GPS observations of precipitable water and implications for the predictability of precipitation during the North American Monsoon

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I. Introduction:
The semi-arid to arid North American Southwest has experienced, in recent decades, tremendous population growth despite limited water supplies. Water availability is highly susceptible to climate variability and change and is therefore of great concern. Climate models generally predict the region will experience warmer and drier winters in the future. During summer, incursions of moist tropical air associated with the North American Monsoon (NAM) bring critical convective precipitation (e.g. Adams and Comrie, 1997; Higgins et al., 2006). Representing deep convective regimes in tropical regions, however, has been problematic in large-scale numerical models (e.g., general circulation models (GCMs)). The NAM, no exception, is represented poorly, if at all, in GCMs (e.g. Lee et al., 2007). As a result, the future behavior of the monsoon is uncertain but may intensify if the land-sea temperature contrast increases. To improve upon this situation, the North American Monsoon Experiment (NAME) was initiated to better understand convective precipitation and its predictability during the NAM and ultimately improve its modeling. This goal is challenging given the complex interplay between moisture, diurnal heating, large and small-scale dynamics and complex terrain in convective rainfall. Results from data gathered during the 2004 NAME field campaign are briefly summarized here and new results assessing precipitation sensitivity to precipitable water vapor in high resolution model simulations are reported.

Since precipitation condenses from water vapor, improving precipitation prediction requires better knowledge of the quantity and distribution of water vapor. As such, water vapor was the focus of the International H₂O Project (IHOP) campaign to gain insight into moist convection in the U.S. Southern Great Plains (Weckworth et al., 2004). Like other remote tropical regions, observing water vapor in the NAM region, particularly Mexico, is challenging. During the monsoon, satellite IR observations of water vapor are limited due to frequent cloudiness and microwave water vapor observations in the region are limited due to uncertainties in land surface emissivity. Radiosondes, somewhat intermittent, are found only in Empalme, Mazatlan and La Paz along the Gulf of California coast, Chihuahua, east of the Sierra Madre Occidental (SMO) mountains and Tucson to the north.

II. Key NAME 2004 results
To improve water vapor observations, we fielded an array of GPS receivers and surface meteorological instrumentation at 6 locations extending from Hermosillo, Sonora to the west to Creel in Chihuahua to the southeast during the 2004 NAME observing period. Precipitable water vapor (PWV) can be derived from GPS receiver measurements to about 1.5 mm (1-sigma) accuracy (Kursinski et al., 2008) in clear and cloudy weather. The GPS receiver and surface instrumentations are simple, robust and well suited to measuring PWV and surface pressure, temperature and humidity in the convectively active remote mountain areas. Our instrumentation and initial findings described in Kursinski et al. (2008) are summarized below.

Monsoon Onset: The 2004 monsoon onset in Sonora, Mexico was evident as a large PWV increase that extended over several days beginning July 1. The water vapor-weighted winds derived from Empalme radiosonde profiles revealed that the rise in moisture during the monsoon onset and a preceding transitional wet period were associated with a shift in the winds from westerly to southerly and southeasterly.

Mid-August dynamical transition: The correlation between both precipitable water and surface specific humidity measured at Mazatlan in the SMO foothills and at Hermosillo some 90 km to the west revealed a dynamical transition in mid-August from smaller, sub-synoptic scale structure to larger,
synoptic-scale moisture structure. During the sub-synoptic phase in the SMO foothills, a positive feedback is indicated where near-daily precipitation supplied moisture maintains 15% higher surface mixing ratios that lower the lifting condensation level, facilitating initiation of moist convection.

**Westward propagation of convection:** Along the western edge of the SMO, precipitation typically occurs hours after the local temperature maximum, triggered by westward propagating convective disturbances. Observing the time-rate-of-change of PW, dPWV/dt, indicates that precipitation is typically preceded by a rapid increase in PWV associated with convergence of water vapor into the column and a sharp decrease in surface temperature associated with dense gust fronts created by evaporatively cooled downdrafts. As noted in other deep convective regimes, downdrafts are critical in storm organization, propagation and modulation of the daily temperature cycle.

III. Sensitivity of NAM precipitation to the initial water vapor field

The NAME PWV and surface condition measurements were utilized to assess the performance of the high resolution Weather Research and Forecasting (WRF) model. However, we discovered immediately that the discrepancies between our observations and WRF simulations were dominated by errors in the analyzed moisture field used to initialize WRF. We therefore focused on the sensitivity of convective precipitation in the WRF simulations to the initial PWV field in the NAM region.

