17.5 GPS-IPW OBSERVATIONS AND THEIR ASSIMILATION INTO THE 20-KM RUC DURING SEVERE WEATHER SEASON

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1. INTRODUCTION

Analyzing the rapidly evolving moisture field is an essential component of severe weather forecasting. GPS integrated precipitable water (GPS-IPW) observations are a new and important asynoptic data source of moisture information for data assimilation. Even in relatively observation-rich areas such as the United States, short-range numerical weather forecasts suffer from inadequate definition of the initial 3-D moisture field due to the high spatial and temporal variability of this field. Generally, there have been three observational sources for atmospheric moisture: rawinsondes, METARs, and satellite (not available in cloudy areas below cloud top). Estimates of IPW from GPS signal time delays can complement these moisture observations. GPS-IPW using zenith total delay provides only a vertically integrated value, by definition, but with at least hourly resolution and in all weather conditions, including those with cloud and even precipitation, conditions when observations are most important for forecasts of the atmospheric moisture. The NOAA Forecast Systems Laboratory has developed, over the past several years, a GPS-IPW network, which now produces high-accuracy, half-hourly, near-real-time measurements at more than 275 stations in the U.S. as of July 2004 (Fig. 1, Gutman et al. 2003).

GPS-IPW data have been assimilated into several developmental versions of the Rapid Update Cycle (RUC) run at the Forecast Systems Laboratory (FSL) since the 60 km RUC in 1997. Ongoing verification of the 60 km 3-h RUC cycle with assimilated GPS-IPW from 1997 through the current time provides a rich database for long-term statistics. Increasing positive impact on short-range relative humidity (RH) forecasts has been evident (shown in section 3 of this paper) as the number of GPS observations assimilated has increased from less than 20 to almost 300 over the United States during the last seven years.

In this paper, we present the most recent results from a series of GPS-IPW data impact studies performed at FSL with the Rapid Update Cycle data assimilation and numerical forecast system. A multi-year parallel cycle using the 60 km RUC with earlier results presented by Benjamin et al. (1998), Smith et al. (2001), and Gutman and Benjamin (2001) has been continued with results through 2003 presented. Statistics from comparisons of 20 km RUC runs with and without GPS data are also included, as well as single case comparisons.

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2. THE RAPID UPDATE CYCLE

The RUC is a numerical weather prediction system used over the lower 48 United States and adjacent areas of Canada and Mexico. It features a very high-frequency (1-h) cycle with mesoscale data assimilation (Benjamin et al. 2004a) and forecast model (Benjamin et al. 2004b) components. Since 1998, the RUC has run with a 1-h update cycle at the U.S. National Centers for Environmental Prediction (NCEP) with forecasts out to 3-h produced hourly and forecasts out to 12-h produced every 3-h. Each hourly analysis in the RUC uses the previous 1-h forecast as a background, and recent data are used to calculate an analysis increment field which modifies the background. The data cut-off time for the RUC is very short, only +20 min for observations valid at the analysis time or over the previous hour. This requires a very short data latency for potential operational assimilation of GPS-IPW observations; this latency has been achieved in the U.S. (Gutman and Benjamin 2001).

In the NCEP operational version as of 2004, the RUC horizontal domain covers the contiguous 48 United States and adjacent areas of Canada, Mexico, and the Pacific and Atlantic oceans with a 20 km grid. A Lambert conformal projection with a 301 by 225 rectangular grid point mesh is used. The grid length is 20.317 km at 35°N. Due to the varying map-scale factor from the projection, the actual grid length in the 20 km RUC decreases to as small as 16 km at the northern boundary. The RUC uses a generalized vertical coordinate configured as a hybrid isentropic-sigma coordinate in both the analysis and model. The RUC hybrid coordinate is discussed in much greater detail in Benjamin et al. (2004a, b).

In order for a high-frequency assimilation cycle to result in improved short-range forecasts, adequate high-frequency observations must exist over the domain of the analysis and forecast model. Over the last 10 years, the volume of observational data over the United States has increased, along with the sophistication of techniques to assimilate those observations.

A summary of observational data available to the FSL version of the RUC as of summer 2004 is shown in Table 1. A large variety of observation types are assimilated, although many of them are limited in horizontal or vertical spatial coverage. The longest-standing atmospheric observing systems, rawinsondes and surface weather observations, are the only ones that provide complete observations of wind, pressure, temperature, and moisture. High-frequency wind observations above the surface are available from commercial aircraft (e.g., Moninger et al. 2003), wind profilers, satellite-estimated cloud motion, and radars (velocity azimuth display, VAD). High-frequency temperature observations above the surface assimilated by the RUC include commercial aircraft and a few from RASS (Radio Acoustic Sounding System). High-frequency moisture observations above the surface used in the RUC analysis are precipitable water retrievals from satellites (GOES and polar orbiter) and from ground-based GPS (Wolfe and Gutman 2000, Gutman and Benjamin 2001), and GOES cloud-top pressure/temperature retrievals (Schreiner et al. 2001).

