THE EFFECTS OF ATMOSPHERIC MOISTURE AVAILABILITY FOR THE NORTHEASTERN ILLINOIS STORM OF 17-18 JULY 1996

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1. INTRODUCTION

In the early 1930s and '40s, hydrologists developed a method to estimate the theoretical upper limit to storm rainfall — known today as the probable maximum precipitation (PMP). This method uses a simple scaling technique to increase observed storm rainfall to reflect higher atmospheric moisture levels. It is assumed that increases in precipitation are proportional to the increases in atmospheric moisture availability. Therefore, observed storm precipitation is maximized with respect to moisture availability using:

$$P_{max} = \left(\frac{PW_{max}}{PW} \right) \times P \qquad (1)$$

where P is the observed storm precipitation, P_{max} is the maximized storm precipitation, PW is the observed precipitable water for the selected storm, and PW_{max} is the maximum observed precipitable water for the same location.

One major problem in this technique is that it ignores the potential changes in storm dynamics resulting from increasing atmospheric moisture availability. That is, increasing atmospheric moisture not only adds additional water vapor that can later precipitate, but also adds additional convective energy (latent heat) that can change the storm dynamics.

In this study, we present an experimental framework for examining the impact of atmospheric moisture availability on storm dynamics and rainfall accumulations using the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model MM5 (Grell et al. (1994). The selected storm in this study is the northeastern Illinois storm of 17-18 July 1996.

2. THE NORTHEASTERN ILLINOIS STORM OF 17-18 JULY 1996

The northeastern Illinois storm of 17-18 July 1996 is an excellent example of an event that would be in PMP estimation. The storm produced a maximum of 43.0 cm of rainfall within 24 hours at Aurora, which was the greatest point rainfall recorded in this century in Illinois and most surrounding states. The 27.9 cm storm rainfall recorded in the southwestern part of the Chicago metropolitan area was the heaviest 24 hr amount ever recorded in the city (Angel and Huff (1999)). Figure 1 shows the total rainfall accumulation for the storm. Detailed storm analysis can be found in Angel et al. (1997), Changnon and Kunkel (1999), Angel and Huff (1999), and Changnon (1999).

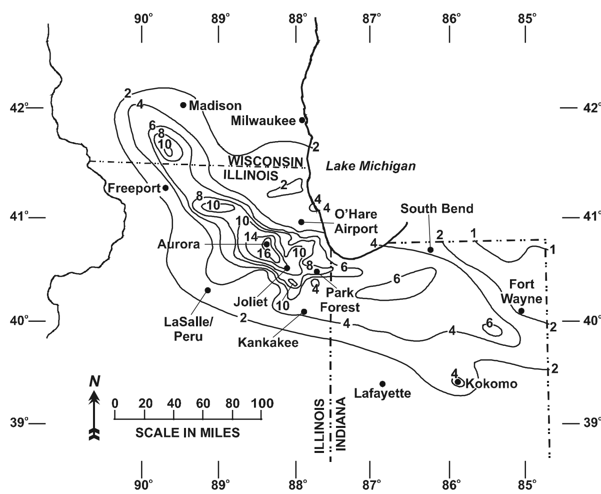

Figure 1: The pattern of total storm rainfall across the Midwest for the Northeastern Illinois storm of 17-18 July 1996 (adapted from Angel et al. 1997).

3. NUMERICAL SIMULATION

The model used to simulate the northeastern Illinois storm of 17-18 July 1996 is the PSU/NCAR mesoscale model MM5 version 2-12. A nested, two-way interactive domain is used for modeling the storm. The domain setup for the numerical simulation is shown in Figure 2. The grid spacing is 90 km for the outer, coarse domain, which covers the United States; 30 km for the intermediate domain; and 10 km for the inner domain covering most of the storm region and center at the Chicago metropolitan area. In the vertical direction, 23 sigma levels were setup for the simulations.

The northeastern Illinois storm of 17-18 July 1996 is one of a series storms produced by the same

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mescoscale convective system that developed in northeastern Nebraska and traveled east-southeastward through Iowa into Illinois and all the way to the east coast. There are several key elements in this storm including the frontal boundary, convective outflow boundaries, cloud boundaries, and low-level jet. Their roles in the initiation and subsequent evolution (including their relationship to the training of convection along the frontal and outflow boundaries) are not fully understood. These factors make the simulation of the storm with MM5 very difficult. Therefore, different initialization times, data analyses, and physical parameterization schemes were tested to simulate the storm. It is found that the precipitation fields for this storm were very sensitive to the initialization time, the first-guess field, the cumulus parameterization scheme, and the planetary boundary layer scheme.

