# Assimilation of ARM WVIOP-96 Data for an Oklahoma Mesoscale Convective System

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## Introduction

The mesoscale observations collected during the Atmospheric Radiation Measurement (ARM) Water Vapor Intensive Observation Period (WVIOP) from September 10 to 30, 1996, provided a unique opportunity to directly assimilate heterogeneous and high-resolution observations into a state-of-art full-physics mesoscale model. The four-dimensional (4-D) variational data assimilation (4DVAR) system is based on the Pennsylvania State University-National Center for Atmospheric Research (NCAR) non-hydrostatic mesoscale model (MM5). A series of experiments were conducted for a strong convective case that occurred on September 19, 1996, over Kansas and Oklahoma. There are two purposes in this study:

1. Derivation of lateral boundary conditions for single column and cloud resolving models by 4-D variational data assimilation technique in the presence of deep convection.

2. Testing the relative importance of the various types of mesoscale observations.

## Observations

During the WVIOP-96, there was a variety of mesoscale observations collected by the ARM Experiment Center (AEC), such as the ground-based Global Positioning System (GPS) precipitable water (PW), wind profiler data, surface parameters from several mesonets (Figure 1), hourly rainfall (Figure 2), etc. These datasets have different spatial and temporal resolutions as well as measurement accuracy.

## Model Description and Experiment Design

The MM5-4DVAR system is a 4-D variational data assimilation system based on the Penn State/NCAR mesoscale model and its full-physics adjoint. The system includes many physics options, such as a Bulk PBL with the surface fluxes, Anthes-Kuo and Grell cumulus parameterization, Dudhia's explicit moisture scheme with ice effects, etc. When a user wants to assimilate a variety of observations with the MM5-4DVAR system, the observation operators, which transform the model variables to the

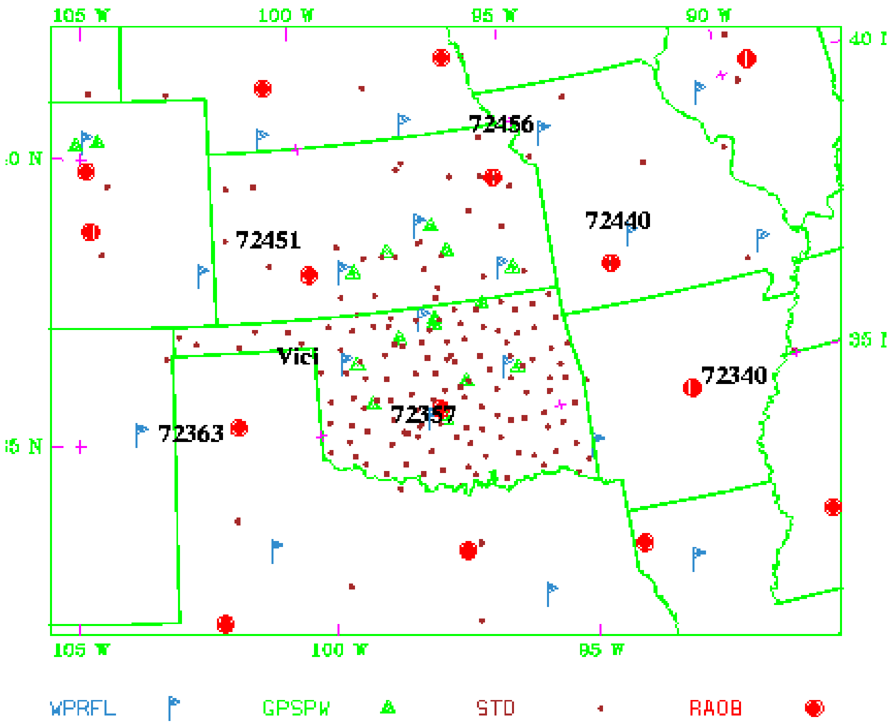


**Figure 1.** The distribution of GPS_PW, wind profiler (WPRF), surface observations (STD), and NWS soundings. The map background shows the model domain used in this study.

observational quantities, and their adjoint, must be developed. And also the weightings to each of the observations must be pre-specified. Here we defined the cost function J as:

$$J = J0 + J1 + J2 + J3 + J4$$

- J0 is the background term. The gridded data from the model initial condition (obtained from an objective analysis of upper-air and surface observations or a short period forecast) are used to represent this term.
- J1 is the term for the GPS PW observations over the 6-h assimilation window.
- J2 is the term for the surface dew point observations over the 6-h assimilation window.
- J3 is the term for the hourly rainfall observations over the 6-h assimilation window.
- J4 is the term for the wind profiler observations over the 6-h assimilation window.

