SHORT-RANGE FORECAST IMPACT FROM ASSIMILATION OF GPS-IPW OBSERVATIONS INTO THE RAPID UPDATE CYCLE

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ABSTRACT

Integrated precipitable water (IPW) estimates derived from time delays in the arrival of Global Positioning System satellite signals (GPS-IPW) are a relatively recent, high-frequency source of atmospheric moisture information available for real-time data assimilation. Different experimental versions of the Rapid Update Cycle (RUC) have assimilated these observations to assess GPS-IPW impact on moisture forecasts. In these tests, GPS-IPW data have proven to be a useful real-time source of moisture information, leading to more accurate short-range moisture forecasts when added to other observations. A multiyear experiment with parallel (one with GPS-IPW processed 24 h after-the-fact, one without) 3-h cycles using the original 60-km RUC was run from 1999-2004 with verification of each cycle against rawinsonde observations (RAOBs). This experiment showed a steady increase in the positive impact in short-range relative humidity forecasts due to the GPS-IPW data as the number of observing sites increased from 18 to almost 300 (as of 2004) across the United States and Canada. Positive impact from GPS-IPW on 850-700 hPa RH forecasts was also evident in 6-h and 12-h forecasts.

Impact of GPS-IPW data was also examined on forecasts from the more recent 20-km RUC, including a 1-h assimilation cycle and improved assimilation and physical parameterizations, now using *real-time* GPS-IPW retrievals available 30 min after valid time. In a 3-month comparison during the March-May 2004 period, 20-km RUC cycles with and without assimilation of GPS-IPW were compared with IPW for 3-, 6-, 9-, and 12-h forecasts. Using this measure, assimilation of GPS-IPW data led to strongest improvements in the 3- and 6-h forecasts, and smaller but still evident improvements in

9- and 12-h forecasts. In a severe convective weather case, inclusion of GPS-IPW data improved forecasts of convective available potential energy (CAPE), an important predictor of severe storm potential, and relative humidity. Positive impact from GPS-IPW assimilation was found to vary over seasons, geographical location, and time of day, apparently related to variations in vertical mixing. For example, GPS-IPW has a stronger effect on improving RH forecasts at 850 hPa at nighttime (than daytime) and in cooler seasons (than warmer) when surface moisture observations are less representative of conditions aloft.

As a result of these studies, assimilation of GPS-IPW was added to the operational RUC run at NOAA/NCEP in June 2005 and to the operational North American Mesoscale (NAM) model (also at NCEP) in June 2006 to improve their accuracy for short-range moisture forecasts.

1. Introduction

Observational tracking of the often rapidly evolving moisture field is an essential component of weather forecasting and numerical weather prediction (NWP). Short-range numerical weather forecast accuracy often suffers from inadequate observational definition of the three-dimensional moisture field due to its high spatial and temporal variability. Currently, three observation systems provide most atmospheric water vapor measurements: rawinsondes, surface stations, and satellites. Of these, only rawinsondes routinely provide full tropospheric moisture profiles but do so with only 12-hour temporal resolution and varying degrees of accuracy and reliability (e.g. Turner et al. 2003). Surface measurements of dewpoint temperature convertible to relative humidity are available with high temporal resolution but are not highly correlated with upper-air moisture. Satellite infrared sounder measurements cannot be used to estimate moisture below stratiform cloud layers, and satellite microwave sounders are only used over open bodies of water because of radiometric contamination from the land.

Bevis et al. (1992, 1994) and Rocken et al. (1995) envisioned the use of GPS for operational weather forecasting. Since then, estimates of integrated precipitable water vapor (IPW), retrieved from Global Positioning System (GPS) signal time delays caused by the wet and dry refractivity of the electrically neutral (i.e. non-dispersive) atmosphere have become available. These estimates of GPS-IPW can complement rawinsonde, satellite, and surface moisture observations. Since November 1994, NOAA/ESRL/GSD (Global Systems Division of the NOAA Earth System Research Laboratory, formerly the NOAA Forecast Systems Laboratory) has assembled a network that produces GPS-IPW

measurements every half-hour at more than 300 stations (as of late 2006) in the U.S. (Fig. 1). This NOAA GPS-IPW network merges data from numerous organizations including the university-based SuomiNet (Ware et al. 2000). The primary change in the NOAA GPS-IPW network between 1999 (mostly in south-central U.S., see Fig. 1 of Smith et al. 2000) and 2005 is in areal coverage.

We consider here whether the accuracy, areal coverage, and density of GPS-IPW data over the United States are adequate to improve short-range forecasts when added to other existing observations. We assess for the first time the impact of assimilating GPS-IPW retrievals into a NOAA operational NWP system *in real time*. We also attempt to explain observed seasonal, geographical, and diurnal variations of GPS-IPW impact.

GPS-IPW data have been assimilated into several developmental versions of the RUC, a mesoscale data assimilation and prediction system (see Section 2). RUC forecasts initialized with and without GPS-IPW data have been compared. The real-time parallel testing of GPS-IPW impact began in 1997 with the 60-km RUC operating on a 3-h cycle (verification described here starts in 1999) and continued through 2004, providing a long-term database for statistical evaluation. Earlier results from these GPS-IPW impact experiments with the 60-km RUC were described by Benjamin et al. (1998), Smith et al. (2000), Gutman and Benjamin (2001), and Gutman et al. (2004). Compared to Gutman et al. (2004), in which 1999-2002 RUC60 results were described, we now present a more thorough description of the 60-km RUC impact experiments with GPS-IPW over the full 6-year period (1999-2004) including further expansion of the GPS network. A more pronounced positive impact on short-range relative humidity

(RH) forecasts became evident (Section 4a) as the number of GPS observations assimilated increased from less than 20 to almost 300 by 2004.

A more recent GPS-IPW impact test is also described, now using the 20-km RUC cycles with advanced data assimilation and model, a 1-h assimilation cycle, and real-time GPS-IPW retrievals (Section 4b). A case study comparison of 20-km RUC forecasts with and without GPS-IPW assimilation investigates the short-range moisture and CAPE forecast for a tornado outbreak on 20 April 2004, correcting a model forecast flaw in this case (Section 5). Section 6 includes a discussion of seasonal, geographical, and diurnal variation of GPS-IPW impact associated with vertical mixing in the boundary layer. Conclusions and 2005-06 changes in operational use of GPS-IPW for operational weather modeling and GPS positioning are summarized in Section 7.

2. The Rapid Update Cycle

The RUC is a high-frequency mesoscale assimilation (Benjamin et al. 2004a) and model (Benjamin et al. 2004b) NWP system used operationally over the lower 48 United States and adjacent areas of Canada and Mexico. Since 1998, the RUC has run with a 1-h update cycle at the U.S. National Centers for Environmental Prediction (NCEP), currently (2006) with forecasts out to 9 h, updated hourly, and forecasts out to 12 h, updated 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 a 3-D analysis increment field that modifies the 3-D gridded background for wind, temperature, pressure, moisture, and other variables. RUC short-range forecasts, initialized using the latest hourly observations, provide guidance for critical applications including aviation and other transportation operations and severe weather forecasting. The observation time window

is minus 1 h to analysis time (see discussion in Benjamin et al. 2004a, section 3b). The RUC has a strict data cutoff time, requiring observations to be available for assimilation by 20 minutes after the analysis valid time. This requires very short data latency for operational assimilation of GPS-IPW observations (started in 2005 in the NCEP RUC, based on this study).

Two different versions of the RUC (RUC60 and RUC20) were used in these experiments, summarized in Table 1. The original version of the NCEP-operational RUC (Benjamin et al. 1994a, b) was configured with a *60-km* grid length on an 81 by 62 horizontal grid with 25 vertical levels running a *3-h* intermittent data assimilation cycle using optimum interpolation (OI). This represented a first operational effort to assimilate high-frequency observations into analyses and subsequent numerical forecasts. This version ran operationally from 1994-1998 (RUC history in Benjamin et al. 2004a, Table 1).

In the 2004 NCEP-operational version used in some of the data impact comparisons described here, the RUC horizontal domain used a *20-km* horizontal grid, 50 vertical levels, and a *1-h* assimilation cycle. All RUC versions use a generalized vertical coordinate configured as a hybrid isentropic-sigma coordinate in both the analysis and model as discussed in much greater detail in Benjamin et al. (2004a, b).

