2.2 OPERATIONAL ASSIMILATION OF GPS-IPW OBSERVATIONS IN THE 13-KM RUC AT NCEP

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1. INTRODUCTION

GPS integrated precipitable water (GPS-IPW) observations are a relatively recent asynoptic data source of moisture information for data assimilation. Short-range numerical weather forecasts suffer from inadequate observational definition of the three-dimensional moisture field due to its high spatial and temporal variability. Generally, there have been three observational sources for atmospheric moisture: rawinsondes, surface, 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 Earth System Research Laboratory (ESRL) Global Systems Division (GSD) 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 300 stations in the U.S. as of June 2005 (Fig. 1, Gutman et al. 2003). This data is now, for the first time, being assimilated into a real-time operational model coming out of the National Centers for Environmental Prediction (NCEP), the 13-km version of the Rapid Update Cycle (RUC13) implemented operationally in June 2005.

GPS-IPW data have been assimilated into several developmental versions of the Rapid Update Cycle (RUC) since the 60-km RUC (RUC60) in 1997. Verification of the 3-h RUC60 cycle with assimilated GPS-IPW from 1997 through 2004 provides a rich database for long-term statistics. Increasing positive impact on short-range relative humidity (RH) forecasts has been evident (shown in section 4 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 GSD with the 13-km Rapid Update Cycle data assimilation and numerical forecast system. Also, a multi-year parallel cycle using the RUC60 with earlier results presented by Benjamin et al. (1998), Smith et al. (2000), and Gutman and Benjamin (2001) has been continued with results through 2004 presented. Statistics from comparisons of 20-km RUC (RUC20) runs with and without GPS data are also included.

2. THE 13-km RAPID UPDATE CYCLE

The 13-km RUC domain was configured with a increase of resolution for each horizontal dimension over the current 20-km resolution (exactly 2/3 of the previous ~20-km grid length). Higher spatial resolution allows more accurate depiction of the actual terrain. The 13-km configuration more faithfully represents coastlines and lake boundaries, and smaller bodies of water can now be resolved. The RUC13 continues to use 50 vertical levels and retains the same isentropic-sigma hybrid coordinate found advantageous in previous RUC versions (Benjamin et al. 2004a,b,c).

The RUC13 analysis implementation at NCEP included the following significant assimilation changes:

- Cycling of all fields at 13-km resolution, including hydrometeor and land-surface variables. Higher horizontal resolution is thus represented in initial conditions for each RUC forecast.
- Assimilation of new observational types: GPS-IPW retrievals, mesonet surface observations, and METAR cloud/visibility reports.
- Modification of moisture analysis variable from ln q (natural logarithm of water vapor mixing ratio) to pseudo relative humidity, defined as q / q-saturation-background. This change reduces occasional noise in moisture fields which were sometimes evident in operational RUC20 analyses. It also allows a unified analysis solution combining in situ and vertically integrated moisture observations.
- Nudging of soil temperature and moisture values at upper soil levels. This modification has been found to substantially improve 2-m temperature and dewpoint forecasts in the warm season.

The new unified variational moisture treatment using

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in situ and precipitable water (PW) observations simultaneously to calculate the 3-D moisture analysis increment also

- Includes RAOB PW values implicitly through the RAOB moisture profile

- Includes GPS-IPW observations, in addition to GOES PW data.

- Includes new moisture QC techniques:
¬ Compares rawinsonde PW with nearby GPS PW values, and flags entire rawinsonde profile if rawinsonde PW varies substantially from nearby GPS stations (Gutman et al. 2005)
¬ Also checks GPS PW observations to see if more than 25% are found to exceed background value by at least 25%, in which case, all GPS PW obs are flagged. This presumes that some problem occurred in the GPS PW processing, possibly from erroneous orbit position information for a particular GPS satellite.

- PW innovations are calculated using new PW-RH variable developed for RUC13 analysis, which exhibits much better spatial coherence than PW itself over regional variations of terrain elevation.

The conditions that we have for flagging GPS observations are based on mean differences between all GPS PW observations and the RUC 1-h forecast of:
1) at least 15% in RH-PW (RH relative to saturated column), considered to be a very large value (typical mean differences over the RUC domain are <1% RH-PW).
or
2) at least 2 mm. (also considered to be an excessively large bias when averaged over the full RUC domain).

