from layer to layer). The computation of the eddy viscosity coefficients is done taking into account "non-local" effects (e.g., the O'Brien profile function). However, the usual use of the term "non-local diffusion" in the literature frequently refers to a scheme that can mix characteristics of the atmosphere beyond the adjoining layer.

The MRF scheme requires the computation of a PBL height. Similar schemes have prognosed the height; the MRF scheme uses a diagnosis on each timestep. This diagnosis is based on the definition of a bulk Richardson number:

$$Ri = \frac{\frac{g}{\theta_v}\frac{\partial \theta_v}{\partial z}}{\left(\frac{\partial V}{\partial z}\right)^2}$$

where g is gravity, V is the wind speed, and θ_v is virtual potential temperature.

Two assumptions are then made by Troen and Mahrt:

- The Richardson number will be assumed to apply over the depth of the boundary layer.
- A critical Richardson number can be defined and used over this depth to compute the boundary layer height.

Typically, the bulk Richardson number is used to determine if the vertical wind shear is adequate to overcome the level of stability and make a layer prone to turbulence. Usually, this has been applied to relatively shallow layers (e.g., of order 100 m), not to entire boundary layer depths that can reach several kilometers. When applied to shallow layers, the theoretical value of the critical Richardson number is usually taken to be 0.25. If the value is more than this, the flow is likely to be laminar; when the value is less, turbulence is likely. Various researchers have used a larger number for the critical Richardson due to discretization and numerical arguments.

If we make the assumptions of Troen and Mahrt, replace ∂z with the symbol h for PBL height, and discretize over the entire PBL depth, we arrive at the expression used for PBL height used in the MRF scheme:

$$h = Ri_{cr}\frac{\theta_{va}\left|V(h)\right|^2}{g\left(\theta_v(h)-\theta_s\right)}$$

where $V(h)$ and $\theta(h)$ are the wind speed and virtual potential temperature at height h, θ_{va} is the virtual potential temperature at the first model level above the ground, and θ_s is a representative air temperature near the surface. θ_s is further defined as:

$$\theta_s = \theta_{va} + \theta_T$$

where θ_T is defined as a "scaled virtual temperature excess near the surface". This term is based on surface layer sensible heat flux and was considered necessary because the scheme was intended for vertical resolutions near the ground that were on the order of 30-50 m, typical of those used in global models. Further, it was limited to a maximum of 3K, since it could become very large if wind speeds were small.

Examination of the PBL computation suggested two immediate possibilities for testing to reduce the PBL heights. First, the PBL depth is directly correlated to the critical bulk Richardson number (Ri_{cr}). The MM5 code uses a Ri_{cr} value of 0.5. Since this number is rather arbitrary, lower values could be tested. The second possibility for sensitivity testing is the scaled virtual temperature excess that is designed to account for a near-surface temperature that is warmer than the lowest-level model temperature. Given that current mesoscale model implementations typically utilize higher grid resolution near the ground than used in global models (e.g., our experiments used a lowest level under 10m), the scaled virtual temperature excess term may be too large for these applications.

In ATMET (2003b), several short diagnostic simulations were run to determine the characteristics of the PBL height and eddy viscosity coefficients that were produced by the MRF scheme. We found that in the early afternoon, the temperature excess was typically 1-2K, with the eddy viscosity coefficients reaching as large as 1000-1500 m^2/s. A short sensitivity simulation was completed with the scaled virtual temperature excess contribution removed. Results indicate that boundary layer depths were reduced by as much as 1000 m during the afternoon hours.

With these brief sensitivity runs, there seemed to be promise to be able to reduce the daytime PBL heights from the MRF scheme to more accurate values. For the current task, we have run longer sensitivity experiments and, based on these results, have run a complete episode and compared it to the previous runs. The results are detailed in the following sections.

2 MM5 TexAQS sensitivity simulations

ATMET performed a series of sensitivity experiments for the TexAQS-2000 episode from 16 August – 7 September and results from three sensitivity experiments were documented (ATMET 2003b). A summary of these three experiments is discussed and then results from a fourth follow-on experiment are presented.

2.1 Summary of Experiments 1, 2, and 3

Experiments 1-3 utilized the MM5 mesoscale model setup with four domains ranging in grid spacing from 108 km down to 4 km and grid 4 centered over the Houston-Galveston area. The experiments were designed to complement TexAQS2000 work completed by Nielsen-Gammon (2001, 2002a,b,c,d) and to improve atmospheric forecasts for the episode by taking advantage of new physics options available in MM5 and by improving the MM5 boundary layer scheme. Results from these initial tests indicated the following:

- Inclusion of the new NOAH LSM in MM5 improved the model forecasts. It is important to correctly initialize the soil temperature and soil moisture to realize the improvements due to the LSM.
- A diurnal temperature bias was noted with cool biases during the early morning and slightly warm biases during the afternoon. More significant warm biases were indicated during convective periods that the model did not capture.
- A significant diurnal wind speed bias was noted with slow daytime biases and high nighttime biases. The slow daytime bias was largely attributed to a "convective contribution" to the total wind speed that is used in the U* computation when the boundary layer is unstable. Removal of this convective contribution eliminated much of the slow daytime wind speed bias.
- A significant dry dew point bias was indicated for nearly all times, especially during the afternoon. This was at least partially attributed to the MRF PBL scheme over-estimating the PBL depth during the afternoon hours. Sensitivity experiments suggested two potential improvements to the MRF PBL scheme: 1) reduce the critical bulk Richardson number used by the scheme and 2) reduce or eliminate the scaled virtual temperature excess that is designed to account for a near-surface temperature that is warmer than the lowest-level model temperature.
- A review of the MM5 TKE schemes was recommended with a comparison to other mesoscale model schemes, and possible modification of the MM5 schemes to allow them to work for more general situations. The review will be covered in a separate report.

2.2 Further investigation of MRF scheme and PBL depth

Results from the completed experiments indicated a consistent over-forecast of the PBL depth diagnosed by the MM5 MRF PBL scheme. A review of the MM5 software suggested two potential improvements:

- reduce the critical bulk Richardson number (Rib_{cr}) used by the scheme
- reduce or eliminate the scaled virtual temperature excess.

Two MM5 sensitivity runs were conducted to test the hypotheses. The first run reduced the Rib_{cr} by half from 0.5 to 0.25 and the second run eliminated the scaled virtual temperature excess.

Both MM5 sensitivity runs generated forecasts for the three-day period from 29 through 31 August, utilizing the MM5 history restart option by initializing the model with data valid at 0000 UTC 29 August from Experiment 3. The 3-day period coincided with an identified Rapid Ozone Formation Event (ROFE) on 30 August. Profiler-observed PBL depths were available from five Houston area sites (Senff 2002). Senff (personal communication) provided profiler data to ATMET for direct comparison to the MM5-predicted PBL depth (Figures 2-4). Somewhat surprisingly, the comparison indicates very little change in predicted PBL depth with the Rib_{cr} cut in half. Removal of the scaled virtual temperature excess did, however, generate markedly improved forecast PBL depths when compared to observations. In some cases (e.g. ELL and HSW on 29 August), nearly all of the high bias was removed. In most cases, however, the predicted PBL depths are still over-forecast, but the overall bias is reduced by at least half.

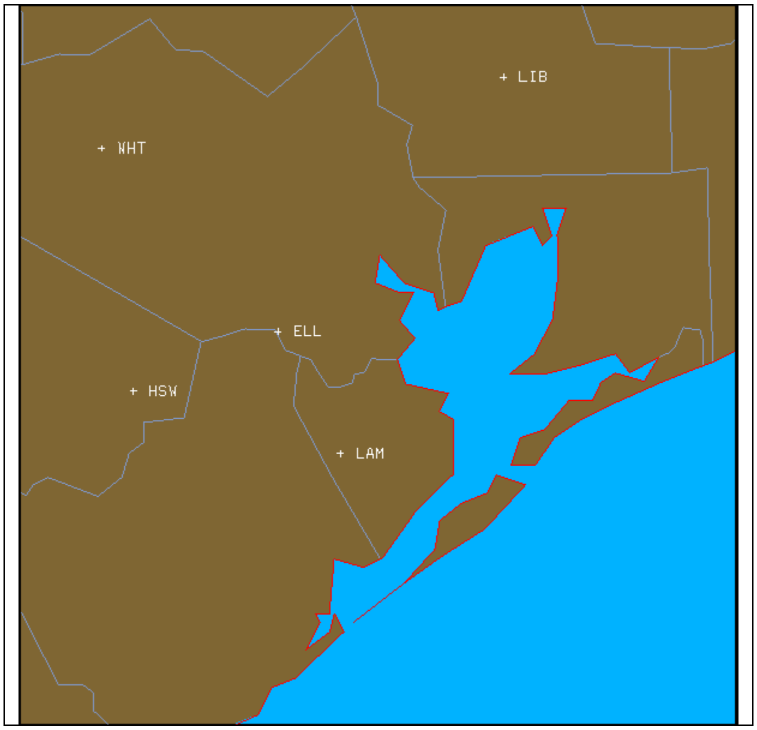
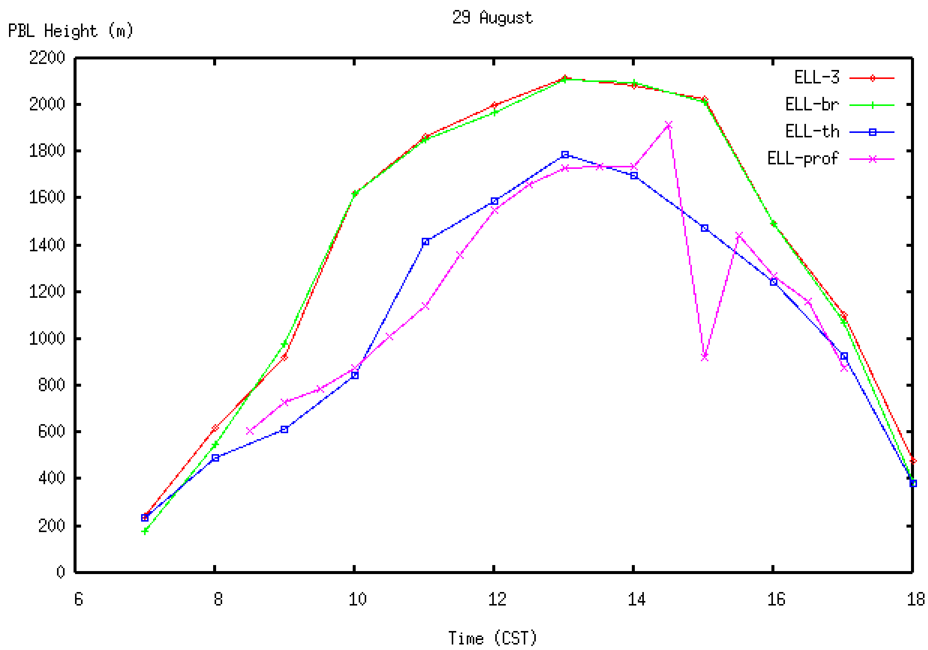
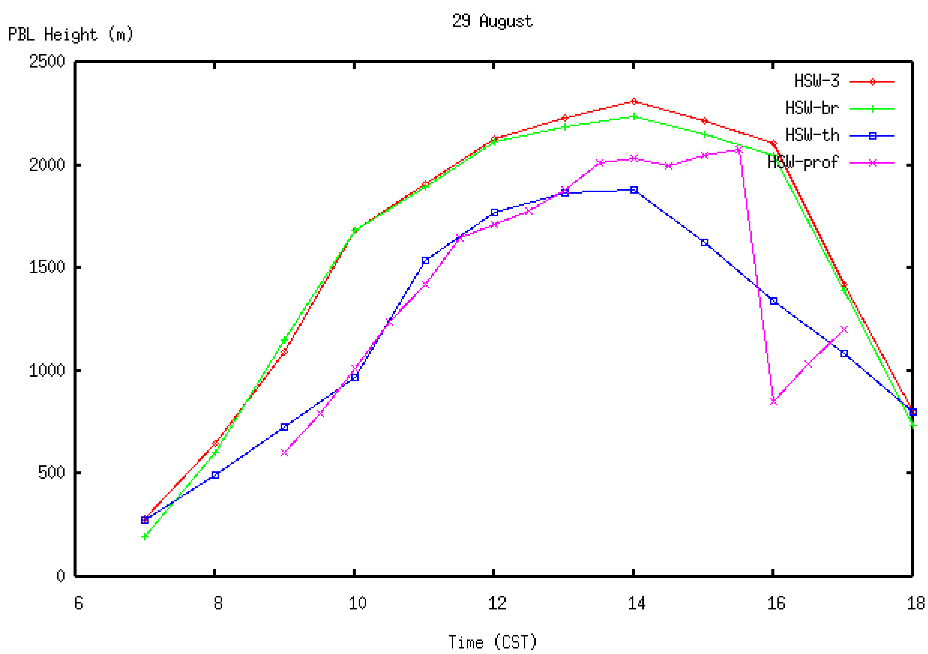
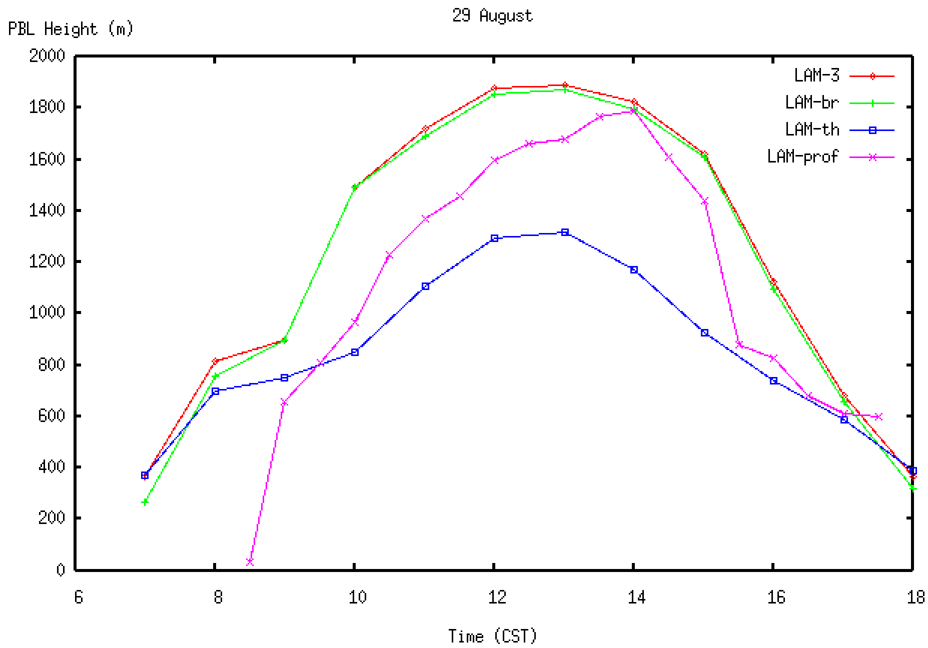
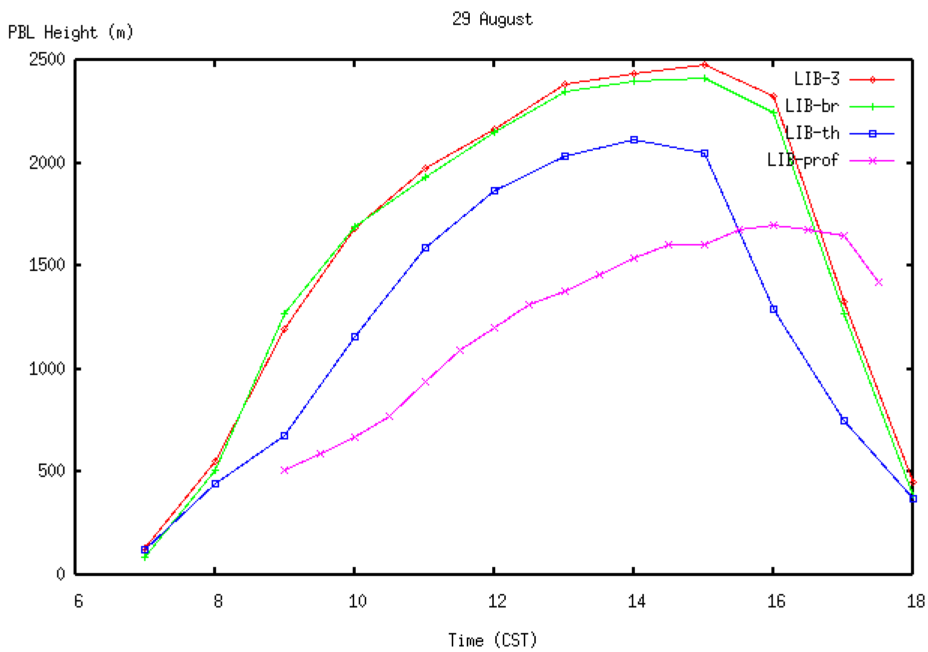