A summary of observational data available to NOAA/ESRL/GSD's version of the RUC as of 2004 is shown in Benjamin et al. 2004a, Table 2. A large variety of observation types is assimilated, although many types are limited in horizontal or vertical spatial coverage. It is important to evaluate new data sources along with already existing data platforms in order to determine their incremental value. 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 (e.g., Benjamin et al. 2004d), satellite-estimated cloud motion (estimating horizontal wind), and radar-estimated (velocity azimuth display, VAD) vertical wind profiles. 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), 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 was analyzed univariately in the RUC analysis (60-km and 20-km). Differences specifically regarding moisture assimilation between RUC60 and RUC20 are identified in Table 1. The assimilation of IPW observations (Smith et al. 2000, section 4) used an optimum interpolation (OI) based columnar adjustment (Kuo et al. 1993) through 2004. In calculating IPW innovations (difference from background RUC forecast), background moisture profiles are first interpolated to the GPS location and then vertically truncated or extrapolated near the surface such that its elevation matches that of the GPS receiver. A 2-D adjustment factor based on IPW innovations was calculated, accounting for estimated observation error standard deviation (GPS: 1.5 mm; GOES: 3 mm) and background PW error standard deviation (5 mm). The 2-D factor was then applied to each level in the background moisture profile as in Kuo et al. (1993) and Smith et al. (2000).

In the 20-km version, the assimilation of GOES cloud-top pressure (Benjamin et al.

2004a) was added (see Table 1 for RUC60/RUC20 moisture assimilation differences), and IPW adjustment was applied only to moisture profiles from surface to 450 hPa (primarily because water vapor above that level usually contributes very little to IPW). The cycled moisture variables in the 20-km RUC included water vapor mixing ratio and five hydrometeor mixing ratio fields (Benjamin et al. 2004a). These three procedures (IPW adjustment, cloud analysis, in-situ analysis steps; see Table 1 for RUC20) were performed sequentially within each of two iterations of an outer moisture analysis loop, in which the moisture background and innovations were updated after each procedure was applied. In this manner, a mutual adjustment between these different moisture observation types was forced. In 2005 as part of the 13-km RUC implementation at NCEP, a fully integrated variational assimilation of both in situ and integrated moisture observations was implemented, replacing the previous OI adjustment described above, but this was not used in the GPS-IPW impact studies described here.

The Rapid Update Cycle is dependent on adequately dense, accurate observations to spatially resolve the 3-D structures of forecast errors. Only with such observations can the 1-h RUC assimilation cycle improve short-range forecasts compared to longer-range forecasts valid at the same time (Benjamin et al. 2004a). Thus, the accuracy and timeliness of real-time GPS-IPW observations and spatial coverage and density of the GPS-IPW network, are all vital if GPS-IPW is to improve operational short-range forecasts, as shown in subsequent sections.

3. GPS Water Vapor Observations

The techniques used to retrieve IPW from ground-based GPS signal delay measurements, the errors associated with them, and applications of these observations

in weather forecasting and climate monitoring have been described and discussed in the peer-reviewed literature for more than a decade. Some of the more important works leading to the quasi-operational implementation of ground-based GPS-IPW measurements in the United States are described in Smith and Weintraub (1953), Saastamoinen (1972), Bevis et al. (1992, 1994), Yuan et al. (1993), Rocken et al. (1993, 1995), Duan et al. (1996), Niell (1996), Ware et al. (2000), Wolfe and Gutman (2000), and Gutman et al. (2004). Many of these references discuss the importance of satellite orbit accuracy in estimating tropospheric signal delays, and progress in reliably providing sufficiently accurate orbital predictions (Ge et al. 2000) has been a primary factor in implementing real-time GPS-IPW retrievals.

The degree to which NWP forecast accuracy can be improved by assimilation of GPS-IPW depends on the relative accuracy of observations vs. background forecasts, both of which contribute to the analysis least-squares solution (Talagrand 1997). Processing and satellite orbit prediction techniques were improved by NOAA and others to reduce GPS-IPW retrieval errors to values smaller than IPW background forecast errors (3-5 mm for warm-season 6-h forecasts over the U. S., Gutman and Benjamin 2001) to allow noticeable forecast improvement. The errors associated with GPS-IPW estimates are usually determined from comparisons with other moisture sensing systems, especially radiosondes and microwave water vapor radiometers. For the most part, NOAA studies have been carried out at the Department of Energy Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) Facility near Lamont, OK (Westwater et al. 1998 and Revercomb et al. 2003). Comparisons between GPS and radiosonde-derived PW indicate a 2.0 mm PW standard deviation difference at the ARM CART site between 1996 and 1999 and a 1.5

mm IPW difference in the International H2O Project (IHOP – 2002) (Birkenheuer and Gutman 2005). These differences include both GPS and RAOB measurement errors and small but non-zero representativeness errors. Comparisons at other facilities around the world are fully consistent with these results (e.g. Tregoning et al. 1998, Edmardson et al. 2000, Haas et al. 2001, and Basili et al. 2002, Guerova et al. 2003). Taken together, these results indicate that the accuracy of GPS-IPW retrievals is comparable to that of radiosonde and microwave water vapor radiometer measurements made under both operational and research conditions, including those encountered during IHOP-2002. Moreover, GPS-IPW observation error is clearly less than the background RUC forecast error for IPW.

About one-half of the sites in the NOAA ground-based GPS-IPW 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 state and local government agencies, universities [including SuomiNet (Ware et al. 2000) at http://suominet.ucar.edu], and some private companies. These organizations acquire dual frequency (L1 = 1575.42 MHz and L2 = 1227.60 MHz) carrier phase GPS observations for high accuracy positioning, navigation and surveying applications, and in the case of SuomiNet also for atmospheric and geodetic research. Most organizations provide these 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 fortuitous commonality between the requirements for high accuracy positioning and atmospheric remote sensing has facilitated the rapid expansion of real-time GPS-IPW data by

NOAA, other meteorological agencies, and universities at low cost and little additional effort.

4. GPS-IPW data impact studies with the Rapid Update Cycle

The GPS-IPW data impact studies for the RUC60 and RUC20 versions discussed in this section were conducted with different emphases, as described in Table 2. For the RUC60 1999-2004 test period, there were no changes in RUC60 model or assimilation code. There was also no change in GPS-IPW retrieval accuracy (Birkenheuer and Gutman 2005) due to the use of precise GPS orbits (computed 24 h or more after real time). In contrast, the RUC20 experiments used *real-time* GPS-IPW retrievals using an 8-h sliding window data processing approach and 2-h orbit predictions (e.g., Gutman et al. 2004, p. 354-355).

4.a RUC60 impact study

From 1994–1998, an earlier version of the RUC ran operationally at NCEP, using 60-km horizontal resolution, 25 vertical levels, stable precipitation based on supersaturation removal, and a 3-h update cycle (designated RUC60 in this paper). Although the RUC60 was replaced operationally at NCEP in 1998, the earlier code continued to run experimentally at ESRL/GSD for this study.

From late 1997 through 2004, parallel data assimilation cycles with the RUC60 were run at NOAA/ESRL/GSD for the purpose of evaluating the effect of GPS-IPW assimilation on numerical forecasts. The two cycles were run identically except that one assimilated GPS-IPW data every 3 h, while the other did not. Both cycles included assimilation of geostationary satellite (GOES) retrievals of IPW, and observations from

rawinsondes (RAOBs), commercial aircraft, wind profilers, and surface stations (METARs).

First we present results for the smaller verification domain in the south central U.S. as shown in Fig. 1. For verification, RUC forecasts of 3-h, 6-h, 9-h and 12-h duration were interpolated to mandatory isobaric levels, where differences were calculated between RAOBs and forecast grids interpolated to those stations.

We define the normalized forecast impact as

$$\text{NFI} = 100 \times \frac{\left(RMS_f(noGPS) - RMS_f(GPS)\right)}{\left(RMS_f(noGPS) - RMS_a(noGPS)\right)} \qquad \text{(Eq. 1)}$$

where RMS_f is the root mean squared difference between RAOBs and forecasts, and RMS_a is the RMS difference between RAOBs and the verifying analysis (same as Eq. 3 in Benjamin et al. (2004d). The denominator in Eq. 1, which varies from 7-8% RH in previous RUC verification (Benjamin et al. 2004a, Fig. 9d), is not actually computed here but is set conservatively as 10% RH. The NFI can be interpreted as percent of total possible improvement if forecast error was reduced to the analysis fit to observations. If it is positive, GPS-IPW observations improve the forecast. It is calculated on a monthly or annual basis and plotted in subsequent figures.