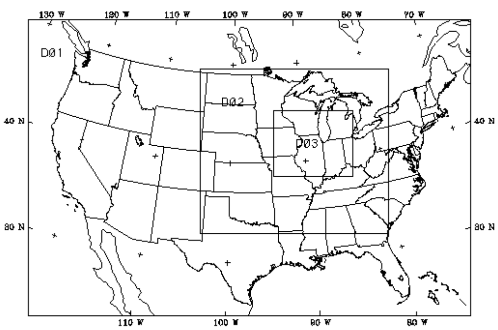

Figure 2: The domain setup for numerical simulation of the July 17-18, 1996 storm.

The final model setup for the northeastern Illinois storm is initialized at 12Z July 17. The ECMWF's (European Centre for Medium-Range Weather Forecasting) TOGA Global Surface and Upper Air Analysis are used for the first-guess field, and the NCEP's (National Centers for Environmental Prediction) Surface Observations and Upper Air Observations are used for the objective analyses to improve the meteorological analyses (the first-guess). Four-dimensional data assimilation was not used. The physical options used in the simulations are the Grell cumulus parameterization scheme, the high-resolution Blackadar planetary boundary layer scheme, and the warm rain explicit moisture scheme.

Basically, the model simulation captures the synoptic frontal movements and storm movement well. The surface and upper-air analyses show good agreement with the observations. The 36 hr model simulated rainfall accumulation is shown in Figure 3. The model simulation generates a rainfall pattern and orientation similar to the observation, but the maximum rainfall occurs in the eastern Iowa and the rainband only has one rain center. Even though the rainfall location is shifted significantly, the model simulation produces a large amount of rainfall (34.0 cm maximum). Therefore, this simulation can provide a useful control run for studying the effects of moisture availability on extreme rainfall.

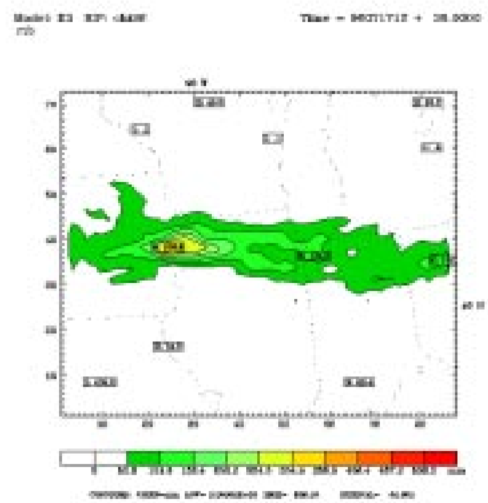

Figure 3: The model simulated 36 hr rainfall accumulation for the inner domain.

4. NUMERICAL EXPERIMENTS

To examine the impact of atmospheric moisture availability on extreme rainfall accumulations using mesoscale modeling, atmospheric profiles must be adjusted in the model initialization. However, there is no unique way to add moisture to an atmospheric profile. Therefore, in this study, we examined three moisture adjustment methods to evaluate the effects of changing initial atmospheric moisture availability.

Zhao et al. (1997) conducted similar experiments and developed a method to mimic the framework of moisture maximization in PMP analysis. This method (referred to as Zhao's method below) adjusts the vertical moisture profile by increasing the mixing ratio by the same percentage. However, values are not allowed to reach saturation. Abbs (1999) also performed similar experiments with a different approach. This method (referred to as Abbs method below) increases the moisture availability by uniformly increasing the temperature of the atmosphere everywhere while maintaining the relative humidity. In this way, the system is still in dynamic balance, but the specific humidity, and hence precipitable water, has been increased. Weisman and Klemp (1982) investigated the effects of vertical buoyancy on convective storm structure and evolution using a three-dimensional cloud model. To increase the convective available potential energy (CAPE) (and the precipitable water as well), the mixing ratio near the surface was increased. In this study, this method (referred to as Weisman and Klemp's method below) was implemented by adding a constant mixing ratio to the levels below 850 mb until the levels approached saturation.

Clearly, these methods for adding moisture to the atmosphere will significantly affect the thermodynamic structure of the atmosphere. Furthermore, measures of atmospheric stability (e.g., CAPE, Bulk Richardson number, Lifted index, and Showalter index) will differ significantly for the three methods, even for the same amount of precipitable water.

This study is designed to adjust the moisture availability over a wide range but within the upper limits of the maximum observed precipitable water of the inner domain. Therefore, the three-dimensional mixing ratio and temperature in the model input files are adjusted based on the selected method. No changes are made for the boundary files.