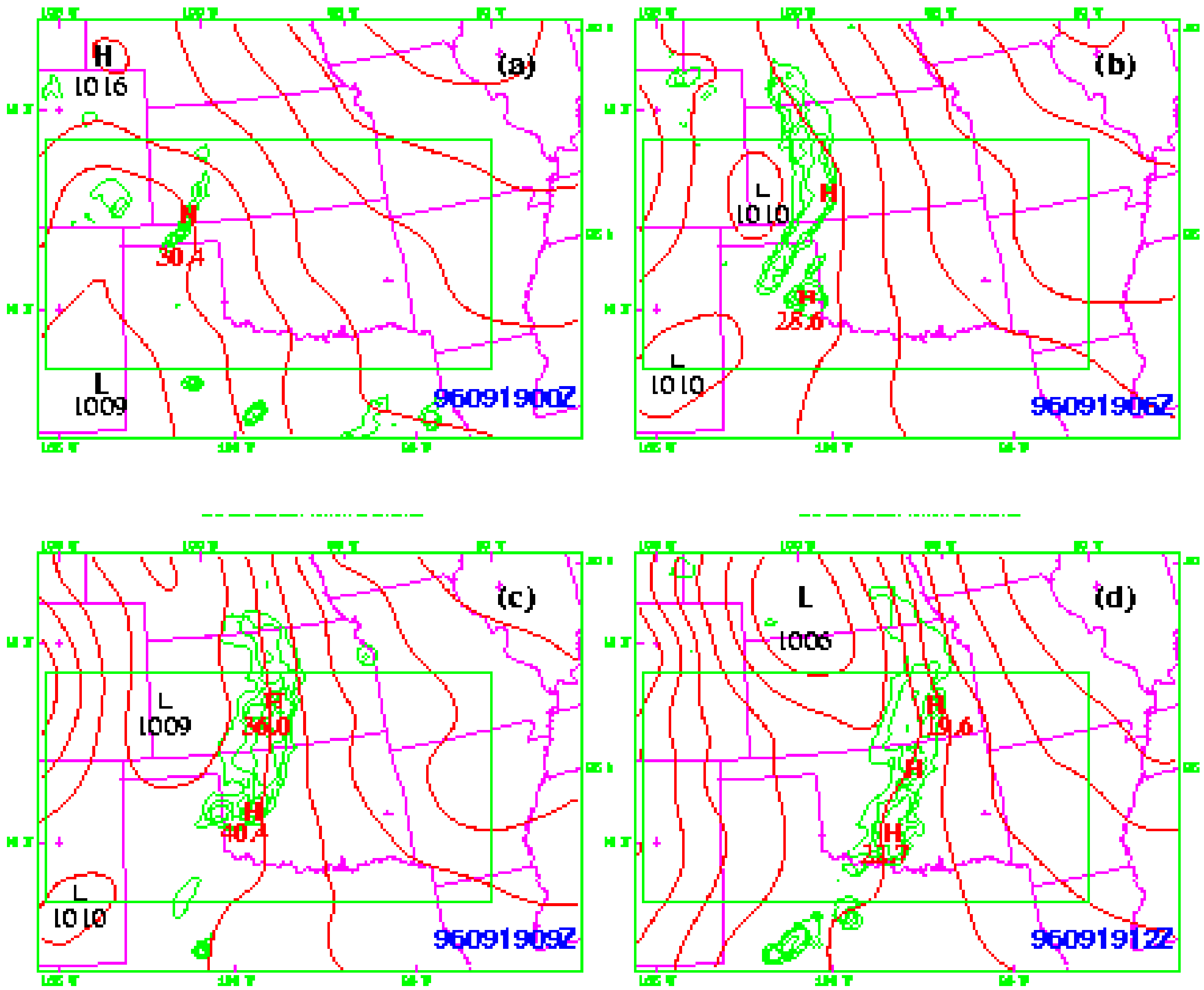


**Figure 2**. Sea level pressure and hourly rainfall analysis at (a) 0000, (b) 0600, (c) 0900, and (d) 1200 UTC September 19, 1996. The contour levels for rainfall are 1, 5, 10, and 25 mm.

The hourly precipitation over this period shows a well-defined squall line that developed and passed over the Kansas to Oklahoma area on September 19 (Figure 2). This strong convective case was chosen for this data assimilation study.