Figure 1: Locations of TEXAQS Houston-area profilers with PBL measurements (LAM = LaMarque, ELL = Ellington, HSW = Houston southwest, LIB = Liberty, and WHT = Wharton).


29 August
PBL Height (m)
Time (CST)
ELL-3
ELL-br
ELL-th
ELL-prof


29 August
PBL Height (m)
Time (CST)
HSW-3
HSW-br
HSW-th
HSW-prof


29 August
PBL Height (m)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6
8
10
12
14
16
18
Time (CST)
LAM-3
LAM-br
LAM-th
LAM-prof


29 August
PBL Height (m)
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
LIB-3
LIB-br
LIB-th
LIB-prof

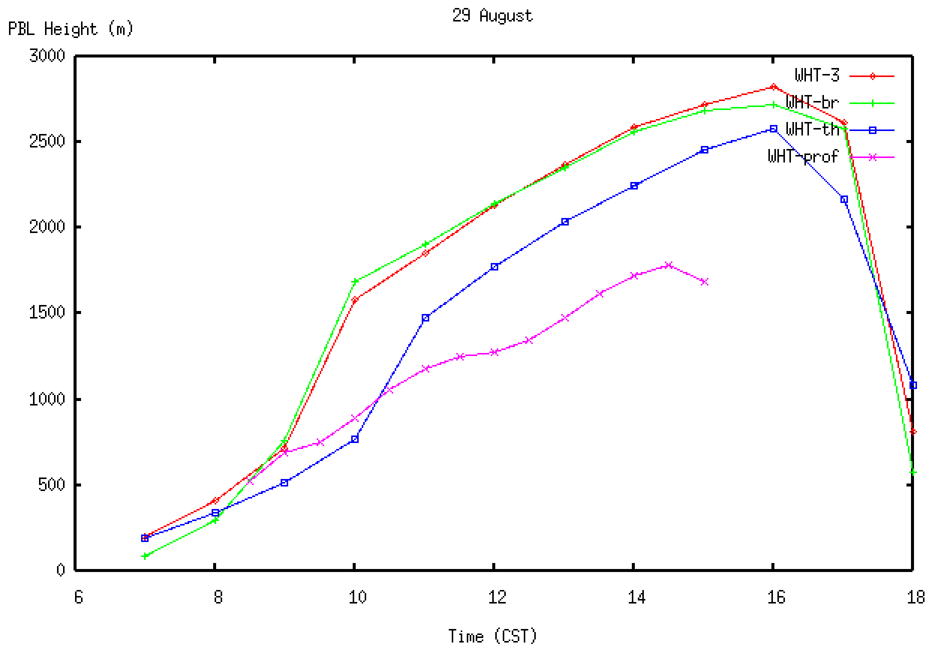
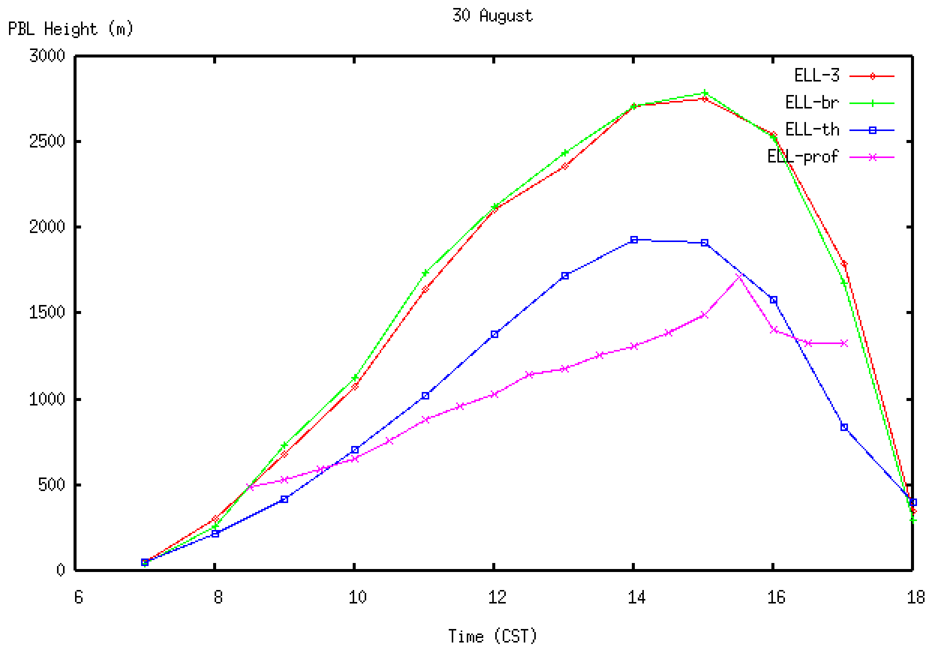
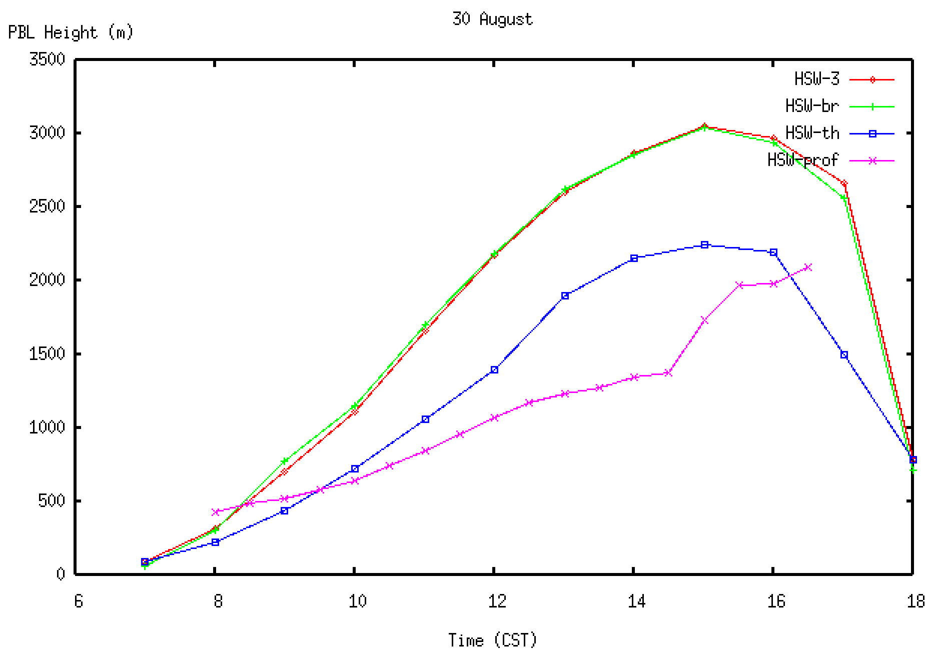
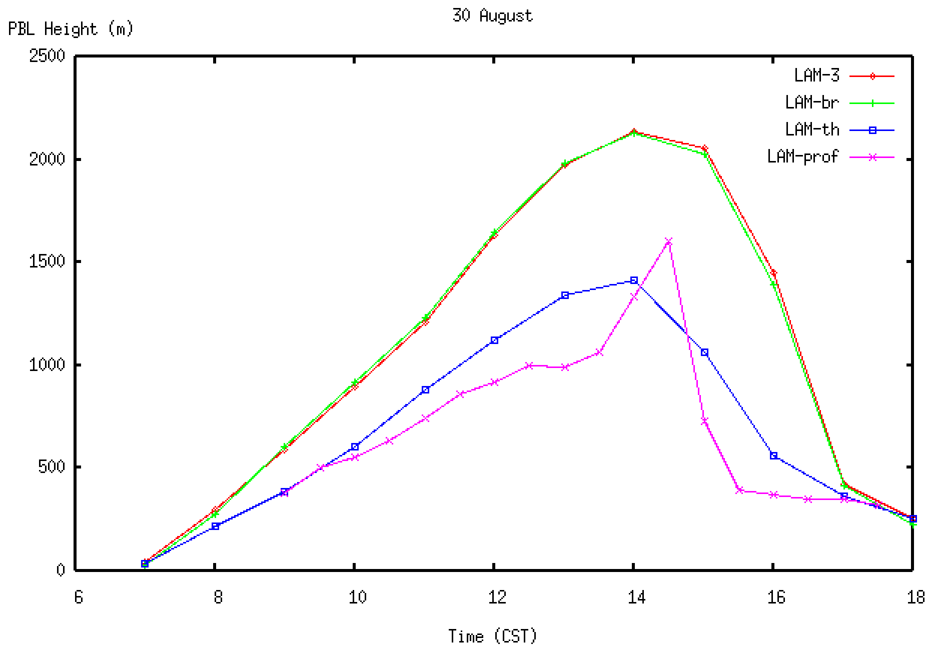
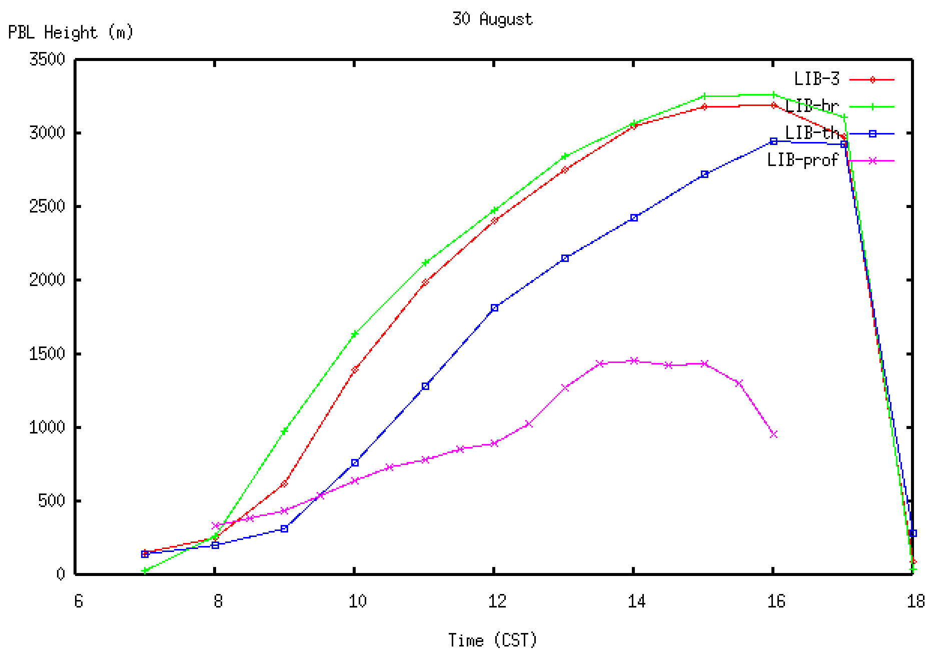


