

IMPACT OF GPS-IPW DATA ON RUC FORECASTS

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1. INTRODUCTION

A primary goal of GPS (Global Positioning System) -based measurements of integrated water vapor (or integrated precipitable water – IPW) is to improve numerical weather predictions of atmospheric water vapor. Water vapor, in turn, will impact such important variables as precipitation and instability. Accurate forecasts of water vapor are generally more difficult than those for other parameters such as wind and temperature. One factor responsible for this is that atmospheric moisture is often highly variable in 3-D space and time, more so than wind or temperature. Observations of moisture are inadequate, even in relatively data-rich areas such over as the United States, to fully resolve these variations. 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 (FSL) has developed, over the past several years, a GPS-IPW network, which now produces high-accuracy, hourly, near-real-time measurements at more than 130 stations in the U.S. as of 11 October 2002 (Fig. 1). (Gutman et al. 2002)

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 (RUC) 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 2002 now available. Two other tests using an advanced 20-km version of the RUC (RUC20) have also been run to evaluate the impact of GPS-IPW data, one in May 2000 to look at severe weather impact, and the other in February 2001 to look at winter weather impact.

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 and

forecast model 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).

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). In 1998, a 40-km, 40-level version (RUC40) was implemented with a considerable increase in complexity of physical parameterizations including mixed-phase (water and ice can co-exist at the same grid point) cloud microphysics, and a 1-h update cycle (Benjamin et al. 1999). In April 2002, a 20-km 50-level version (RUC20) with further improvements in analysis and model techniques was operationally implemented at NCEP (Benjamin et al. 2002).

3. GPS-IPW DATA IMPACT STUDIES WITH RUC60

Since late 1997, FSL has conducted 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 optimal interpolation (OI) technique. As described by Smith et al. (2001), a two-dimensional analysis of the precipitable water analysis increment field (ΔPW , using differences between observations and the forecast background interpolated to observation locations) is performed as part of the RUC OI analysis. A percentage change in PW is calculated as $PW\% = \Delta PW / PW_{bkg}$. This factor is used to modify the water vapor mixing ratio (q_v) at each analysis level. The q_v field modified by the PW analysis is then used as the new background for an analysis using in situ q_v observations.

Previous RUC60 GPS-IPW impact tests for 1998-2001 have shown a modest positive (decreased forecast error) impact from use of GPS-IPW data for short-range forecasts of relative humidity (RH) (Table 1). 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 100 in 2002.

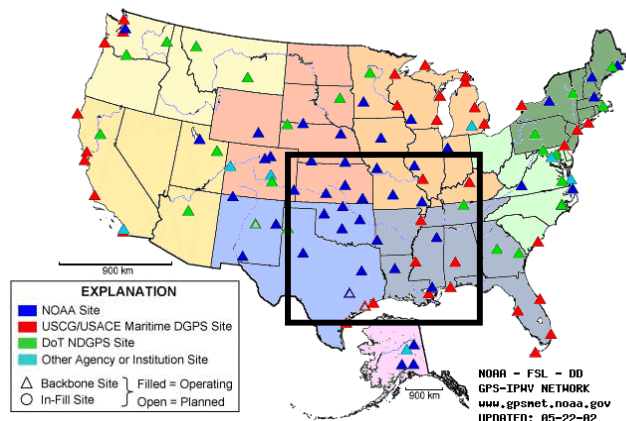


Figure 1. The NOAA GPS network as of 11 October 2002. The black box is the inner verification area containing 17 RAOB sites.

The NOAA GPS-Met network with 138 stations available as of 11 October 2002 is shown in Fig. 1. Many of these stations are GPS sites installed for various geodetic purposes for which meteorological observation packages were added.

No. of Stations	18	56	67	100+
Period	1998-99	2000	2001	2002 Jan-Sep
Level (hPa)				
850	1.5	3.8	3.9	3.0
700	1.1	4.1	6.3	6.5
500	0.7	2.1	2.0	2.0
400	0.3	0.1	-0.4	-0.7
Mean 850-500	1.1	3.3	4.1	3.8

Table 1. 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). Values for 2002 could well improve as we go into the fall/winter season where GPS impact is stronger.