Three basic experiments are conducted: 1) NO4DVAR; 2) 4DVAR6H1; and 3) 4DVAR6H2 (Figure 3). The first one is a 12-h standard forecast, the second is 6-h assimilation from 0000 to 0600 UTC and 6-h forecast from 0600 to 1200 UTC, and the third is the 6-h assimilation from 0600 to 1200 UTC September 19, 1996.

### Structure of the Strong Convection

To inspect in detail the forecast of convection over central Oklahoma, Figure 6 compares the cross section perpendicular to the squall line (Figure 4e) at 1200 UTC September 19, for Exp. 4DVAR6H2 and the objective analysis from MM5 modeling system based on the NWS conventional observations. A well-defined convective system with a scale about 130 km is produced by Exp. 4DVAR6H2. The maximum vertical motion of 3 m/s co-located with a plume of high equivalent potential temperature (Thetae > 336 K). The objective analysis based on the conventional data did not reveal this structure of strong convection. So the 4DVAR technique may provide a dynamically consistent dataset to drive the single column model in the presence of deep convection.

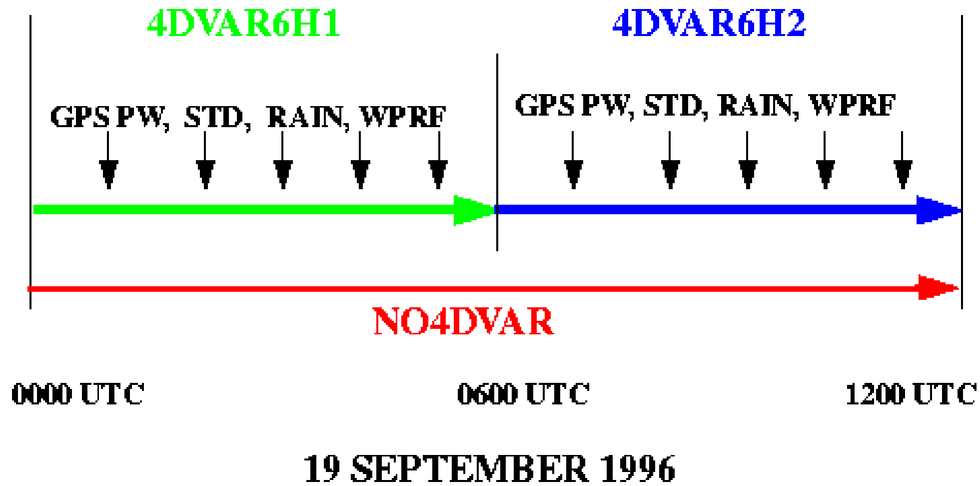


**Figure 3**. Diagram for showing the experiment design.

### Verifications Against the NWS Rawinsonde Data

Based on the vertically integrated rms error, Exp. 4DVAR6H2 had a 7% improvement (1.16 g/kg, Figure 7a) in moisture compared with NO4DVAR (1.24 g/kg), but a 22% improvement (1.47oC, Figure 7b) in temperature compared with NO4DVAR (1.88oC). The moisture improvement is mainly in the upper troposphere while the temperature improvement is in the lower troposphere. When verifying over the four downstream sites, the vertically integrated rms error of specific humidity is reduced to 0.96 g/kg (23% improvement, solid line in Figure 8).

## Data Impact in 4DVAR

To assess the impact of different types of observation, we conducted a set of sub-experiments of assimilation by eliminating each type of observation in Exp. 4DVAR6H2, which are NO_GPS (GPS precipitable water data excluded); NO_STD (surface dew point data, excluded), NO_RAIN (hourly rainfall data excluded), and NO_WPRF (wind profiler data excluded).