5. PRELIMINARY RESULTS

Many aspects, including storm evolution, rainfall accumulation, thermal structure, and surface analysis have been analyzed to evaluate the effects of atmospheric moisture availability. The results show that the storm dynamics are very sensitive to the initial atmospheric moisture. Storm structure and evolution not only depend on the amount of atmospheric moisture, but also depend on the vertical distribution of the moisture. In this paper, we only present the results from the precipitation. Figure 4, 5, and 6 are the 36 hr rainfall accumulation as precipitable water ratio is 1.1 for Zhao, Abbs and Weisman and Klemp's method. These figures show the changes in rainfall patterns for the different moisture adjustment methods.

Figure 7 shows the variation of maximum 36 hr rainfall accumulation with the changes in precipitable water for all three methods. The bold solid straight line represents the theoretical relationship of the PMP. None of the methods shows good agreement with the PMP linear assumption. Note that for Weisman and Klemp's method, the maximum precipitation is significantly than for the other methods. In extreme rainstorms, two major components are abundant low level moisture and strong updrafts (convective energy). Weisman and Klemp's method effectively enhances these two components while retaining sounding profiles very close to the observed pre-storm conditions. This may be the reason that Weisman and Klemp's method produces excessive rainfall with small increases in precipitable water.

Figure 8 shows the variation of average 36 hr rainfall accumulation (i.e. average over the inner domain) with the changes in precipitable water for all three methods. In contrast, the averaged precipitation tends to scale linearly with the changes in precipitable water, but with a slope greater than that assumed in PMP moisture maximization. Hart (1982) showed using a simple water budget model that for constant wind convergence, precipitation scales linearly with precipitable water with a slope of 1 (the PMP assumption). However, the numerical simulations suggest increasing moisture availability increases large-scale wind convergence, which leads to greater average precipitation over the region.

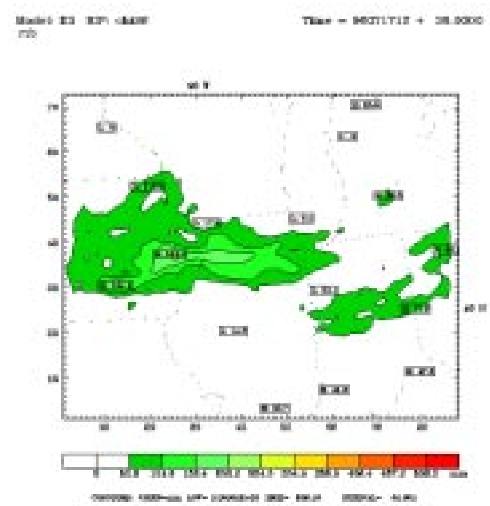

Figure 4: The model simulated 36 hr rainfall accumulation as precipitable water ratio is 1.1 for Zhao's method.

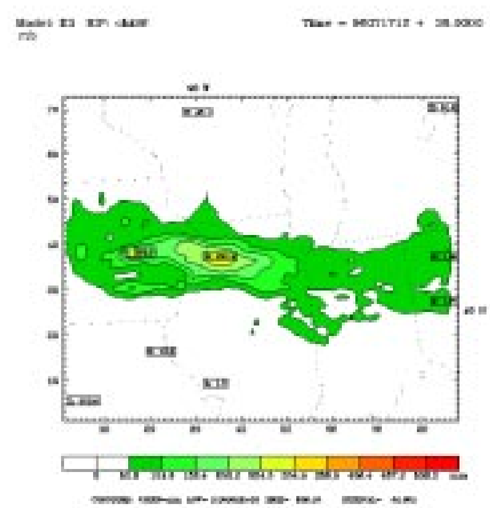

Figure 5: The model simulated 36 hr rainfall accumulation as precipitable water ratio is 1.1 for Abbs's method.

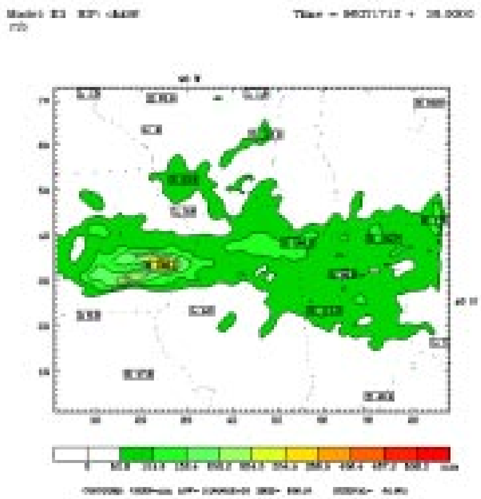

Figure 6: The model simulated 36 hr rainfall accumulation as precipitable water ratio is 1.1 for Weisman and Klemp's method.