3. GPS-MET NETWORK AND DATA

The NOAA GPS-Met network with around 300 stations available as of June 2005 is shown in Fig. 1. Many of these stations are GPS sites installed for various geodetic purposes for which meteorological observation packages were added.

ESRL/GSD has been evaluating the accuracy and precision of GPS-IPW retrievals in most climatological regions of North America (from arctic to semi-tropical), during all seasons and weather conditions since November, 1994. We have also investigated the engineering aspects of a GPS water vapor system to assess its suitability as an operational weather and climate observing system for NOAA. We have determined that GPS water vapor measurements can be made with high reliability under all weather conditions. Retrieval accuracies have been shown to be comparable to, or better than, integrated rawinsonde measurements without the well-known problems at high humidity or low temperature. The major shortcoming of the system is that GPS meteorological (GPS-Met) techniques currently provide only zenith scaled measurements that contain (in themselves) no information about the vertical distribution of moisture in the atmosphere. However, rudimentary techniques to assimilate these observations into numerical weather prediction models have been developed that improve short-term moisture forecasts at lower levels in the atmosphere, with the greatest improvements occurring during the cold months (Smith et al., 2000; Gutman and Benjamin, 2001). Given the low system cost and high reliability, GPS-IPW appears to be a cost-effective observing system, and there appear to be no technical impediments to its operational implementation within the U.S. National Weather Service (NWS).

For improved NWP forecasts, it is essential that typical IPW observation errors are well below short-range IPW forecast errors (2-5 mm for warm-season 6-h forecasts over the US, as described in Gutman and Benjamin 2001). The accuracy of GPS-IPW observations (generally < 1 mm, Gutman and Benjamin 2001) is a result of the retrieval and processing techniques outlined in this section. A more detailed, recent summary on GPS-IPW accuracy is provided by Gutman et al. (2004).

GPS moisture observations are an unanticipated spin-off from GPS technology wherein atmospherically-induced GPS positioning errors that are estimated and removed in geodesy are now used as observations for atmospheric science. NOAA/ESRL/GSD currently acquires GPS and ancillary surface observations of atmospheric pressure and temperature every 30 min from a network of fixed sites distributed primarily over the contiguous United States (Fig. 1). The GPS measurements consist of continuous dual frequency carrier phase and range observations of the radio signals transmitted by all GPS satellites in view. These measurements are used to compute the position of the GPS antenna in near real time, compare the currently observed position with its known position, and attribute the differences to various sources of measurement error according to a model described in Gutman et al. (2004). A major source of error in the calculation of antenna position is the radio-refractivity of the lower (electrically neutral) atmosphere. Variations in refractivity caused by changes in temperature, pressure, and water vapor along the paths of the GPS radio signals slow and bend the radio signals. This causes an apparent delay in the arrival time of the radio signals from that expected, assuming a constant speed of propagation

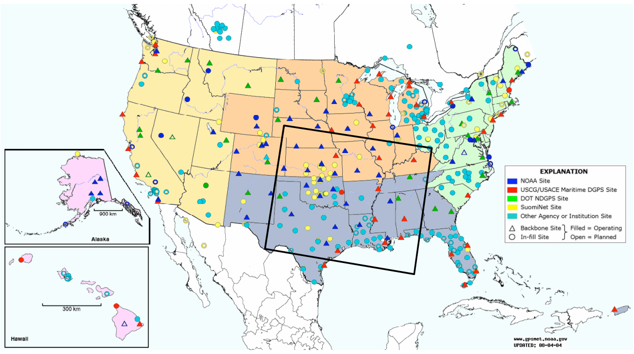

Fig. 1. The NOAA GPS network as of June 2005. The black box is the inner verification area containing 17 RAOB sites. (http://www.gpsmet.noaa.gov)

and purely geometric considerations. This error is called the tropospheric signal delay, and the technique used to estimate it in an absolute sense as a free parameter in the calculation of antenna position is discussed in Duan et al. (1996), and Marshall et al. (2001).