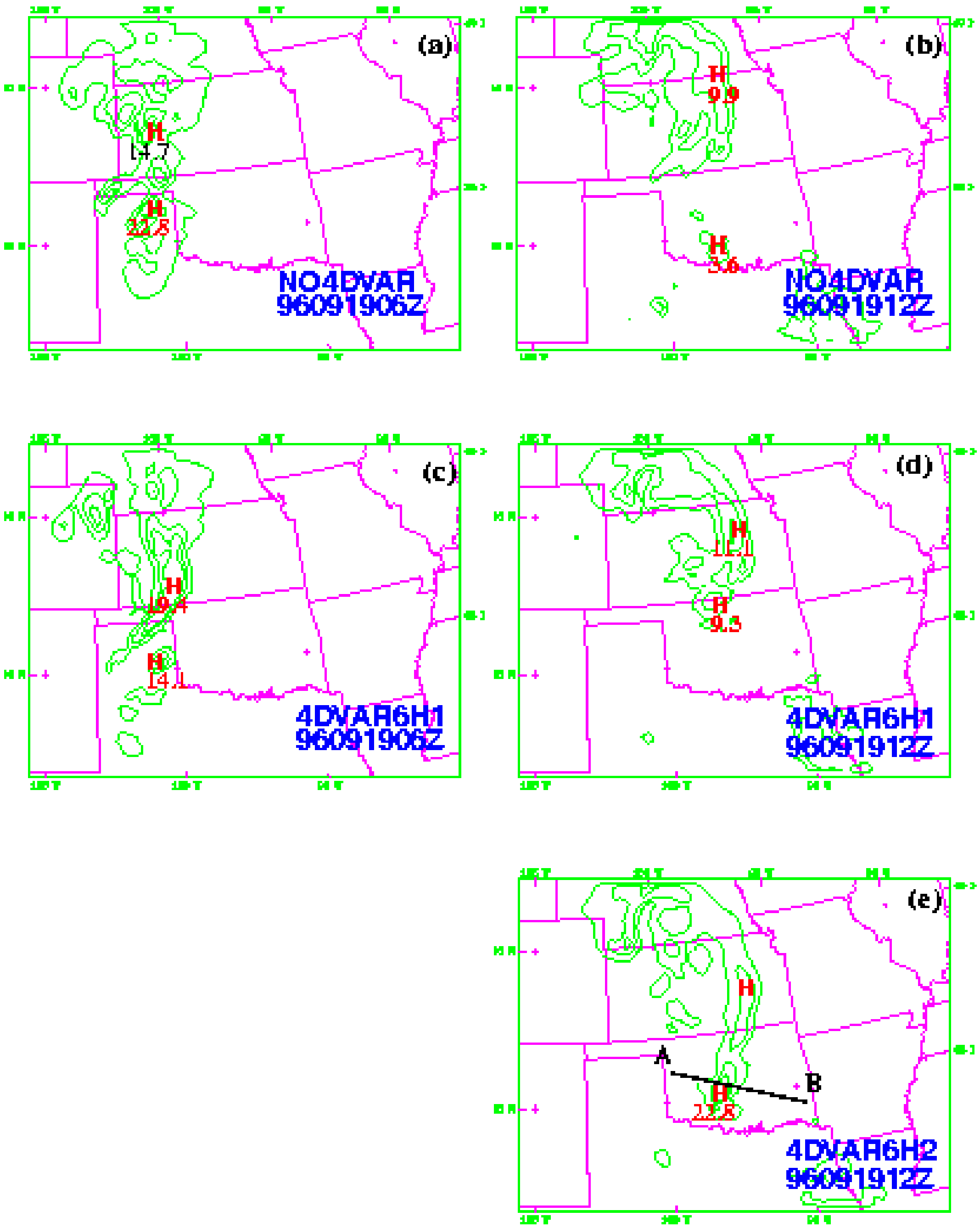


**Figure 4**. The hourly rainfall (a) ending at 0600 and (b) 1200 UTC September 19, from NO4DVAR, and (c) ending at 0600 and (d) 1200 UTC September 19 from 4DVAR6H1, and (e) 1200 UTC September from 4DVAR6H2. The contour levels are same as Figure 2. The line AB in (e) indicates the position of the cross section in Figure 6.