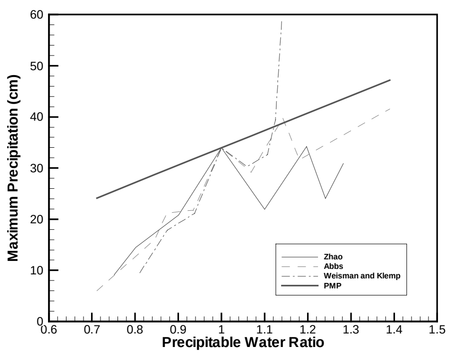

Figure 7: the variation of 36 hr maximum rainfall accumulation as precipitable water ratio varies from 0.7 to 1.4.

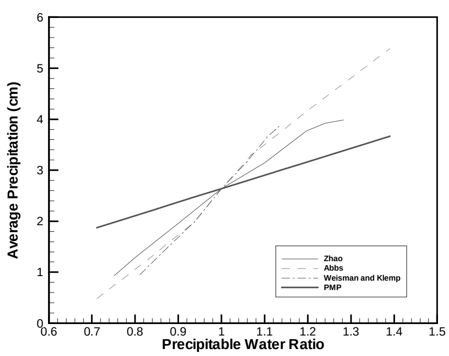

Figure 8: the variation of 36 hr storm rainfall averaged over the inner domain as precipitable water ratio varies from 0.7 to 1.4.

6. CONCLUDING REMARKS

In this paper, we propose three moisture adjustment methods to evaluate the effects of atmospheric moisture on storm dynamics and rainfall accumulation. Furthermore, the results are used to test the linear assumption in the PMP analysis. It is found that the rainfall pattern and accumulation are very sensitive to the moisture adjustment methods. However, the methods to adjust the atmospheric moisture are not limited in the proposed three methods. We are searching for more moisture adjustment methods to improve the moisture maximization for the PMP analysis.

Another issue for using mesoscale modeling in PMP estimation is that the model has to have the capability to simulate the selected storm. For the 17-18 July 1996 storm, MM5 has difficulty representing the convective initiation and the training along frontal and outflow boundaries, together with the interaction of these boundaries and subsequent convective formation. Improving the model capability to simulate the storm is an important topic in the future.

7. REFERENCES

Abbs, D. J., 1999: A numerical modeling study to investigate the assumptions used in the calculation of probable maximum precipitation. Water Resources Research, Vol. 35, No. 3, Page 785-796.

Angel, J. R. and F. A. Huff, 1999: Record flood-producing rainstorms of 17-18 July 1996 in the Chicago metropolitan area. Part II: Hydrometeorological characteristics of the rainstorms. Journal of Applied Meteorology, Vol. 38, Page 266-272.

Angel, J. R., S. A. Changnon, D. Changnon, F. A. Huff, P. Merzlock, S. R. Silberberg, and N. E. Westcott, 1997: The record rainstorm on July 17-18, 1996 in northern Illinois. Illinois State Water Survey, 160 pp. (Misc. Publ. 182).

Changnon, S. A., 1999: Record flood-producing rainstorms of 17-18 July 1996 in the Chicago metropolitan area. Part III: Impacts and responses to the flash flooding. Journal of Applied Meteorology, Vol. 38, Page 273-280.

Changnon, S. A. and K. E. Kunkel, 1999: Record flood-producing rainstorms of 17-18 July 1996 in the Chicago metropolitan area. Part I: Synoptic and mesoscale features. Journal of Applied Meteorology, Vol. 38, Page 257-265.

Grell, G. A., J. Dudhia and D. R. Stauffer, 1994: A description of the fifth-generation Penn State/NCAR mesoscale model (MM5). NCAR/TN-398+STR, National Center for Atmospheric Research, Boulder, Colorado.

Hart, T.L., 1982: Survey of probable maximum precipitation using the synoptic method of storm transposition and maximization. Workshop on Spillway Design, AWRC Conf. Ser., Vol. 6, Aust. Gov. Print. Serv.,Canberra, Australia.

Weisman, M. L. and J. B. Klemp, 1982: The dependence on numerically simulated convective storms on vertical wind shear and buoyancy. Monthly Weather Review, Vol. 110, Page 504-520.

Zhao, W., J.A. Smith and A. A. Bradley, 1997: Numerical simulation of a heavy rainfall event during the PRE-STORM experiment". Water Resources Research, Vol.33, No. 4, Page 783-799.