Current information on surface pressure and mean column temperature, currently estimated from nearby surface measurements, are used to parse the tropospheric signal delay into its wet and dry components, and map the wet component into integrated (total column) precipitable water vapor (IPW) as described in Bevis et al. (1992, 1994), Wolfe and Gutman (2000), and Gutman et al. (2004).

About one-half of the sites in the NOAA ground-based GPS meteorology (GPS-Met) network belong to NOAA and several other U.S. federal government agencies including the U.S. Department of Transportation and the U.S. Coast Guard. The remaining sites belong to various federal, state and local government agencies, universities (including SuomiNet at http://www.suominet.ucar.edu), and some private companies who collect GPS observations which they primarily use for high accuracy positioning. As a rule, these organizations provide their GPS observations in real time or nearly so to the Continuously Operating Reference Station (CORS) network operated by NOAA's National Geodetic Survey (http://www.ngs.noaa.gov/CORS). The carrier phase and range observations can also be used for weather forecasting and other applications described by Gutman et al. (2005), McMillin et al. (2005), and Birkenheuer and Gutman (2005) if a sufficiently accurate estimate of surface pressure (currently from nearby surface meteorological observations) is readily available (Gutman et al. 2003). A fortuitous commonality between the requirements for high accuracy positioning and atmospheric remote sensing has facilitated the rapid expansion of real-time GPS-IPW data at low cost and little additional effort.

Additional information on GPS-IPW processing and applications is described by Wolfe and Gutman (2000), Gutman and Benjamin (2001), Gutman et al. (2003) and Gutman et al. (2004).

4. PREVIOUS GPS-IPW/RUC STUDIES

4.1 *1998-2004 RUC60 GPS-IPW statistics*

The 2004 RUC60 GPS-IPW impact tests show a continued increase in the positive impact over that shown in previous years (Table 1, Fig. 2). This continued increase in impact is wholly attributable to the increased number of GPS-IPW stations over the U.S.. 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 7.1% in 2004. 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 and 13-km versions of the RUC.

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 five calendar years 2000-2004). 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 1 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.

We have also looked at the impact over the entire CONUS. Fig. 6 shows that while less than the impact seen over the smaller verification area, as the number of observations has increased nationwide, and the density of the GPS sites is also increasing, the same trend of improved RH forecasts due to GPS station density is seen.

Stations	18	56	67	100+	200+	275
Period	98-99	2000	2001	2002	2003	2004
Level						
850	1.5	3.8	3.9	5.0	5.4	7.7
700	1.1	4.1	6.3	6.5	7.0	9.9
500	0.7	2.1	2.0	2.4	3.1	3.7
400	0.3	0.1	-0.4	-0.5	1.0	1.9
850-500	1.1	3.3	4.1	4.6	5.2	7.1

Table 1. 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).

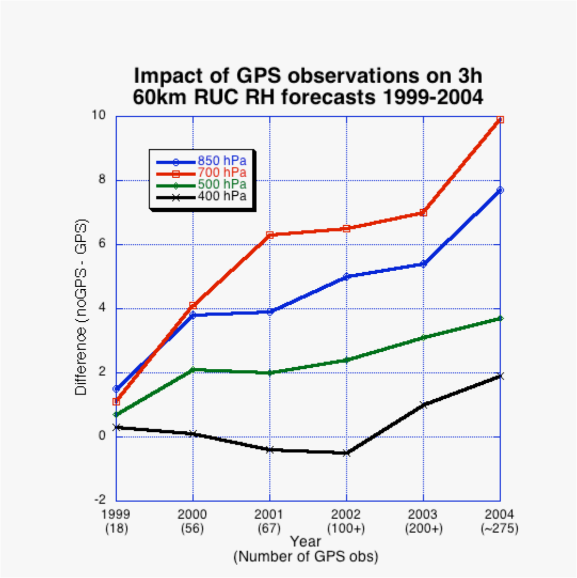

Fig. 2. Percent reduction of 3-h relative humidity forecast error from the 60-km RUC (as in Table 2) due to the inclusion of GPS-IPW data at 850, 700, 500 and 400 hPa averaged by year for 1999-2004.