Figure 2: MM5 predicted PBL heights (m) for 29 August 2000 from Experiment 3 (red), reduced Rib$_{cr}$ sensitivity run (green), removed scaled virtual temperature excess sensitivity run (blue) compared to profiler observations (purple). Houston-area profiler station locations include Ellington (ELL), Houston southwest (HSW), LaMarque (LAM), Liberty (LIB), and Wharton (WHT) (Senff 2002).


30 August
PBL Height (m)
3000
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
ELL-3
ELL-br
ELL-th
ELL-prof


30 August
PBL Height (m)
3500
3000
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
HSW-3
HSW-br
HSW-th
HSW-prof


30 August
PBL Height (m)
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
LAM-3
LAM-br
LAM-th
LAM-prof


30 August
PBL Height (m)
3500
3000
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
LIB-3
LIB-br
LIB-th
LIB-prof

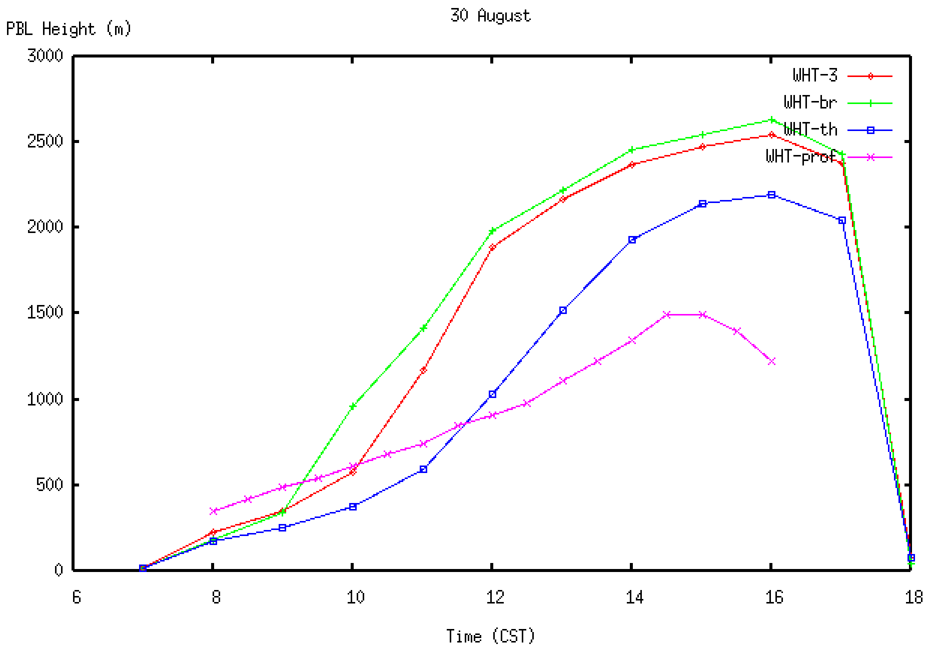
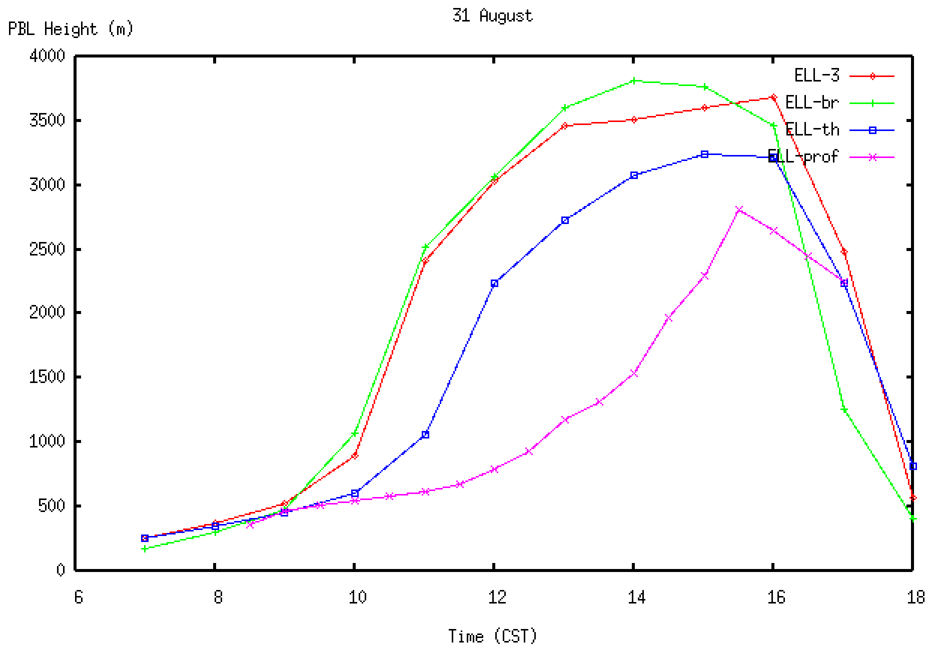
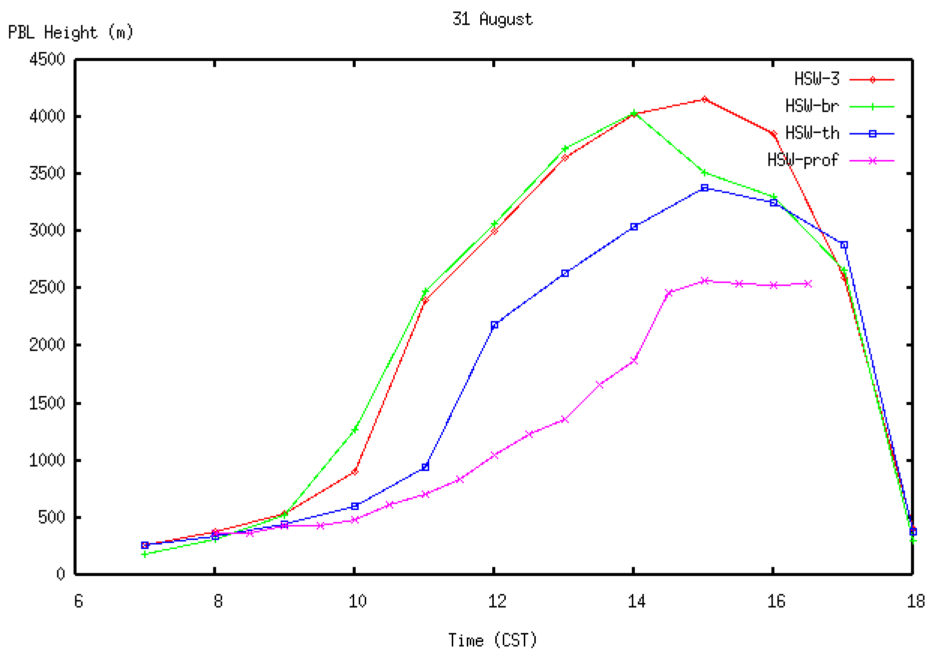
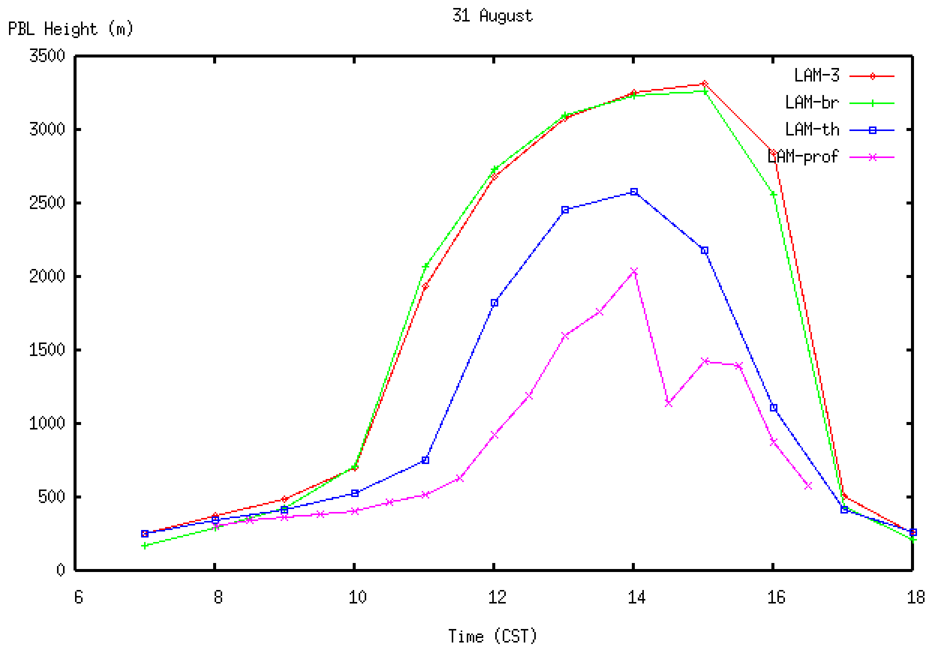
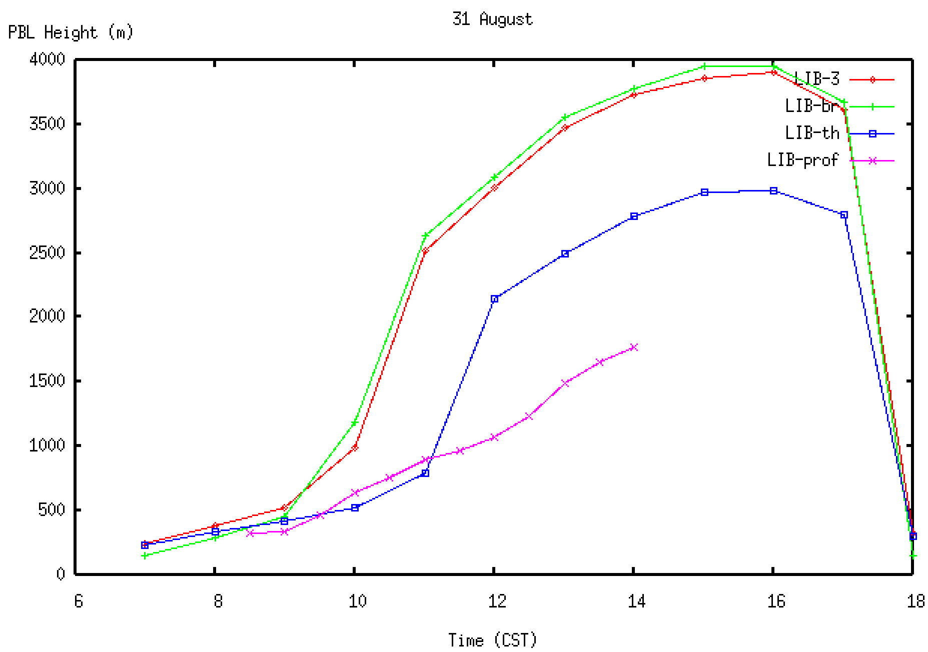


Figure 3: MM5 predicted PBL heights (m) for 30 August 2000 from Experiment 3 (red), reduced Rib$_{cr}$ sensitivity run (green), removed scaled virtual temperature excess sensitivity run (blue) compared to profiler observations (purple). Houston-area profiler station locations include Ellington (ELL), Houston southwest (HSW), LaMarque (LAM), Liberty (LIB), and Wharton (WHT) (Senff 2002).