Figure 2 shows NFI for relative humidity (RH) 3-h forecasts at four isobaric levels: 850, 700, 500, and 400 hPa for the south-central U.S. verification domain. RUC60 GPS-IPW impact tests for 1999–2004 over this domain show a modest positive impact (decreased RMS forecast error) from use of GPS-IPW data for short-range forecasts of RH, strongest at 700 and 850 hPa. This impact increased over the duration of the RUC60 study as more GPS-IPW stations became available over the U.S., increasing from only 18 in 1999 to over 275 in 2004 (Fig. 2, horizontal axis labels). Since no

change occurred in to the RUC60 model, the analysis code or GPS-IPW accuracy, this continued year-to-year improvement is wholly attributable to the increased number (areal coverage) of GPS-IPW stations over the U. S.

Impact from GPS-IPW has been greatest at 850 hPa and 700 hPa isobaric levels. Generally, water vapor mixing ratio (and the temperature-dependent saturation vapor pressure) is largest near the surface, so IPW observations appear to be more highly correlated with lower tropospheric RH than RH in mid- or upper troposphere. The vertical difference in GPS impact was not forced by the assimilation design (section 2). The percentage improvement (normalized forecast impact, same normalization for all geographic areas and periods) from assimilation of GPS-IPW observations at the 700 hPa level over the south-central U.S. increased from 1.1% in 1999 to 4.9% in 2002, up to 7.9% in 2004. The improvement at 700 hPa is larger than at 850 hPa (Fig. 2), and will be discussed later in Section 6.

Figure 3 shows the impact of the GPS-IPW observations on 3-h RUC60 forecasts over the *full RUC domain* for 2000-2004. Though the early GPS-IPW sites were concentrated in the central and southern U. S. within the small verification box (see Smith et al. 2000), over time the network has expanded to cover most of the lower 48 United States. Contrasting Fig. 3 (national domain) with Fig. 2 (south-central U.S. domain), GPS impact over the full RUC domain at 850 hPa in 2004 (6.6%) was as large as that over the smaller south-central U.S. The impact at 700 hPa is smaller over the full RUC domain than the south-central U.S. domain, linked to the deeper boundary layer mixing in the south-central domain discussed in section 6. The GPS-IPW impact is clearly related to *areal coverage* and probably to *observation density* also, though there is less support for that assertion in these results.

For longer-range forecasts, improvement to national-scale RH forecasts from GPS assimilation was fairly strong at 6 h and still evident at 12 h at the 850-hPa and 700-hPa levels (Table 3, for 2004 only). The strong improvement at 3-h (Fig. 3 and Table 3) dropped by only 1/3 in the 6-h forecast (Table 3) for both the 850-hPa and 700-hPa levels. (Discussion of diurnal variation in the GPS impact, also shown in Table 3, is deferred until Section 6.)

The monthly variation in the RUC60 at 850 hPa and 700 hPa in the south-central U.S. verification area is illustrated in Fig. 4 (percent improvement in 3-h RH forecasts for by month for the five calendar years 2000–2004). The verification at 850 hPa (Fig. 4a) shows a definite seasonal trend, with stronger positive impact in the transitional "shoulder" seasons in February/March and September/October. This pattern was much less evident at 700 hPa (Fig. 4b). Weaker and less frequent synoptically driven changes in the warm season are a factor in lower overall GPS impact in summer. The larger seasonal variation of GPS impact at 850 hPa than at 700 hPa will also be related to seasonal variations in vertical mixing through the boundary layer in Section 6.

Aliasing occurs in applying an observation innovation over a layer to adjust a vertical profile (e.g., IPW vs. moisture profile). While improving the forecast accuracy at one level in a given case, sometimes the adjustment degrades forecast accuracy at another level. Figure 5, showing day-to-day effects on GPS-IPW impact at 850 hPa (Fig. 5a) and 700 hPa (Fig. 5b), reveals some verification times with slight negative impact, even though the annually averaged impact (Figs. 2) is positive. It also shows significant day-to-day and level- to-level variation in GPS-IPW impact. Also noted on Fig. 5a and 5b are the percentage of runs with a positive, negative, and null impact. (Note precision limitation in caption.) Over the six years of the RUC60 experiment, the

percentage of negative cases for 700 hPa has held relatively steady around 20%; however, the percentage of positive cases in this conservative measure increased from 27% (for 1999; see Gutman et al. 2004, Table 3) to almost 58% in 2004 (Fig. 5b).

4.b RUC20 impact study

We now consider differences in forecast skill between versions of the 20-km RUC with (RUC20-GPS) and without (RUC20-noGPS) assimilation of GPS-IPW data during a spring period from March through May 2004. As stated in Table 2, IPW observations are used for verification of the RUC20 forecasts. IPW is an *absolute* measure of atmospheric moisture content, available hourly, thus allowing more frequent forecast verification and a different verification perspective compared to verification using *relative* humidity (from rawinsondes) as used for the RUC60 impact study. We calculated temporal correlation of GPS-IPW observation error for this study as 0.07 at a 3-h period, adequately small for IPW forecast verification in this study. Forecast skill for IPW at 3-h, 6-h, 9-h, and 12-h duration is considered.

For the RUC20 impact study, a NOAA/ESRL/GSD GPS-IPW web site (http://gpsmet.noaa.gov/cgi-bin/ruc.cgi) was developed for interactive assessment of the impact of GPS-IPW data on the RUC 20-km short-term moisture forecasts. Mean and RMS difference statistics were calculated between the GPS-IPW observations and RUC20 forecast values (RUC20-GPS and RUC20-noGPS) over all sites. Summary difference fields between RUC20 forecasts with and without GPS-IPW assimilation were also determined from this comparison tool.

For the spring 2004 verification period, Figure 6 shows the RMS differences between RUC20 gridded estimates (analysis, forecasts at 3-h, 6-h, 9-h, 12-h) of total precipitable water vapor (for RUC20-GPS and RUC20-noGPS cycles) and GPS-IPW

observations at an average of 275 GPS-Met sites in the full RUC domain over the 3-month period. (Analysis difference from GPS-IPW observations indicates only the degree to which GPS-IPW observations are fit and is included for calibration of the forecast results.)

The reduction of IPW forecast error from assimilating GPS-IPW (difference between RUC20-noGPS and RUC20-GPS scores) was largest at 3-h but evident out to 12-h (Fig. 6). RUC-noGPS forecast error holds constant at about 3.0 mm IPW over the 3-12h forecast range. Assimilating GPS (RUC20-GPS) reduced the IPW error at 3 h by 0.7 mm, a substantial improvement (about 25% of overall error), and at 12 h by 0.2 mm (about 7% error reduction). The IPW bias (Fig. 7) was reduced at both the 3 and 6-h forecast times for the RUC with GPS-IPW, but also showed a drying effect from the RUC model in both the RUC with and without GPS-IPW.

5. RUC20 case study - 20 April 2004

A significant tornado outbreak occurred in the midwestern U. S. on 20 April 2004, with 53 tornadoes reported, most in Illinois and Indiana (Fig. 8) and centered at 2300-0000 UTC. The convective available potential energy (CAPE) in forecasts from the RUC20 and other operational models was underestimated in the area of the severe storms, according to the NCEP Storm Prediction Center (SPC) (S. Weiss, personal communication), and this deficiency in CAPE was largely due to insufficient moisture in the forecast lower troposphere.

At 1200 UTC 20 April, an amplifying trough was evident in the northern High Plains in 850-hPa heights, with strong south-southwesterly flow ahead of the trough from Texas northward toward Illinois and Indiana (Fig. 9a). Twelve hours later (Fig. 9b), a

deepening 850-hPa closed low had formed over southern Minnesota, with southwesterly winds over central Illinois increasing from 10 kts (5 m/s) at 1200 UTC to 40 kts (20 m/s) at 0000 UTC, bringing moist air rapidly into the region and increasing the potential for severe convective storms. A very sharp IPW moisture boundary was evident at 1200 UTC (Fig. 10a) from Iowa toward West Virginia, with IPW < 15 mm to the north and > 30 mm to the south. Moist air with IPW > 30 mm swept northward during the subsequent 12-h period (Fig. 10b).

GPS-IPW time series data (Fig. 11) from GPS sites in Illinois show a marked increase in IPW on 20 April, with the IPW almost doubling from around 15 mm to over 30 mm in just 6 h, first at Winchester, IL and then at Rock Island, IL (about 150 km north). These abrupt changes are not captured by the 12-hourly RAOB data (diamonds shown in Fig. 11).

The then-operational version of the 20-km RUC 1-h intermittent assimilation cycle was rerun for this case over a 24-h period in four experiments (Table 4) with and without GPS-IPW data. The hourly assimilation cycles for all experiments began at 0000 UTC 20 April 2004, starting from the same (no GPS) 1-h forecast from 2300 UTC 19 April 2004, and continued through 0000 UTC 21 April 2004.