The moisture field is analyzed univariately in the RUC analysis (using the logarithm of the water vapor mixing ratio as the analysis variable). Two other moisture analysis procedures are also carried out: 1) the assimilation of GOES cloud-top pressure (Benjamin et al. 2004a) and 2) the assimilation of integrated precipitable water (IPW) observations, using an optimum interpolation (OI) based columnar adjustment (Smith et al. 2001). These three procedures are performed sequentially within each of two iterations of an outer moisture analysis loop in which the moisture background and innovations are updated after each procedure is applied. In this manner, a mutual adjustment between these different observation types is forced.

Data Type	~Number	Frequency
Rawinsonde	80	/12 h
NOAA 405 MHz profiler wind	31	/ 1 h
PBL (915 MHz) profiler wind	24	/ 1 h
RASS virtual temperatures	10	/ 1 h
VAD winds (WSR-88D radars)	110-130	/ 1 h
Aircraft (ACARS)	1400-4500	/ 1 h
Surface/METAR	1500-1700	/ 1 h
Surface/Mesonet	2500-4000	/ 1 h
Buoy	100-150	/ 1 h
GOES precipitable water	1500-3000	/ 1 h
GOES cloud drift winds	1000-2500	/ 1 h
GOES cloud-top pressure/temp	~10 km res	/ 1 h
SSM/I precipitable water	1000-4000	/ 6 h
GPS precipitable water	240	/ 1 h
Ship reports	10s	/ 3 h
Reconnaissance dropsonde	0 - a few	/ variable

TABLE 1. Observational data used in the FSL version of the RUC as of summer 2004.

3. GPS-IPW DATA IMPACT STUDIES WITH RUC60

From 1994-1998, an earlier version of the RUC ran at NCEP, using 60 km horizontal resolution, 25 vertical levels, stable precipitation based on saturation removal, and a 3-h update cycle (designated RUC60 in this paper).

Since late 1997 through the current time, FSL has continued parallel data assimilation cycles with the RUC60 for the purpose of evaluating the effect of GPS-IPW assimilation on numerical forecasts. The two cycles are run identically except that one assimilates GPS-IPW data every 3-h, whereas the other one does not. Both cycles include assimilation of geostationary satellite (GOES) retrievals of IPW, and observational data from rawinsondes, commercial aircraft, wind profilers, and surface stations (METARs). The assimilation method used in the RUC60 tests is an OI technique. Even though the RUC60 has poorer accuracy than more recent versions of the RUC, this ongoing GPS sensitivity test for the last six years is valuable in that the only change over that period is the number of GPS stations.

RUC60 GPS-IPW impact tests for 1998-2003 have shown a modest positive (decreased forecast error) impact from use of GPS-IPW data for short-range forecasts of relative humidity (RH) (Table 2). This impact has increased each year as more GPS-IPW stations have become available over the U.S., increasing from only 18 in 1999 to over 275 in 2004.

The NOAA GPS-Met network with over 275 stations available as of 4 August 2004 is shown in Fig. 1. Many of these stations are GPS sites installed for various geodetic purposes for which meteorological observation packages were added.

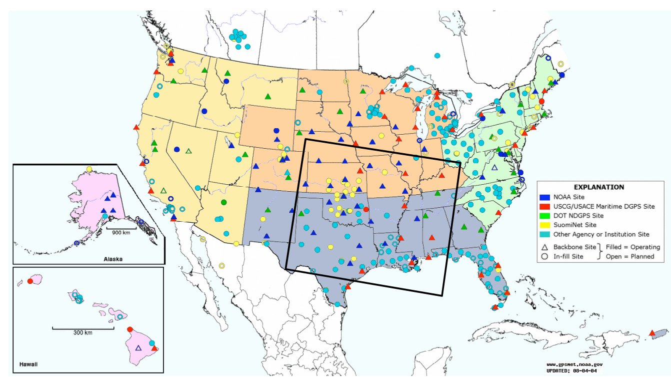

Fig. 1. The NOAA GPS network as of 4 August 2004. The black box is the inner verification area containing 17 RAOB sites.

(http://www. gpsmet.noaa.gov)

The 2003 RUC60 GPS-IPW impact tests show a continued increase in the positive impact over that shown in previous years (Fig. 2). This continued increase in impact is wholly attributable to the increased number of GPS-IPW stations over the US. No software changes in the RUC60 have been made for any part of the system, including data assimilation and forecast model. Impact at 850 hPa and 700 hPa has been the greatest. The percentage improvement from assimilation of GPS-IPW observations averaged over the 850-500 hPa layer has increased from 1.1% in 1999 to 3.3% in 2000, and now up to 5.2% in 2003. Layer improvement is important to look at due to the aliasing effect of applying a column value to a multi-layer moisture profile. While improving the fit to RAOBs at one level, sometimes the adjustment inadvertently reduces the fit at another level. Noting that the impact above 500 hPa was usually negative in the RUC60 led to the decision to only apply the adjustment to the moisture profile at 500 hPa and below in the 20 km version of the RUC.

