Assimilation of Precipitable Water Measurements into a Mesoscale Numerical Model

YING-HWA KUO AND YONG-RUN GUO*

National Center for Atmospheric Research**, Boulder, Colorado

ED R. WESTWATER

Wave Propagation Laboratory/NOAA, Boulder, Colorado

(Manuscript received 23 December 1991, in final form 30 September 1992)

ABSTRACT

Significant progress has been made over the past decade in the development of remote-sensing instruments to profile wind and temperature. However, the current technology of profiling water vapor remotely is still far from perfect. Although some promising optical research systems, such as the Raman lidar, can provide high vertical resolution profiles of water vapor, it may be years before they are generally available. Currently, there are several systems that can measure the vertically integrated water vapor (i.e., precipitable water) with a high degree of accuracy. In this paper we use a simple method to assimilate precipitable water measurements (possibly from a network of dual-channel ground-based microwave radiometers or a satellite-based system) into a mesoscale model. The basic idea is to relax the predicted precipitable water toward the observed value, while retaining the vertical structure of the model humidity field. We test this method with the special 3-h soundings available from the Severe Environmental Storms and Mesoscale Experiment. The results show that the assimilation of precipitable water into a mesoscale model recovers the vertical structure of water vapor with an accuracy much higher than that from statistical retrieval based on climatology. The improved analysis due to assimilation also leads to improved short-range precipitation forecasts.

1. Introduction

There has been significant progress in the development of remote-sensing instruments over the last decade. The UHF and VHF Doppler radar wind profilers provide highly accurate wind measurements within the troposphere and lower stratosphere at a temporal and vertical resolution never before possible (Hogg et al. 1983; Strauch et al. 1984). A demonstration network of 31 wind profilers has been deployed over the continental United States. Following the successful development of the wind profiler, a technological breakthrough in the remote sensing of temperature has come forth by applying radio acoustic sounding system (RASS) techniques to wind profiling radars (May et al. 1988, 1989, 1990). RASS combines radar and acoustic techniques to measure the lower- and mid-tropospheric profiles of virtual temperature with the same vertical resolution (<300 m) as the radar employed (Marshall et al. 1972; May et al. 1989).

In contrast to the successful profiling of wind and temperature with remote sensors, our ability to measure water vapor is rather limited. For example, the High-Resolution Interferometer Sounder (HIS) measures the infrared spectrum (4–18 μm) with very high spectral resolution (λ/Δλ = 3000), for profiling temperature and water vapor throughout the lower troposphere (Smith et al. 1989). Despite the high spectral resolution, during clear conditions, HIS does not provide humidity measurements much above 650 mb, and has a vertical resolution of about 200 mb above the bottom 1 km. During clouds, the ability to profile vapor is reduced both in range and in accuracy (Smith et al. 1990).

Currently, a highly sophisticated Raman lidar (Melfi et al. 1989) can measure high vertical resolution profiles of water vapor, but its operation is degraded during daytime and will not probe through clouds. This technology is promising, but it may be years before it becomes routinely available and affordable.

Although there is a lack of affordable remote-sensing instruments for detailed atmospheric moisture profiling, several systems can provide highly accurate measurements of vertically integrated water vapor (the precipitable water). For example, the dual-channel ground-based microwave radiometer (MWR) provides the vertically integrated water vapor and the integrated liquid water (Hogg et al. 1983; Westwater et al. 1985). The infrared and visible radiometers on the National

** The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Dr. Ying-Hwa Kuo, NCAR Mesoscale Prediction Section, P.O. Box 3000, Boulder, CO 80307-3000.

© 1993 American Meteorological Society
Oceanic and Atmospheric Administration GOES satellites provide precipitable water images with a horizontal resolution of 30 km and a temporal resolution of 60–90 min over cloud-free regions. A brief review of some of these systems is presented in the Appendix.

Water vapor is an extremely important variable for severe weather forecasting and operational numerical weather prediction, because moisture distribution is directly related to the formation of clouds and precipitation. Moreover, it is well known that water vapor has significant small-scale variations in time and space (Lilly and Perkey 1976). There is an urgent need to develop better instruments for water vapor profiling and to formulate a better strategy to retrieve the vertical structure of water vapor from these measurements.

Along a different line of research, Kuo and Guo (1989, hereafter referred to as KG) have shown encouraging results on the assimilation of wind-profiler observations for mesoscale numerical weather prediction. In a simulation study, KG demonstrated that the assimilation of time-continuous wind-profiler observations is effective in recovering mesoscale circulations that are not properly resolved by the conventional observing network (due to inadequate horizontal resolution), while at the same time it limits the error growth for large-scale circulations. The improved initial state leads to further improvement in the subsequent forecast.

Given the fact that precipitable water can be measured by a number of observing systems with a high degree of accuracy, and given the encouraging results of four-dimensional data assimilation, it is desirable to examine the feasibility of assimilating precipitable water measurements into a mesoscale model. The assimilation of precipitable water has two potential benefits: 1) to create a better initial state for the model, and 2) to retrieve the vertical structure of water vapor from the observed precipitable water field.

In this paper, we develop a simple method to assimilate precipitable water measurements (possibly from a network of MWRs or a satellite-based microwave sensor) into a mesoscale model. Because a network of MWRs is not available, we perform a feasibility study using the 3-h special soundings from SESAME 1979 (Severe Environmental Storms and Mesoscale Experiment). The detailed humidity soundings are used to simulate a set of precipitable water measurements from a hypothetical network of MWRs. These simulated precipitable water measurements are then assimilated into the model. The detailed humidity observations are used as verification of the retrieved vertical structure of water vapor. Section 2 of this paper discusses the assimilation methodology. Section 3 describes the SESAME 1979 case chosen for this study. The evolution of a control simulation without data assimilation is given in section 4, and the impact of moisture assimilation is presented in section 5. Our conclusions are summarized in the final section.

2. Methodology

a. Data assimilation procedure

In this study we use the Newtonian nudging technique for data assimilation. A detailed description of this technique can be found in Anthes (1974), Hoke and Anthes (1976), and Stauffer and Seaman (1990), and is therefore not repeated here. As discussed by KG and Stauffer and Seaman (1990), there are two frequently used nudging approaches. The first method, called station nudging, nudges the model variables toward individual station observations, where and when they are available. The other approach, called analysis nudging, relaxes the model fields toward the gridpoint analyses of observations. Both approaches are employed in this study. (We conducted a comparison study between analysis nudging and station nudging for moisture assimilation, and found that analysis nudging performed slightly better.) Following the analysis nudging procedure, for a given variable \( \alpha \), the model's prognostic equation is written as

\[
\frac{\partial p^* \alpha(t)}{\partial t} = F + G p^* [\alpha_{\text{obs}}(t) - \alpha(t)],
\]

where \( F \) is the normal model forcing terms (including advection), \( \alpha_{\text{obs}} \) is the gridpoint analysis toward which the model is being nudged, \( G \) is the nudging coefficient, and \( p^* \) is defined as \( p - p_t \), where \( p_t \) is surface pressure and \( p \) is the pressure at the top of the model (100 mb). Based on previous experiments (see KG and Guo and Kuo 1988), we choose \( G \) to be \( 3 \times 10^{-4} \text{ s}^{-1} \) for this study.

b. Assimilation of precipitable water

The variable \( \alpha \) in (1) can be any model predictive variable, such as wind, temperature, or specific humidity. However, this equation cannot be used directly for the assimilation of precipitable water (PW), because PW is not a three-dimensional model predictive variable (even though the specific humidity is). In this study, we use a simple method to assimilate PW. The basic idea is to nudge the model's PW toward the observed value while retaining the vertical structure of the model's humidity field.

