3.3 ONGOING ASSESSMENT OF GPS-IPW IMPACT ON RUC FORECASTS

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1. INTRODUCTION

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. This is partly a consequence of 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, hourly, near-real-time measurements at more than 230 stations in the U.S. as of October 2003 (Fig. 1, Gutman et al. 2003).

GPS integrated precipitable water (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 60km 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 over 200 over the United States during the last six 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 60km RUC with earlier results presented by Benjamin et al. (1998), Smith et al. (2001) and Gutman and Benjamin (2001) has been continued with results from January-September 2003 now available. Statistics from comparisons of 20km RUC runs with and without GPS data are also included.

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. 2003a) and forecast model (Benjamin et al. 2003b) 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 2003, 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. (2003a,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 RUC as of spring 2003 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

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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. 2003a) 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	200	/ 1 h
Ship reports	10s	/ 3 h
Reconnaissance dropsonde	0 - a few	/ variable

TABLE 1. Observational data used in the RUC as of late 2003.

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 (60-km horizontal resolution) 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 200 in 2003.

The NOAA GPS-Met network with over 250 stations available as of 25 October 2003 is shown in Figure 1. Many of these stations are GPS sites installed for various geodetic purposes for which meteorological observation packages were added.

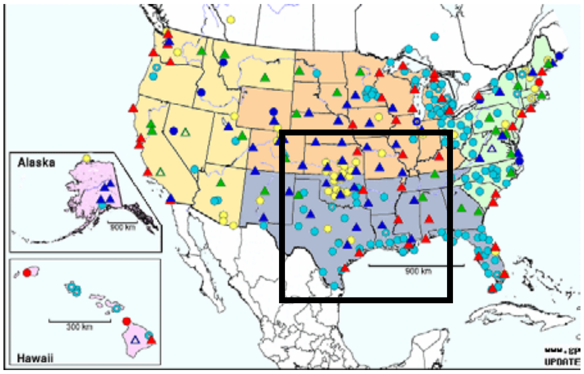


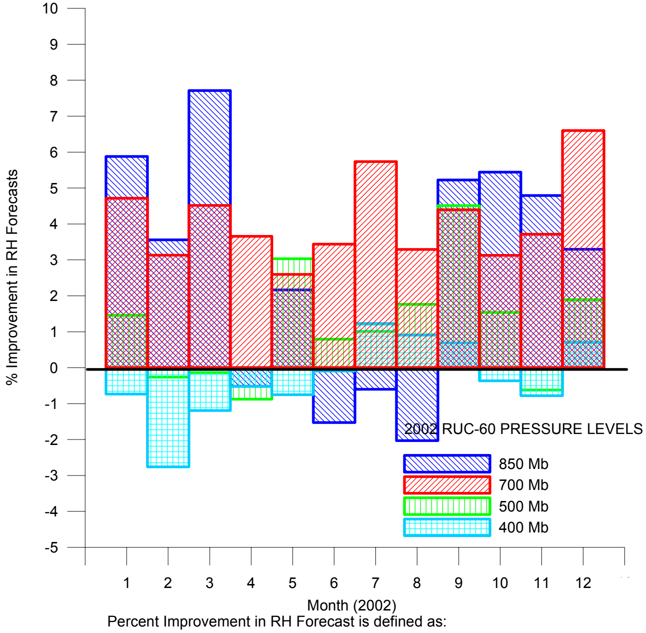
Fig 1. The NOAA GPS network as of 25 October 2003. The black box is the inner verification area containing 17 RAOB sites.

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

Stations	18	56	67	100+	200+
Period	98-99	2000	2001	2002	2003 Jan-Sep
Level					
850	1.5	3.8	3.9	5.0	4.8
700	1.1	4.1	6.3	6.5	7.5
500	0.7	2.1	2.0	2.4	3.3
400	0.3	0.1	-0.4	-0.5	1.1
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. 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 (GPS – no-GPS) normalized by forecast error (approximated as 10% relative humidity in this table).

The 2002-03 RUC60 GPS-IPW impact tests show a continued increase in the positive impact over that shown in previous years (Table 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 (first nine months only). The impact for 2003 will probably increase from these numbers, since the fall and winter months typically show much more impact on average than the summer months. The monthly variation is illustrated in Fig. 2 (percent improvement in 3-h RH forecasts for each month in 2002). The 850 hPa layer (dark blue diagonal hatching) verification shows a definite seasonal trend, with stronger positive impact in the winter months than the summer months, however no other level shows that type of result. Figures 3 and 4 show the actual twice-daily verification values that went into Table 2 and Fig. 2 for the entire year of 2002 at both the 850 hPa and 700 hPa levels respectively. Again, a seasonal response is evident in the 850 hPa verification that is not in the 700 hPa verification. Figure 3 and 4 also show that there is significant day-to-day variation in GPS-IPW impact.