Stations	18	56	67	100+	200+
Period	98-99	2000	2001	2002	2003
Level					
850	1.5	3.8	3.9	5.0	5.4
700	1.1	4.1	6.3	6.5	7.0
500	0.7	2.1	2.0	2.4	3.1
400	0.3	0.1	-0.4	-0.5	1.0
850-500	1.1	3.3	4.1	4.6	5.2

Table 2. Percentage reduction of 3-h relative humidity forecast error (using RUC60) from assimilation of GPS-IPW data. Forecast error is assessed by computing forecast-observed difference with rawinsonde observations at 17 stations in the south-central U.S. Percentage reduction is error difference (noGPS – GPS) normalized by forecast error (approximated as 10% relative humidity in this table).

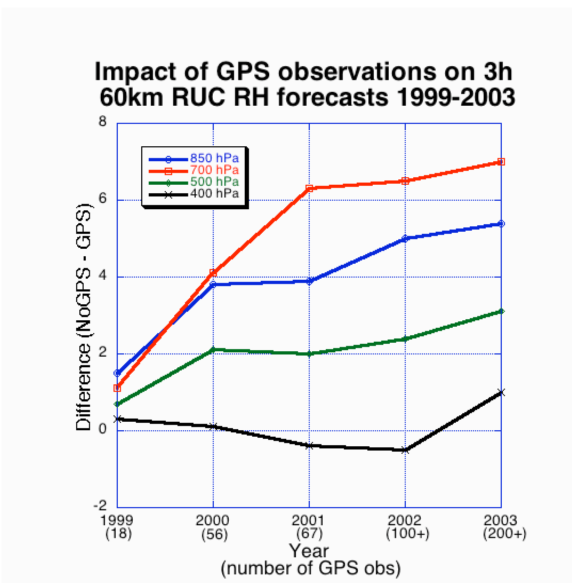

Fig. 2. Percent reduction of 3-h relative humidity forecast error from the 60 km RUC (as in Table 2) due to the inclusion of GPS-IPW data at 850, 700, 500 and 400 hPa averaged by year for 1999-2003.

The monthly variation in the RUC60 at 850 hPa is illustrated in Fig. 3 (percent improvement in 3-h RH forecasts for each month for the four calendar years 2000-2003). The verification shows a definite seasonal trend, with stronger positive impact in the transitional weather months of February/March and September/October. This pattern is not seen at the other verification levels. Figures 4 and 5 show the actual twice-daily verification values that went into Table 2 and Figs. 2 and 3 for the entire year of 2003 at both the 850 hPa and 700 hPa levels respectively. Again, a seasonal response is evident in the 850 hPa verification that is not as pronounced in the 700 hPa verification. Figures 4 and 5 also show that there is significant day-to-day and level-to-level variation in GPS-IPW impact.

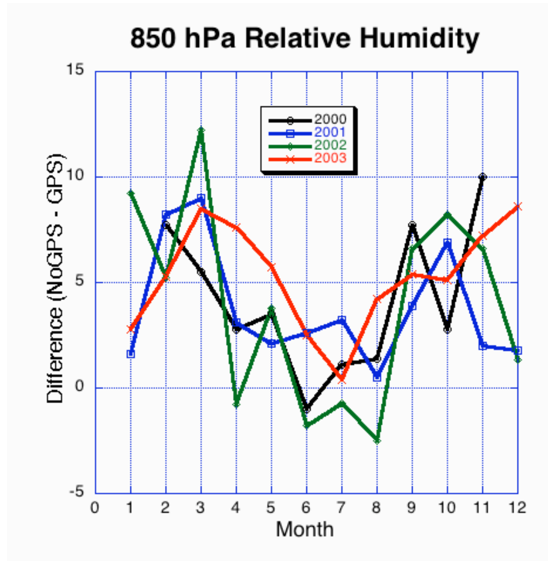

Fig. 3. Percent reduction of 3-h relative humidity forecast error from the 60 km RUC (as in Table 2) due to the inclusion of GPS-IPW data at 850 hPa averaged by month for years 2000 – 2003.

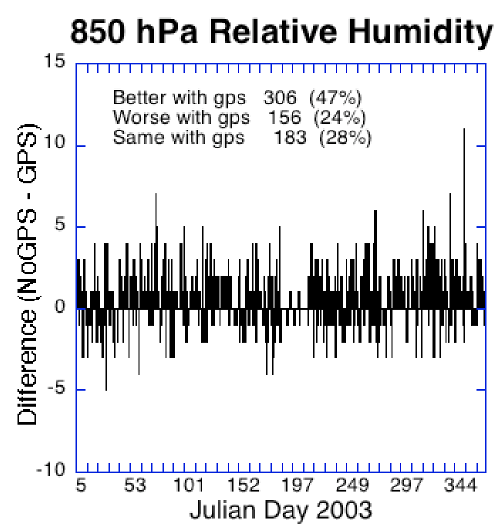

Fig. 4. Percent reduction of 3-h relative humidity forecast error from the 60 km RUC (as in Table 2) due to the inclusion of GPS-IPW data for 850 hPa over calendar year 2003.