We first construct a three-dimensional field of "observed" water vapor based on the observed PW and the vertical structure of the model humidity field. The observed PW is obtained from the vertical integration of the objective analysis of specific humidity (to be discussed in section 2c),

\[
PW_{\text{obs}} = \frac{p^*}{g} \sum_{k=1}^{KP} q_{\text{ana}}(k) \Delta \sigma(k),
\]

where \( q_{\text{ana}}(k) \) is the objective analysis of specific humidity at \( k \)th layer derived from the 3-h SESAME soundings, \( \Delta \sigma(k) \) is the thickness of the \( k \)th layer, and
KP is the total number of layers. Similarly, we can obtain the model saturation precipitable water $PW_{sat}$ by using the model saturation specific humidity $q_{sat}(k)$ derived from the model temperature $T_m(k)$. When the $PW_{obs}$ is greater than the $PW_{sat}$, we simply set the "observed" specific humidity, $q_{obs}(k)$, to the model saturation specific humidity $q_{sat}(k)$. Otherwise, the following iteration procedure is performed:

(a) use the model humidity field $q_{m}(k)$ as the first guess of the observed specific humidity $q^{(1)}_{obs}(k)$;

(b) calculate the precipitable water $PW^{(n)}_{obs}$,

$$PW^{(n)}_{obs} = \frac{P_m}{g} \sum_{k=j}^{KP} q^{(n)}_{obs} \Delta \sigma(k); \text{ initially } n = 1, \quad (3)$$

(c) if $| \left[ PW_{obs}/PW^{(n)}_{obs} \right] - 1 | < 0.01$, $q^{(n)}_{obs}(k)$ is the observed specific humidity $q_{obs}(k)$, and the iteration ends. Otherwise,

(d) calculate

$$q^{(n+1)}_{obs}(k) = q^{(n)}_{obs}(k) \frac{PW_{obs}}{PW^{(n)}_{obs}}; \quad (4)$$

(e) set $q^{(n+1)}_{obs}(k) = q_{sat}(k)$ at level $k$ where $q^{(n+1)}_{obs}(k) > q_{sat}(k)$, and go back to step (b).

Usually it takes no more than 2 iterations for the procedure to converge, but in the rare situation, more iterations are needed. To save computer time, we terminate this procedure after 20 iterations. The iteratively adjusted profile of specific humidity is then assimilated into the model following (1).

c. Mesoscale model and data analysis

The model used in this study is the Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model version 4 (MM4) described by Anthes et al. (1987). The computational domain is shown in Fig. 1, and has a horizontal mesh of 49 × 55 and a grid distance of 40 km. There are a total of 23 layers in the vertical. The middle of these layers are defined at $\sigma = 0.025, 0.075, 0.125, 0.175, 0.225, 0.275, 0.325, 0.375, 0.425, 0.475, 0.525, 0.575, 0.625, 0.675, 0.725, 0.775, 0.82, 0.865, 0.91, 0.945, 0.97, 0.985, 0.995$. The precipitation physics includes a Kuo-type cumulus parameterization scheme (Kuo and Anthes 1984) and a resolvable-scale non-convective precipitation parameterization. The planetary boundary layer (PBL) formulation was originally developed by Blackadar (1979), which includes surface fluxes of sensible heat, latent heat, and momentum.

During SESAME, special soundings were launched at 3-h intervals from 1200 UTC 10 April 1979 to 1200 UTC 11 April 1979 at approximately 35 stations [including both the routine National Weather Service (NWS) and supplementary stations; see Fig. 1]. Objective analysis is performed first at 12-h intervals by using the National Meteorological Center's global analysis as the first guess, and then by enhancing it with rawinsonde observations through successive correction. This analysis is then linearly interpolated in time to 3-h intervals to serve as the first-guess field for the analysis of the 3-h special soundings. The objective analyses are performed on an expanded grid with a mesh size of 76 × 109 and a grid interval of 40 km. The final analyses for model initialization and for data assimilation are extracted from the expanded analyses. The lateral boundary condition is obtained from linear interpolation of the 12-h analyses.

d. Experiment design

Table 1 summarizes the ten numerical experiments performed for this study. All the experiments are initialized at 1200 UTC 10 April 1979 and are run for 24 h. The first experiment is called CNTL, which is a straight 24-h control forecast without data assimilation. This experiment serves as the benchmark for assessing the effectiveness of data assimilation. The subsequent nine experiments include data assimilation of different combinations of variables with different temporal resolutions. In all these experiments data assimilation is performed during the entire 24-h model integration (unless stated otherwise). Experiment V assimilates wind field only; T for temperature only; VT for wind and temperature; VTPW for wind, temperature, and precipitable water; VPW for wind and precipitable water; VQ for wind and specific humidity; and VTO for wind, temperature, and specific humidity. These seven experiments assume that observations are available at 3-h intervals. The 3-h temporal resolution is limited by the SESAME sounding frequency. For actual re-
mote-sensing instruments, much higher temporal resolution is available (e.g., 6 min for wind profilers and 2 min for MWR). To assess the impact of temporal resolution, VTPW6 and VTPW12 are performed in the same way as that of VTPW, except that the temporal resolution of the data (wind, temperature, and precipitable water) is degraded to 6 and 12 h, respectively. Although the primary interest of this study is PW assimilation, we include both wind and temperature in the assimilation procedure. With the continued development and deployment of wind profilers and RASS, profiling of wind and temperature is expected to be routinely available in the foreseeable future. Currently, RASS soundings in the demonstration network wind profilers are usually available to about 5 km AGL (Moran et al. 1991).

3. Overview of the SESAME 1979 case

The SESAME was conducted during the spring of 1979, with a goal of studying the structure and dynamics of mesoscale weather systems. Three-hour soundings were taken from conventional NWS and supplementary stations (see Fig. 1) on six intensive observing periods, each lasting for 24 h. During the first experimental day, from 1200 UTC 10 April to 1200 UTC 11 April 1979, two separate convective systems occurred within the observing network. The first system erupted at about 1800 UTC 10 April, to the west and south of the Red River valley. The southern part of this system produced numerous tornadoes and hail storms in the area (see Albert et al. 1980). The second system formed over west-central Texas at about 0130 UTC 11 April, and developed into a squall line that extended to the northeast and moved slowly eastward throughout the experiment period. The synoptic environment and its interaction with mesoscale convective systems in this case have been the subject of several papers (Carlson et al. 1980; Moore and Fuehlberg 1981; Anthes et al. 1982; Kuo and Anthes 1984). This case is briefly summarized here as it relates to this study.

Surface analysis at 1200 UTC 10 April 1979 shows a 988-mb cyclone over the Colorado–Wyoming border, with a cold front trailing southward into New Mexico (Fig. 2a). A dryline, indicated as a dot–dashed line, lay several hundred kilometers ahead of the cold front. A stationary front was positioned along the Gulf coast. Over the Oklahoma–Kansas border, a southerly low-level jet (LLJ) with a maximum speed of 17 m s\(^{-1}\) was transporting warm and moist air northward (not shown). At upper levels, a major jet streak (Fig. 3a) was located over the United States–Mexico border at the base of a deep trough.