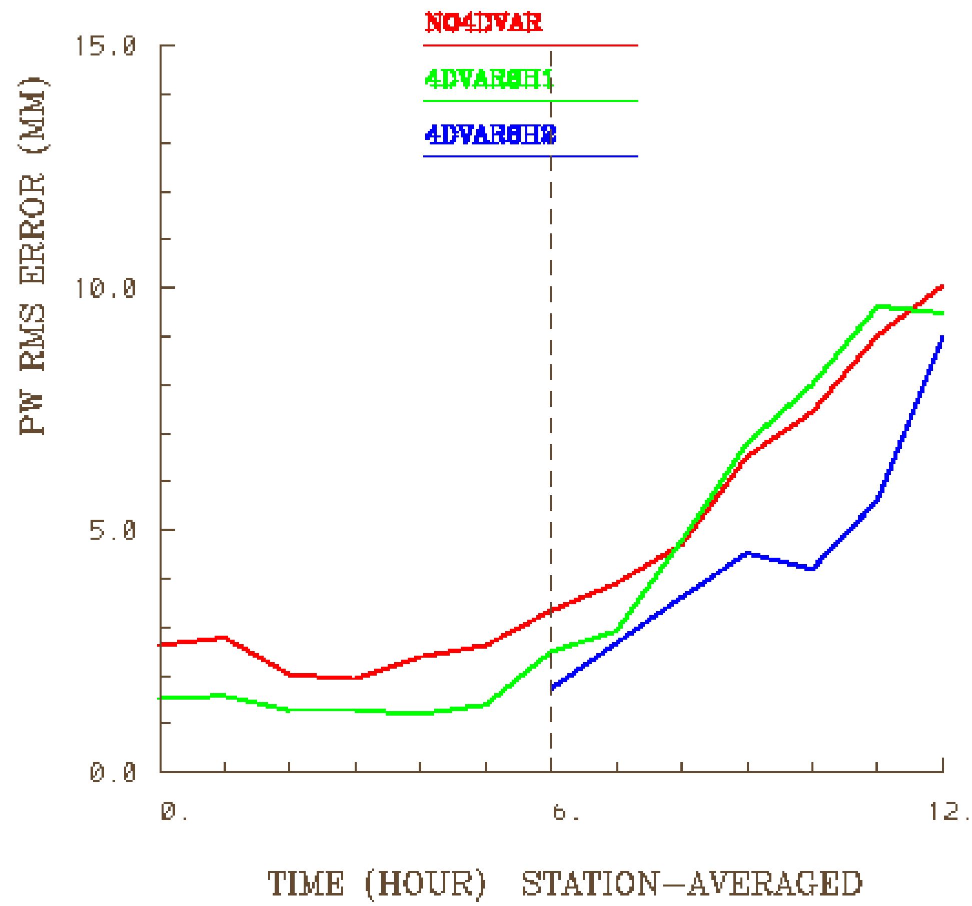


**Figure 5**. Time series of the rms error of precipitable water vapor over ground-based GPS sites from 0000 to 1200 UTC September 19, 1996, for Exp. NO4DVAR (green line), 4DVAR6H1 (red line), and 4DVAR6H2 (blue line).

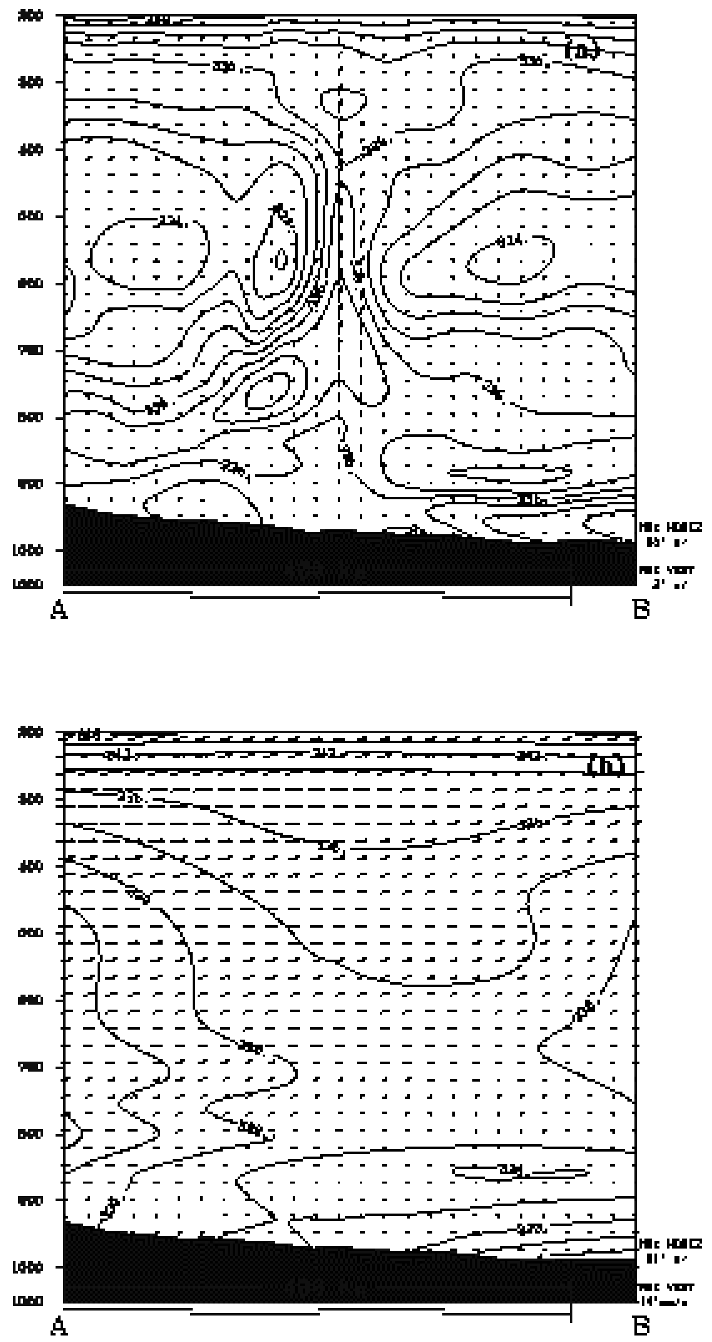


**Figure 6**. The cross section of wind and equivalent potential temperature perpendicular to the squall line (Figure 4e) at 1200 UTC September 19, 1996, (a) Exp. 4DVAR6H2, and (b) objective analysis based on conventional observations.