Verification of RH forecasts against RAOBs was performed for both 1200 UTC 20 April 2004 and 0000 UTC 21 April 2004. For the first 12 h of ingesting GPS-IPW, differences were slight, with comparable results for most of the RH forecasts valid at 1200 UTC (not shown). A strong impact (Exp. 2 vs. Exp. 1) due to GPS-IPW assimilation is evident in RH forecasts valid at 0000 UTC 21 April 2004 (Table 5), especially at 700 hPa. These results are for the boxed area in the south central U.S. (Fig. 1), which includes the area of interest for this case study. One possible reason for

the more pronounced improvement at 700 hPa (reduced RH error from ~20%RH to ~14%RH) (Table 5) is that the surface observations, another high-frequency moisture observation source, have less influence farther aloft. The smaller effect at 850 hPa is consistent with the RUC60 results in the same south central U.S. area (Fig. 2).

Changes in IPW forecasts were clearly associated with improvements in forecasts of CAPE. Figures 12a and 12b show the 3-h CAPE forecast initialized at 2100 UTC and valid at 0000 UTC from RUC forecasts with (Exp. 2) and without (Exp. 1) GPS-IPW assimilation, respectively. Although many of the areas of CAPE are similar, e. g., the CAPE maxima in both Nebraska and Oklahoma (the other areas of severe weather in this case), there is a clear difference over Illinois and Indiana, where the experiment with GPS-IPW shows much more CAPE from northern through east-central Illinois into central Indiana, where severe storms occurred. While still relatively modest, these CAPE values from the 3-h forecast that included the GPS-IPW data are closer to the prestorm sounding value near 1000 J kg^{-1} estimated by SPC in northern and central Illinois for this case (S. Weiss, personal communication).

The difference in IPW between Exp. 2 (with GPS) and Exp. 1 (no GPS) is shown for the analysis (Fig. 13a) at 2100 UTC 20 April and 3-h forecasts (Fig. 13b) valid at 0000 UTC 21 April. GPS-IPW observations moisten the 3-h forecast in Illinois/Indiana by greater than 7 mm (Fig. 13b), corresponding to the area of increased CAPE (Fig. 12a) also from GPS-IPW assimilation. This moistened area showed temporal continuity, traced back to near St. Louis, MO at 2100 UTC (Fig. 13a, about 5 mm) and farther south-southwestward to southern MO at 1800 UTC (>3 mm, not shown) and western Arkansas at 1500 UTC (weaker, not shown). The overall shape of moistening (green and blue) also showed continuity (Figs. 13a vs. 13b).

Two further experiments (Exps. 3, 4 – defined in Table 4) were conducted for the 20 April 2004 case, adding a modification to the use of surface observations in the RUC analysis to account for PBL depth (Benjamin et al. 2004c), with and without GPS-IPW assimilation. Inclusion of this PBL-based assimilation method alone (Exp. 3) further improved the CAPE forecast (Fig. 14a) about as much as adding the GPS data (Exp. 2), showing that much of the important moisture was in the boundary layer. Thus, using surface observations more effectively and adding GPS-IPW together (Exp. 4) shows an even greater increase in the 3-h forecast of CAPE (Fig. 14b). Only in Exp. 4 did CAPE values exceed 1000 J kg^{-1} in east central Illinois, the amount estimated by SPC in this area at 0000 UTC 21 April 2004 based on rawinsonde and surface observations.

6. Seasonal, diurnal, and geographical variations in GPS impact.

In this section, we discuss seasonal, diurnal, and geographical variations in GPS impact in RUC20 and RUC60 comparisons and link these to vertical mixing in the boundary layer.

The reduced IPW forecast error from RUC20 assimilation of GPS-IPW is shown directly in Table 6 for all four seasons. As shown in Fig. 15 and Table 6, the improvement in the IPW 3-h forecast from GPS-IPW assimilation is strongest in summer (1.0 mm) and weakest in winter (0.3 mm). Mean IPW (absolute) moisture values are themselves larger in summer because saturation values of IPW rise with temperature. In contrast, GPS impact on *relative* humidity is similar year-round at 700 hPa and actually smaller in summer at 850 hPa (Fig. 4 for the south-central U.S.).

A further investigation of seasonal variation of NWP moisture forecasts reveals that RH forecast errors decrease substantially over the U.S. in summer at 850 hPa but not at

700 hPa, independent of the type of moisture observations assimilated. A 4-year (2002-2005) summary of operational RUC 3-h RH forecast errors at 850 hPa and 700 hPa shows this behavior (Fig. 16), and a similar behavior occurs for RUC 12-h forecasts and Eta/NAM 12-h forecasts (not shown). The 700-hPa vs. 850-hPa RH error difference in Fig. 16 clearly shows this seasonal variation. We conclude that this is due to deeper vertical mixing within a typically deeper planetary boundary layer (PBL) during the summer, often extending above 850 hPa but much less often extending up to 700 hPa (especially in the eastern and central U.S.) Deeper vertical mixing reduces vertical gradients of specific humidity, and a larger fraction of integrated precipitable water is within this layer of roughly constant specific humidity. This stronger coupling of 850-hPa moisture with the surface in summer through vertical mixing in the model's PBL scheme implies that during summer surface observations have proportionally more influence on subsequent 850 hPa forecast RH than in winter (also more in day than at night). In winter (or night), when the boundary layer is typically shallower, the 850-hPa level is less influenced by surface observations and the influence of GPS-IPW observations is proportionally stronger.

We also examined the diurnal variation of GPS impact over 2004 in the RUC60 experiments. Table 3 (b, c) shows that GPS impact is somewhat larger overnight in both 3-h and 6-h forecasts valid at 1200 UTC than in daytime (forecasts valid at 0000 UTC). Surface moisture observations are more highly correlated in daytime than at night with moisture aloft, especially at 850 hPa, due to deeper daytime mixing. GPS-IPW cannot add as much additional information during the day at 850 hPa as during the night, when surface observations are less representative of conditions aloft due to the typical nocturnal thermal inversion.

Overall, seasonal, geographical, and diurnal variations of vertical mixing of moisture through the PBL are clearly related to variations of GPS impact.

7. Conclusions

The question stated in the introduction was whether GPS-IPW observations were adequate in areal coverage, density and accuracy to produce improved short-range forecasts of water vapor content when added to already existing observations over the U.S. Both RUC60 and RUC20 assimilation/model GPS-IPW impact studies indicated lower moisture forecast errors out to 12-h duration when GPS-IPW data were assimilated. The RUC60 study indicates that the annual increase in forecast skill (verified with RAOB RH observations) was correlated with the year-by-year increase in GPS-IPW areal coverage and number of observations over the lower 48 United States. The number of GPS-IPW stations increased from 18 in 1999 up to almost 300 in 2004 and over 350 at this writing (September 2006). This study demonstrated for the first time a positive impact from assimilating *real-time* GPS-IPW retrievals with predicted GPS satellite orbit positions in the RUC20 tests (precise orbits were used for RUC60 retrievals in delayed real time). The RUC20 study also confirmed the 3h-12h reduction in moisture forecast errors (verified primarily with IPW observations) from assimilation of GPS-IPW data with a 1-h assimilation cycle and while incorporating more competing observations than were used in RUC60 experiments.

A case study from 20 April 2004, a challenging day for severe weather forecasters, shows the GPS-IPW data to be very useful in improving the 20-km RUC moisture and related CAPE forecasts. Assimilation of GPS-IPW data resulted in a much improved 3-

h model forecast including a focused area of higher IPW and CAPE in east central Illinois and central Indiana where a tornado outbreak occurred.

Significant variations in GPS-IPW forecast impact were found to be related to seasonal, regional, and diurnal variations in PBL mixing.

As noted by previous GPS researchers, GPS moisture observations are a fortuitous application of GPS technology, using positioning (actually, timing) errors to estimate integrated moisture, and thereby benefit weather forecasting. In turn, assimilation of GPS-IPW, especially into 3-dimensional hourly update cycles like the RUC, can allow more accurate GPS positioning by allowing improved *a priori* estimates of tropospheric propagation errors (Ahn et al. 2006), a likely boon to widespread GPS positioning applications independent of weather forecasting.

Culminating this multiyear impact study with the RUC60 and RUC20 techniques, GPS-IPW observations were introduced into the operational RUC at NCEP with the implementation of the 13-km RUC in June 2005, including a technique to detect GPS satellite orbit prediction errors and prevent assimilation of erroneous GPS-IPW data in these situations. This is the first NOAA use of GPS-IPW observations in any of its operational weather forecast models, and was followed one year later by implementation of GPS assimilation into the NCEP North American Mesoscale (NAM) model in June 2006.