Within the subsequent 12 h, the cyclone moved slowly southeastward and intensified (Fig. 2b). The cold front now extended from the tip of the Oklahoma Panhandle into western Texas. The distance between the cold front and the dryline was shortened. However, the dryline remained a few hundred kilometers ahead of the cold front. The stationary front moved northward and became a warm front associated with the cyclone. Within this 12-h period, the LLJ had intensified and moved southeastward, with its speed increased to 26.5 m s\(^{-1}\) (not shown). A dramatic change also took place at the upper levels. An upper-level jet streak (with a maximum speed of 54.2 m s\(^{-1}\)) developed over eastern Kansas (Fig. 3b) to the north of the region of intense convective activities over central Oklahoma and the Oklahoma–Kansas border (see Fig. 4d). This jet streak is likely to have been caused by enhanced baroclinity due to convective heating at upper levels, as suggested by Anthes et al. (1982).

During the next 12 h, the cyclone intensified slightly and moved eastward (Fig. 2c). The cold front advanced southeastward, curving from western Kansas through eastern Oklahoma into eastern Texas. By 1200 UTC 11 April, the dryline became collocated with the cold front. The LLJ also shifted rapidly eastward to a position over western Mississippi and intensified slightly (not shown). At 300 mb, the upper-level jet streak over eastern Kansas further intensified to a maximum speed of 71.4 m s\(^{-1}\) (Fig. 3c). Another jet streak at the base of the trough had moved into western Texas by this time.
Fig. 2. Surface analysis at (a) 1200 UTC 10 April, (b) 0000 UTC 11 April, and (c) 1200 UTC 11 April 1979. Solid lines are sea level pressure (mb) dashed lines are temperatures (°C) at the lowest model level (σ = 0.995), and the dot-dashed line shows the location of the dryline.

Fig. 3. The 300-mb wind field for (a) 1200 UTC 10 April, (b) 0000 UTC 11 April, and (c) 1200 UTC 11 April 1979. Dashed lines show the wind speed (m s⁻¹). Line AB in (c) corresponds to the cross section shown in Fig. 16.
The 3-h accumulated rainfall during the SESAME period is shown in Fig. 4. Heavy rainfall did not start until 1800 UTC 10 April, which coincided with the Wichita Falls tornado outbreak. The area of heavy precipitation quickly expanded, and by 0000 UTC 11 April, it covered nearly all of Oklahoma (Fig. 4d). The precipitation pattern shows a distinct northeast-southwest orientation. During the 3-h period ending at 0300 UTC 11 April the precipitation area occupied most of Kansas and central Oklahoma (Fig. 4e). The squall line produced heavy precipitation at its leading edge and lighter precipitation to its rear. The system moved eastward, and the precipitation area continued to expand with time. By 1200 UTC 11 April, the squall line was still intact, producing heavy precipitation over Indiana, Illinois, Missouri, Arkansas, Oklahoma, and Texas.

The Oklahoma City station (OKC in Fig. 1) was in the vicinity of severe weather and the squall line during most of the period. It is of interest to examine the development of the thermodynamic structure at this station, which is shown in Fig. 5a. At 1200 UTC 10 April (dot-dashed line), a shallow capping inversion was found below 850 mb. The air was from the south or southeast and was relatively moist underneath the inversion. The veering of the low-level winds with height indicates warm advection in the lower troposphere. Above the inversion, southwesterly flow prevailed, and the air was very dry in the middle troposphere. With the development of the strong south-southwesterly wind below 500 mb with speeds exceeding 30 m s⁻¹ at 0000 UTC 11 April, and the transport of warm moist air from the Gulf of Mexico, considerable warming and moistening took place in the 12-h period ending
at 0000 UTC 11 April (Fig. 5a, dashed line). The capping inversion was raised to 800 mb, and the sounding became nearly saturated from the surface up to 400 mb. This sounding was unstable for parcels lifted above the inversion. Indeed, heavy rainfall occurred in the vicinity of OKC at this time (Fig. 4d and 4e). Following the passage of the cold front and the squall line, significant drying took place in the lower and upper levels as evidenced by the 1200 UTC 11 April sounding (Fig. 5a, solid line). A low-level inversion at 850 mb with very low humidity and a moist layer at 600 mb are also features of this sounding. This type of sounding has been referred to as an “onion-shaped” sounding (Zipser 1977) and is often found behind a mesoscale convective system. The low-level warming and drying is believed to be caused by mesoscale unsaturated downdrafts, while the midlevel moistening is related to mesoscale stratiform clouds.

4. Evolution of the control simulation

In this section we describe the evolution of the control simulation (CNTL), which serves as a benchmark for comparison with subsequent data assimilation experiments. Figure 6 shows the 12-h and 24-h forecasts of sea level pressure and lowest σ-level (40 m above the ground) temperature. At 0000 UTC 11 April (12-h forecast, Fig. 6a), the predicted cyclone of 986 mb was 2 mb weaker than the analysis (Fig. 2b), and was located 150 km to the north of the observed position. The overall temperature pattern compares favorably with the observation over the Texas–Oklahoma region. The warm air mass over the Texas–Mexico border, with temperatures exceeding 30°C, was reasonably well simulated. The LLJ was predicted over the Oklahoma–Texas border with an intensity (23 m s⁻¹, not shown) slightly weaker than that observed. At 300 mb, the
Also, the 24°C isotherm extended much further inland than the observation. At 850 mb, the LLJ over central Mississippi had a maximum speed of 39.3 m s\(^{-1}\) (not shown), much stronger than the observed intensity of 28.6 m s\(^{-1}\). The large-scale flow patterns at this level are reasonably accurate, however.

Substantial errors are found in the upper-level flows at 1200 UTC 11 April (Fig. 7b). The model predicted an elongated jet streak, extending from northern Mexico to southeastern Kansas, with very little along-stream velocity variation. The wind speed was about 60 m s\(^{-1}\) along the jet. In the observation, two separate jet streaks were found: one over eastern Kansas with a core of

model produced a broad jet streak over western Texas and another minor jet streak over northeastern Kansas (Fig. 7a). In the observation, the jet streak over Texas had a much narrower extent, and the jet streak over eastern Kansas was considerably stronger and better defined (Fig. 3b).

The 24-h prediction of the Colorado cyclone is quite successful (Fig. 6b). The observed and simulated cyclone positions were almost identical (Fig. 2c), and the predicted cyclone was only 1 mb deeper (982 versus 983 mb). The position and intensity of the cold front are well simulated. However, the surface temperature shows a warm bias near the Gulf coast. For example, the predicted surface temperature of 28.8°C over southern Texas was 6°C warmer than the observation.

Fig. 5. (a) The Oklahoma City sounding at 1200 UTC 10 (dot-dashed line), 0000 UTC 11 (dashed line), and 1200 UTC 11 (solid line) April 1979. (b) The Oklahoma City sounding at 0000 UTC (dashed line) and 1200 UTC (solid line) on 11 April 1979 as predicted by CNTL. The dot-dashed line is the dewpoint after model precipitable water was adjusted to the observed value.

Fig. 6. Sea level pressure at 4-mb intervals (solid) and lowest-level temperature (\(\sigma = 0.995\)) at 4°C intervals (dashed) for (a) 12-h forecast valid at 0000 UTC 11 April and (b) 24-h forecast valid at 1200 UTC 11 April 1979 for CNTL.
shown in Fig. 9. It increased from 0.1 cm initially (which represents the difference between actual station observation and the objective analysis) to a value of 0.5 cm in 6 h, which is approximately 30%–40% of the observed PW. Apparently, the model did not handle the water vapor (or precipitable water) field very well. The exact source of these errors is not known. However, it is likely to be caused by a combination of errors in horizontal advection (through the lateral boundaries), precipitation physics, surface and boundary-layer processes, and the numerics of the model. It should be noted that the magnitude of bias error in PW is approximately 0.1–0.15 cm throughout the simulation period, which is considerably smaller than the rms error. This implies that the rms PW error was largely 71.4 m s\(^{-1}\) and the other over northern Mexico (Fig. 3c). Although the orientation and the position of the jet stream are reasonably accurate in the prediction, significant errors exist in the detailed jet-streak structure, especially over the Oklahoma–Kansas area.