The 2001-02 RUC60 GPS-IPW impact tests show a continued increase in the positive impact over that shown in previous years (Table 1). This continued increase in impact is attributed 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 3.8% in 2002 (first nine months only). The impact for 2002 will probably increase from these numbers, since the fall and winter months show much more impact on average than the summer months. This seasonal variation is illustrated in Figure 2, which is the percent improvement in 3h RH forecasts for each month in 2000. Figures 3 and 4 show the actual twice daily verification values for the entire year of 2001 for both 850 hPa and 700 hPa respectively; again the summer months show less impact overall.

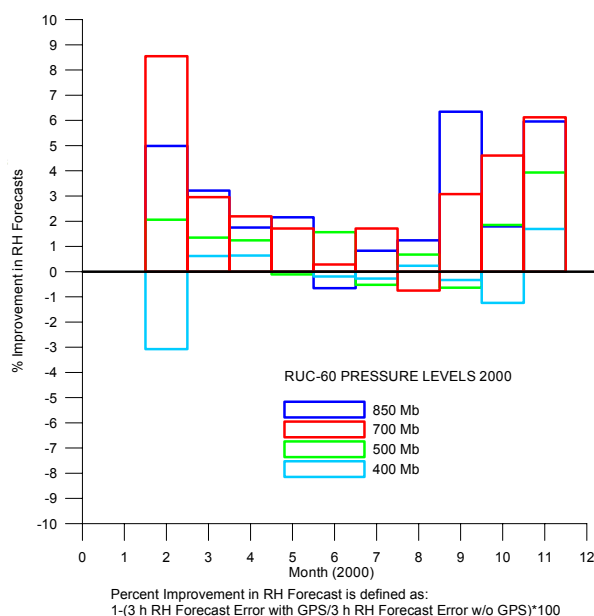


Fig. 2. Percent improvement (as in Table 1) from inclusion of GPS-IPW data by month and level - 2000.

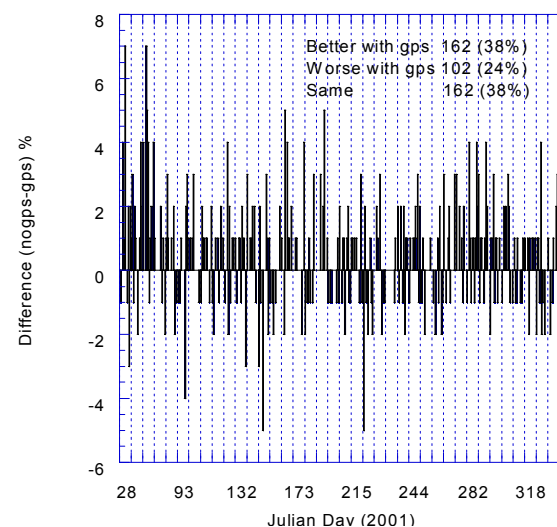


Figure 3. Percent improvement from inclusion of GPS-IPW data for twice-daily verification for 2001 at the 850 hPa level.

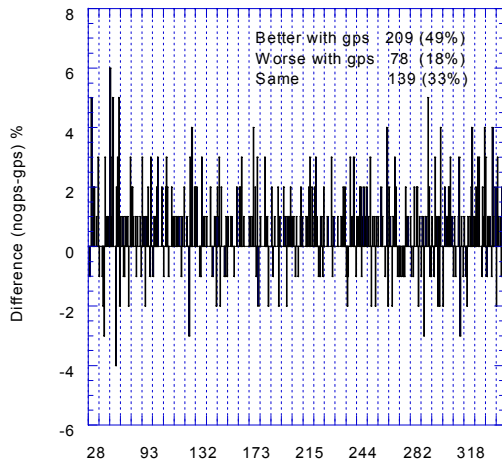


Fig. 4. Same as Fig.3 but for 700 hPa level.

4. RUC20 IMPACT TESTS

Two sets of retrospective runs using the 20km RUC have been recently conducted, consisting of parallel cycles with and without assimilation of GPS-IPW observations. The first was 25-29 May 2000, a 5-day period of active convective weather over the central and eastern United States. The second set of runs was for 4-13 February 2001. During both periods, the number of GPS-IPW stations available was around 55. In the RUC20 experiment, GPS-IPW observations were assimilated hourly rather than every 3 h as with the RUC60 experiments. The number of other data types assimilated in both RUC20 cycles was also increased over the number of types in the RUC60 experiments. The RUC20 experiments included hourly assimilation of surface and wind profiler data, velocity azimuth display (VAD) data from US Doppler radars, and cloud-top pressure/temperature and cloud-drift wind data from GOES satellites.