The results of this paper depend on the data assimilation techniques used, which are continually improving. For instance, variational analysis techniques will be tested allowing direct assimilation of zenith wet delay observations (delay of the satellite signal due to atmospheric moisture), avoiding the retrieval of precipitable water values. It is

hoped that this will further improve the impact of GPS-related moisture information on short-range numerical predictions.

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FIGURE CAPTIONS

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

Fig. 2. Normalized forecast impact (NFI, as defined by Eqn. (1)) for the 3-h relative humidity (RH) forecast error (using RUC60) from assimilation of GPS-IPW data. Impacts at 850, 700, 500, and 400 hPa averaged by year for 1999-2004 are shown. Forecast error is assessed by computing forecast-observed RH difference with rawinsonde observations at 17 stations in the south-central U.S (within rectangle in Fig. 1). Normalized forecast impact is defined by Eq. (1) in the text.

Fig. 3. Same as Fig. 2, but for the entire RUC domain including approximately 85 RAOB stations over continental U.S. and adjacent areas of Canada and Mexico.

Fig. 4. As in Fig. 2 by month for years 2000–2004. a) For 850 hPa. b) For 700 hPa. (Note: Some months were missing due to processing problems.)

Fig. 5. Percent (not normalized) reduction of 3-h RH forecast error twice daily (0000 and 1200 UTC) from the 60-km RUC due to the assimilation of GPS-IPW data over calendar year 2004. Positive means that RUC-GPS had lower RH error scores for that verification time. Precision in statistics (averaged over 17

RAOBs in south-central U.S.) is 1%; differences less than 1% over 17 stations are rounded to zero. a) For 850 hPa. b) For 700 hPa.

Fig. 6. RMS IPW difference (mm) for RUC20 IPW analysis/forecast grids against GPS-IPW observations at ~275 sites in the RUC CONUS domain. Statistics are for the 3-month period from 1 March–31 May 2004. RUC20 with GPS is solid; RUC20 without GPS is dashed.

Fig. 7. Same as Fig. 6 but for bias (RUC gridded IPW minus GPS observed IPW).

Fig. 8. Severe weather reports for 20 April 2004, courtesy of the NCEP Storm Prediction Center. Locations of the GPS sites for Rock Island, IL, (blue R) and Winchester, IL, (red W) as well as the RAOB sites for Davenport, IA, (green Q) and Lincoln, IL, (pink L) are also plotted.

Fig. 9. Analysis of 850-hPa heights (black contours, units – dm), temperature (red dashed contours, units - °C), and dewpoint (green solid contours, for >8°C), wind (blue flags, long barb is 10 kts). Courtesy of NCEP Storm Prediction Center. a) Valid at 1200 UTC 20 April 2004. b) Valid at 0000 UTC 21 April 2004 (12 h later).

Fig. 10. Precipitable water analysis from 20km RUC analysis (Exp. 2 - cycle assimilating GPS-IPW observations. a) Valid at 1200 UTC 20 April 2004. b) Valid at 0000 UTC 21 April 2004.

Fig. 11. IPW observations (units – cm) for 19-22 April 2004. GPS-IPW time series at Rock Island, IL, (blue) and Winchester, IL, (red). IPW plots every 12 h from rawinsondes at Davenport, IA, (green diamonds) and Lincoln, IL, (pink diamonds).

Fig. 12. 3h forecast of CAPE (convective available potential energy) initialized 2100 UTC 20 April 2004 valid at 0000 UTC 21 April. Contours are in 250 J kg^{-1} increments. a) from Exp. 2 (20-km RUC with GPS-IPW) b) for Exp. 1. (20-km RUC without assimilation of GPS-IPW).

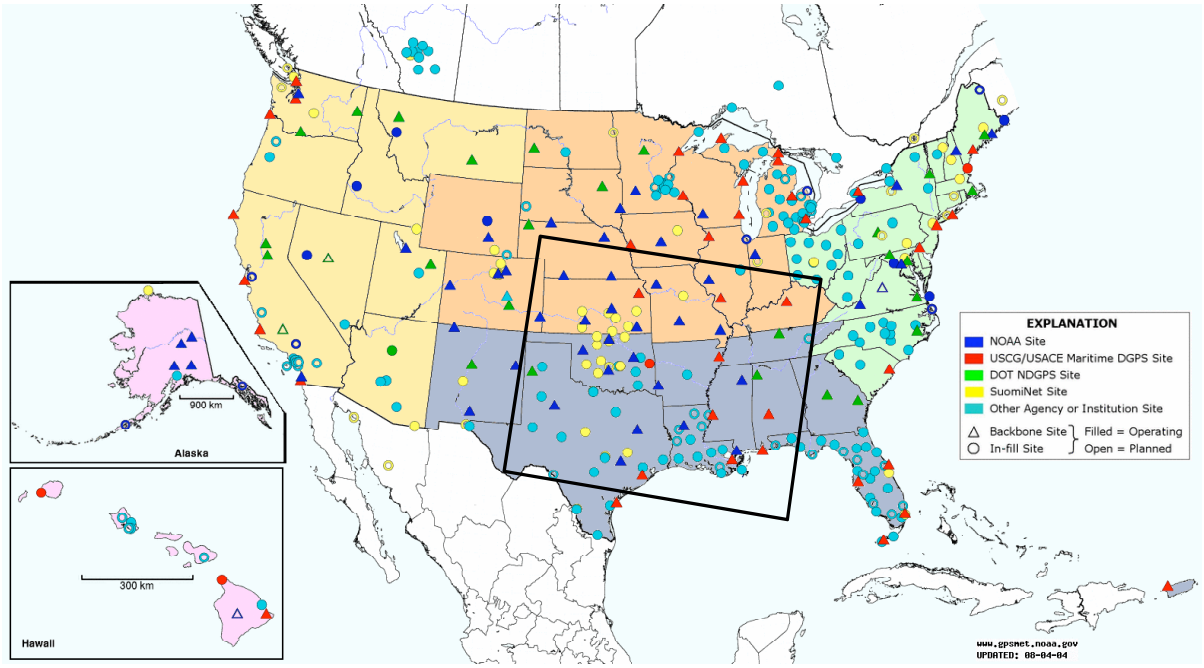
Fig. 13. IPW difference (mm) between Exp. 2 (20-km RUC with GPS) and Exp. 1 (without GPS). Difference is defined as (Exp. 2 – Exp. 1). a) Analysis valid at 2100 UTC 20 April 2004 and b) 3-h forecast valid at 0000 UTC 21 April 2004. Green/blue areas indicate moister conditions in Exp. 2 from assimilation of GPS-IPW data; orange/pink areas indicate drier conditions. Contours are in 2-mm increments starting at 1 mm. Black diamonds are the location of the GPS sites.

Fig. 14. a) Same as Fig. 12 but for Exp. 3 (with the PBL-based surface assimilation and without GPS-IPW data). b) Same as Fig. 12 but Exp. 4 (with both the PBL-based surface assimilation scheme and GPS-IPW assimilation).

Fig. 15. RMS error for RUC 3-h forecasts IPW against all GPS-IPW observations in RUC domain (including lower 48 United States) with 30-day running average from Dec 2003 to Jan 2005. Shown are RUC without GPS-IPW assimilation (solid),

RUC with GPS-IPW assimilation (dashed), and difference (boxes- RUC-noGPS minus RUC-GPS).

Fig. 16. 3-h relative humidity forecast error from the operational RUC model at 850 hPa (top, solid), 700 hPa (top, crosses), and 700-850 hPa error difference (bottom, boxes) from January 2002 through April 2006 for full national RUC domain. A 30-day running mean was applied to verification every 12 h at RAOB launch times, and missing values are from missing data in the ESRL/GSD verification archive.