To examine the humidity prediction, we show the time–height section of specific humidity bias error averaged over all the rawinsonde stations within the domain (Fig. 8). The model results were interpolated to the observational sites and compared directly against the soundings. A large positive bias was found in the lower half of the troposphere, except for a small negative bias at \(\sigma = 0.75\) (about 800 mb) at 2100 UTC 10 April 1979. The positive bias was the largest close to the ground. The time evolution of rms PW error is
due to phase error in moisture distribution, instead of bias error.

The precipitation forecast for the last 12-h period of the simulation is shown in Fig. 10. The 3-h precipitation ending at 0300 UTC 11 April (Fig. 10a) assumed an irregular shape over Oklahoma and its vicinity, with a maximum amount of 12.4 mm. Heavy rainfall was predicted over the Alabama–Mississippi border, which was not observed (Fig. 4e). On the other hand, the observed precipitation over western Louisiana was not captured. During the next 3 h (Fig. 10b), the model rainfall (produced largely by convective parameterization) moved eastward, in accordance with the observed squall line, but was not shown as a southwest–northeast-oriented rain belt. The observed 3-h rainfall ending at 0900 UTC 11 April exhibited a continuous line, with three rainfall maxima over central Texas, eastern Oklahoma, and the Illinois–Missouri border, respectively (Fig. 4g). The corresponding model precipitation did not display a well-defined shape, although heavy rainfall over central Texas was captured (Fig. 10c).

During the final 3-h period, the model precipitation (Fig. 10d) deviated significantly from the observation (Fig. 4h). Excessive rainfall was predicted over southern Illinois and western Tennessee, while the observed heavy precipitation over eastern Illinois, southeastern Missouri, and northwestern Arkansas was missed. Also, the model precipitation over eastern Texas became excessive.

To provide a quantitative assessment, we compute the threat scores of 3-h accumulated rainfall over box A in Fig. 1 for the threshold values of 1.0, 2.5, and 5.0 mm. The results for the period of 1800 UTC 10 to 1200 UTC 11 April for the control and the data assimilation experiments are summarized in Table 2. (There was little precipitation during the period between 1200 and 1800 UTC 10 April in both the observation and the model.) Averaged over the six 3-h periods, the threat

---

**Fig. 10.** The 3-h rainfall ending at (a) 0300 UTC, (b) 0600 UTC, (c) 0900 UTC, and (d) 1200 UTC 11 April 1979 for CNTL.
TABLE 2. Threat score averaged over six periods of 3-h precipitation from 1800 UTC 10 to 1200 UTC 11 April for various experiments.

<table>
<thead>
<tr>
<th>Threshold</th>
<th>1 mm</th>
<th>2.5 mm</th>
<th>5 mm</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNTL</td>
<td>0.32</td>
<td>0.19</td>
<td>0.11</td>
<td>0.20</td>
</tr>
<tr>
<td>V</td>
<td>0.39</td>
<td>0.31</td>
<td>0.23</td>
<td>0.31</td>
</tr>
<tr>
<td>T</td>
<td>0.24</td>
<td>0.15</td>
<td>0.10</td>
<td>0.17</td>
</tr>
<tr>
<td>VT</td>
<td>0.34</td>
<td>0.23</td>
<td>0.17</td>
<td>0.26</td>
</tr>
<tr>
<td>VTPW</td>
<td>0.36</td>
<td>0.30</td>
<td>0.27</td>
<td>0.31</td>
</tr>
<tr>
<td>VQ</td>
<td>0.38</td>
<td>0.31</td>
<td>0.26</td>
<td>0.32</td>
</tr>
<tr>
<td>VPW</td>
<td>0.37</td>
<td>0.28</td>
<td>0.20</td>
<td>0.28</td>
</tr>
<tr>
<td>VTPW6</td>
<td>0.32</td>
<td>0.24</td>
<td>0.19</td>
<td>0.25</td>
</tr>
<tr>
<td>VTPW12</td>
<td>0.30</td>
<td>0.20</td>
<td>0.14</td>
<td>0.21</td>
</tr>
</tbody>
</table>

scores are 0.32, 0.19, and 0.11 for the three thresholds, respectively. The skill score falls off with larger precipitation thresholds, indicating that the model has less skill predicting heavier precipitation.

The model soundings at OKC valid at 0000 UTC 11 April and 1200 UTC 11 April are shown in Fig. 5b. In comparison with the observed sounding at OKC (Fig. 5a), the intensity of the south-southwesterly flow at 0000 UTC 11 April was underpredicted. At 700 mb, the model wind speed was 15 m s\(^{-1}\), while that in the observation was twice as large. The predicted sounding was not as moist in the midtroposphere, and the capping inversion below 800 mb was not simulated. The inversion did not appear even at 1200 UTC 11 April, although a dry layer was predicted at around 800 mb. The main problem is that the model sounding was more than 5°C warmer than the observation near the surface. Because of the missing temperature inversion, the model sounding at OKC did not display an onion shape.

5. Results of data assimilation experiments

In this section we will assess the impact of four-dimensional data assimilation. Although the terms "forecast" and "prediction" will be loosely used to describe the results of data assimilation experiments, it is important to keep in mind that they are no longer free forecasts, because the model is strongly constrained by the observations. The accuracy of the model results (particularly for those variables that are not nudged) during the assimilation period can be used to assess the effectiveness of the assimilation. In this regard, the model precipitation forecast is a particularly useful field, because rainfall rate is not assimilated and its accuracy is sensitive to various dynamical and thermodynamical processes of the model.

a. Sea level pressure and overall flow pattern

The assimilation of wind field alone (V) resulted in a significant improvement in the model flow fields. Figure 11a shows the 24-h forecast of sea level pressure and lowest level temperature for V. The central pressure of the Colorado cyclone at 1200 UTC 11 April 1979 was 985 mb, with a near-perfect positioning (see Fig. 2c). The low-level wind field compares favorably with the observed flow structure and, in particular, with both the position and intensity of the LLJ (not shown). Figure 11b shows the 24-h forecast of 300-mb wind valid at 1200 UTC 11 April 1979. An elongated jet streak was located over the Kansas-Oklahoma area, with a shape and intensity much closer to the observation than CNTL forecast. However, the speed of the jet was about 5 m s\(^{-1}\) weaker than the observation, and the jet streak on the Mexico-Texas border was still absent.