A key ingredient in reproducing realistic behavior is model resolution. Summertime mid-latitude precipitation correlation scales east of the Rocky Mountains are generally much smaller than those in winter and smaller than the resolution of most GCMs (Kursinski and Mullen, 2008). Since 2003, we have used WRF to forecast NAM precipitation allowing us to experiment with and identify the configuration that produces the best overall simulations of NAM precipitation. We use 1.8 km resolution which is the resolution at which the accumulated convective precipitation became constant as resolution increases.

For the simulations presented here, we employed the WRF Model V2.2 with a 7.2 km grid outer domain and a 1.8 km grid inner domain and 37 vertical levels. NCEP's ETA 40 km model analysis was used to initialize the WRF simulations and provide periodic boundary conditions for the outer domain. The physics packages utilized are Lin cloud microphysics, RRTM longwave radiation, Goddard short wave radiation, Monin-Obukhov ETA surface-layer, Noah land-surface, and the Mellor-Yamada-Janic TKE PBL scheme. In our experience in forecasting precipitation in the Southwest U.S., the Lin et al. microphysics scheme provides the best spatially distributed rainfall patterns, and more realistic amounts compared to other schemes. No convective parameterization was used as shallow and deep convection are resolved explicitly at this resolution.

For the preliminary precipitation sensitivity results presented here we chose two days, a medium precipitation day (July 29, 2004) and somewhat higher precipitation on the following day (July 30, 2004). To assess precipitation sensitivity to changes in PWV, we scaled the ETA analyzed precipitable water vapor field to 95%, 100% and 105% and used each to initialize a WRF model run. Cases were initialized at 5 a.m. local time when convective activity is generally minimal to avoid problems with the inability of ETA analysis resolution to capture the increasingly complex moisture field as convective activity increased during the day.

Figure 1 shows the accumulated precipitation simulated by WRF for July 29, 2004 initialized by the ETA PWV field scaled to 95%, 100% and 105% of its nominal field. There is clearly a large overall increase in precipitation but the detailed response is complex. In fact, while most cells received more precipitation as PWV increased, precipitation in individual grid cells can either increase or decrease as PWV is increased. Extreme changes in precipitation at individual grid points as the initial PWV was increased by 5% ranged from 70 mm less precipitation to 90 mm more precipitation.
Figure 1. WRF simulations of accumulated precipitation for 3 different initial PWV fields, 95%, 100% and 105% of the ETA analysis PWV for July 29, 2004. Black dots indicate the locations of our GPS receivers. Triangles indicate the Empalme and Chihuahua radiosonde locations. Precipitation statistics in Figure 2 were derived in the southeastern region enclosed by the thin blue line.

Figure 2. Average accumulated precipitation versus average initial PWV for July 29 and 30, 2004. Solid lines indicate averages over all grid points in the southeast region in Figure 1. Dashed lines indicate precipitation averaged over the subset of grid points in the southeast region experiencing precipitation.

Figure 2 shows how accumulated precipitation averaged over the convectively active, southeastern region of the model domain (see Figure 1) increases as the early morning PWV increases. Precipitation sensitivities on both days are quite large. On July 29, 2004, average precipitation increases by 6 mm for every 1 mm of added average PWV. On July 30, precipitation increases more gradually with PWV. Interestingly, conditions on July 30 require about 5 mm or 15% less PWV to produce the same precipitation as on July 29.
IV. The accuracy of analyzed PWV

Now, to assess our ability to predict precipitation, we must determine the uncertainty in the initial water vapor field and contrast it with the sensitivity discussed in the previous section. To quantify the initial water vapor field error, we compared the NCEP North American Regional Reanalysis (NARR) PWV with the measured GPS PWV field. The NARR analyses are on a 32 km grid at 29 pressure levels, produced using the Eta 32km/45-layer model output every 3-hours.

For our comparisons of the NARR and GPS PWV estimates, we used the NARR grid point closest to each GPS location and coincident within 15 minutes. The results are summarized in Table 1. Figure 3 shows the scatter of the NARR versus GPS PWV values at Mazatan, Sonora, Mexico, revealing both random and systematic discrepancies between the two data sets. The quadratic fit in the figure indicates the range of NARR PWV values is somewhat compressed on average relative to that measured by GPS. On average NARR produces 12 mm when GPS measures 9 mm of PWV whereas when GPS measures 56 mm, NARR shows 50 mm. The scatter about the curve has a 1-sigma spread of about 5 mm which, given the 1.5 mm GPS PWV errors, is due primarily to the NARR procedures.