The preprocessing for GPS-IPW data is improved for the RUC20 experiment over that performed with RUC60. In the RUC20, corrections are performed for the elevation difference between the GPS site and the model terrain at that point. Also, no modifications are made in the analysis due to precipitable water observations at levels above 500 hPa. This was based on the results shown in Table 1, which shows no consistent positive impact above 500 hPa. This indicates that there is generally no positive correlation between RUC60 forecast error of IPW and that of q_v at levels above 500 hPa. Another assimilation change made with RUC20 is that a multipass iteration is performed for the moisture analysis, repeating the 2-D PW analysis, adjustment of the q_v field using cloud-top data, and the in situ q_v analysis, to force some mutual consistency in the analysis to each of these observation types.

The effect of GPS-IPW assimilation on 3-h RUC20 RH forecasts for the May 2000 experiment is shown in Fig. 5. The effect was strong at 850 hPa, with a 7% reduction in relative humidity forecast error for both the 17 rawinsonde stations in the south central US and even for the full 85-station network over the entire RUC20 domain. The effect of GPS-IPW assimilation was somewhat smaller at higher isobaric levels, especially for the full domain.

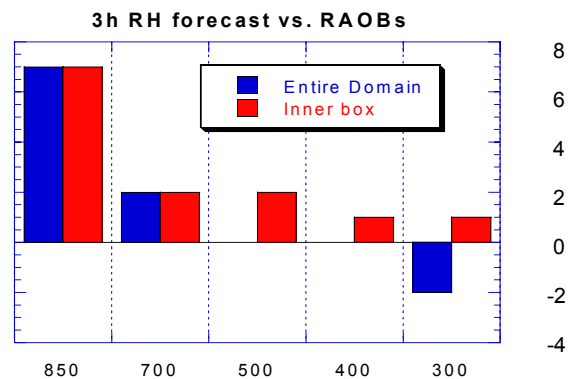


Figure 5. Reduction of 3-h relative humidity forecast error due to assimilation of GPS-IPW observations for 24-29 May 2000 period using RUC20 assimilation system. Vertical axis in percent (normalized by forecast error), horizontal axis is pressure in hPa.

The RUC20 data impact experiment also showed a positive impact on precipitation forecasts, as indicated by comparing precipitation equitable threat scores (ETS) from forecasts with and without GPS-IPW assimilation. Other tests have shown that, in general, the precipitation forecast skill for the RUC20 system is much improved over that of the RUC60 version, due to improved precipitation-related parameterizations, improved data assimilation, and higher spatial resolution. The ETS for 24-h precipitation was calculated by verifying against a 24-h gauge-based precipitation analysis produced daily at NCEP. The 24-h precipitation amounts from the RUC20 were produced by adding two 12-h forecasts.

The equitable threat score (ETS) may be interpreted as follows: ETS is higher for an increased number of grid boxes with forecasts accurately showing values at least equal to the observed values at a given threshold. Conversely, ETS is lower as the number of 'false alarm' incorrect forecasts increases for that same threshold. As shown in Fig. 6, the equitable threat score from the May 2000 RUC20 experiment including hourly GPS-IPW assimilation is slightly higher for all 24-h precipitation thresholds except the 1.5" threshold, for which there were very few observations during this 5-day period. This improvement in precipitation forecasts from assimilation of GPS-IPW over this period is notable in that precipitation is verified over the entire RUC domain.

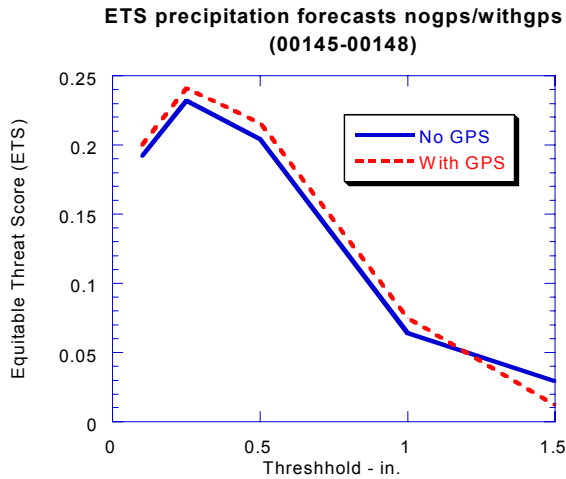


Figure 6. Equitable threat score for RUC20 cycles with and without assimilation of GPS-IPW observations for 24-29 May 2000 period.