In the subsequent data assimilation experiments, the
prediction of the sea level pressure field and upper- and lower-level winds is very similar to that of V. Therefore, they are not repeated here. Despite similarity in the sea level pressure and wind field prediction, significant differences are found among these data assimilation experiments in the forecast of precipitation and moisture distribution, which will be the subjects of the following subsections.

b. Precipitation forecast

With the assimilation of the wind field, dramatic improvement was found in the model precipitation forecast. The 3-h rainfall of V, shown in Fig. 12, reveals a line pattern associated with the squall line that was not found in the CNTL forecast without data assimilation (Fig. 10). The erroneous precipitation over the Alabama-Mississippi border, seen in CNTL, was substantially reduced. It was completely eliminated after 0600 UTC 11 April. The orientation and position of the model precipitation compared very favorably with the observed rainfall during the 6-h period ending at 0600 UTC 11 April 1979. During the 3-h period ending at 0900 UTC, the model rainfall over western Illinois was weaker than observed, while that over Oklahoma and Texas was heavier than observed. However, both the pattern and location of the model precipitation are much better than those of CNTL (compare Figs. 10c, 12c, and 4g). During the period between 0900 and 1200 UTC 11 April, the observed squall line moved eastward and produced heavy precipitation over most of Illinois, southeastern Missouri, and northwestern Arkansas (Figs. 4g and 4h). The model squall line moved eastward at a slower speed, and heavy rainfall was produced over eastern Oklahoma and northern Texas (Figs. 12c and 12d). Although the model squall line remained intact, the precipitation pattern and location were increasingly different from the observation.

Fig. 12. The 3-h rainfall ending at (a) 0300 UTC, (b) 0600 UTC, (c) 0900 UTC, and (d) 1200 UTC 11 April 1979 for V.
later in the period (compare Figs. 4h and 12d). Averaged over six 3-h periods and over the three precipitation thresholds, the mean threat score is 0.31, which is 50% higher than that of CNTL (0.2). The threat score for the 5-mm threshold for V (0.23) is twice that of CNTL (0.11). This indicates that the precipitation forecast of V represents a significant improvement over that of CNTL.

In VT, we assimilate both the wind and temperature fields into the model. A very strong squall line developed in this experiment and produced extremely heavy rainfall over Kansas, Oklahoma, and Texas (Fig. 13). The maximum 3-h rainfall ending at 0600 UTC 11 April reached 85.4 mm, while those in V and the observation were 14.4 and 21.3 mm, respectively. Excessive rainfall persisted until 0900 UTC 11 April. The squall line stalled and moved very little during the simulation period. A positive aspect of this experiment is that the erroneous rainfall over the eastern part of the model domain, found in CNTL, was largely removed. The mean threat score for VT is 0.26 (Table 2), which is higher than that of CNTL, but is the lowest among all the data assimilation experiments.

The lack of positive impact on precipitation forecast with the inclusion of temperature in VT raises many questions. If the temperature analysis was of good quality (which we believe it was), why should we not obtain better results? Was the lack of impact due to some sort of imbalance between the wind and the mass fields? Or was it due to the ineffectiveness of temperature insertion in mesoscale data assimilation? To answer these questions, we performed an experiment with the assimilation of temperature field alone (T). The threat score averaged over the three precipitation thresholds was 0.17, which is even lower than that of CNTL. Apparently, the temperature nudging alone is

---

**Fig. 13.** The 3-h rainfall ending at (a) 0300 UTC, (b) 0600 UTC, (c) 0900 UTC, and (d) 1200 UTC 11 April 1979 for VT.
not effective in mesoscale data assimilation. Given the fact that the wind field nudging by itself (V) performed very well and temperature nudging (T) performed so poorly, it is clear that the poor performance of VT is a result of temperature nudging rather than imbalance between the wind and mass fields.

The lack of positive impact in temperature assimilation was also found in many previous studies. Hoke and Anthes (1976) showed that the dynamic initialization technique (similar to the one used here) is not well suited for initializing mesoscale disturbances when only temperature and pressure data are available. For horizontal scales less than 2000 km in midlatitudes, the winds are by far more important than the mass in the dynamic initialization process. In a study of four-dimensional data assimilation in the monsoon region, Ramamurthy and Carr (1988) found that the temperature assimilation alone did not offer appreciable improvement over wind-only assimilation when the two variables were inserted together. In contrast, a combination of wind and moisture data provided the most positive results. Although a detailed investigation of the issues related to temperature assimilation is very important, it is beyond the scope of this paper. Our primary objective in this study is precipitable water assimilation.

With the addition of precipitable water to the assimilation procedure in VTPW, the excessive rainfall associated with the squall line in VT was considerably reduced (Fig. 14). The rainfall amount compared much more favorably with the observed precipitation intensity. However, the model missed the rainfall over central Texas during the 3-h period ending at 0600 UTC 11 April 1979. During the subsequent 6-h period, the model precipitation moved eastward at a speed similar to the observation. For the 3-h rainfall ending at 0900 UTC 11 April (Fig. 14c), three distinct centers were found over the Illinois–Missouri border, western

![Fig. 14. The 3-h rainfall ending at (a) 0300 UTC, (b) 0600 UTC, (c) 0900 UTC, and (d) 1200 UTC 11 April 1979 for VTPW.](image-url)
Arkansas, and central Texas, which compared favorably with the observation (Fig. 4g). However, the peak rainfall amounts at two of the centers were underestimated by 50%. The model was able to simulate the eastward movement of the squall line, in accordance with the observation. This is particularly evident in the final 3-h rainfall ending at 1200 UTC 11 April 1979. The mean threat score of VTPW is 0.31 (Table 2), the same as that of V. We note that VTPW performed slightly better than V for the threshold of 5.0 mm and slightly worse for the threshold of 1.0 mm.

Assimilating profiles of specific humidity (VTQ) instead of PW did not result in further improvements in the model precipitation forecast (Fig. 15). For the 3-h rainfall ending at 0600 UTC 11 April, VTQ missed the precipitation over northwestern Missouri (Fig. 15b), which was captured in VTPW. The orientation and location of the squall-line precipitation during the last 6-h period of the forecast was not as good as that in VTPW. The mean threat score of VTQ is very close to that of VTPW.

The lack of impact on precipitation forecast with the assimilation of profiles of specific humidity does not necessarily imply that profiles of water vapor are not useful in mesoscale data assimilation. The problem, in fact, is not associated with the water vapor itself, but rather is related to the atmospheric moisture structure, the measurement capability, and the data assimilation method. It is well known that moisture exhibits significant mesoscale variation in time and space (see Lilly and Perkey 1976). Because of the lack of temporal and spatial resolution in the conventional rawinsonde network, moisture is often not properly sampled. As a result, the mesoscale moisture structure is often aliased to larger scales, and bull's-eye patterns are frequently seen in a moisture analysis using the conventional rawinsonde data. Stauffer and Seaman (1990) reported that assimilation of specific humidity from the con-

Fig. 15. The 3-h rainfall ending at (a) 0300 UTC, (b) 0600 UTC, (c) 0900 UTC, and (d) 1200 UTC 11 April 1979 for VTQ.
ventional rawinsonde network resulted in a degradation of model precipitation forecast. Although the temporal resolution was 3 h for the SESAME soundings, the spatial resolution was approximately 250 km. The lack of spatial resolution can compromise the quality of the moisture analysis, particularly over regions of strong moisture gradient such as in the vicinity of the squall line and the dryline. Nudging the model moisture fields toward a “diffused” moisture analysis can result in a loss of strong mesoscale moisture gradients developed in the model. On the other hand, the assimilation of PW measurements does not pose such a strong constraint and allows the model moisture structure to be better preserved.