31 August
PBL Height (m)
4000
3500
3000
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
ELL-3
ELL-br
ELL-th
ELL-prof


31 August
PBL Height (m)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
HSW-3
HSW-br
HSW-th
HSW-prof


31 August
PBL Height (m)
3500
3000
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
LAM-3
LAM-br
LAM-th
LAM-prof


31 August
PBL Height (m)
4000
3500
3000
2500
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time (CST)
LIB-3
LIB-br
LIB-th
LIB-prof

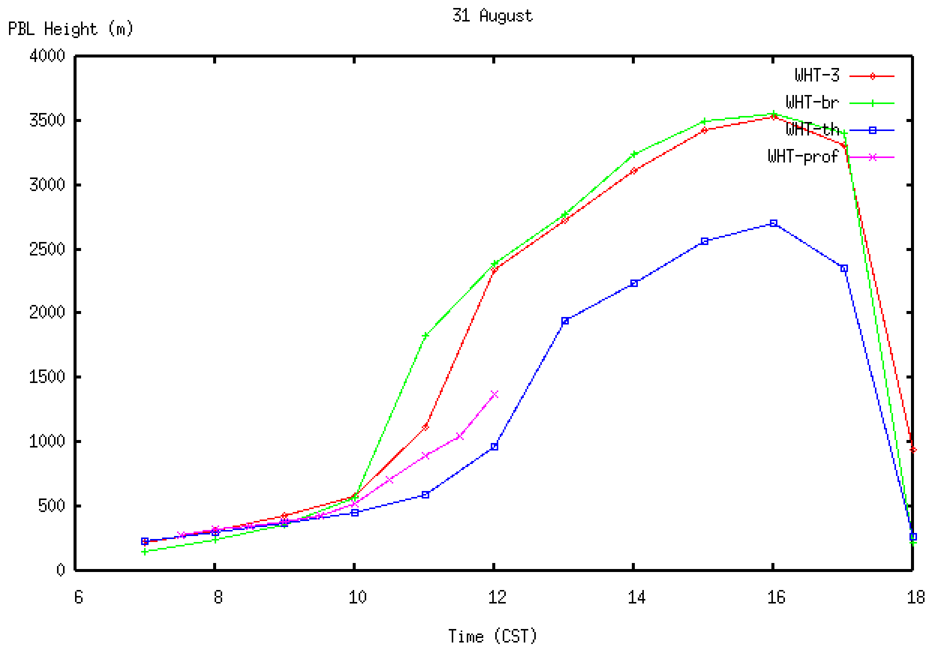


Figure 4: MM5 predicted PBL heights (m) for 31 August 2000 from Experiment 3 (red), reduced Rib$_{cr}$ sensitivity run (green), removed scaled virtual temperature excess sensitivity run (blue) compared to profiler observations (purple). Houston-area profiler station locations include Ellington (ELL), Houston southwest (HSW), LaMarque (LAM), Liberty (LIB), and Wharton (WHT) (Senff 2002).

2.3 Experiment 4 – Removal of thermal excess term

A fourth, full episode run based on the positive results of removing the thermal excess term in the MRF PBL scheme was completed for the complete episode period from 16 August through 7 September. The MM5 model configuration was set so that the only difference between Experiments 3 and 4 was the removal of the thermal excess term.

2.3.1 *Results*

Graphical images of the plotted fields from all four experiments are located on our web site at: http://bridge.atmet.org/tceq/forecast.shtml. Experiment 4 statistical validation results for all observations (typically 75 stations) available within grid 4 are summarized in Figures 4-6. Overall, despite significant improvements in the forecast PBL depth, little differences are noted between Experiments 3 and 4 for temperature and wind speed. Small improvements in forecast dew point are indicated with somewhat less of a dry bias. Although greatest improvement is observed on the days with the largest dry bias, the overall dry bias still exists and remains significant on a number of days.

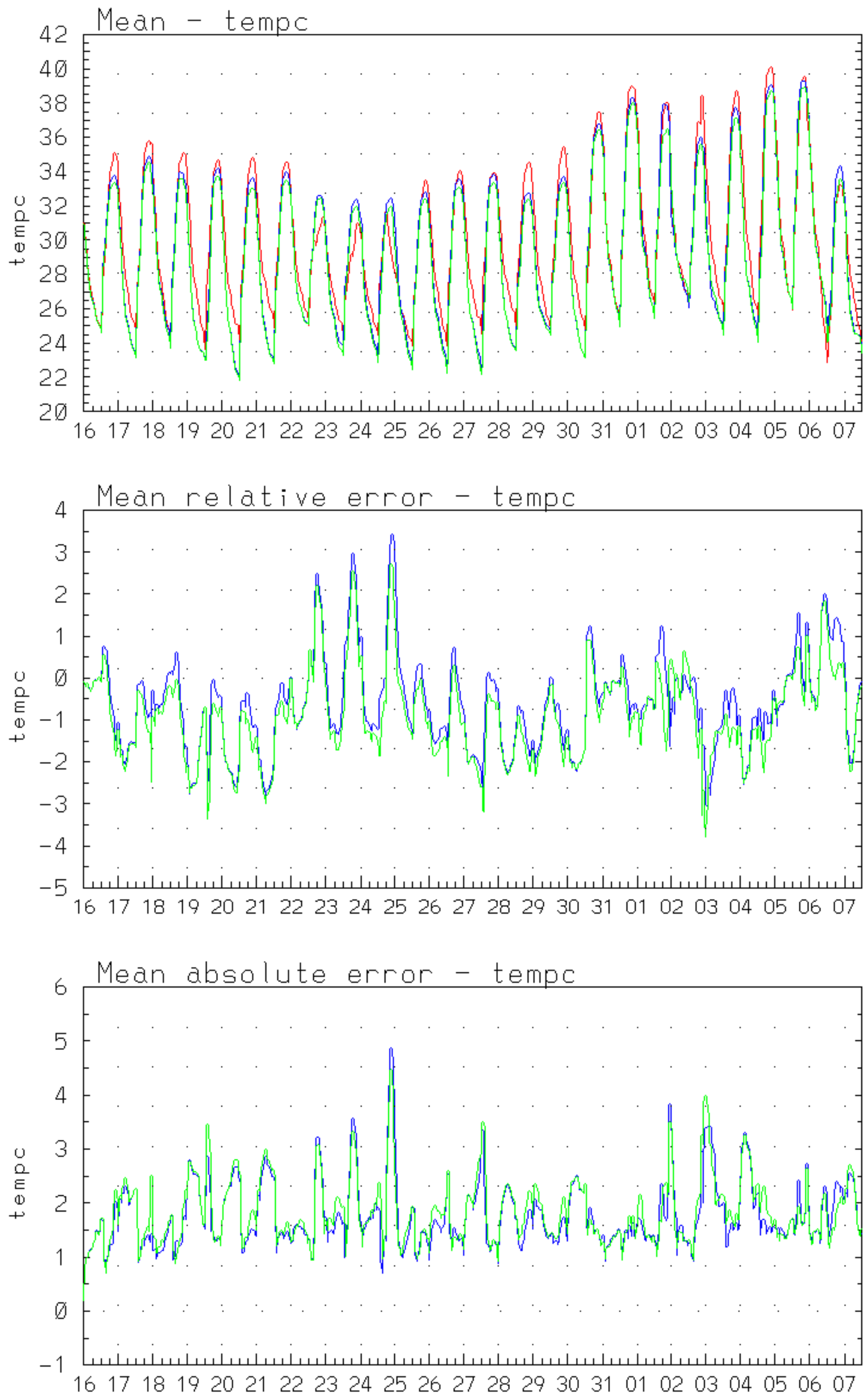


Figure 5: Hourly temperature (C) statistics for Experiments 3 (blue) and 4 (green) using all observations (red) available within grid 4.

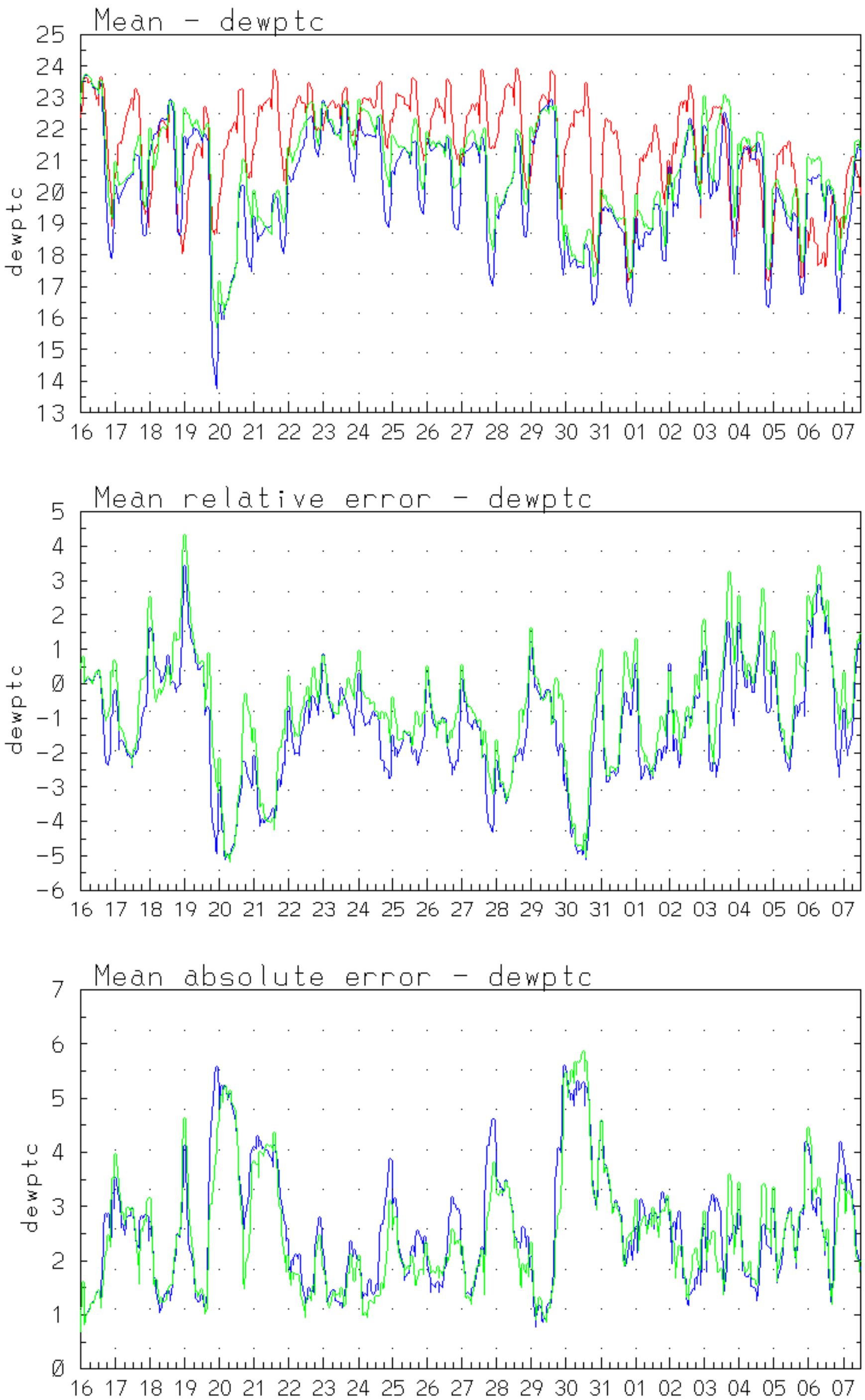
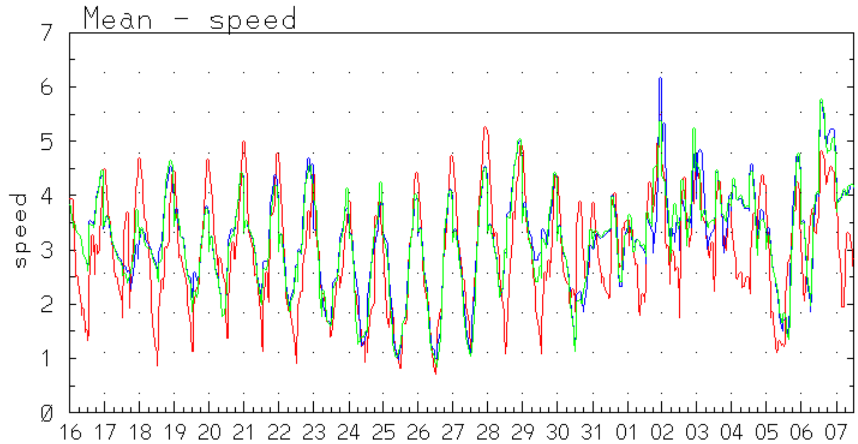
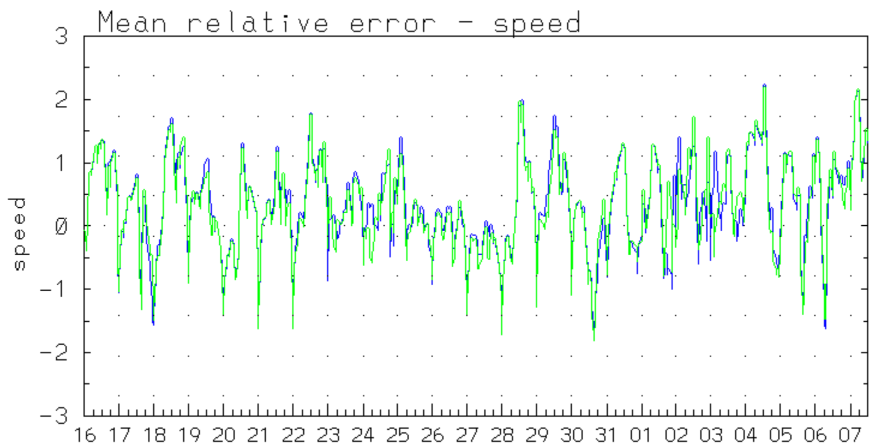


Figure 6: Hourly dew point (C) statistics for Experiments 3 (blue) and 4 (green) using all observations (red) available within grid 4.