5. CASE STUDIES

On 24 May 2000, an outbreak of severe weather occurred from the central to northeastern U.S. (Fig. 7). We will contrast 24-h precipitation forecasts from the two RUC20 runs with and without GPS, as well as fields of relative humidity (RH) at both 850 hPa and 700 hPa. The NCEP gauge analysis of precipitation is shown in Fig. 8. Unfortunately, probably due to the severe weather, data from KY/TN were unavailable for that day. The corresponding 24-h forecast (sum of two 12h forecasts) from the RUC20 GPS run and NOGPS run are shown in Figs. 9 and 10. The influence of the GPS data is more apparent in the forecast of precipitation intensity than in its location, for this case. The analyzed precipitation maximum on the MO/AR border, which is coincident with a large cluster of severe hail and tornado reports is captured much better by the run with GPS data, along with the PA/NY hail region.

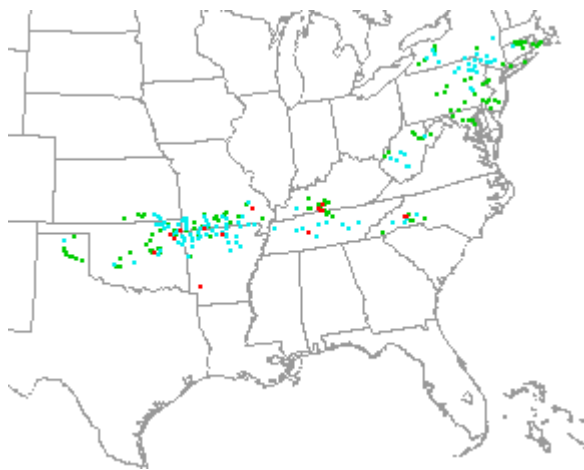


Figure 7. Severe weather reports for 24 May 2000.

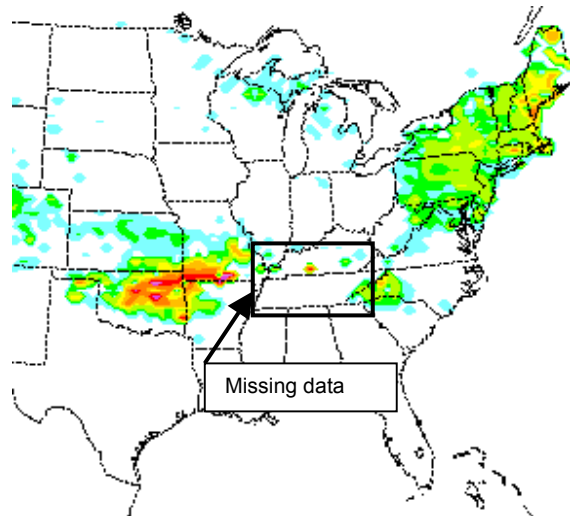


Figure 8. NCEP gauge precipitation analysis for 24 May 2000. Missing data in KY/TN.

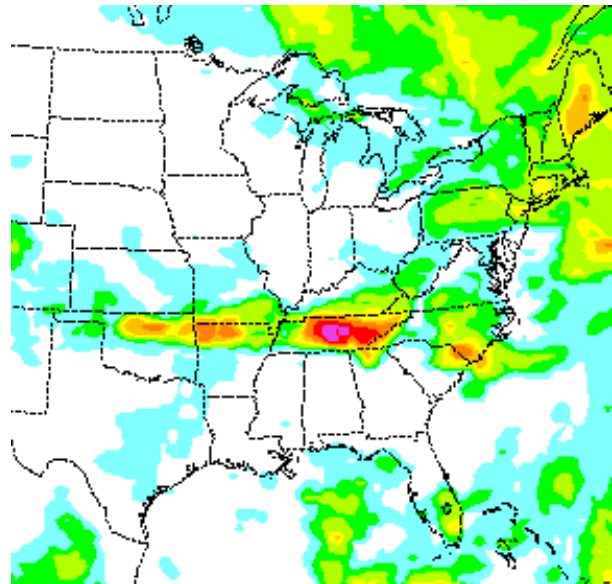


Figure 9. RUC20 precipitation (sum of two 12-h forecasts) for run with GPS 24 May 00.