<table>
<thead>
<tr>
<th>Location</th>
<th>bias (mm)</th>
<th>Stdev (mm)</th>
<th>Fractional Stdev</th>
</tr>
</thead>
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<tr>
<td>Creel</td>
<td>1.22</td>
<td>2.5</td>
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</tr>
<tr>
<td>Yecora</td>
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<td>11%</td>
</tr>
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<td>17.7%</td>
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<td>13.5%</td>
</tr>
<tr>
<td>Hermosillo</td>
<td>3.14</td>
<td>5.3</td>
<td>11%</td>
</tr>
<tr>
<td>Empalme sonde</td>
<td>-1.86</td>
<td>3.4</td>
<td>7%</td>
</tr>
</tbody>
</table>

The standard deviation of the NARR PWV errors relative to GPS range from 11 to 18%. The smaller 7% discrepancy between the NARR and the Empalme radiosonde PWV is presumably because the Empalme data has been assimilated into the NARR. While the NARR water vapor errors are fairly good, the sensitivity described in the previous section suggests PWV errors of this magnitude lead to large errors in model precipitation. According to the sensitivity study, a 14% PWV error like that at Mazatan can overestimate the domain average precipitation by 15 to 30 mm.
V. Conclusions

Our results represent an initial quantification of a key issue regarding precipitation forecasting in the NAM region. The results are limited to only two days of simulations and have assessed sensitivity only to PWV. Still, our evaluations over the past 4 years indicate this model simulates precipitation behavior rather realistically in the NAM region but that the model sensitivity results must be considered seriously.

Our preliminary results indicate that when conditions are right to support moist convection and precipitation, the sensitivity of precipitation to small changes in the water vapor field is quite large within the high resolution WRF simulations. This sensitivity suggests that present knowledge of water vapor in the NAM region is inadequate to accurately forecast precipitation there.

We also found that the peak precipitation sensitivity for July 29 was about 40\% higher than on July 30. The threshold PWV at which precipitation begins to occur is higher on July 29 as well. We speculate that this variation in sensitivity is associated with differences in large-scale forcing between the two days. On July 30, the mid-level northeasterly flow was very favorable for organized storms in the Mexican states of Sonora and Sinaloa to propagate from the high terrain into the coastal areas. As a result, the 95, 100 and 105\% July 30 case storm organization exhibited similar overall structure despite differences in PWV. In general, the more important the large mesoscale to synoptic forcing, the less one would expect the modes of convection to be sensitive to small changes in PWV. In contrast, the 29 July case exhibited lighter mid and upper level winds over Sonora with less organization suggesting that varying PWV is more important to convective storm development when storms are less organized.

We note that our simulations have so far only addressed sensitivity to PWV not the vertical variation in water vapor. Distributing the changes in PWV throughout the troposphere might lead to less entrainment of dry air resulting in more precipitation whereas adjusting the PWV only in lowest 100 mb, say, might have larger impacts on the intensity of convection and its rain production. Nevertheless, as an initial sensitivity study, very small changes in PWV are clearly important in model simulations of precipitation.

The most obvious implication of the sensitivity study presented here is that short-term warm season precipitation forecasts in the NAM region will be poor, particularly in Mexico, until the moisture analysis accuracy is improved significantly. This in turn requires that better moisture observations be made in the area which, given the limitations of satellite observations, will likely have to come from a combination of upward looking surface observations and more balloon measurements. An inexpensive network of GPS receivers at a subset of the precipitation gauge locations (Gochis et al., 2004) would dramatically improve the present data void in Mexico and measure interannual variability and long term trends. The same arguments may also be made for other deep convection regimes of the tropics where high temporal and spatial resolution data is entirely lacking.

In terms of predictive skill, the significantly better realism of the high resolution simulations presented here relative to poor performance of coarser resolution models (e.g., Lee et al., 2007) suggest that, at the moment, accurate representation of convective precipitation in the NAM area requires very fine model resolution to explicitly model convection accurately, resolution that will not appear in global climate models anytime soon. Regional models imbedded in GCMs may succeed, but will be numerically intensive. Without such fine scale explicit modeling, the sensitivity we have identified will have to be captured via parameterizations derived from high resolution results, assuming such results can be verified. Although it is not clear if present observational sampling is sufficient, we will attempt to assess the realism of the WRF precipitation sensitivity using rain gauge (Gochis et al., 2004) and GPS PWV observations to determine the true precipitation sensitivity to variations in early morning PWV.

Acknowledgements

We thank Francina Dominguez for extracting the NARR data collocated with the GPS data. We also thank Jay Fein and NSF for funding the data acquisition via the Small Grant for Exploratory Research 0434790, after we were unable to secure funding from NOAA, and supporting some of this data analysis via grant 0551448. We also thank ONR for funding the computer cluster used to generate the simulations presented here. We thank Bob Maddox for many helpful comments regarding this research and this manuscript.
References