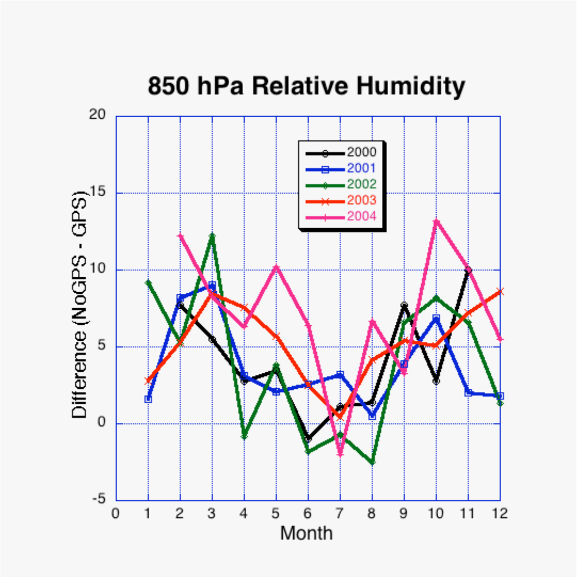

Fig. 3. Percent reduction of 3-h relative humidity forecast error from the 60-km RUC (as in Table 2) due to the inclusion of GPS-IPW data at 850 hPa averaged by month for years 2000 – 2004.

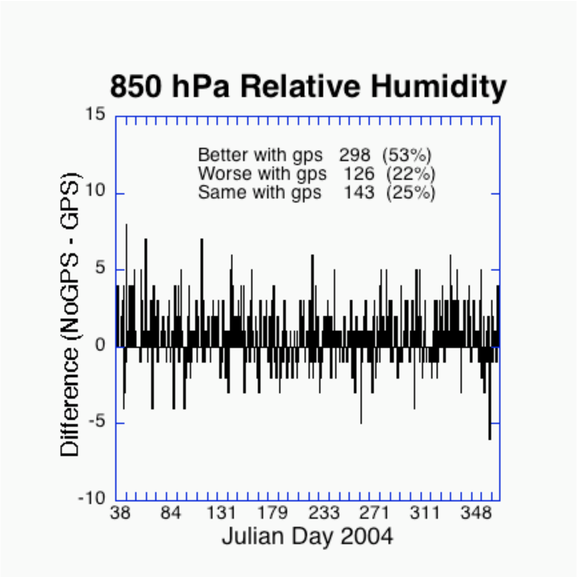

Fig. 4. Percent reduction of 3-h relative humidity forecast error from the 60-km RUC (as in Table 2) due to the inclusion of GPS-IPW data for 850 hPa over calendar year 2004.

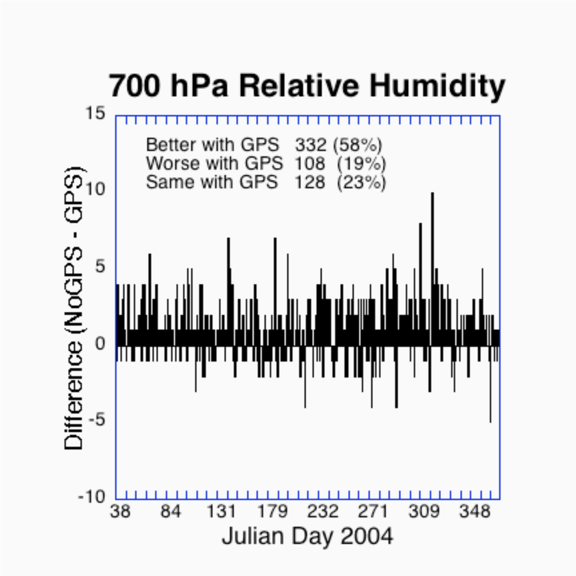

Fig. 5 Same as Fig. 4, for 700 hPa.

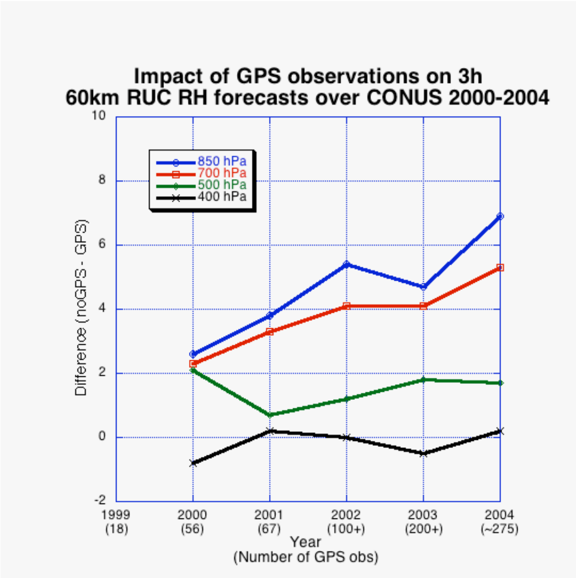

Fig. 6. Same as Fig. 2, but for entire US.