Figures 11-12 illustrate the distribution of the moisture information in the RUC. Figure 11 shows a difference field between the GPS and NOGPS runs for a 3h forecast valid at 1200 UTC 24 May 2000 of RH for the 850 hPa level, showing plumes of moisture/drying being advected along the analyzed flow at 850 hPa for 0600 UTC shown in Fig. 12.

A second RUC20 experiment was run for February 2001 to investigate the impact of GPS in a winter case. Verification of RH reflects the results from the 60km long-term study, where the largest impact is for the 3h forecasts at 850 hPa, of around 7%. Difference fields comparing both GPS and NOGPS runs with the

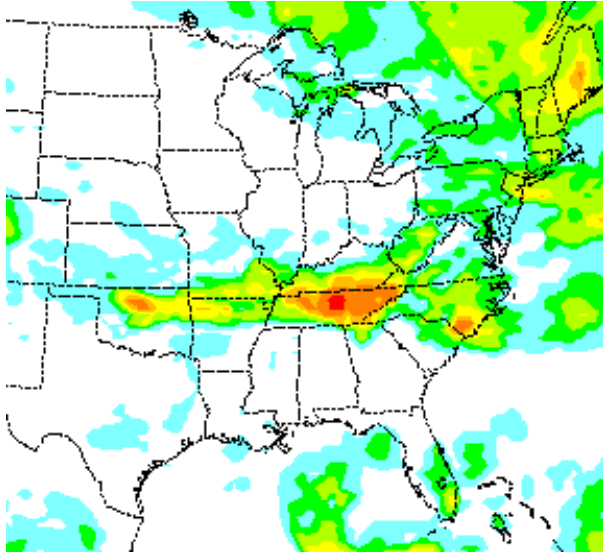


Figure 10. RUC20 precipitation (sum of two 12-h forecasts) from the NOGPS run for 24 May 2000.

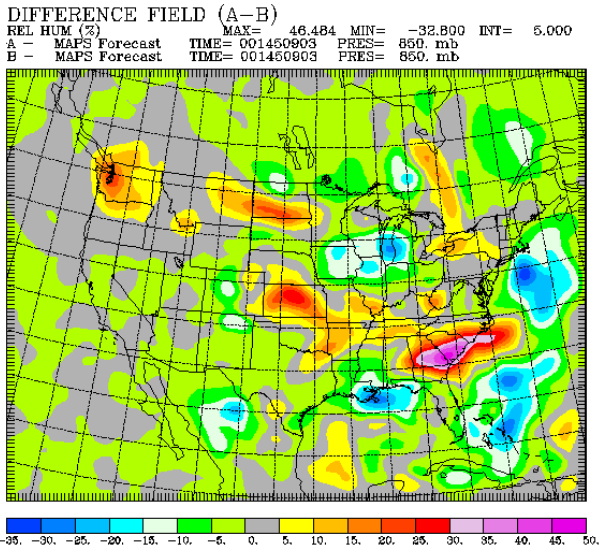


Figure 11. Difference field between the 3h forecasts of 850 hPa RH for the GPS-noGPS runs valid at 1200 UTC 24 May 2000. Yellow-pink is drier with GPS, green-blue wetter with GPS. Note how areas follow the streamlines in Fig. 12.

verifying analysis for 9 February 2001 can be seen in Figures 13 and 14. A reduction in the forecast error is evident across much of the south and eastern US. The maximum error is still in LA, but the magnitude and area covered by the errors is greatly reduced. The area of OK/AR/MO is also much better forecast in the run using GPS data, reflecting the fact that this is the densest part of the network. This was also an area of improved precipitation forecasts. Nearly identical errors are seen over the northern Rockies - an area with little to no GPS information. These visual results echo the statistics that

WIND MAG M/S MAX= 23.741 MIN= 0.000 INT= 2.000
 A - MAPS Analysis TIME= 001450600 PRES= 850. mb