To support this hypothesis we show in Fig. 16 two-dimensional wind vectors, potential temperature, and relative humidity along a cross section cutting across the squall line at 1200 UTC April 11 for VTPW and VTQ. The location of the cross section is shown in Fig. 3c. Although the wind field and the temperature field are nearly identical in these two experiments, there are significant differences in the model relative humidity fields. The experiment that assimilated PW produced a column of high humidity at the leading edge of the squall line and in the middle atmosphere behind the squall line. Mesoscale downdrafts with low humidity occurred in the lower troposphere behind the squall line. Strong horizontal and vertical humidity gradients were found in the vicinity of the squall line. In VTQ, which assimilated three-dimensional analyses of humidity (e.g., profiles of specific humidity at each grid point) directly, these features can still be identified. However, the horizontal and vertical gradients are all substantially reduced. The most dramatic difference is the moisture structure at the leading edge of the squall line. Experiment VTQ was unable to produce a continuous column of high humidity. Nudging toward a humidity analysis with limited horizontal resolution, the assimilation procedure removed mesoscale humidity structures produced by the model. With higher resolution moisture data, it is possible that assimilation toward profiles of water vapor directly may produce better results than assimilation of precipitable water. However, with an insufficient horizontal resolution, direct assimilation of three-dimensional moisture analysis may not necessarily be beneficial.

To further assess the value of precipitable water assimilation, we conducted VPW, which assimilated only wind and precipitable water without temperature. Interestingly, the evolution of the model precipitation in VPW (Fig. 17) and its threat scores were similar to that of VTPW. Likewise, we also found that the results of VQ are very close to VTQ. In terms of precipitation forecast during the assimilation period, these results suggest that temperature data does not provide further improvement over wind and moisture assimilation. With the assimilation of wind and moisture fields, the model's moisture convergence (which is directly related to the precipitation intensity in the Kuo scheme) is strongly constrained by the observations. This apparently has a positive impact on the model precipitation forecast. The superiority of VPW over VQ again supports the effectiveness of PW assimilation (Table 2).

c. Prediction of moisture fields

The rms PW errors for selected data assimilation experiments were shown in Fig. 9. Without assimilation of moisture, the PW rms error in V and VT was similar to that of the control. For experiments that assimilated either PW or specific humidity, the PW rms error remained small (<0.2 cm) throughout the forecast.

Figure 18 shows the time–height section of specific humidity bias error (model minus analysis) for V, VT, VTPW, and VPW. For all the experiments, there was a positive water vapor bias below σ = 0.9, and a negative bias in the layer between σ = 0.85 and σ = 0.65. Experiment VT (Fig. 18b), with an excessive precipi-
d. Vertical structure of humidity

A very important objective of this study is to see if assimilation of PW can retrieve the vertical structure of humidity. For this purpose we calculate the rms error of specific humidity averaged over eight sounding times (from 1500 UTC 10 to 1200 UTC 11 April at 3-h intervals), and present the results in Fig. 19. Below $\sigma = 0.55$ ($\sim 600$ mb), where most of the moisture is located, the rms specific humidity error is in the range of 1.7–2.5 g kg$^{-1}$ for CNTL. The assimilation of wind field (V) reduced the rms specific humidity error slightly above 850 mb, but did not perform better than CNTL below that level. Overall, there is a small but insignificant improvement over CNTL. The assimilation of wind and temperature in VT produced the least accurate results, with errors larger than those of CNTL below 600 mb. The addition of PW in VTPW resulted in a significant improvement in the vertical structure of the humidity field. The rms specific humidity error was substantially less than those of CNTL, V, and VT throughout the troposphere. The performance of VPW is slightly better than VTPW, especially near the surface. Figure 19 also shows the rms specific humidity error for VTQ. Note that the rms specific humidity error does not vanish for this experiment. It was about 1 g kg$^{-1}$ below 850 mb, and decreased grad-
usually with height. The rms specific humidity errors do not vanish for two reasons. First, the objective analysis of specific humidity is used in the analysis nudging procedure. This analysis can differ slightly from the station observations. Second, nudging is a gradual relaxation procedure, not a direct replacement.

Another way of checking the quality of the final assimilated field is to examine the individual soundings. Figure 20 shows the OKC soundings at 1200 UTC 11 April as simulated by V, VT, VTPW, and VPW. In comparison with the observed onion-shaped sounding shown in Fig. 5, the soundings predicted by V and VT contain significant errors. The sounding in V did not show an inversion at 850 mb. Moreover, the sounding was too moist below 900 mb, and too dry above 600 mb. The inclusion of temperature in VT improves the temperature structure in the sounding and, in particular, the location of the inversion. However, the entire sounding was too moist, with dewpoint temperature higher than that of the observed sounding (Fig. 5a) by 5°–10°C throughout the troposphere. The sounding predicted by VTPW, while admittedly not perfect, compares most favorably with the observed sounding. The low-level temperature inversion and the drying were all captured, although the middle moist layer was predicted at a level approximately 100 mb too high. The humidity structure as simulated by VPW resembles that of VTPW. However, the low-level temperature was warmer than the observation by several degrees, and the inversion was located at a slightly lower elevation. Overall, the sounding predicted by VPW is superior to those of V and VT.

One might argue that, given the observed PW, the
model sounding (such as the one provided by CNTL) can be adjusted to satisfy the observed PW. Essentially, the model humidity field is used as a first guess for moisture retrieval. The resulting sounding structure can then be improved. The key question here is whether a continuous assimilation is necessary to retrieve the vertical structure of humidity. Figure 5b shows the CNTL sounding after the adjustment (the dot-dashed line). The adjustment resulted in drying throughout the entire troposphere. It is clear that even though the model PW is now consistent with the observed value, the vertical structure of the sounding is by no means improved. This is particularly true in view of the fact that the model temperature remains unchanged in the adjustment. These results suggest that a continuous assimilation of available observations is essential in producing improved profiles of atmospheric temperature and humidity structures.

e. **Comparison with statistical retrieval**

Westwater et al. (1985) used a statistical technique based on climatology to derive vertical profiles of water vapor from MWR radiometric measurements in addition to surface observations of pressure, temperature, and humidity at Denver. They compared the retrieved water vapor fields directly with rawinsonde measurements over a two-year period and found that the rms difference of water vapor integrated over the bottom 5 km of the atmosphere was 1.7 mm for a sample of 1252 soundings. It is important to note that these results may not be generally applicable because the Denver soundings are climatologically very dry. To compare the results from data assimilation with these from a similar technique, we performed statistical retrievals for 23 NWS stations within the SESAME domain (see Fig. 1) based on 19 years of data (from 1973 to 1991).
For each station, we selected the 0000 and 1200 UTC soundings for April of each year. This comprised a total of 1140 (=60 x 19) soundings for each station. Excluding the soundings at 1200 UTC 10, 0000 UTC 11, and 1200 UTC 11 April 1979, a total of 1137 soundings were available for the derivation of multiple linear regression equations. It is important to note that the number of data available for this purpose varied from level to level and from station to station. In particular, only limited observations were available at upper levels (above 300 mb). To ensure statistical significance, no regression equations were derived if the number of datum was less than 40. Following Westwater et al. (1985), we derived a multiple regression equation for each level at each station, which can be written as the following:

\[ q_v(k) = \beta_0(k) + \sum_{i=1}^{4} \beta_i(k)X_i, \]  

where \( q_v(k) \) is the specific humidity at each level \( k \) for each station, \( \beta_0(k) \) is the regression constant, and \( \beta_i(k), i = 1, \ldots, 4 \) are the regression coefficients. Here \( X_i, i = 1, \ldots, 4 \) are PW, surface pressure, surface temperature, and surface relative humidity, respectively. The observed PW fields derived from the SESAME soundings and surface observations were then used to predict the specific humidity at each vertical level \( k \) for each station. Although Westwater et al. (1985) used brightness temperatures in their profile retrievals, the use of (5) is essentially equivalent.