Percent Improvement in RH Forecast is defined as:
1-(3 h RH Forecast Error with GPS/3 h RH Forecast Error w/o GPS)*100

Fig. 2. Percent improvement (as in Table 1) from inclusion of GPS-IPW data by month and level - 2002.

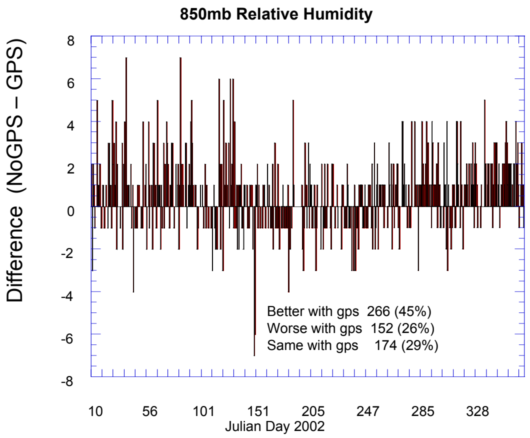


Fig. 3 Percent improvement (as in Table 1) from inclusion of GPS-IPW data by month and level for 850 hPa over calendar year 2002 for the 60 km RUC.

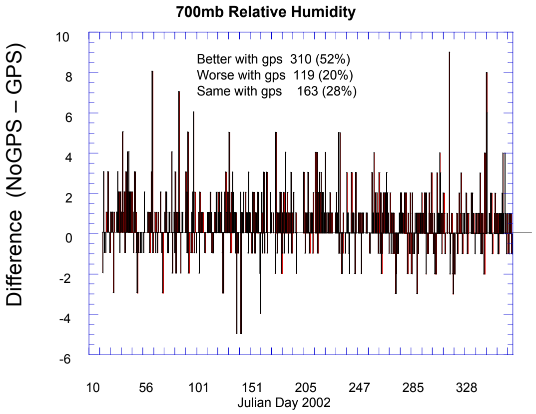


Fig. 4 Percent improvement (as in Table 1) from inclusion of GPS-IPW data by month and level for 700 hPa over calendar year 2002 for the 60-km RUC.

5. GPS IMPACT 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://waylon.fsl.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) retrievals 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 retrievals with the RUC20 runs at FSL that contain GPS-IPW retrievals. Users can interactively view national and regional plots and animations to compare GPS-IPW with output from the RUC20 model runs and the GOES-12 satellite images.

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

Contoured mean and difference plots comparing RUC20 analysis with 1-hour forecasts, and RUC20 analysis with 3-hour forecasts are available for both the RUC20 with GPS-IPW and the RUC20 without GPS-IPW. An example of how this type of plot can be used to detect apparently erroneous RAOBs can be seen in Figure 5. The three RAOB sites of ILN (Wilmington, OH), IAD (Dulles, VA), and NKX (San Diego, CA) are all showing values of precipitable water that are much too moist when compared to the previous hour's FSL RUC forecast, which does not include the 1200 UTC RAOBs. Note the good agreement over most of the US between the 1-h forecast and the analysis outside of those outliers.

Maps that display the GPS retrievals, 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 retrievals and model values. The time series plots show 5-day regional means and biases between the GPS-IPW and the model values. An example corresponding to the analysis/forecast/observation differences illustrated in Fig. 5 can be seen in Fig. 6.

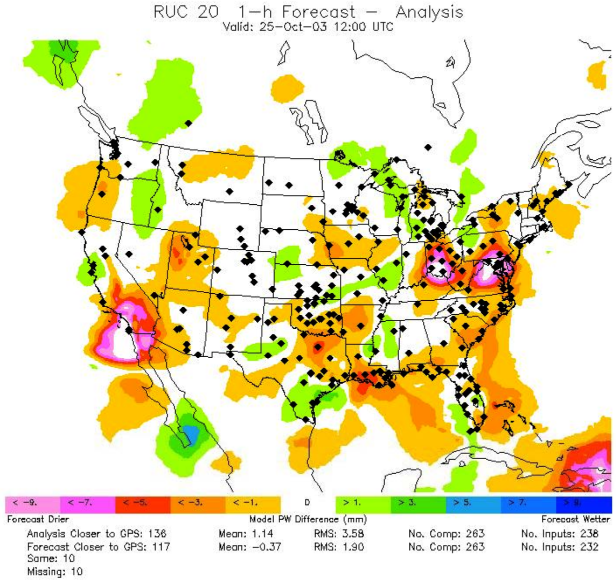


Fig. 5 RUC20 with GPS 1h PW forecast valid at 1200 UTC 25 October 2003 minus RUC20 PW analysis from 1200 UTC 25 October 2003. Both are from FSL RUC cycle with assimilation of GPS data. Pink areas show the forecast is over 9 mm drier than the analysis, indicating that the RAOBs in those areas may be erroneously too moist.