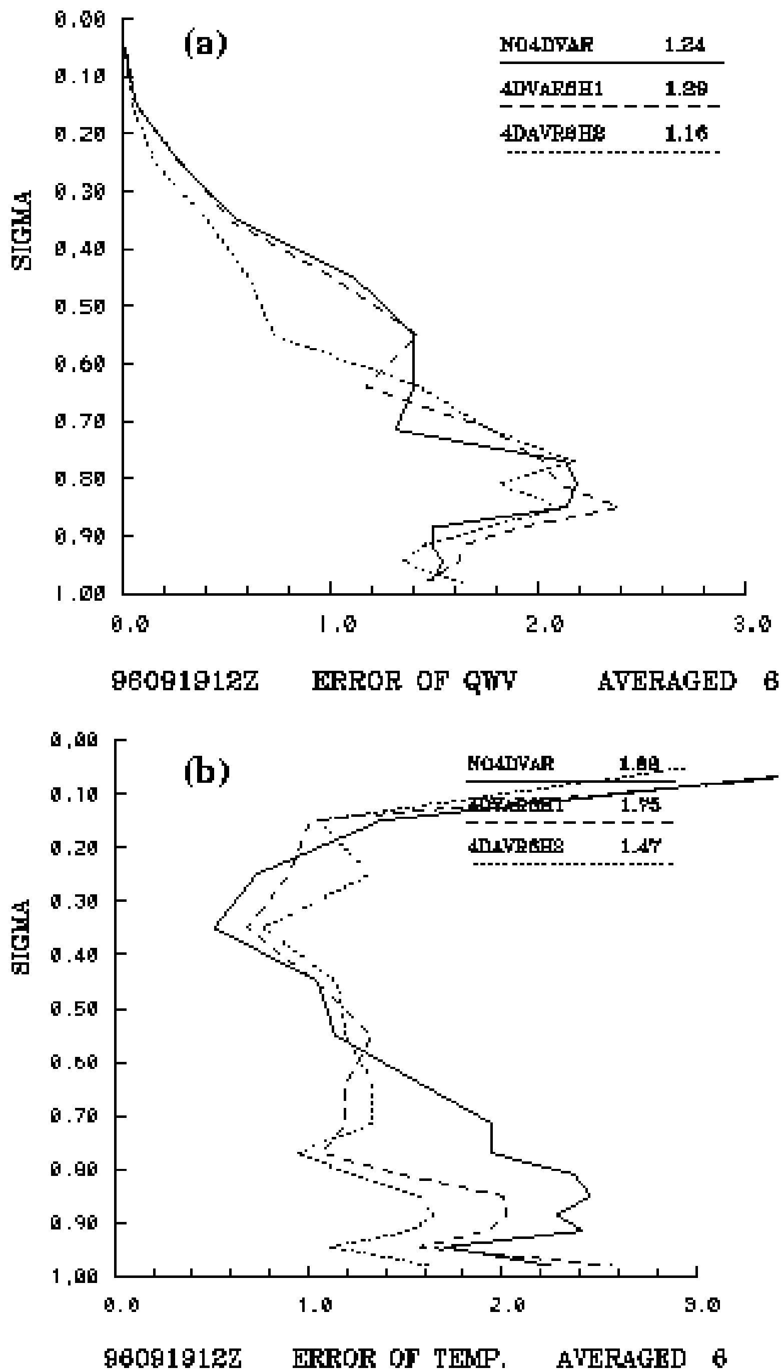


**Figure 7**. The vertical profile of rms errors verifying against NWS RAOB data at 1200 UTC September 19, 1996, over six sites in the central part of the domain. (a) Specific humidity (g/kg), and (b) temperature (oC).