Table 3 summarizes the vertically integrated specific humidity rms error for various experiments and the statistical retrieval calculated over the 23 NWS stations. Averaged over the eight time periods, the vertically integrated rms specific humidity error was 1.31 g kg\(^{-1}\) for the statistical method (STAT), while that for CNTL and VTPW and VPW was 1.38, 1.07, 1.08 g kg\(^{-1}\), respectively. It is clear that dynamic retrieval via PW assimilation performed better than the statistical method. However, the straight model forecast without data assimilation (CNTL) gave slightly worse results than the statistical retrieval. The mean error associated with the statistical method is nearly 30% more than that of VTPW. This clearly shows the importance of PW assimilation in retrieving a better vertical structure of humidity. The statistical retrieval does have respectable skill, however. When compared with persistence (PERT), the statistical method had 40% less error than that of persistence (2.03 g kg\(^{-1}\)).

\[ f. \] Impact of temporal resolution

A very important property of remote sensing instruments such as MWR, wind profiler, and RASS is their high temporal resolution. It is of interest to examine the impact of temporal resolution on the results of data assimilation. Experiments VTPW6 and VTPW12 were performed in the same way as VTPW, except the temporal resolution of the data (wind, temperature, and precipitable water) was degraded to 6 and 12 h, respectively. Figure 21 shows the rms PW errors for these two experiments. For both experiments the errors were suppressed whenever data were available. However, errors increased rapidly when there were no data. The 3-h rainfall ending at 0900 UTC 11 April for VTPW6 and VTPW12 are shown in Fig. 22. The precipitation forecast for these two experiments is inferior to that of VTPW (see Figs. 14c and 4g). The threat scores presented in Table 2 also confirm our subjective assessment. It is clear that the temporal resolution had a significant impact on the final assimilated fields. With the availability of PW measurement at a temporal resolution significantly higher than 3 h (2 min for MWR), the use of the actual MWR measurements should lead to even more optimistic results than those of VTPW.

\[ g. \] Impact on short-range prediction

The foregoing discussion focused on the performance of the model during the data assimilation period. Strictly speaking, these are not pure “forecasts” or “predictions,” because the model evolution was strongly constrained by the observations. A very important question concerning this study is: Does assimilation of PW (or data assimilation in general) improve short-range precipitation forecast? To answer this question, we perform a series of 6-h forecasts starting at 0000 UTC, 0300 UTC, and 0600 UTC 11 April for selected data assimilation experiments. Therefore, for

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>21</th>
<th>24</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNTL</td>
<td>1.08</td>
<td>1.44</td>
<td>1.28</td>
<td>1.28</td>
<td>1.59</td>
<td>1.31</td>
<td>1.63</td>
<td>1.46</td>
<td>1.38</td>
</tr>
<tr>
<td>V</td>
<td>1.05</td>
<td>1.30</td>
<td>1.29</td>
<td>1.27</td>
<td>1.59</td>
<td>1.44</td>
<td>1.50</td>
<td>1.63</td>
<td>1.38</td>
</tr>
<tr>
<td>VT</td>
<td>1.04</td>
<td>1.17</td>
<td>1.31</td>
<td>1.19</td>
<td>1.50</td>
<td>1.65</td>
<td>1.72</td>
<td>1.92</td>
<td>1.44</td>
</tr>
<tr>
<td>VPW</td>
<td>0.97</td>
<td>1.13</td>
<td>0.96</td>
<td>1.03</td>
<td>1.26</td>
<td>1.10</td>
<td>1.02</td>
<td>1.20</td>
<td>1.08</td>
</tr>
<tr>
<td>VTPW</td>
<td>0.94</td>
<td>1.04</td>
<td>1.03</td>
<td>1.03</td>
<td>1.24</td>
<td>1.09</td>
<td>1.00</td>
<td>1.21</td>
<td>1.07</td>
</tr>
<tr>
<td>VTQ</td>
<td>0.56</td>
<td>0.60</td>
<td>0.54</td>
<td>0.56</td>
<td>0.81</td>
<td>0.53</td>
<td>0.57</td>
<td>0.61</td>
<td>0.60</td>
</tr>
<tr>
<td>STAT</td>
<td>1.21</td>
<td>1.16</td>
<td>1.13</td>
<td>1.09</td>
<td>1.54</td>
<td>1.51</td>
<td>1.67</td>
<td>1.35</td>
<td>1.31</td>
</tr>
<tr>
<td>PERT</td>
<td>1.01</td>
<td>1.78</td>
<td>1.92</td>
<td>2.00</td>
<td>2.06</td>
<td>2.15</td>
<td>2.08</td>
<td>2.60</td>
<td>2.03</td>
</tr>
</tbody>
</table>
The forecast experiments initialized at 0000, 0300, and 0600 UTC 11 April, 12, 15, and 18 h of data assimilation had been performed. Table 4 shows the mean threat score averaged over six 3-h periods for these experiments. The results of CNTL (straight forecast without data assimilation) are also included for comparison. Except for VT, all the experiments with data assimilation performed superior to CNTL in all precipitation thresholds. The improvements in precipitation forecast due to data assimilation is even more pronounced for higher precipitation thresholds. A comparison between VTPW and V and VT clearly shows the positive impact of precipitable water assimilation. For example, for the threshold value of 2.5 mm, the threat score for VTPW is 0.33, while those for V and VT are 0.27 and 0.24, respectively. We note that in terms of short-range precipitation forecasts, the inclusion of temperature leads to improved results when both V and PW are included in the assimilation procedure. This is evidenced by a comparison between VPW and VTPW, which have a mean threat score of 0.27 and 0.33, respectively.

6. Summary and discussion

In this paper we examine the usefulness of assimilating precipitable water measurements, possibly from a system such as a ground-based microwave radiometer, into a mesoscale model. A total of ten numerical experiments were performed using a version of the PSU–NCAR Mesoscale Model with a grid spacing of 40 km and 23 vertical layers. The 3-h sounding data collected during the SESAME 1979 were used to simulate precipitable water measurements from a hypothetical network of microwave radiometers for assimilation into the model, and to serve as verification. During the 24-h study period, an intense squall line developed within the observing network and persisted throughout the period.

The control experiment without data assimilation simulated the overall flow pattern reasonably well. However, the model forecasts contained sizeable errors in the detailed structure of the upper-level jet, the intensity and position of a low-level jet, and the precipitation associated with the system. Significant errors were found in the moisture prediction, both in the vertical structure of the humidity field and in the distribution of precipitable water.

Assimilation of wind fields into the model resulted in a significant improvement in the overall flow pattern. The prediction of the squall-line precipitation was also
improved considerably. The wind-field assimilation was able to reproduce the line pattern associated with the squall-line precipitation, even though the model squall line propagated eastward at a slower speed. Considerable errors in the precipitable water and the vertical structure of humidity remained in this experiment, however.

Assimilation of both wind and temperature fields led to a degradation of forecast as compared with the assimilation of wind field alone. The squall-line precipitation was excessive, and the squall line stalled. Because of excessive precipitation and because of the stagnation of the squall line, the model soundings did not agree with the observed soundings. This experiment has the highest error in moisture prediction and lowest precipitation forecast scores among all the experiments. The lack of impact is attributed to the ineffectiveness of temperature insertion in mesoscale data assimilation.