4.2 *GPS-IPW impact studies with RUC20 – spring 2004*

4.2.1 Data processing and comparisons using the GPS-Met Weather Models and Satellite Images web stie

We now consider differences in forecast skill between versions of the 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/ruc.cgi) allowed for interactive assessment of the impact of Global Positioning System meteorology (GPS-Met) integrated (total column) precipitable water vapor (GPS-IPW) retrieval data on the RUC 13-km and 20-km analyses and short-term moisture forecasts. This web-based application compares several RUC runs (the operational runs from NCEP as well as developmental runs at GSD) against the GPS-IPW observations as well as satellite images. Users can interactively view national and regional plots and animations to compare GPS-IPW observations with output from the model runs and the GOES satellite images (http://gpsmet.noaa.gov/cgi-bin/sat/goes.cgi).

For each hourly model run, contour plots of the RUC IPW can be generated, creating 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 can also be displayed.

Contoured mean and difference plots comparing RUC analysis with 1-h forecasts, and RUC analysis with 3-h forecasts are produced for all RUC model runs.

For maps that display the GPS observations and the RUC model runs at each GPS 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.

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.

4.2.2 RUC20 results from 1 March – 31 May 2004

Using the data archive made available through the web site, a spring verification period for March – May 2004 has been investigated. This dataset using the operational RUC20 at NCEP and the backup RUC20 at GSD is valuable because at this point, the operational RUC had no GPS-IPW data being assimilated, effectively making for a data denial experment. Figure 7 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 8 depicts differences from GPS-IPW observations for 3-h RUC forecasts with GPS-IPW (GSD 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 RUC20 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 2 shows complete results for the RUC20 analyses with and without GPS-IPW.

Figures 8-11 and Tables 3-6 show differences in forecast skill between GPS and no-GPS RUC20 cycles at 3, 6, 9, and 12-h. These statistics show that there is forecast improvement from assimilation of GPS-IPW out through 12-h forecast duration. 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).

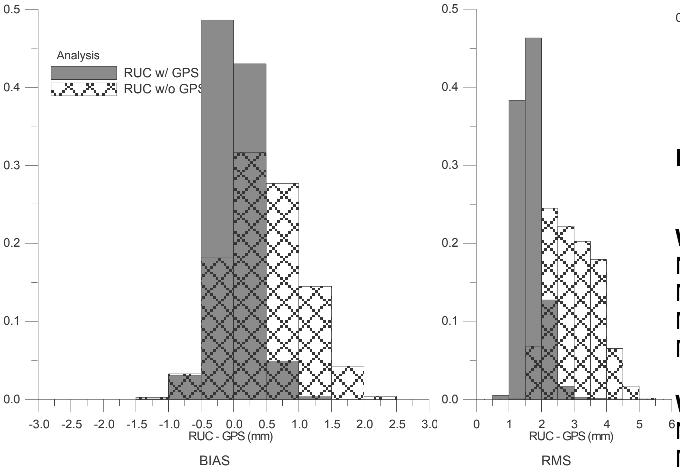

Fig. 7 Histograms of IPW differences (mm) between RUC analyses and GPS-IPW retrievals at ~275 sites in the RUC CONUS domain. Mean differences (left) and standard deviations of differences (right) for 01 March - 31 May 2004. RUC model with GPS is solid; RUC without GPS is hatched. Difference defined as RUC model IPW – GPS IPW. Vertical 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 2. 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.