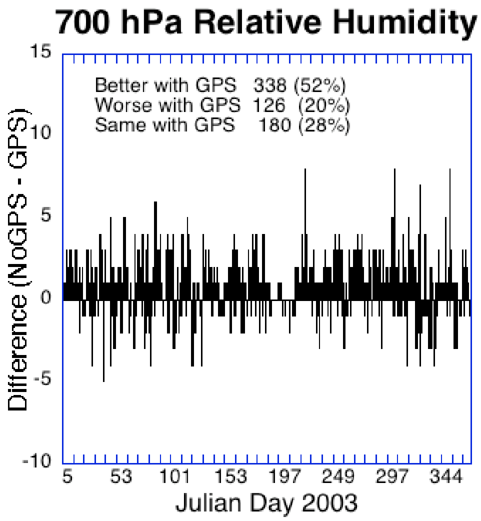

Fig. 5 Same as Fig. 4, for 700 hPa.

4. GPS-IPW IMPACT STUDIES WITH RUC20

We now consider differences in forecast skill between versions of the 20 km RUC (RUC20) with and without assimilation of GPS-IPW data. The GPS-Met Weather Models and Satellite Images web site (http://gpsmet.noaa.gov/cgi-bin/ruc20/ruc20.cgi) allows forecasters and researchers to assess the impact of Global Positioning System meteorology (GPS-Met) integrated (total column) precipitable water vapor (GPS-IPW) retrieval data on the RUC 20 km analyses and short-term moisture forecasts. This web-based application compares the RUC20 runs at NCEP that do not ingest GPS-IPW observations with the RUC20 runs at FSL that contain GPS-IPW data in real time. Users can interactively view national and regional plots and animations to compare GPS-IPW observations with output from the RUC20 model runs and the GOES-12 satellite images.

For each hourly model run, contour plots of the RUC20 IPW, either with or without GPS-IPW, can be generated, displaying comparisons of the model values with the GPS retrievals at each GPS site. Mean and RMS difference statistics between the GPS-IPW observations and model values over all sites in the plot region are displayed.

Contoured mean and difference plots comparing RUC20 analysis with 1-h forecasts, and RUC20 analysis with 3-h forecasts are available for both the RUC20 with GPS-IPW and the RUC20 without GPS-IPW.

Maps that display the GPS observations, the RUC20 with GPS-IPW, and the RUC20 without GPS-IPW at each GPS site are also available. At each site, the values are color coded by the differences between the GPS retrieval and the model value closest to the GPS retrieval. The symbol on the map indicates which model produced the value closest to the GPS observation.

Histogram plots and time series plots can be obtained from any of these differences as well. The histogram plots show the distribution of the differences between the GPS-IPW observations and model values. The time series plots show 5-day regional means and biases between the GPS-IPW and the model values. An example of the fields that can be utilized from the web page can be seen in section 5, the difference in two 3-h forecasts with and without GPS-IPW.

Information is also available for each GPS site. If a user zooms in on the site, a 5-day time series plot will be created that has information at that site corresponding to the type of plot they are viewing. If RAOBs are available at the site, this information is also displayed so the user can compare the two data sources directly.

Using the data archive made available through the web site, a spring verification period for March – May 2004 has been investigated. Figure 6 shows histograms of differences between RUC analysis estimates of total precipitable water vapor and GPS-IPW retrievals at an average of 240 GPS-Met sites in the RUC CONUS region over the 3-month period. Figure 7 depicts differences from GPS-IPW observations for 3-h RUC forecasts with GPS-IPW (FSL RUC20) and without GPS-IPW (NCEP RUC20). The actual hourly differences in the analyses with GPS-IPW data are mostly within 1 mm, with a mean difference of just 0.005 mm, showing that the RUC is drawing closely for the GPS-IPW observations. The operational RUC without GPS-IPW observations shows a bit of a moist bias, with a mean of .49 mm. The standard deviations are also much lower, 1.65 mm for the analyses with GPS-IPW, versus 2.97 for the analyses without. Table 3 shows complete results for the RUC analyses with and without GPS-IPW.