Mean - speed
speed
7
6
5
4
3
2
1
Ø
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 01 02 03 04 05 06 07


Mean relative error - speed
speed
3
2
1
Ø
−1
−2
−3
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 01 02 03 04 05 06 07

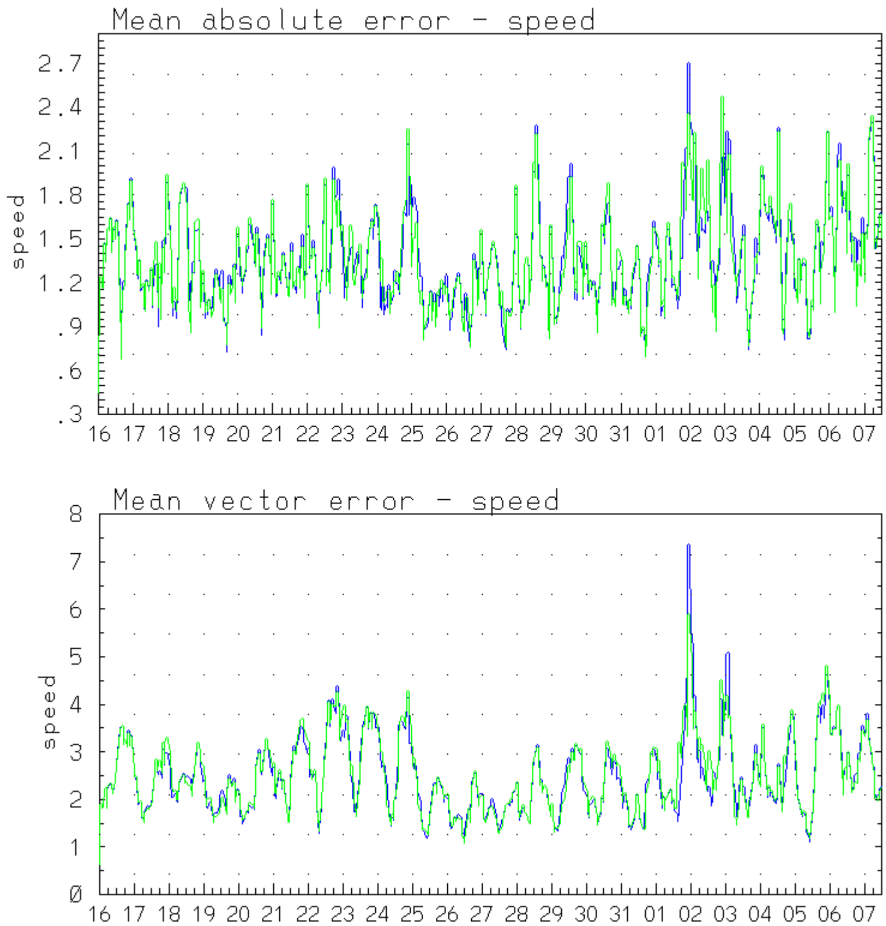
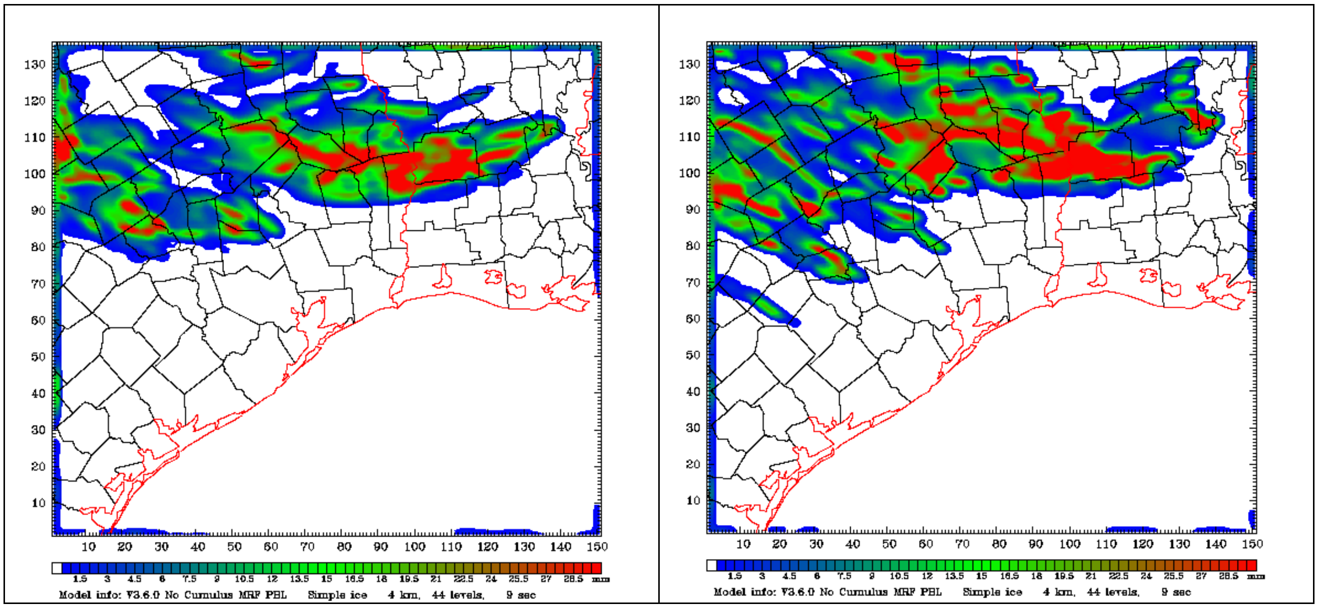


Figure 7: Hourly wind speed (ms^{-1}) statistics for Experiments 3 (blue) and 4 (green) using all observations (red) available within grid 4.

Minor differences between Experiments 3 and 4 are evident in the precipitation forecasts. In general, Experiment 4 predicted somewhat larger areas of precipitation coverage with slightly larger amounts. Compared to observations, Experiment 3 tended to miss the periods of convective activity especially prior to August 30. Although Experiment 4 did generate more precipitation, the basic patterns are similar to Experiment 3 and significant improvements to forecast precipitation are not apparent. For example, Figure 8 illustrates a comparison of predicted 24-hour total liquid precipitation. Experiment 4 indicates greater precipitation coverage and amount than Experiment 3, but similar to Experiment 3 the coverage is too far inland compared to observations.


1.5 3 4.5 6 7.5 9 10.5 12 13.5 15 16.5 18 19.5 21 22.5 24 25.5 27 28.5 mm
Model info: V3.6.0 No Cumulus MRF PBL Simple ice 4 km, 44 levels, 9 sec
1.5 3 4.5 6 7.5 9 10.5 12 13.5 15 16.5 18 19.5 21 22.5 24 25.5 27 28.5 mm
Model info: V3.6.0 No Cumulus MRF PBL Simple ice 4 km, 44 levels, 9 sec

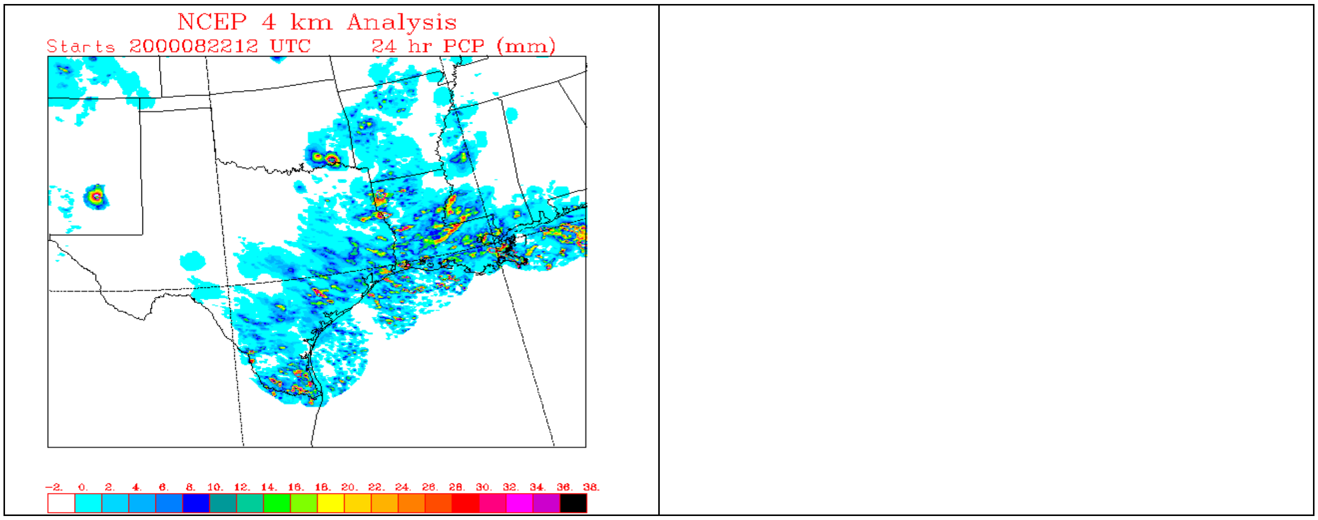


Figure 8: 24-h total precipitation (mm) ending at 1200 UTC 23 August 2000 for a) Experiment 3, b) Experiment 4, and c) NCEP 4 km Stage 4 analysis.

2.3.2 *PBL height comparisons*

Observations of PBL depth derived from airborne lidar are displayed in Figure 9 for 29 and 31 August. This time period, as described with more detail in the previous report (ATMET 2003b) is especially interesting because a meteorological "regime shift" occurred on 30 August with a wind change from light southeasterly to strong westerly. Note the much deeper PBL observed on 31 August, a post-regime shift day, and PBL depths increase from southeast to northwest away from the water.

Figures 10 and 11 illustrate a comparison of predicted PBL heights for Experiments 3 and 4 on 29 August. Both experiments capture the overall patterns and trends with progressively deeper heights from southeast to northwest. Experiment 4 maximum PBL depths of about 2000 m are, however, about 500 m lower than Experiment 3 forecasts, which compare more favorably to the maximum lidar observed depths. The wholesale collapse of the PBL after 2300 UTC, which is largely overdone, is evident in both experiments.

Similar results are noted in a comparison of predicted PBL heights for Experiments 3 and 4 on 31 August (Figures 12 and 13). Both experiments capture the much greater PBL depths observed following the meteorological regime shift. Maximum predicted PBL heights for Experiment 4 are again about 500 m less than experiment depths that compare more favorably with lidar observations. The collapse of the PBL after 2300 UTC is also observed in both experiments.