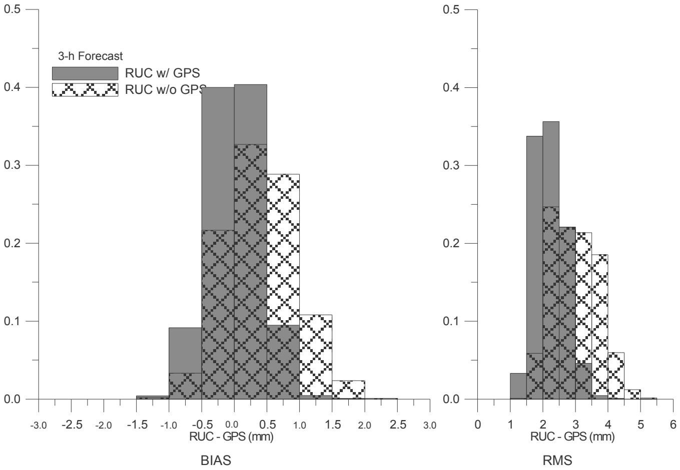

Fig. 8. Same as Fig. 7 but for 3-h RUC forecasts.

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
Minimum	-1.14	1.47
Maximum	2.21	5.37
Mean	0.40	**2.98**

Table 3. Same as Table 2 but for 3-h forecast

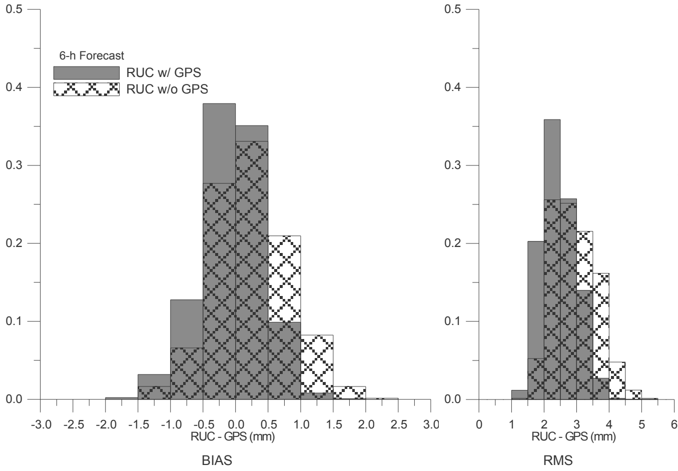

Fig. 9. Same as Fig. 7 but for 6-h RUC forecasts.

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 4. Same as Table 2 but for 6-h forecast.

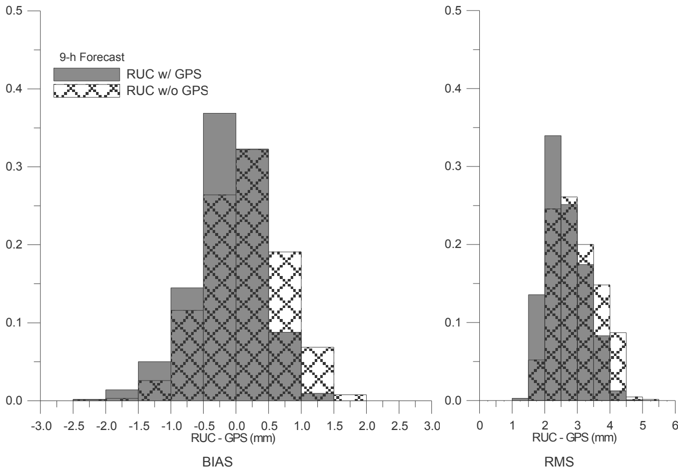

Fig. 10. Same as Fig. 7 but for 9-h RUC forecasts.

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 5. Same as Table 2 but for 9-h forecast

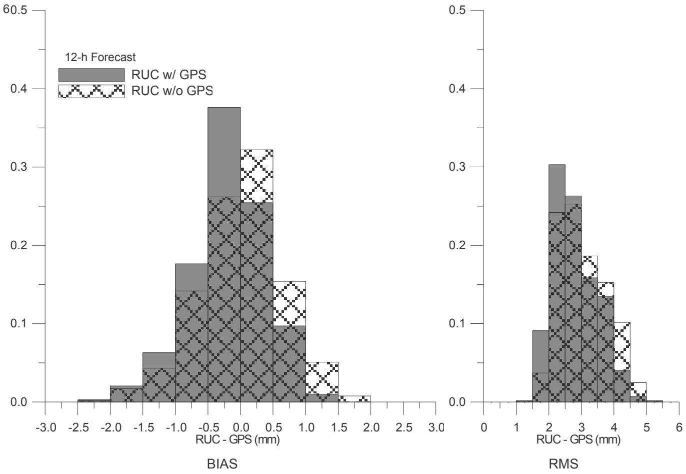

Fig. 11. Same as Fig. 7 but for 12-h RUC forecasts.