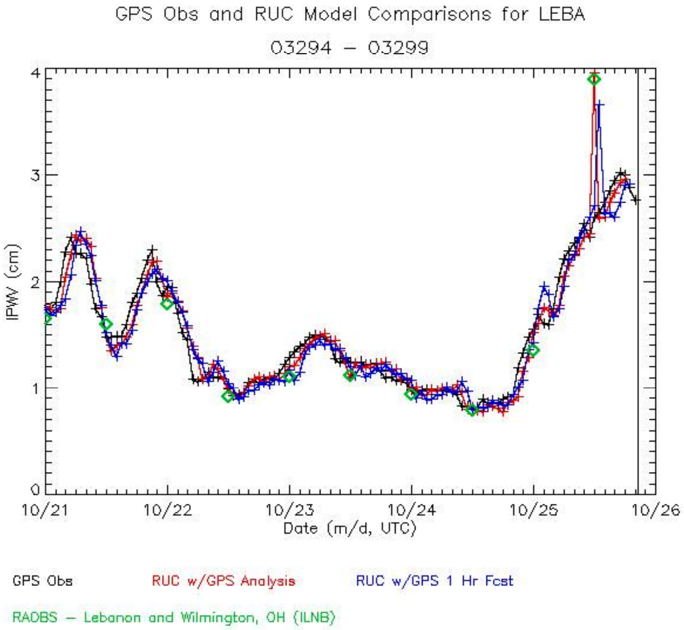


Fig. 6. Example of time series plot for Lebanon, OH 21 October 2003 through 26 October 2003. Note spike on 25 October corresponding to the overly moist RAOB for Wilmington, OH (ILN) at 12Z 25 October (Fig.7).

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 corresponding to the type of plot they are viewing. If RAOBs are available at the site, this information is also displayed. Figure 7 shows the extremely moist sounding from ILN which caused the jump in the time series in Fig. 6.

Using the data archive made available through the website, a sample verification period of 90 days from 25 July to 22 October 2003 has been investigated. Figure 8 shows histograms of differences between RUC analyses – estimates of total precipitable water vapor and GPS-IPW retrievals at over 200 GPS-Met sites in the RUC CONUS region over a 3-month period. Figure 9 depicts differences from GPS observations for 3h RUC forecasts with GPS (FSL RUC20) and without GPS (NCEP RUC20). The actual hourly differences in the analyses with GPS data are mostly within 1 mm, with a mean difference of just 0.25 mm, showing that the RUC is drawing closely for the GPS observations. The operational RUC without GPS observations shows a bit of a moist bias, with a mean of 1.16 mm. The standard deviations are also much lower, 2.36 mm for the analyses with GPS, versus 3.94 for the analyses without. Table 3 shows complete results.

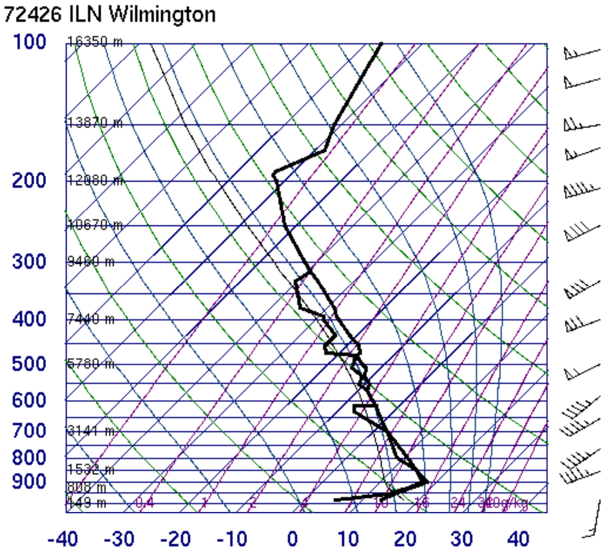


Fig. 7. Skew-T diagram for Wilmington, OH 1200 UTC 25 October 2003. (Courtesy – University of Wyoming).