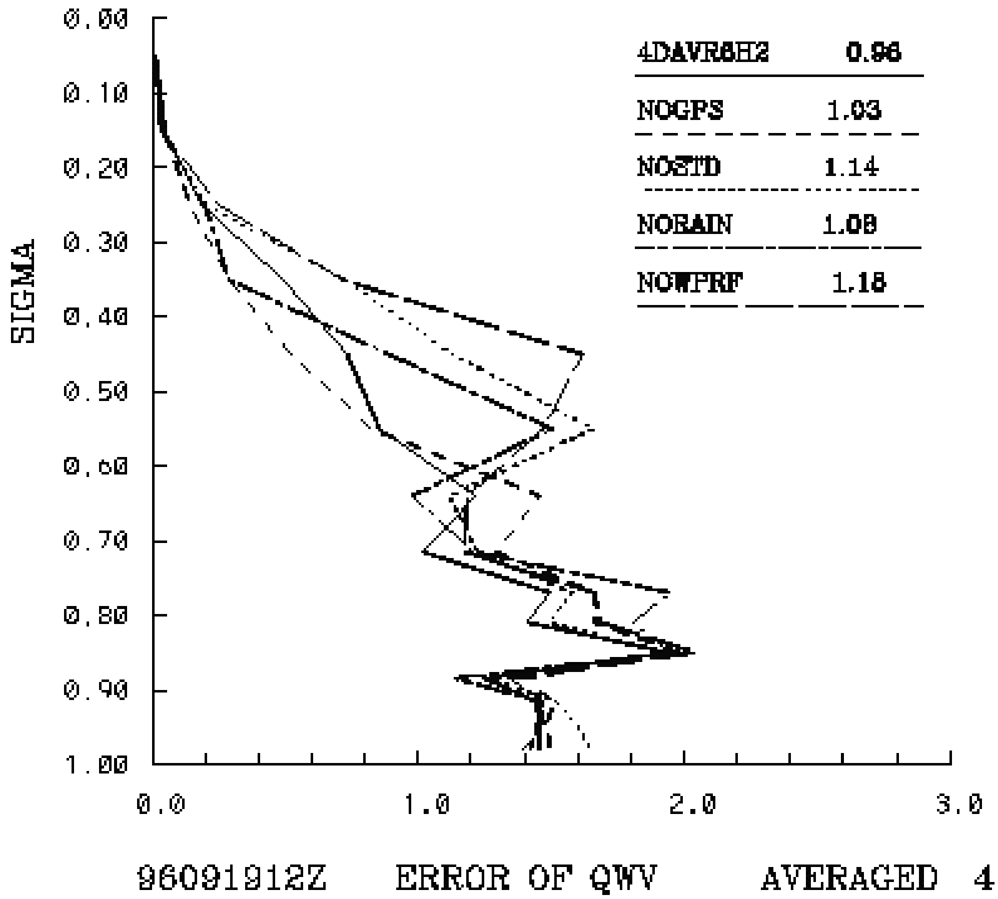


**Figure 8**. Same as Figure 7a but for Exp. 4DVAR6H2, NO_GPS, NO_STD, NO_RAIN, and NO_WPRF verifying over four downstream observed sites (72456, 72440, 72357, and 72340 in Figure 1).