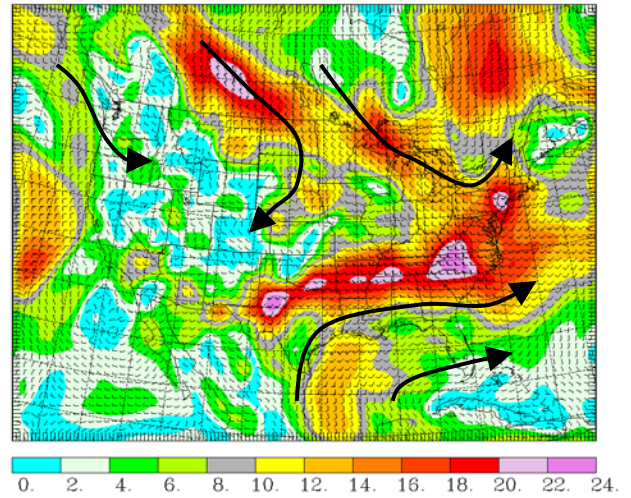


Figure 12. 850 hPa wind field analysis from 0600 UTC 24 May 2000. Note how GPS influence from Fig. 11 is in good agreement with the wind field.

show the RUC is using the GPS information to improve the moisture 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 and precipitation over the United States. The multi-year RUC60 parallel cycle test has been extended into 2002, 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 number of GPS-IPW stations over the U.S., over 100 stations as of early 2002.

Two tests from 24-29 May 2000 and 4-13 February 2001 were carried out using a 20-km version of the RUC. These tests also showed improvements in relative humidity and precipitation numerical forecasts resulting from assimilation of GPS-IPW observations. The impact on precipitation forecasts was stronger than in previous longer-term tests with the 60-km RUC, although this may be related to the shortness of the RUC20 test periods. GPS-IPW improved the precipitation forecast of amount and distribution on 24 May 2000, a severe weather day across much of the U.S. It also reduced errors in the short-range forecast of relative humidity, as was shown for 8 February 2001.

7. ACKNOWLEDGMENTS

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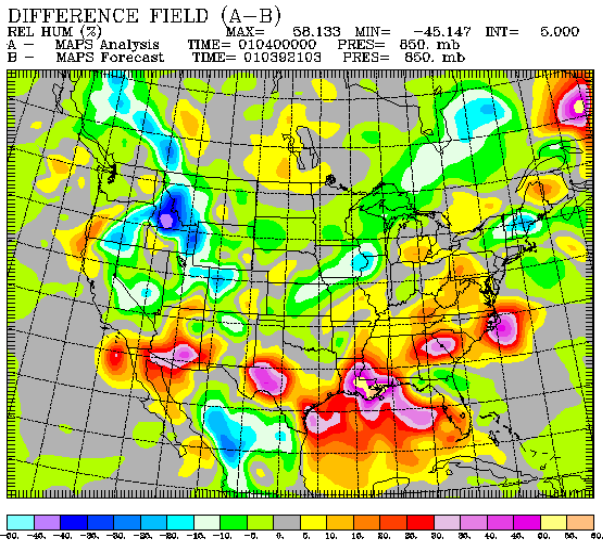


Figure 13. Difference field for GPS run of 3h forecast from 2100 UTC 8 February 2001 and the analysis from 0000 UTC 9 February 2001. Forecast RH greater are green-blue contours, forecast RH drier are the yellow-red contours.

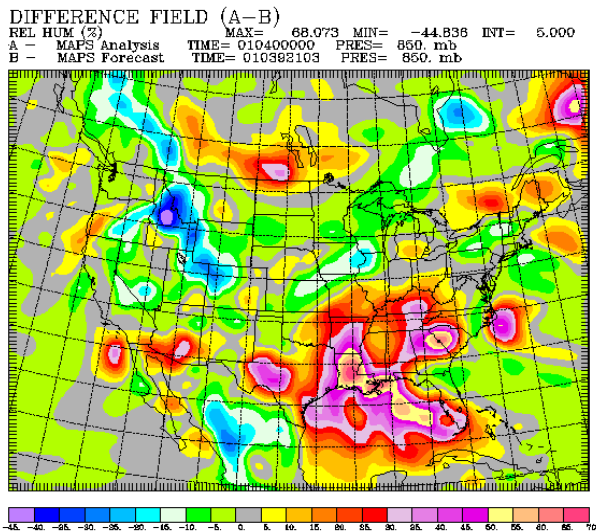


Figure 14. Same as Figure 13, but for the noGPS 3h forecast.