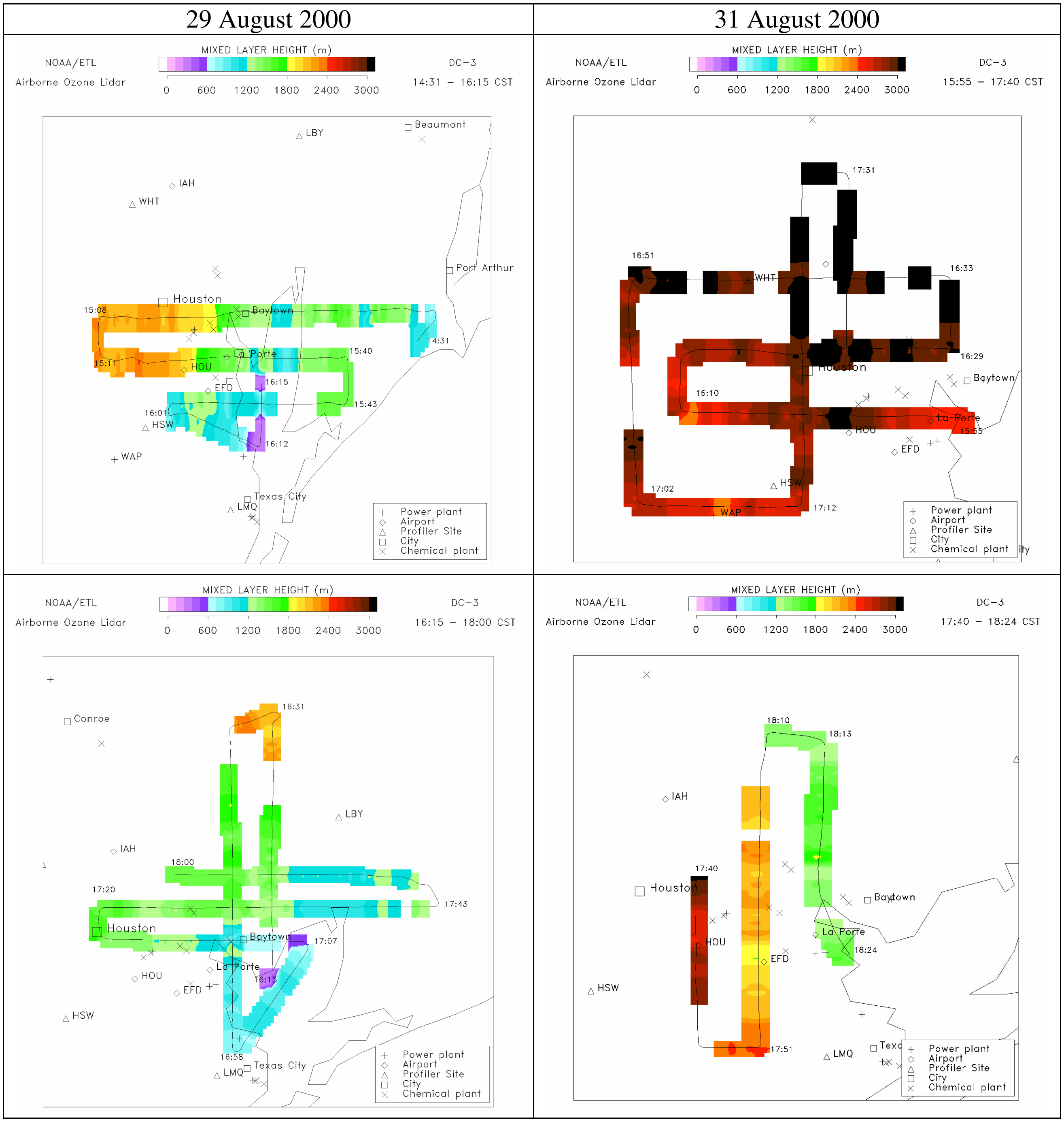


Figure 9: Planview plots of mixing depth derived from airborne lidar data for 29 and 31 August, for 2 different flight segments on each day. All images are excerpted from Senff et al. (2002).

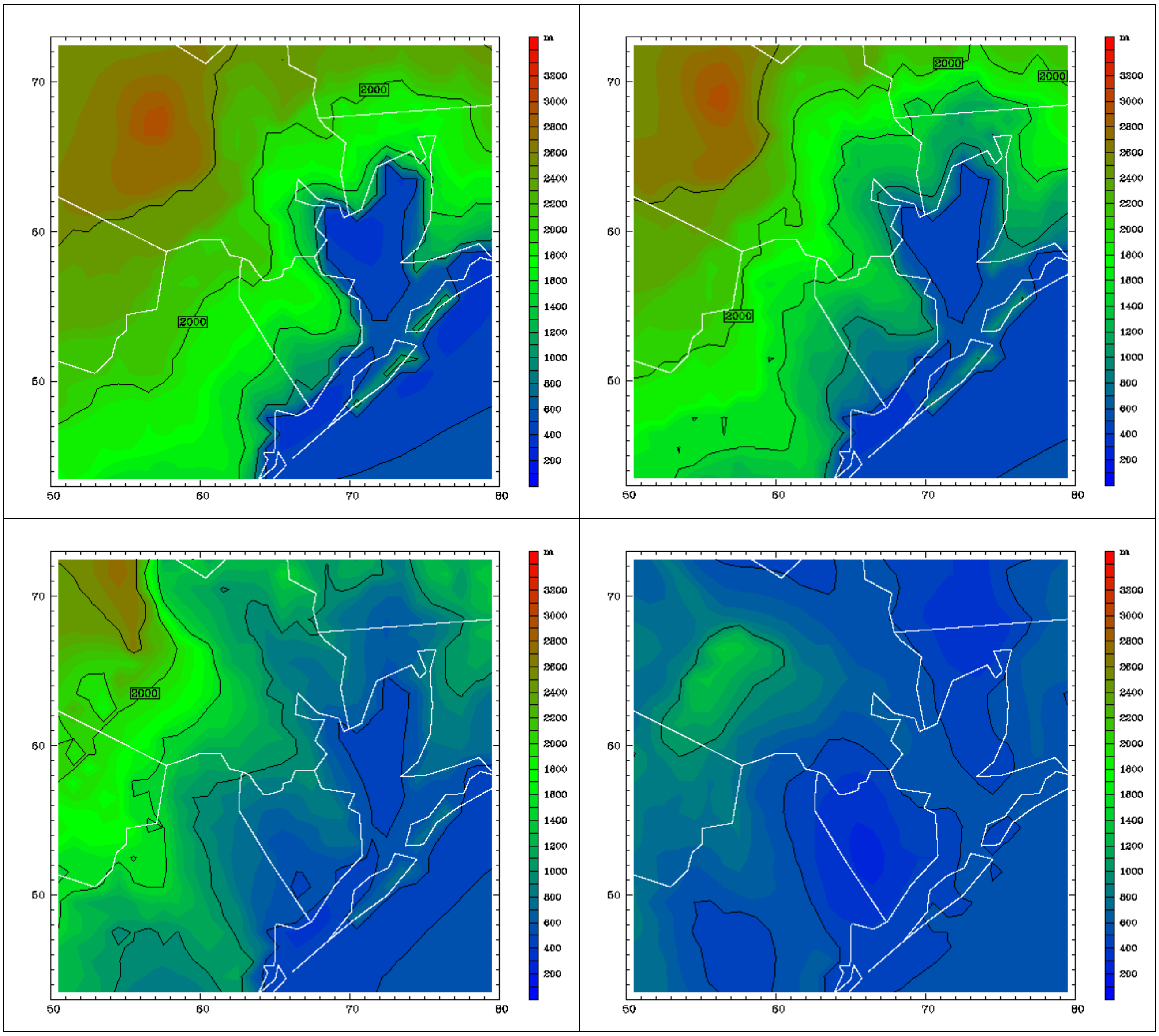


Figure 10: Experiment 3 MM5 predicted planetary boundary layer height (m) for a) 2100 UTC 29 August, b) 2200 UTC 29 August, c) 2300 UTC 29 August, and d) 0000 UTC 30 August. Contour interval = 500 m.

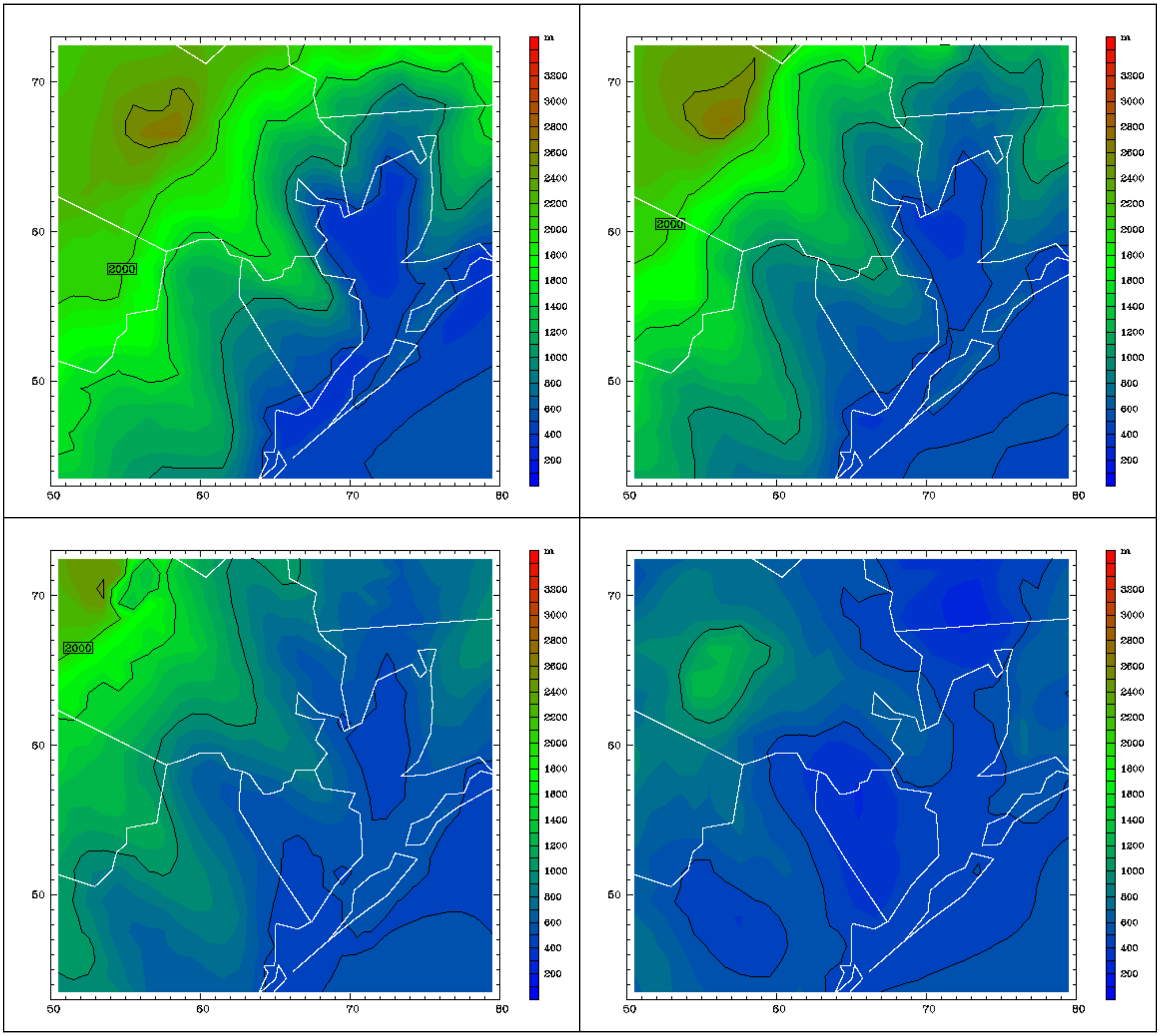


Figure 11: Experiment 4 MM5 predicted planetary boundary layer height (m) for a) 2100 UTC 29 August, b) 2200 UTC 29 August, c) 2300 UTC 29 August, and d) 0000 UTC 30 August. Contour interval = 500 m.