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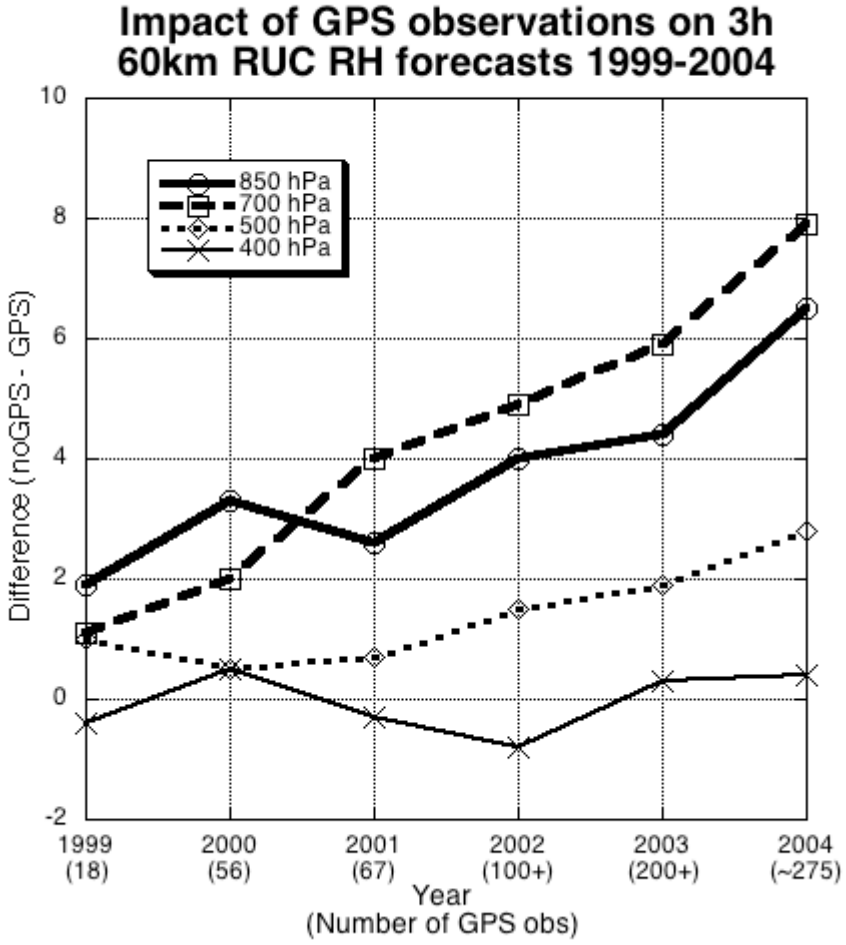

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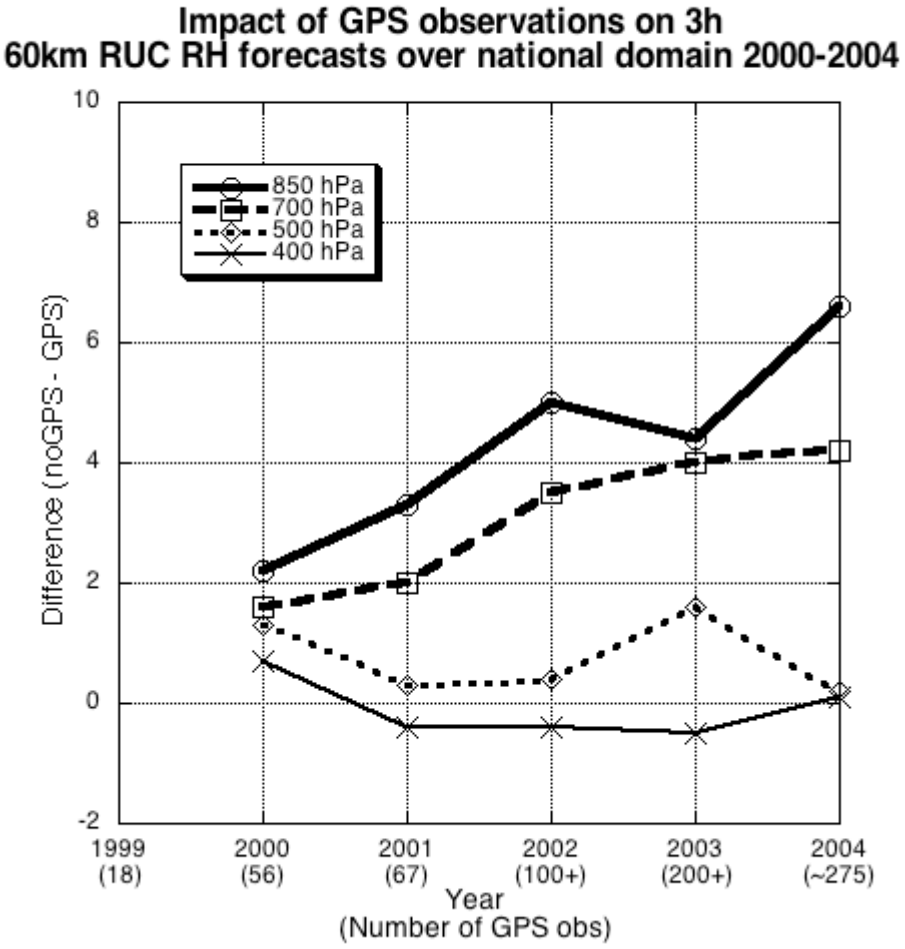

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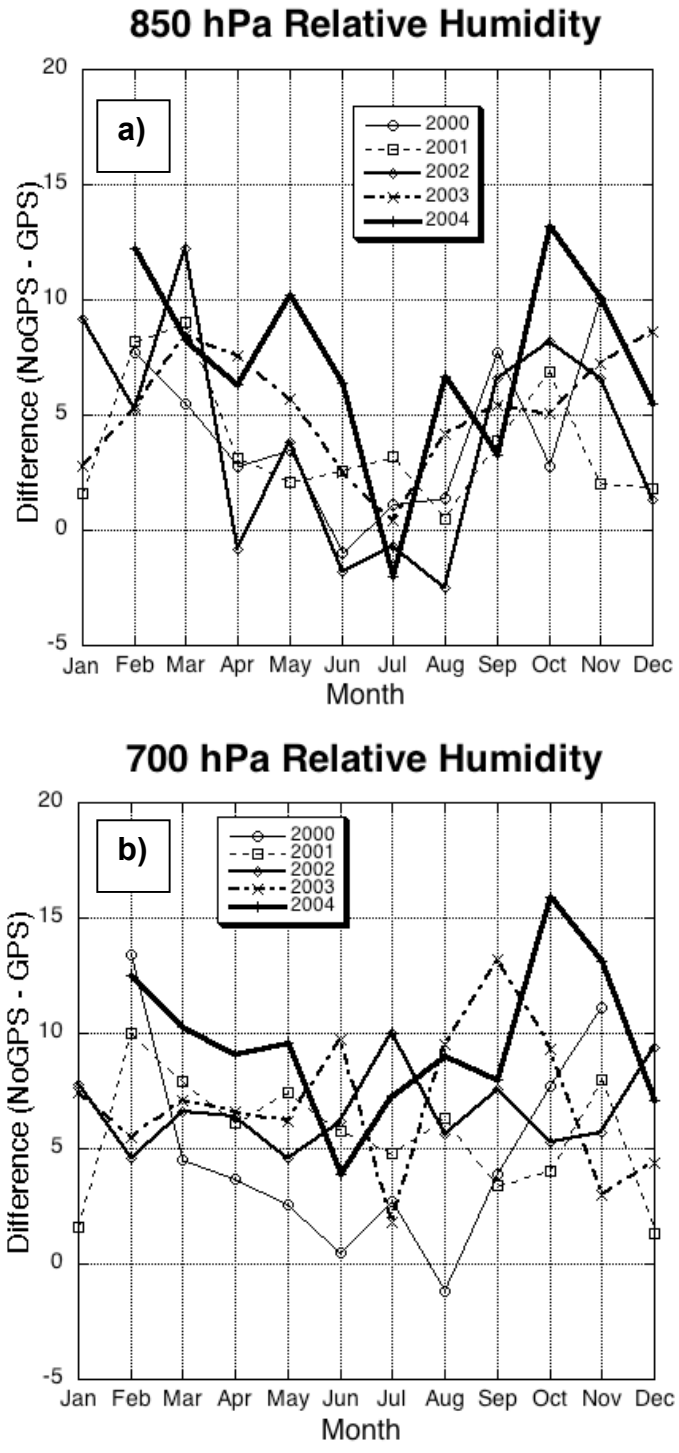