Figures 7-10 and Tables 4-7 show differences in forecast skill between GPS and no-GPS RUC cycles at 3, 6, 9, and 12-h. These statistics illustrate there is forecast improvement from assimilation of GPS-IPW out through 12-h. At 3-h, the rms error is 2.22 mm for the run with GPS vs. 2.98 mm for the run without GPS. The corresponding bias for the run assimilating the GPS data is also very low, .01 mm, compared to .40 mm for the no GPS run. The 6-h forecasts with GPS assimilation also show demonstrable additional skill, with a mean bias of 0.06 mm for the run with GPS as opposed to 0.16 mm for the run without GPS, and RMS errors of 2.46 mm (with GPS) versus 3.01 mm (without GPS). While diminished, the 9-h and 12-h forecasts still show some improvement in skill, with the 9-h rms 2.63 (with GPS) vs. 2.98 (without GPS) mm, and the 12-h 2.81 (with GPS) vs. 3.04 (without GPS) mm. Biases are of the same magnitude at 9-h (although the run with GPS is on the dry side and the run without GPS is too wet), however the 12-h forecasts show a definite dry bias, -0.195 (with GPS) compared to 0.017 mm (without GPS).

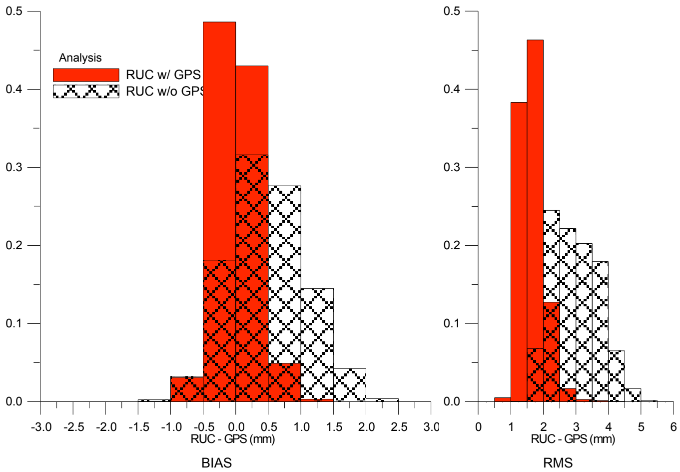

Fig. 6 Histograms of IPW differences (mm) between RUC analyses and GPS-IPW retrievals at ~275 sites in the RUC CONUS domain. Mean differences (left) and standard deviations of differences (right) for 01 March - 31 May 2004. RUC model with GPS in red; RUC without GPS is hatched. Difference defined as RUC model IPW – GPS IPW. Left axis is percent of total observations.

With GPS	RUC-GPS	RMS
Number	2200	2200
Minimum	-1.27	0.90
Maximum	1.47	4.20
Mean	0.005	**1.65**
Without GPS	RUC-GPS	RMS
Number	2030	2030
Minimum	-1.32	1.50
Maximum	2.4	5.22
Mean	0.49	**2.97**

Table 3. Statistical comparison (bias errors left and standard deviation right) of RUC 20 km analyses with and without GPS-IPW retrievals for the 3 month period from 01 March to 31 May 2004.

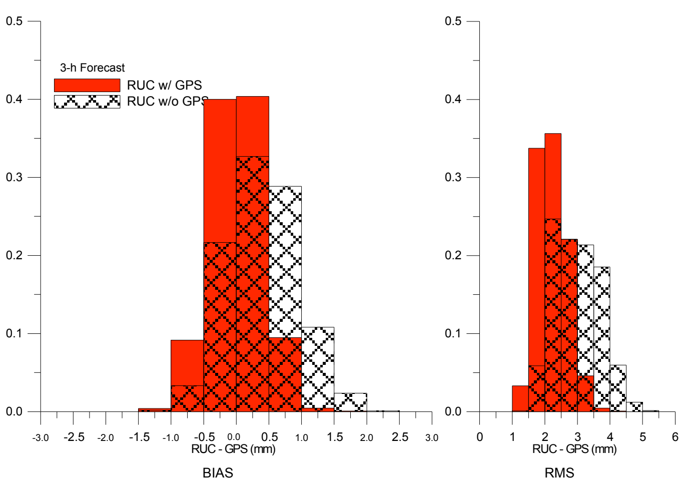

Fig. 7. Same as Fig. 6 but for 3-h RUC forecasts.

With GPS	RUC-GPS	RMS
Number	2172	2172
Minimum	-1.26	1.20
Maximum	1.75	5.19
Mean	0.01	**2.22**
Without GPS	RUC-GPS	RMS
Number	1989	1989
Min	-1.14	1.47
Max	2.21	5.37
Mean	0.40	**2.98**