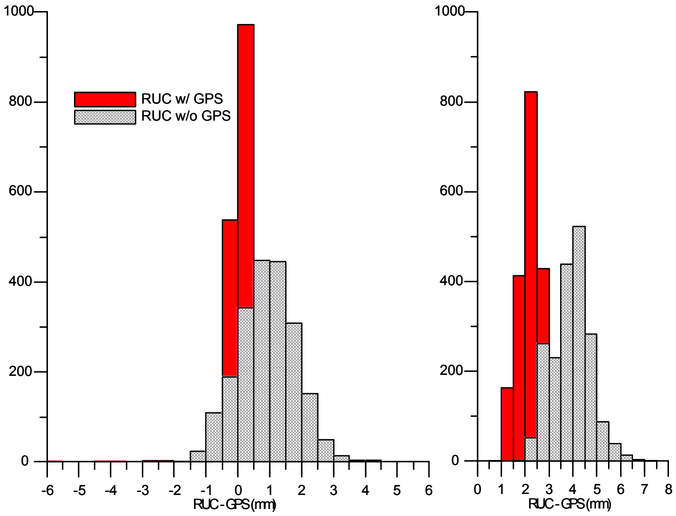


Fig. 8 Histograms of IPW differences (mm) between RUC analyses and GPS IPW retrievals at ~225 sites in the RUC CONUS region. Mean differences (left) and standard deviations of differences (right) for 25 July - 22 Oct 2003. RUC model with GPS in red; RUC without GPS is hatched. Difference defined as RUC model PW – GPS PW.

With GPS	RUC-GPS	RMS
Number	2135	2135
Minimum	-5.85	1.00
Maximum	3.49	7.12
Mean	0.2538	**2.36**
Without GPS	RUC-GPS	RMS
Number	2103	2103
Minimum	-2.04	1.98
Maximum	4.7	7.01
Mean	1.155	**3.94**

Table 3. Statistical comparison (RMS errors left and standard deviation right) of RUC 20-km analyses with and without GPS PW retrievals for the 90-day period from 25 July to 22 October 2003.

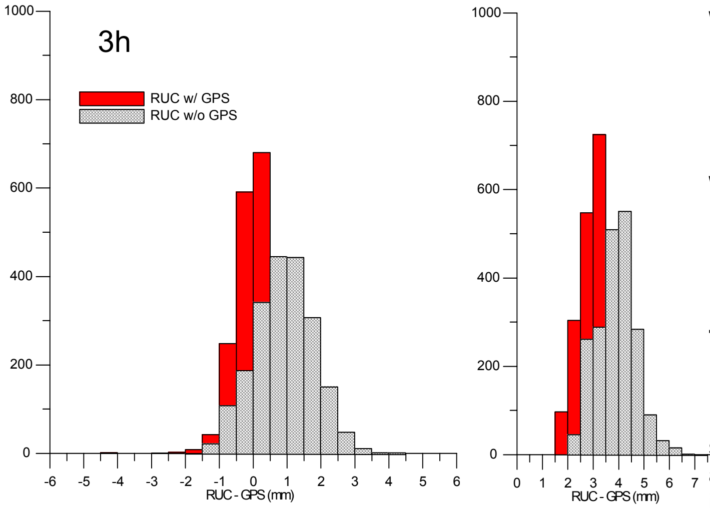


Fig. 9. Same as Fig. 8 but for 3-h RUC forecasts.

With GPS	RUC-GPS	RMS
Number	2131	2131
Minimum	-7.57	1.57
Maximum	4.26	8.75
Mean	0.1261	**3.07**

Without GPS	RUC-GPS	RMS
Number	2089	2089
Min	1.57	2.16
Max	8.75	7.03
Mean	3.07	**3.92**

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

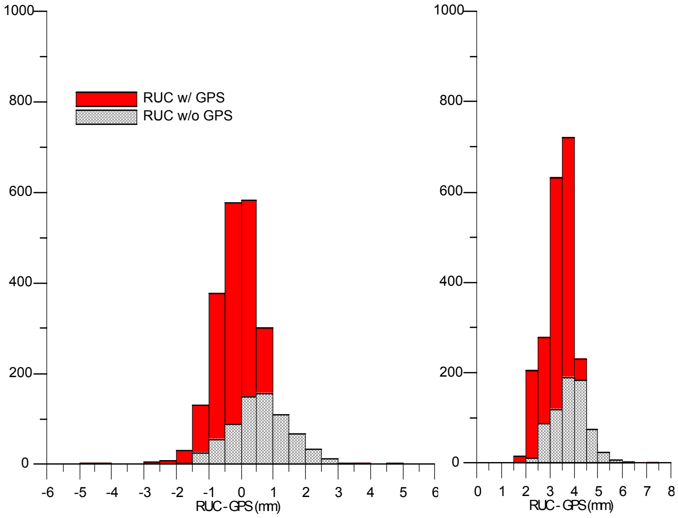


Fig. 10. Same as Fig. 8 but for 6-h RUC forecasts.