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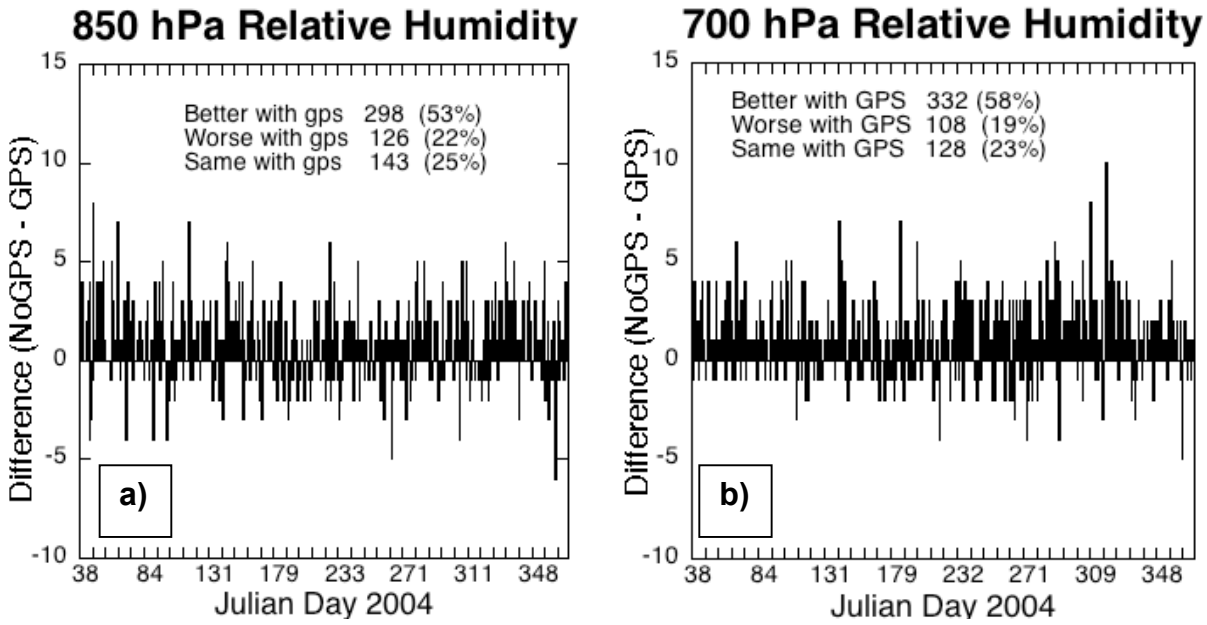

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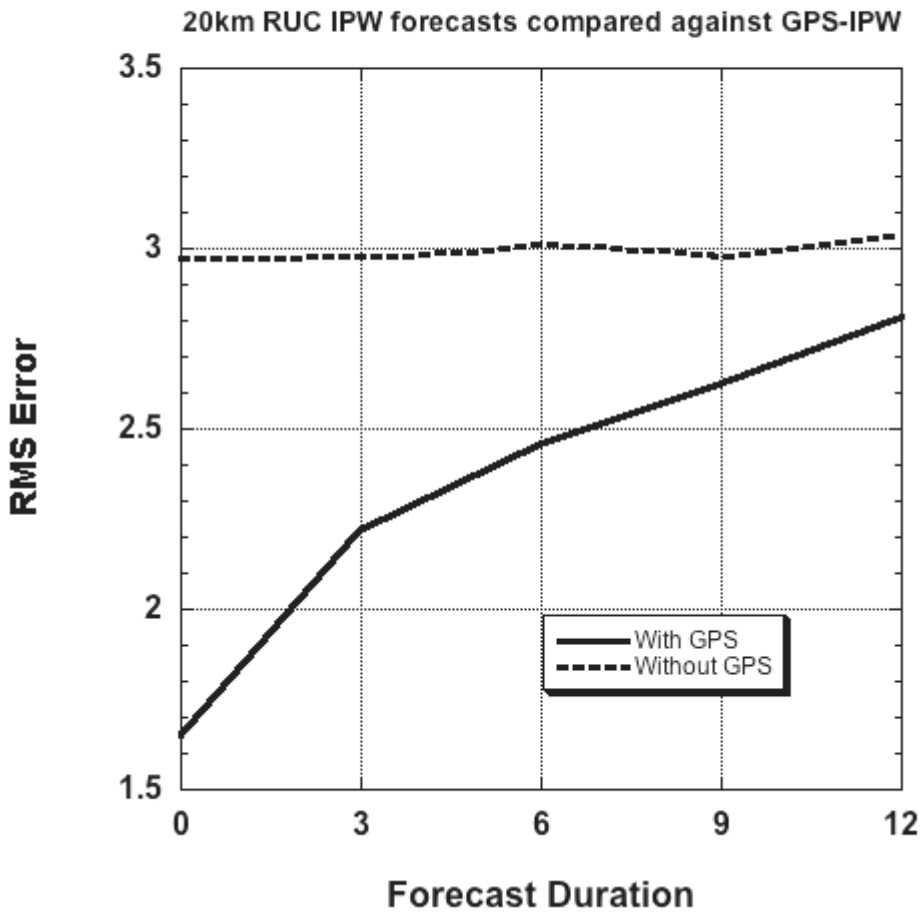

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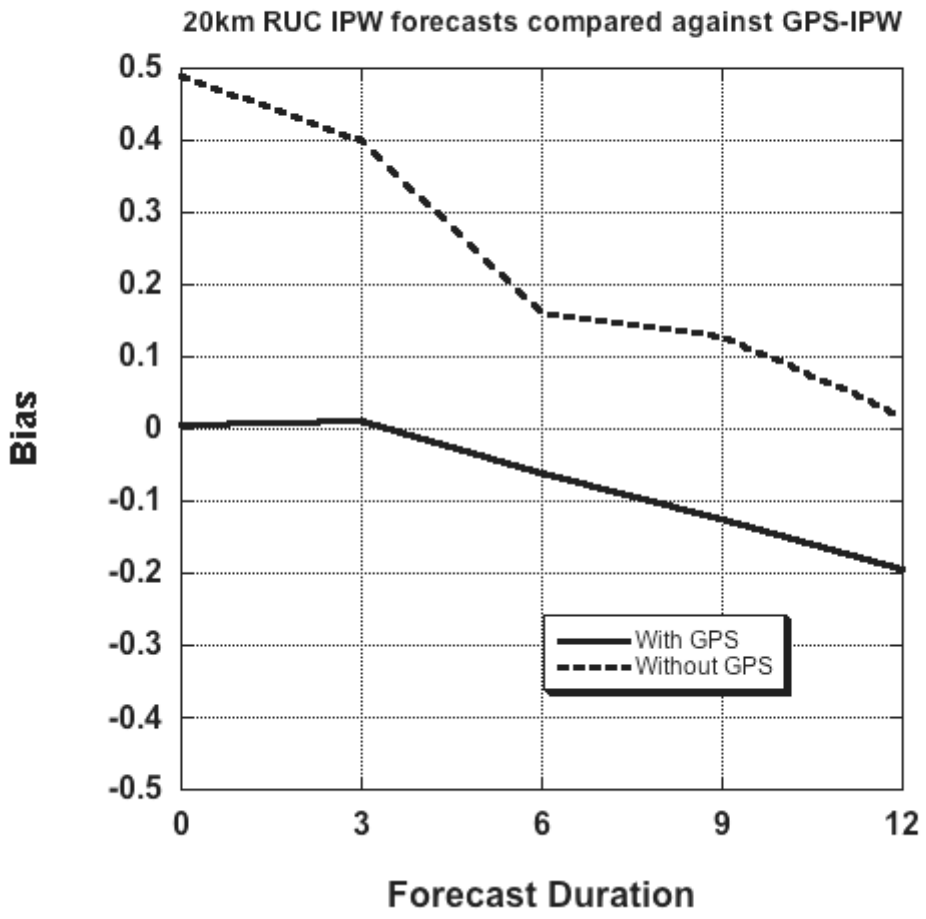

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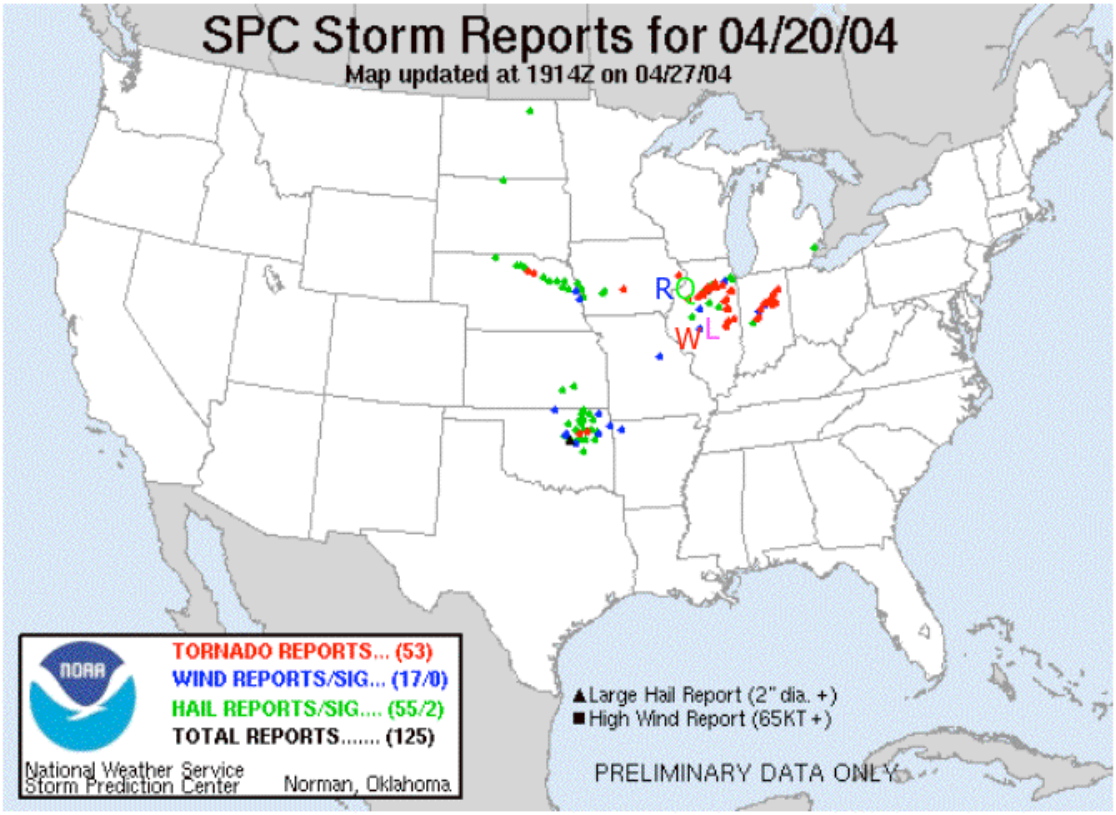