Table 4. Same as Table 3 but for 3-h forecast

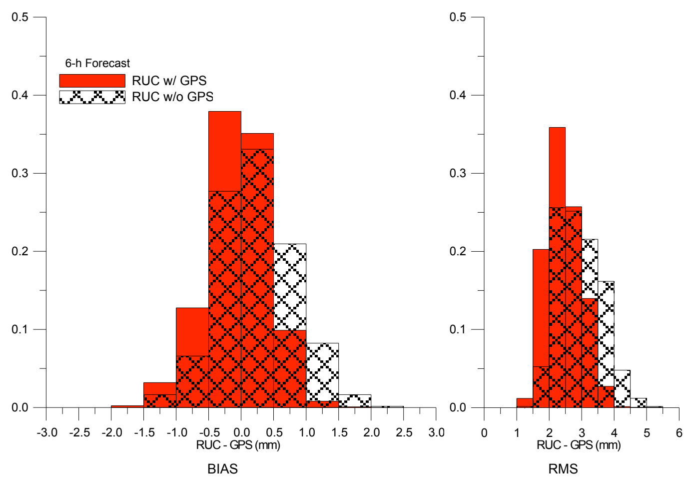

Fig. 8. Same as Fig. 6 but for 6-h RUC forecasts.

With GPS	RUC-GPS	RMS
Number	2196	2196
Minimum	-1.57	1.31
Maximum	1.77	5.29
Mean	-0.06	**2.46**
Without GPS	RUC-GPS	RMS
Number	668	668
Minimum	-21.13	1.46
Maximum	2.31	5.05
Mean	0.16	**3.01**

Table 5. Same as Table 3 but for 6-h forecast.

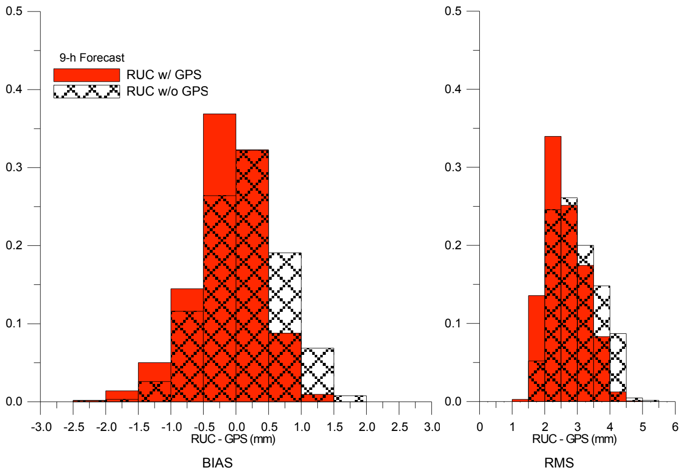

Fig. 9. Same as Fig. 8 but for 9-h RUC forecasts.

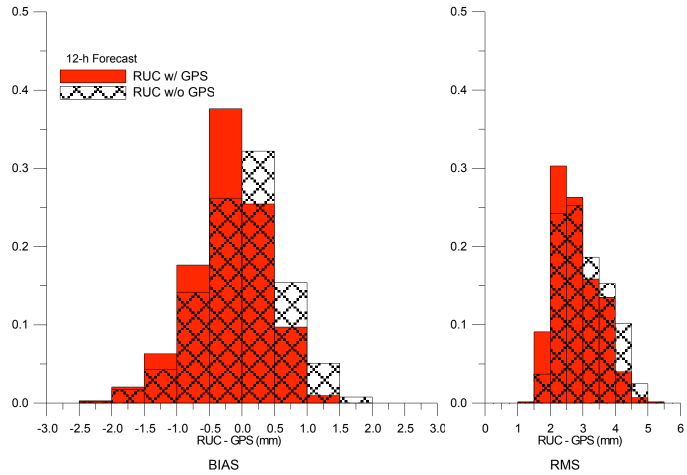

Fig. 10. Same as Fig. 8 but for 12-h RUC forecasts.

With GPS	RUC-GPS	RMS
Number	2196	2196
Minimum	-2.38	1.43
Maximum	1.49	4.88
Mean	-0.126	**2.63**
Without GPS	RUC-GPS	RMS
Number	655	655
Minimum	-2.16	1.54
Maximum	1.9	5.20
Mean	0.128	**2.98**

Table 6. Same as Table 3 but for 9-h forecast

With GPS	RUC-GPS	RMS
Number	726	726
Minimum	-2.20	1.49
Maximum	1.14	5.17
Mean	-0.195	**2.81**
Without GPS	RUC-GPS	RMS
Number	649	649
Minimum	-2.03	1.46
Maximum	1.62	5.13
Mean	0.017	**3.04**

Table 7. Same as Table 3 but for 12-h forecast

5. CASE STUDY - 20 APRIL 2004

A significant midwestern U. S. tornado outbreak occurred on 20 April 2004, with 53 tornadoes reported, the majority being in Illinois and Indiana (Fig. 11). It was also a day in which the severe weather potential was not well forecast in that area.