With GPS	RUC-GPS	RMS
Number	2131	2131
Minimum	-4.52	1.8
Maximum	3.88	7.21
Mean	-0.06361	**3.40**

Without GPS	RUC-GPS	RMS
Number	696	696
Minimum	-1.57	2.11
Maximum	4.82	6.15
Mean	0.6185	**3.84**

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

Figures 9-12 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 out through 9 h. At 3 h, the rms error is 3.07 vs. 3.92 mm. The 6h forecasts still show demonstrable skill, with a mean difference of -0.06 for the run with GPS as opposed to 0.62 for the run without GPS, and RMS errors of 3.4 with GPS versus 3.8 without GPS. But, by the 12-h forecast the two runs are very close.

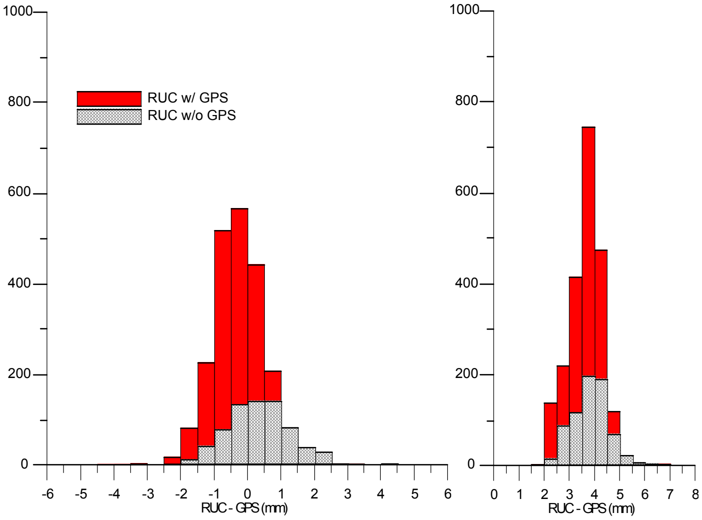


Fig. 11. Same as Fig. 8 but for 9-h RUC forecasts.

With GPS	RUC-GPS	RMS
Number	2131	2131
Minimum	-4.38	1.92
Maximum	3.05	6.9
Mean	-0.2957	**3.65**

Without GPS	RUC-GPS	RMS
Number	697	697
Minimum	-2.17	2.2
Maximum	4.43	6.18
Mean	0.3263	**3.82**

Table 6. Same as 3 but for 9h forecast

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 US over 100 stations as of early 2002.

An interactive webpage is allowing real time assessment of GPS impact on the 20km RUC, enabling the identification of suspect observations and highlighting the areas where the GPS is making its contributions. Running statistics can also be calculated from the hourly 20km 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 20km forecasts and analyses.

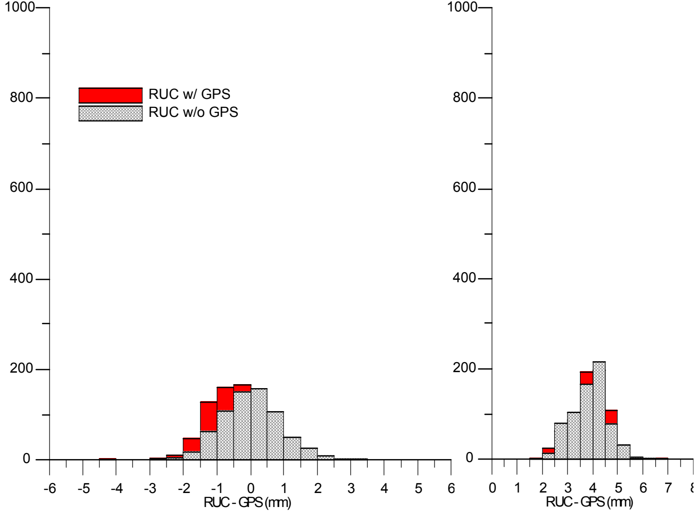


Fig. 12. Same as Fig. 8 but for 12-h RUC forecasts.

With GPS	RUC-GPS	RMS
Number	709	709
Minimum	-4.13	1.98
Maximum	2.13	6.72
Mean	-0.4805	**3.91**

Without GPS	RUC-GPS	RMS
Number	696	696
Minimum	-2.23	2.23
Maximum	3.25	6.01
Mean	0.0319	**3.89**

Table 7. Same as 3 but for 12h forecast

7. ACKNOWLEDGMENTS

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