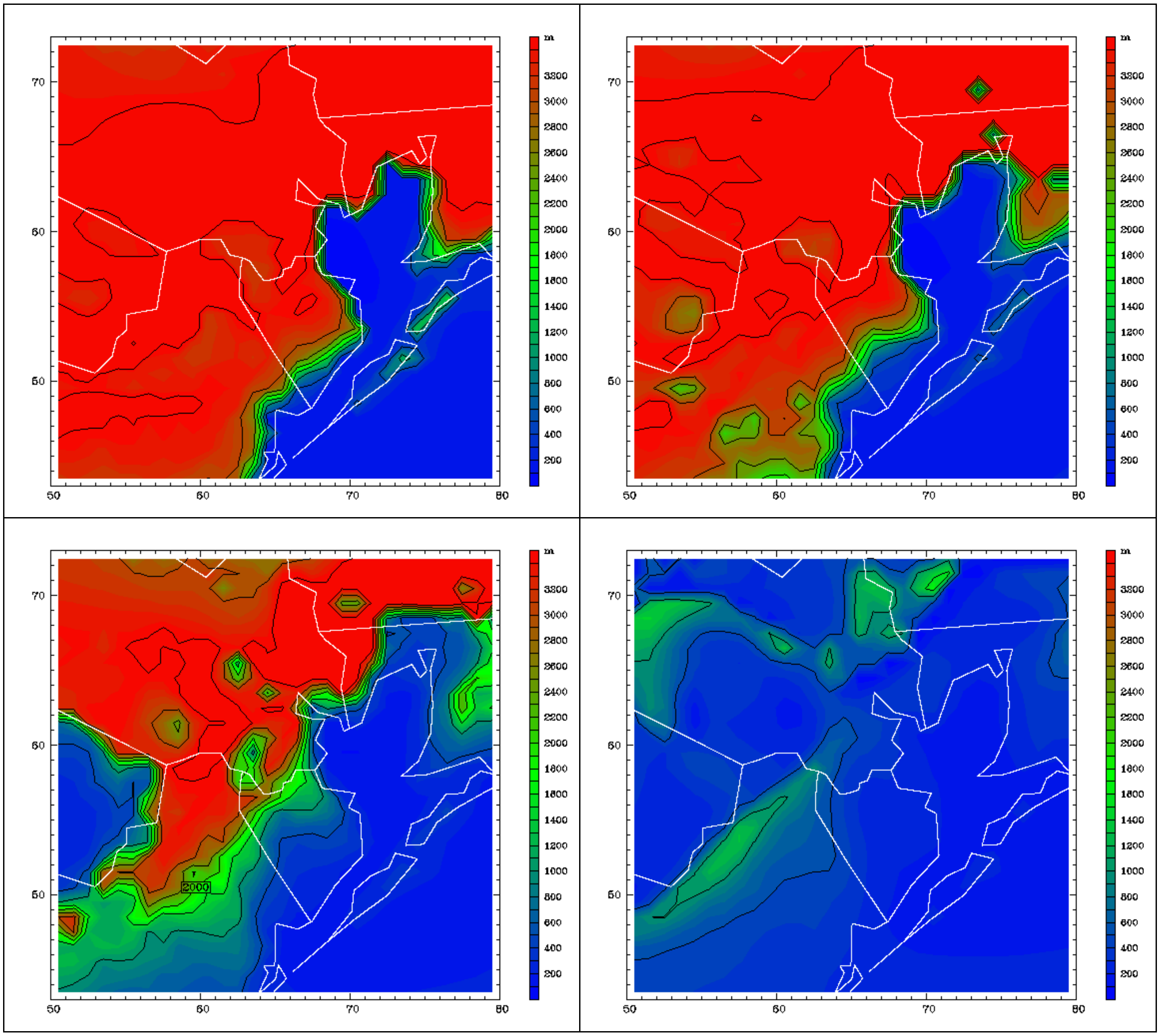


Figure 12: Experiment 3 MM5 predicted planetary boundary layer height (m) for a) 2100 UTC 31 August, b) 2200 UTC 31 August, c) 2300 UTC 31 August, and d) 0000 UTC 1 September. Contour interval = 500 m.

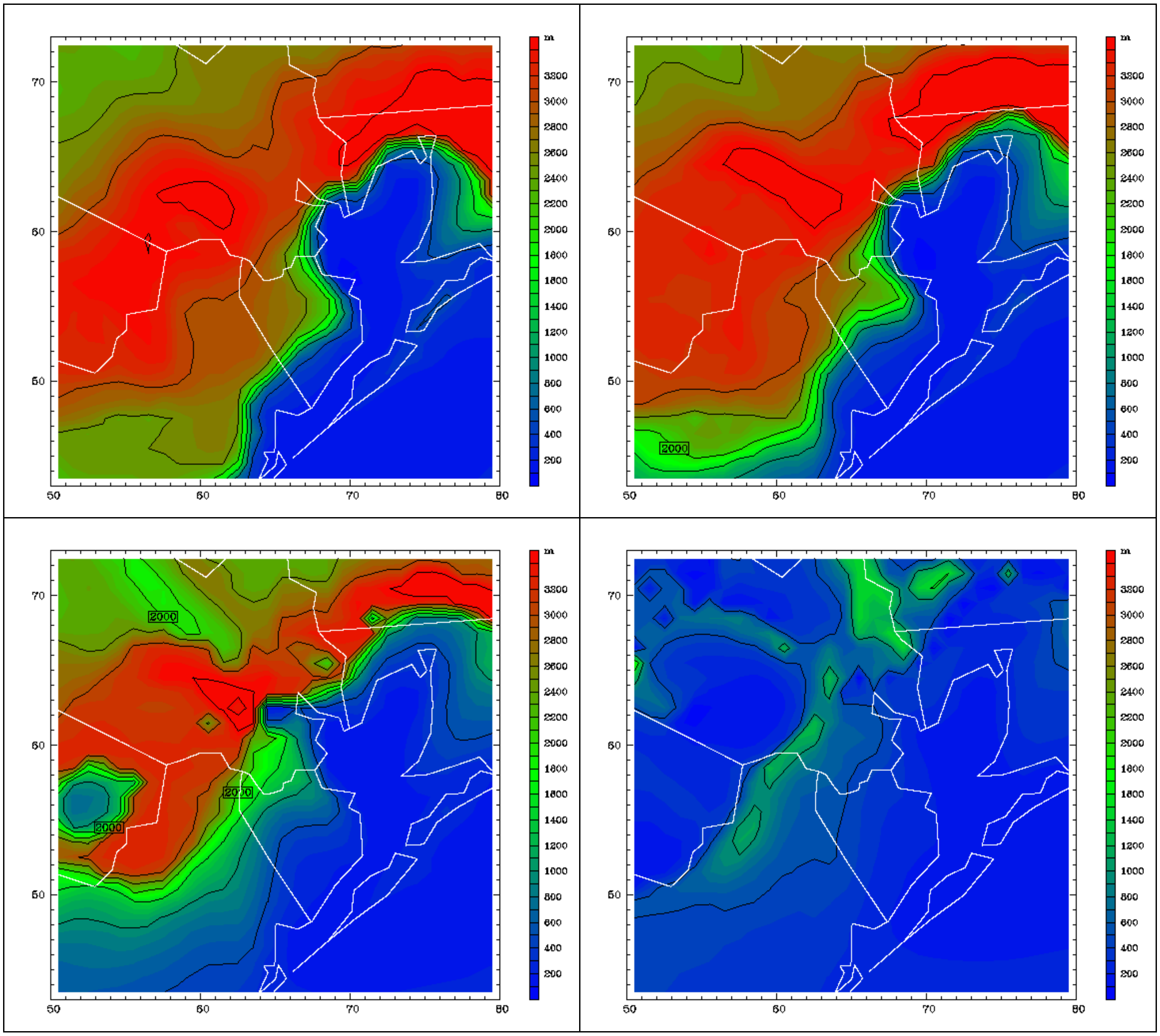
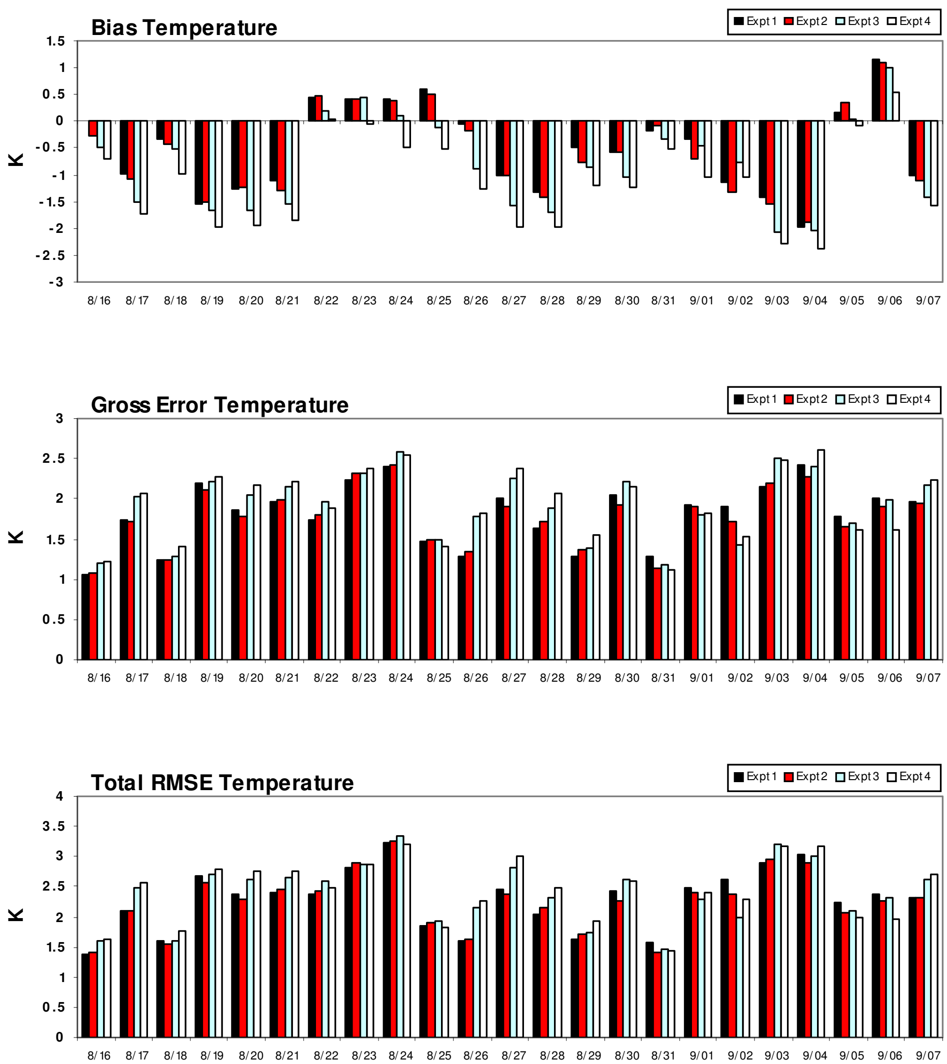


Figure 13: Experiment 4 MM5 predicted planetary boundary layer height (m) for a) 2100 UTC 31 August, b) 2200 UTC 31 August, c) 2300 UTC 31 August, and d) 0000 UTC 1 September. Contour interval = 500 m.

2.3.3 *Statistical comparison of all experiments*

Validation results for all experiments were generated with a statistical evaluation package called METSTAT, which was provided to ATMET by Environ. Hourly statistics for Experiments 1, 2, and 3 were presented in the previous report (ATMET 2003b) for model domain 4 predictions against two subsets of observations located in the Houston and Beaumont vicinities. The METSTAT package can also display daily statistics for several runs on the same plot. Figures 14-16 show a direct comparison of daily statistics for temperature, dew point, and wind from all four experiments. Statistics were generated as in the previous report using observed data from 30 Houston area observation sites as defined by TNRCC.

Daily temperature biases (Figure 14) were generally cool (1 to 1.5 K) except during the more convectively active period of 22-25 August that was not captured well by the model. Experiments 3 and 4 showed slightly greater cool biases. These runs, which had the "convective velocity" term removed from the U* computation, predicted stronger afternoon wind speeds that likely contributed to somewhat cooler afternoon temperatures. The index of agreement remained greater than 0.9 for all experiments and all time periods except during the previously noted convectively active period of 22-24 August.



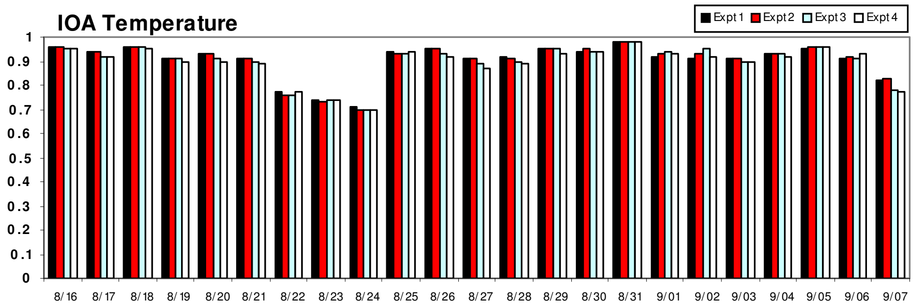
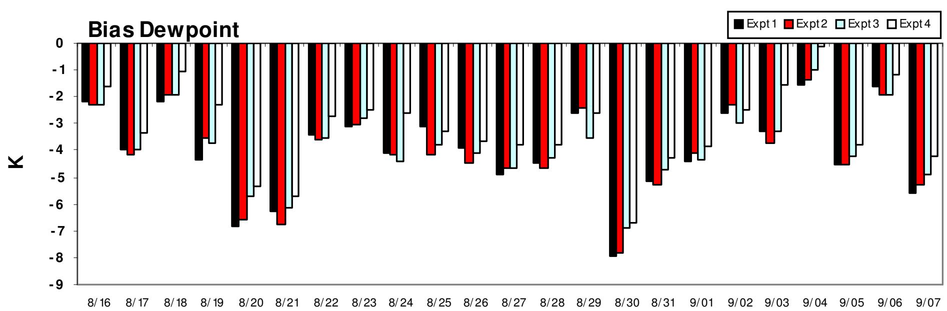
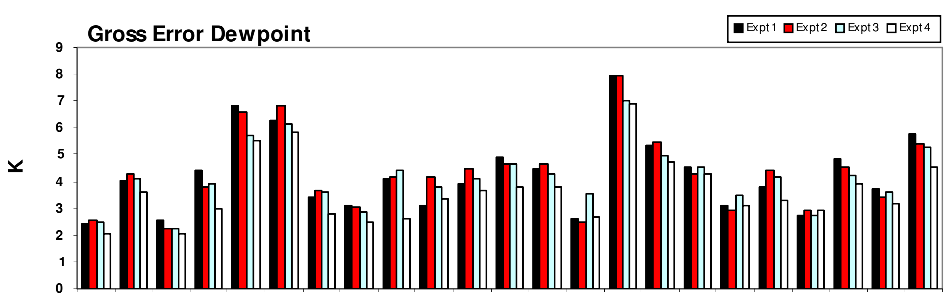


Figure 14: METSTAT daily temperature (K) statistics for Experiments 1, 2, 3, and 4 using 30 Houston area observations.