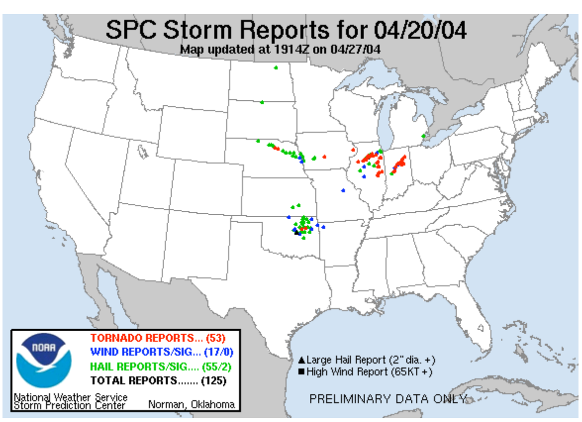

Fig.11. Severe weather reports for 20 April 2004, courtesy of the National Weather Service's Storm Prediction Center.

GPS water vapor traces from stations in the area show a marked increase in IPW between 1200 UTC and 1800 UTC, with the IPW almost doubling from around 1.5 cm to over 3 cm in just 6 hours (Fig. 12). This rapid change also occurred between RAOB times, which would make it more difficult for the models to analyze.

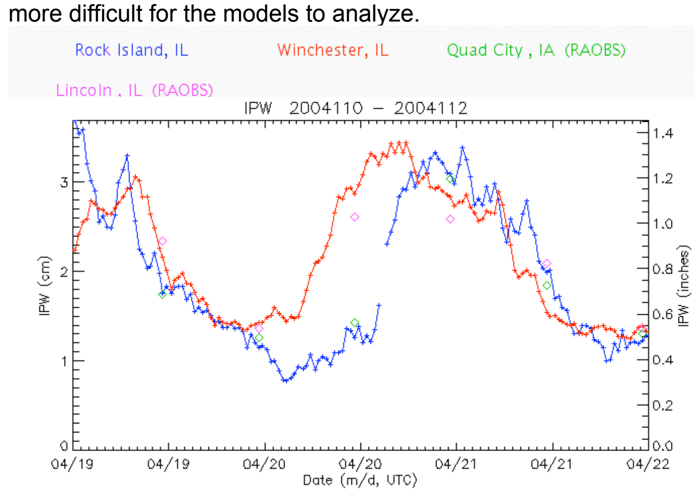

Fig. 12. GPS-IPW plots at Rock Island, IL (blue) and Winchester, IL (red); RAOB plots at Quad Cities, IA (green) and Lincoln, IL (pink) for 19 April 2004 through 21 April 2004. Note rapid increase in IPW on 20 April 2004.

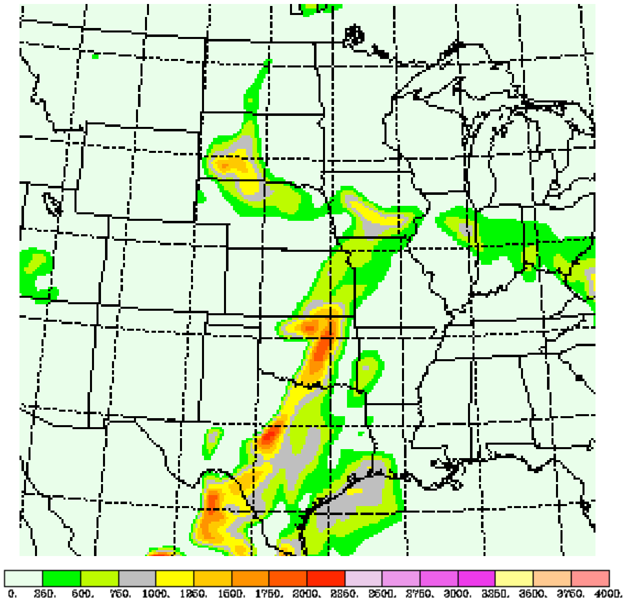

Fig. 13. 3-h forecast of CAPE from 2100 UTC 20 April 2004, from the run with GPS-IPW. Contours are in 250 J kg^{-1} increments.

The operational version of the 20 km RUC has been rerun for this case in a data denial experiment, one run with GPS-IPW data and the other run without. The runs began at 0000 UTC 20 April 2004 from the same (no GPS) one hour forecast from 2300 UTC 19 April 2004.

Verification of relative humidity forecasts against RAOBs was done for both 1200 UTC 20 April 2004 and 0000 UTC 21 April 2004. The first 12-h of ingesting GPS-IPW differences were slight, with comparable results for most of the forecasts valid at 1200 UTC. More impact is seen in the forecasts valid at 0000 UTC 21 April 2004, with an improvement of 1% at 850 hPa and 6% at 700 hPa for the 3-h forecast from 2100 UTC 20 April, reflecting the RUC60 result showing 700 hPa as the level with most impact. The 6-h forecast from 1800 UTC had improvement of 3% at 700 hPa and 4% at 500 hPa. For this case, there is also marked improvement even out at the 9-h (7% at 700 hPa, 2% at 500 hPa) and 12-h (6% at 700 hPa, 1% at 500 hPa). These results are for the boxed area in the Midwest shown in Fig. 1, which includes the area of interest for this case study. One reason for the improvement being more pronounced at 700 hPa and 500 hPa is that the surface observations, one of the major asynoptic sources of moisture information, have less influence aloft.