Assimilation of wind, temperature, and precipitable water gave significantly superior results to those of assimilation of wind field alone or assimilation of both wind and temperature fields. The model squall line developed and moved eastward at a speed comparable to the observation. The rainfall intensity also compared favorably with the observed rainfall rate. The positive precipitable water bias found in earlier experiments was greatly reduced. Most importantly, the assimilation of precipitable water was found to substantially reduce the error in the model humidity field. Assimilation of precipitable water can retrieve the vertical structure of humidity with a higher accuracy than the statistical method. The vertically integrated rms error in specific humidity was 1.07 g kg\(^{-1}\) for dynamic retrieval via data assimilation, while that of statistical retrieval based on climatology was 1.31 g kg\(^{-1}\).

Assimilation of profiles of water vapor (specific humidity) instead of precipitable water did not produce further improvement in the precipitation forecasts. In fact, the results were slightly inferior to those with assimilation of precipitable water. This is attributed to the relaxation of model moisture field toward a diffused moisture analysis that has limited horizontal resolution.

An additional experiment that assimilated wind and precipitable water (without temperature) produced precipitation forecasts in the assimilation period as good as that of assimilation of wind, temperature, and precipitable water. However, in terms of subsequent short-range precipitation forecast, the inclusion of temperature data along with the wind and moisture field was found to yield positive results. These results suggest that the temperature data should be used only together with wind and moisture assimilation.

Further data assimilation experiments with temporal resolution degraded to 6 and 12 h yield significantly degraded results. This shows that the temporal resolution of the data has a strong influence on final assimilated fields. With data available at a temporal resolution of 6 min (or higher), assimilation of actual wind profiler, RASS, and MWR measurements should give even more optimistic results than the assimilation of 3-h SESAME sounding data.

Although these results based on only one case are considered preliminary, they do show that precipitable water measurements provided by a ground-based microwave radiometer are valuable and useful for mesoscale data assimilation and numerical weather prediction. The assimilation of precipitable water data creates a good moisture analysis that is of higher quality than the statistical method, and has a positive impact on short-range numerical weather prediction. It is desirable to generalize these results with an additional case study. It should also be noted that the methodology developed here can also be applied to the assimilation of precipitation water measurements from a geostationary satellite (e.g., Birkenheuer 1991). However, the satellite measurements are not available during cloudy conditions, which imposes a severe constraint on the assimilation technique.

As discussed in the Appendix, increasingly better sources of precipitable water data will be available in the next decade. These soundings will have improved horizontal and temporal resolution, as well as being less sensitive to the contaminating effects of clouds. Coupled with the continued deployment of wind profilers and advanced data assimilation techniques, these data should add substantially to our ability to monitor and predict the four-dimensional behavior of tropospheric water vapor.

**Acknowledgments.** This project was partially supported by the Department of Energy Atmospheric Radiation Measurement Program under Project DOE IA DE A105-90ER 61070. We thank Walter Dabberdt for fruitful discussion during the course of this study, and Judy Schroeder, Stan Benjamin, and two anonymous reviewers for critical reviews and constructive suggestions.

**APPENDIX**

**Potential Sources of Precipitable Water Data**

Currently, precipitable water (PW) can be measured remotely in several ways. From space, data from both geostationary and polar-orbiting satellites are available.

---

**Table 4.** Threat scores averaged over two periods of 3-h accumulated rainfall (0-3 h and 3-6 h forecasts) for the three 6-h forecast experiments that were initialized at 0000 UTC, 0300 UTC, and 0600 UTC 11 April 1979.

<table>
<thead>
<tr>
<th>Threshold</th>
<th>1 mm</th>
<th>2.5 mm</th>
<th>5 mm</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNTL</td>
<td>0.38</td>
<td>0.23</td>
<td>0.14</td>
<td>0.25</td>
</tr>
<tr>
<td>V</td>
<td>0.38</td>
<td>0.27</td>
<td>0.18</td>
<td>0.28</td>
</tr>
<tr>
<td>VT</td>
<td>0.37</td>
<td>0.24</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>VPW</td>
<td>0.39</td>
<td>0.26</td>
<td>0.17</td>
<td>0.27</td>
</tr>
<tr>
<td>VTPW</td>
<td>0.45</td>
<td>0.33</td>
<td>0.21</td>
<td>0.33</td>
</tr>
<tr>
<td>VTQ</td>
<td>0.45</td>
<td>0.32</td>
<td>0.22</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Several techniques are also available over land, but not routinely. The most frequently available soundings are from the Visible–Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) on the NOAA GOES satellite (Smith 1983). Data from this instrument are used to produce images of PW with a horizontal resolution of about 30 km and a temporal resolution of 60–90 min. The VAS instrument is a combination of visible and infrared radiometers, and hence, its PW images are restricted to cloud-free regions. In the clear regions, and after using radiosonde-based regression retrievals, the resulting PW accuracy is about 3 mm rms. Data with similar accuracy are available from the TIROS-N Operational Vertical Sounder (TOVS) available from NOAA polar-orbiting satellites (Smith et al. 1979). With two polar orbiters, such soundings are available roughly four times per day in clear regions with a horizontal resolution of roughly 110 km at the subsatellite point. Again, moisture soundings are available only during clear conditions. However, the presence of microwave sounders in the TOVS instrument package helps substantially in the cloud screening process. Another technique, currently available on research high-altitude aircraft, is the Airborne Visible–Infrared Imaging Spectrometer (AVIRIS) (Gao et al. 1992). Clear-air soundings from this instrument can be processed to yield PW images with horizontal resolution of 1 km, an accuracy of about 1 mm, and a precision of 3%. This instrument is planned for satellite deployment in the next decade (Goetz and Herring 1989).

In addition to satellite-based observations over land, ground-based techniques are also available. Ground-based microwave radiometers (MWRs) (Westwater and Snider 1989) can derive PW with an absolute accuracy of about 1 mm rms, with a temporal resolution of 30 s, and in clear and cloudy conditions. These instruments will not provide soundings during rain rates greater than 5–10 mm h⁻¹. Data from a limited network of these instruments have been used to provide accurate “tie-down” points for VAS images (Birkenheuer 1991). With the combination of ground- and satellite-based soundings, accurate and high horizontal resolution measurements of PW may someday be available. A primary limitation of MWR is its current expense. However, new applications of monolithic microwave integrated circuit technology (Sukamoto et al. 1992) may dramatically reduce the price of these instruments. Another promising ground-based technique has been suggested by Bevis et al. (1992). It relies on measurements made by the Global Positioning System (GPS). Preliminary estimates suggest that the clear-air accuracy of the GPS determinations of PW would be poorer than that of MWRs but that they might be superior during rain and heavy clouds. Finally, we mention ground-based infrared (Smith et al. 1991) and solar-optical (Reagan et al. 1992) radiometric techniques. Their accuracy would be slightly lower than MWRs during clear conditions, and they could not provide PW during clouds.

Nearly all weather operational satellite determinations of PW over the oceans are currently being achieved with the Defense Military Satellite Programs Special Sensor Microwave/Imager (SSM/I) (Alishouse et al. 1990). In general, these data have an accuracy of about 3 mm rms, and are available during nonprecipitating conditions. It is necessary to screen the data for precipitation and sea ice before determining PW. The differences in performance of the SSM/I and TOVS are due to microwave sensors, which yield accurate data except during precipitation and land contamination. The next generation NOAA polar-orbiting satellites will carry sensors that are expected to produce data of the quality provided by the SSM/I. These satellites will carry the 20-frequency microwave radiometers called Advanced Microwave Sounding Units (Rao et al. 1990), which may yield PW over lands as well as oceans.

REFERENCES