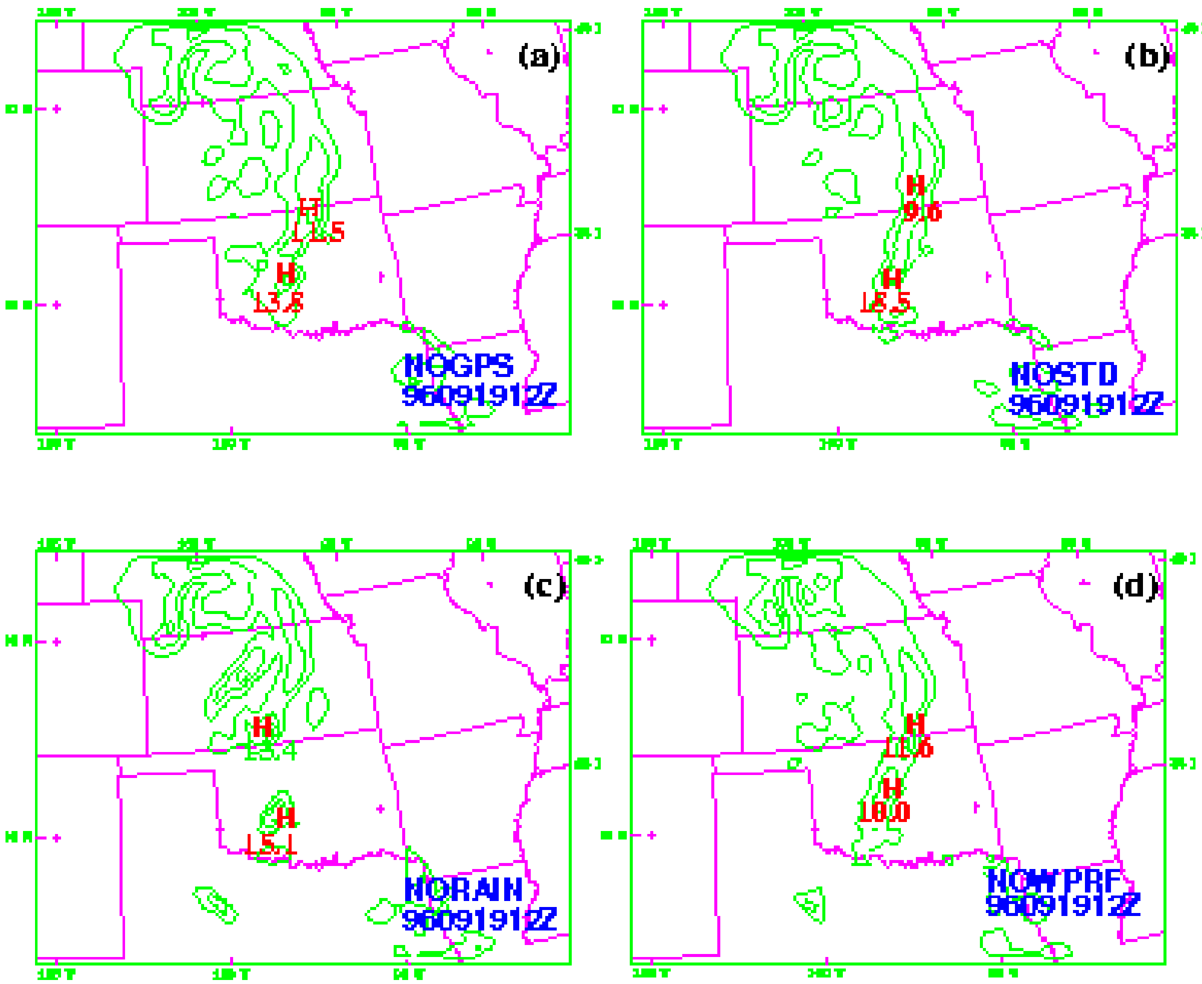


**Figure 9**. The hourly rainfall forecasts ending at 1200 UTC September 19, 1996, for Exp. (a) NO_GPS, (b) NO_STD, (c) NO_RAIN, and (d) NO_WPRF.

Figure 8 showed the moisture verification against NWS RAOB data over four downstream stations, and Figure 9 gave the hourly rainfall forecasts ending at 1200 UTC September 19, 1996. Without GPS PW data, the maximum rainfall was reduced to 13.6 mm (Figure 9a) from 22.8 mm (Figure 4e), but the moisture rms error was only increased from 0.96 to 1.03 g/kg (Figure 8). But exclusion of surface dew point data increased the rms error from 0.96 to 1.14 g/kg (Figure 8), while the rainfall forecast was only changed little. So the GPS PW data helped to fit the rainfall and the surface data improved the vertical structure of moisture. Without rainfall data assimilated, convection with a rainfall of 15.1 mm was still predicted (Figure 9c), and the moisture rms error was increased moderately (1.08 g/kg). With the wind-profiler data removed, the maximum rainfall in central Oklahoma was much less (10 mm) than that in 4DVAR6H2, and the error was increased to 1.18 g/kg. So wind-profiler data was a key component in obtaining the correct mesoscale development.

## Conclusions

1. The MM5-4DVAR system with a complete physics package successfully assimilated real heterogeneous mesoscale observations collected during ARM WVIOP-96 for a strong convective case. The hourly rainfall, GPS-based precipitable water, surface dew point, and wind-profiler data were well assimilated into the mesoscale model and produced a dynamically consistent 4-D dataset, which can provide lateral boundary conditions to drive a single column model.

2. By eliminating selected observation types sequentially in 4DVAR experiments, we found that GPS PW observations helped provide a better fit to the observed rainfall, and gave improved vertical structure to moisture in combination with the surface dew point assimilation. The inclusion of rainfall data in 4DVAR was useful to the recovery of the vertical structure of moisture and the rain pattern. However, even without rainfall data assimilation, the strong convective system could still reproduced by 4DVAR if other mesoscale observational information was assimilated. The wind-profiler data was found to be the most important data in obtaining the best fit to observed rainfall and good recovery of the vertical structure of moisture.