Improved moisture forecasts aloft also improve the forecasts of Convective Available Potential Energy (CAPE). Figure 13 shows the 3-h forecast of CAPE from 2100 UTC valid at 0000 UTC. Figure 14 is the same image from the run without GPS-IPW. While many of the areas of CAPE are similar, showing CAPE maxima in both NE and OK (the other areas of severe activity), there is a difference over IL/IN where the run with GPS shows much more CAPE over the region which was hit with severe weather.

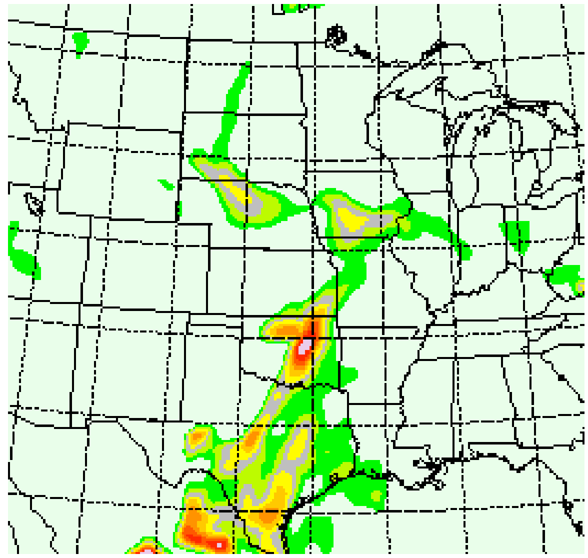

Fig. 14. Same as Fig. 13, but for the run without GPS-IPW.

The difference in IPW for the 3-h forecasts from 2100 UTC is illustrated in Fig. 15. This plot was generated in real time from the GPS-Met Weather Models and Satellite Images web site described in section 4. The GPS-IPW is moistening the forecast in the IL/IN region by as much as 7 mm, as might be expected by the increase in CAPE shown in Fig. 13.

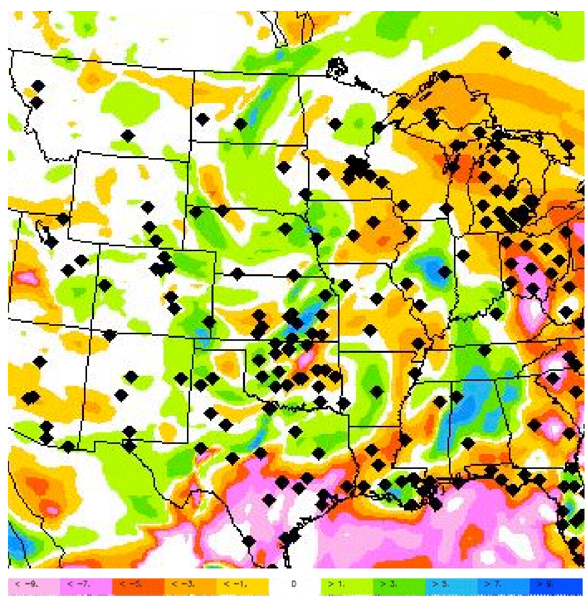

Fig. 15. Plot of the difference between the 20 km RUC run using GPS-IPW data and the 20 km RUC run without GPS data for the 3-h forecast from 2100 UTC 20 April 2004 valid at 0000 UTC 21 April 2004. Green/Blue areas indicate moistening by the GPS-IPW data, Orange/Pink areas indicate drying. Contours are in 2 mm increments starting at 1 mm. Black diamonds are the location of the GPS sites.

6. CONCLUSIONS

Results of recent GPS-IPW data impact tests using 60 km and 20 km versions of the Rapid Update Cycle model/assimilation system show modest improvements in short-range forecasts of atmospheric moisture over the United States. The multi-year RUC60 parallel cycle test has been extended into 2003, showing a stronger effect on 3-h relative humidity forecasts in the lower troposphere each successive year. This improvement is attributable to the continued increase in the number of GPS-IPW stations over the U.S., with almost 300 stations as of July 2004.

An interactive web page is allowing real time assessment of GPS impact on the 20 km RUC, highlighting the areas where the GPS is making its contributions. Running statistics can also be calculated from the hourly 20 km RUC runs, comparing the grids to both RAOB and GPS observations. These statistics also show a positive impact of the GPS data on both the 20 km analysis and forecasts out to 12-h.

A case study from 20 April 2004, a difficult day of severe weather forecasting, shows the GPS-IPW data to be very useful in improving the 20 km RUC moisture forecasts, especially in the off hours between RAOBs. Better moisture forecasts result in better forecasts of important severe weather indices such as CAPE.

7. ACKNOWLEDGMENTS

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