Daily dew point biases (Figure 15) were dry for the entire episode in all four experiments. The previous report (ATMET 2003b) addressed this issue and found the dry bias to be at least partially attributed to the over-prediction of the PBL depth. Small, but noticeable improvements, are evident in successive experiments from 2 through 4. This is likely the result of improved afternoon wind speed forecasts in Experiment 3 and improved PBL height predictions in Experiment 4.





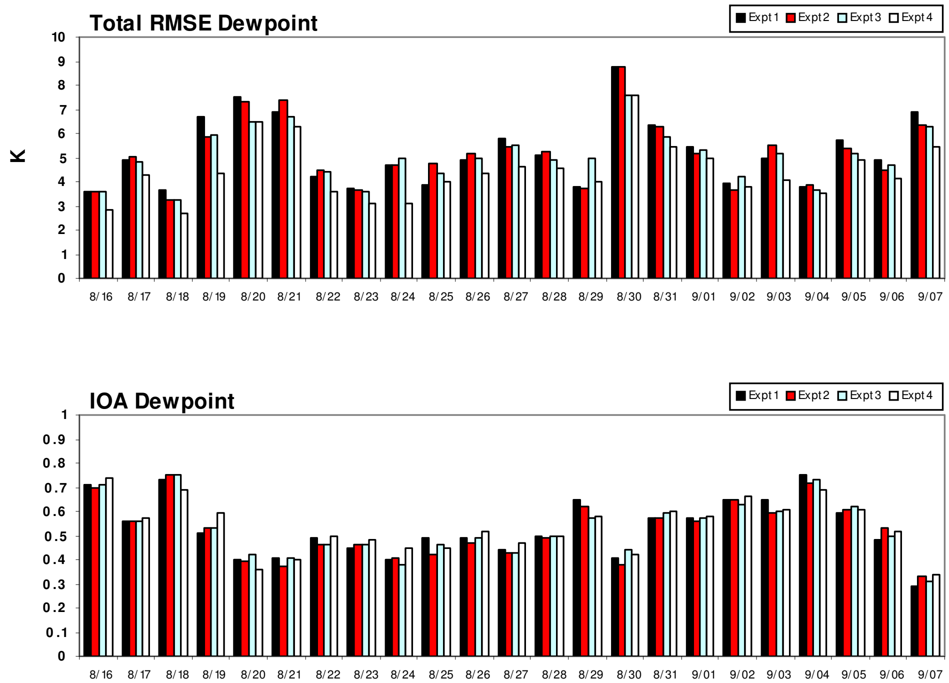
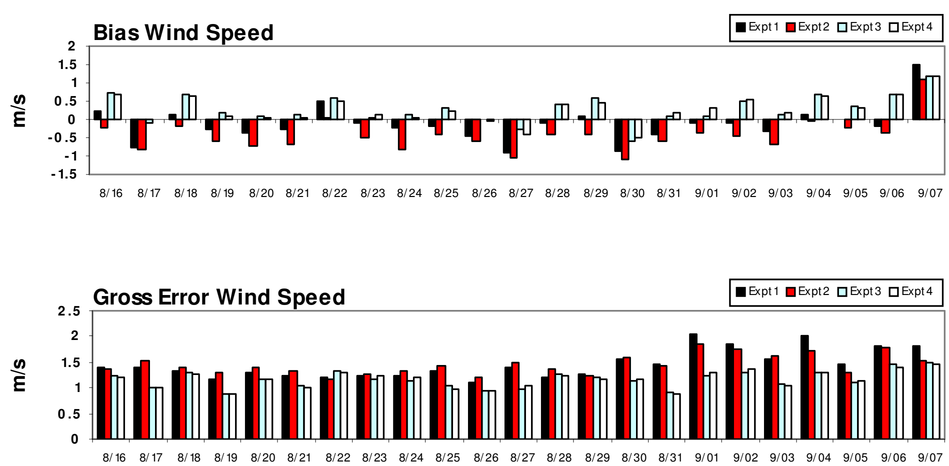


Figure 15: METSTAT daily dew point (K) statistics for Experiments 1, 2, 3, and 4 using 30 Houston area observations.

Daily wind speed biases (Figure 16) were generally slow for the episode in Experiments 1 and 2, and were neutral to slightly fast for Experiments 3 and 4. This has been attributed to the removal of the "convective velocity" term from the U* computation that allows for stronger afternoon wind speeds and improved forecast wind speed accuracy.



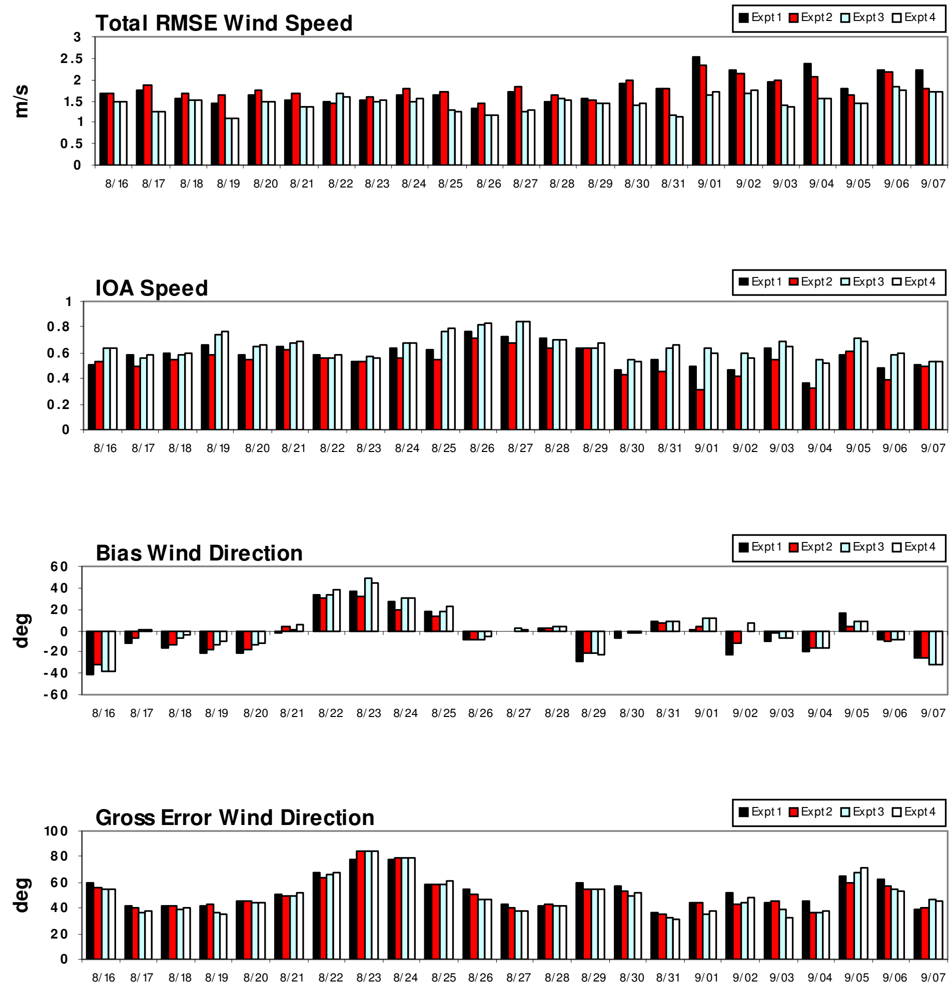


Figure 16: METSTAT daily wind speed (ms^{-1}) and direction (deg) statistics for Experiments 1, 2, 3, and 4 using 30 Houston area observations.

3 Summary

A series of four sensitivity experiments was performed for the TexAQS-2000 episode from 16 August – 7 September. These experiments utilized the MM5 mesoscale model setup with four domains ranging in grid spacing from 108 km down to 4 km on grid 4 centered over the Houston-Galveston area. Results from the first three tests were presented in a previous report (ATMET 2003b). This report investigated the over-prediction of PBL height noted in Experiments 1, 2, and 3. A fourth experiment addressed this issue and results suggest the following:

- Reducing the critical bulk Richardson number (Rib_{cr}) by half in the MM5 MRF PBL scheme did not produce significant changes in predicted PBL heights.
- Removal of the scaled virtual temperature excess term in the PBL depth calculation generated significantly improved predictions of PBL height, although a high bias is still observed. Improvements were not noted in the too rapid collapse of the PBL near sunset.
- Improvements to PBL depth prediction created only marginal improvements to the surface variable verifications and the previously noted dry dew point bias. Insignificant changes were noted for temperature and wind.
- While the removal of the thermal excess term made significant improvements in simulated PBL heights in this case, this may not be a permanent fix for all cases. We expect that if coarser vertical grid spacings near the ground are used, the results may be better by using the perturbation. It seems that the size of the excess should be scaled by the depth of the lowest model layer.

4 Acknowledgements

Christoff Senff, NOAA Environmental Technology Laboratory (ETL), provided profiler and radiosonde PBL height observations to ATMET. Wayne Angevine, NOAA Aeronomy Laboratory, provided the wind profiler height measurements to ETL. Carl Berkowitz and Chris Doran, Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, provided quality controlled radiosonde data to ETL.

5 References

ATMET, 2002a: High resolution (1.33 km) MM5 modeling of the September 1993 COAST episode: Sensitivity to model configuration and performance optimization. Final report to Texas Natural Resource Conservation Commission, 15 February 2002, 63 pp.

ATMET, 2002b: RAMS Simulations for TexAQS 2000 Episode. Final report to Texas Natural Resource Conservation Commission, 31 August 2002, 65 pp.

ATMET, 2003a: MM5 Simulations for TexAQS 2000 Episode. Interim report to HARC, January 2003, 65 pp.

ATMET, 2003b: MM5 Simulations for TexAQS 2000 Episode. Final Report to HARC, August 2003, pp.

Hong, S-Y and H-L Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.*, **124**, 2322-2339.

Nielsen-Gammon, John W., 2001: Initial modeling of the August 2000 Houston Galveston ozone episode. Report to the Technical Analysis Division, Texas Natural Resource Conservation Commission, December 19, 2001, 71 pp.

Nielsen-Gammon, John W., 2002a: Evaluation and comparison of preliminary meteorological modeling for the August 2000 Houston-Galveston ozone episode. Report to the Technical Analysis Division, Texas Natural Resource Conservation Commission, February 5, 2002, 83 pp.

Nielsen-Gammon, John W., 2002b: Meteorological modeling for the August 2000 Houston-Galveston ozone episode: PBL characteristics, nudging procedure, and performance evaluation. Report to the Technical Analysis Division, Texas Natural Resource Conservation Commission, February 28, 2002, 109 pp.

Nielsen-Gammon, John W., 2002c: Meteorological modeling for the August 2000 Houston-Galveston ozone episode: METSTAT statistical evaluation and model runs from March-June 2002. Report to the Technical Analysis Division, Texas Natural Resource Conservation Commission, June 21, 2002, 23 pp.

Nielsen-Gammon, John W., 2002d: Meteorological modeling for the August 2000 Houston-Galveston ozone episode: Improved data assimilation and statistical evaluation. Report to the Technical Analysis Division, Texas Natural Resource Conservation Commission, August 29, 2002, 30 pp.

Senff, C., R. Banta, L. Darby, W. Angevine, A. White, C. Berkowitz , C. Doran, 2002: Spatial and Temporal Variations in Mixing Height in Houston. Final report for TNRCC project F-20. 58 pp.

Troen, I., and L. Mahrt, 1986: A simple model of the atmospheric boundary layer: Sensitivity to surface evaporation. *Bound.-Layer Meteor.*, **37**, 129-148.