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 6. Same as Table 2 but for 12-h forecast

5. OPERATIONAL USE OF GPS-IPW IN RUC13 – SUMMER-FALL 2005

The RUC13 became operational on 28 June 2005, ushering in a new era of GPS-IPW observation assimilation. The observations going into the operational RUC at NCEP are provided by NOAA/ESRL, but due to timing constraints, the number of observations available for use in the operational RUC13 is less than those available for the

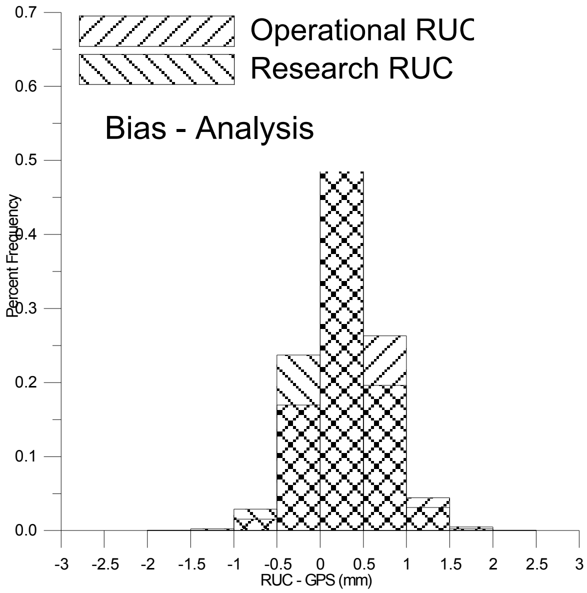

Fig. 12 Histograms of IPW differences (mm) between RUC analyses and GPS-IPW retrievals at ~300 sites in the RUC CONUS domain. Mean differences for 01 August - 31 October 2005. Operational RUC13 is backslash; Research RUC13 is forwardslash. Difference defined as RUC model IPW – GPS IPW.

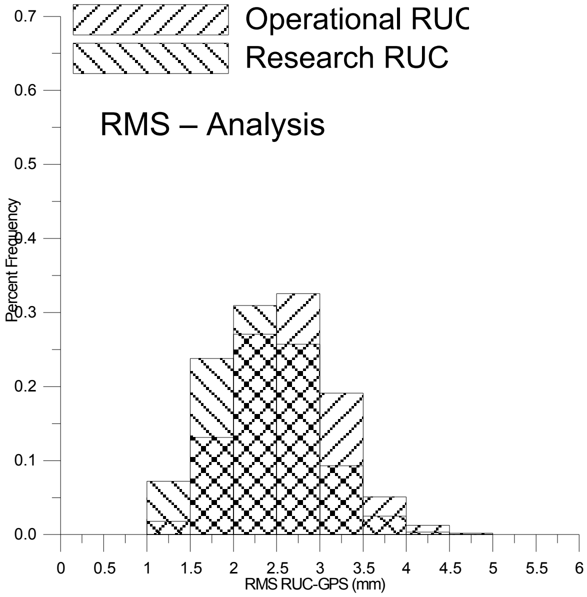

Fig. 13 Histograms of IPW differences (mm) between RUC analyses and GPS-IPW retrievals at ~300 sites in the RUC CONUS domain. Standard deviations of differences for 01 August - 31 October 2005. Operational RUC13 is backslash; Research RUC13 is forwardslash. Difference defined as RUC model IPW – GPS IPW.

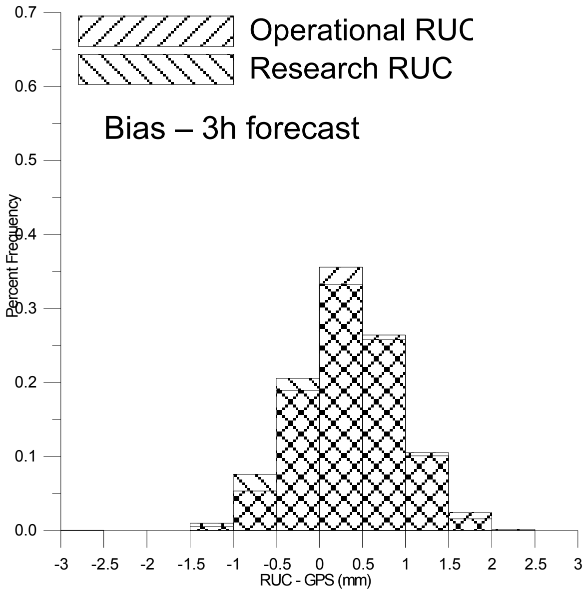

Fig. 14 Same as Fig. 12, but for 3h forecasts.

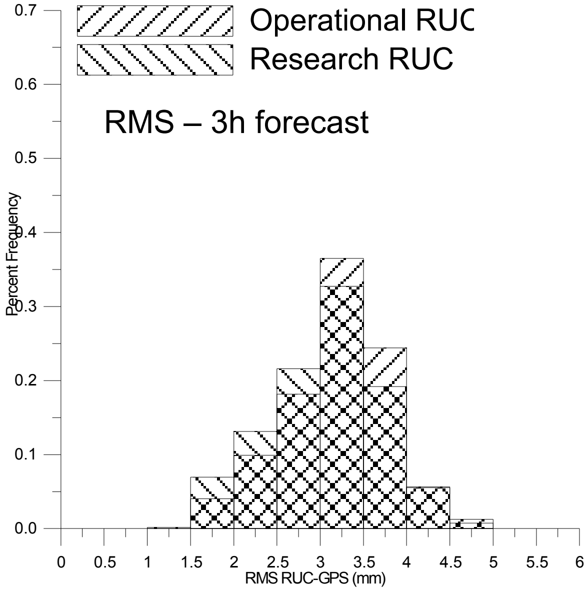

Fig.15 Same as Fig. 13, but for 3h forecast.

research RUC13 run at ESRL/GSD. This difference is, on average, around 219 GPS-IPW observations going into the research RUC13 versus around 160 GPS-IPW observations going into the operational RUC13. Using the capabilities on the interactive website, as described in section 4.2.1, the impact of the slightly degraded (~27%) dataset can be seen in Figs. 12-15. While quite similar overall, the research RUC13, assimilating a greater number of GPS-IPW observations, has a smaller bias and error compared to the GPS-IPW observations than the operational RUC13 for both the analysis and 3-h forecast. The analysis improvement in the bias (Table 7) is .1 mm, or 30%, and the improvement in the RMS error in the analysis is .31 mm or 12%. In the 3h forecast (Table 8), the differences are slighter, with the bias difference being .07 mm or 18% and the rms difference being .13 mm or 4%. Once again, an increase in the amount of GPS-IPW data going into the model translates to improved moisture forecasts in the RUC.

Operational	
Number	1853
Bias	0.33
RMS	**2.64**
Research	
Number	1998
Bias	0.23
RMS	**2.33**

Table 7. Bias and RMS errors for the research and operational RUC13 models for 1 August – 31 October 2005.

Operational	
Number	1663
Bias	0.38
RMS	**3.20**
Research	
Number	1968
Bias	0.31
RMS	**3.07**

Table 8. Same as Table 7 but for 3-h forecast

6. CONCLUSIONS

The RUC13 is the first operational NCEP model to assimilate GPS-IPW observations in real time. Using lessons learned in the RUC60 and RUC20 assimilation of GPS-IPW, better assimilation techniques and quality control of observations have improved the consistency of positive impact from this new data source.

Previous results of 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 2004, 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 over 300 stations as of June 2005.

An interactive web page is allowing real-time assessment of GPS impact on the 13-km RUC, highlighting the areas where the GPS is making its contributions. Running statistics can also be calculated from the hourly 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 analysis and forecasts.

In all of our studies, the density of the data network and number of available observations for assimilation have a definite impact on the quality of the moisture analysis in the RUC.

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