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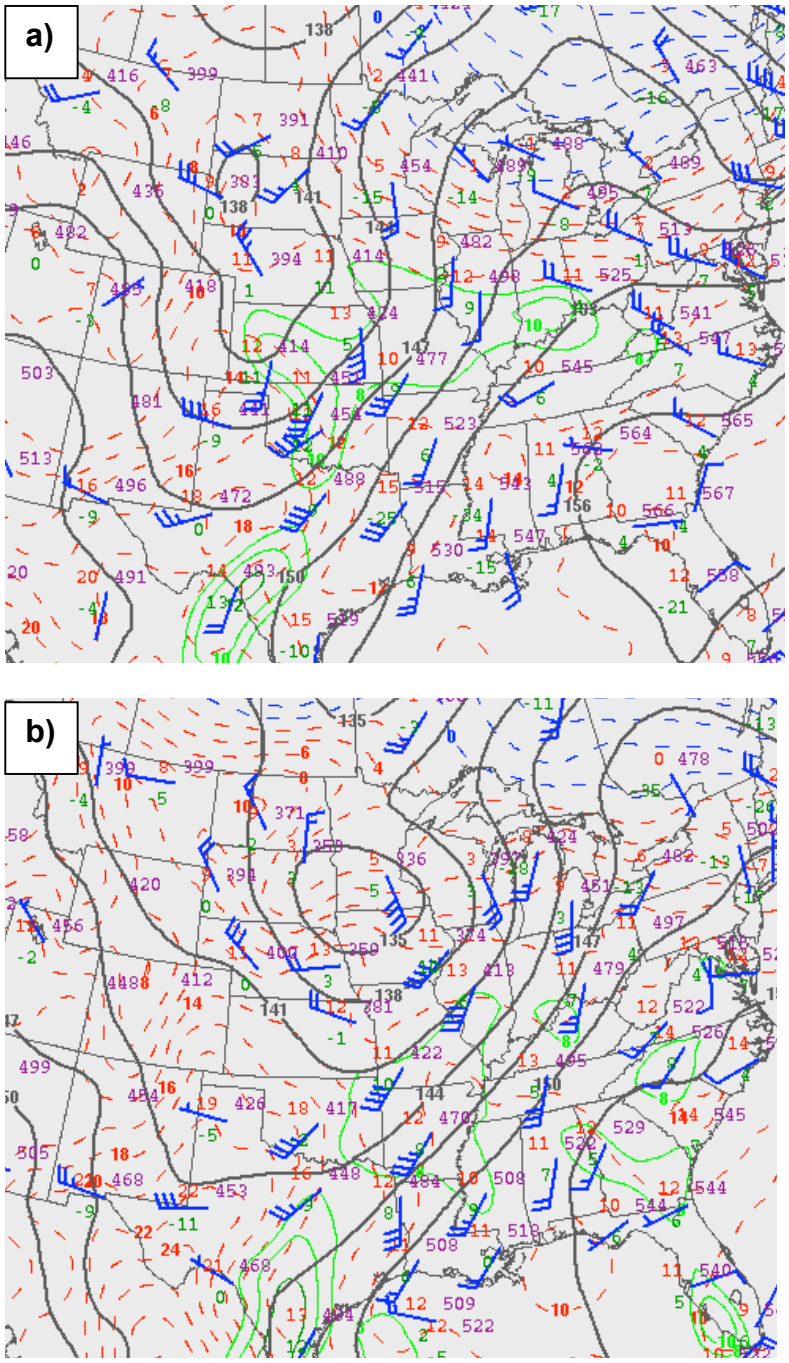

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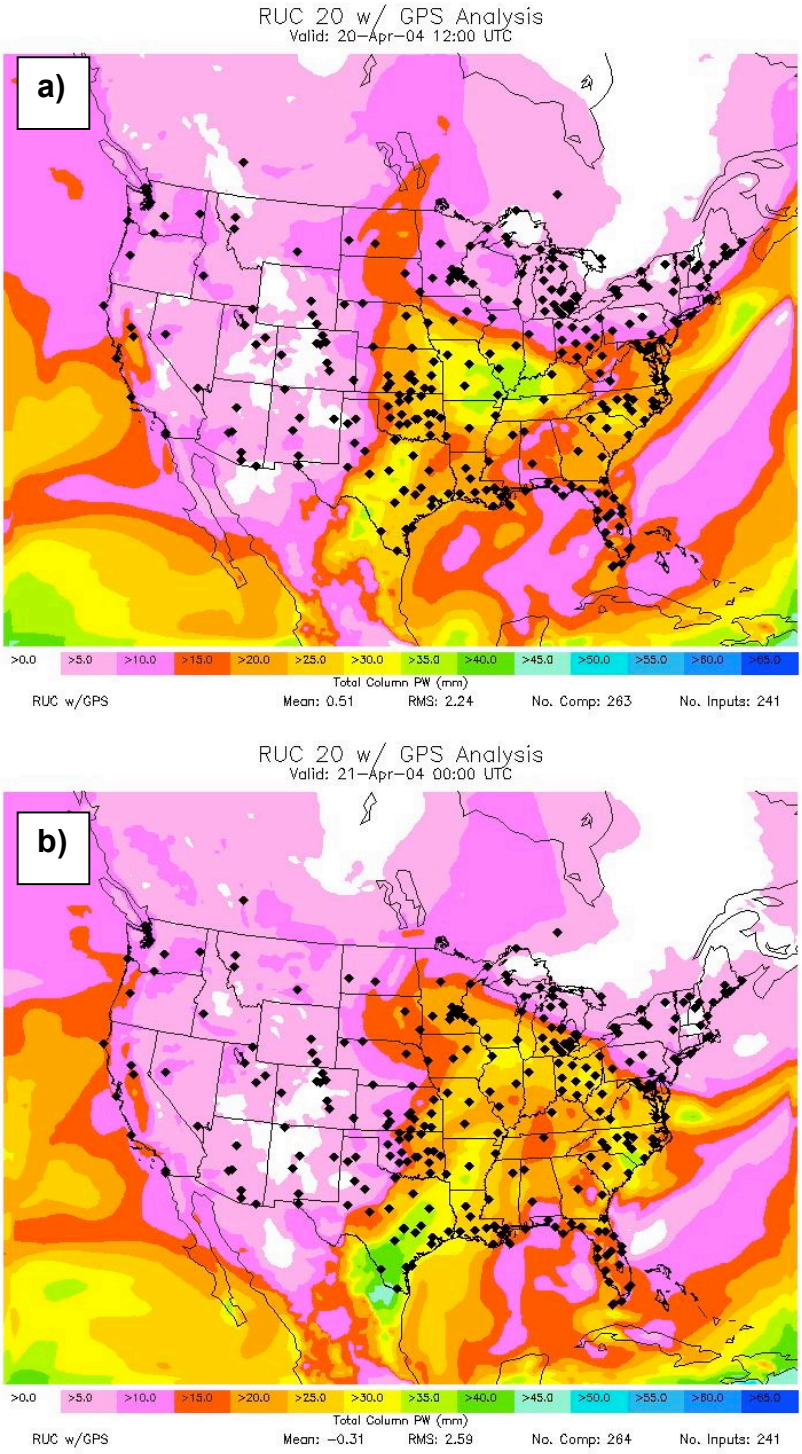

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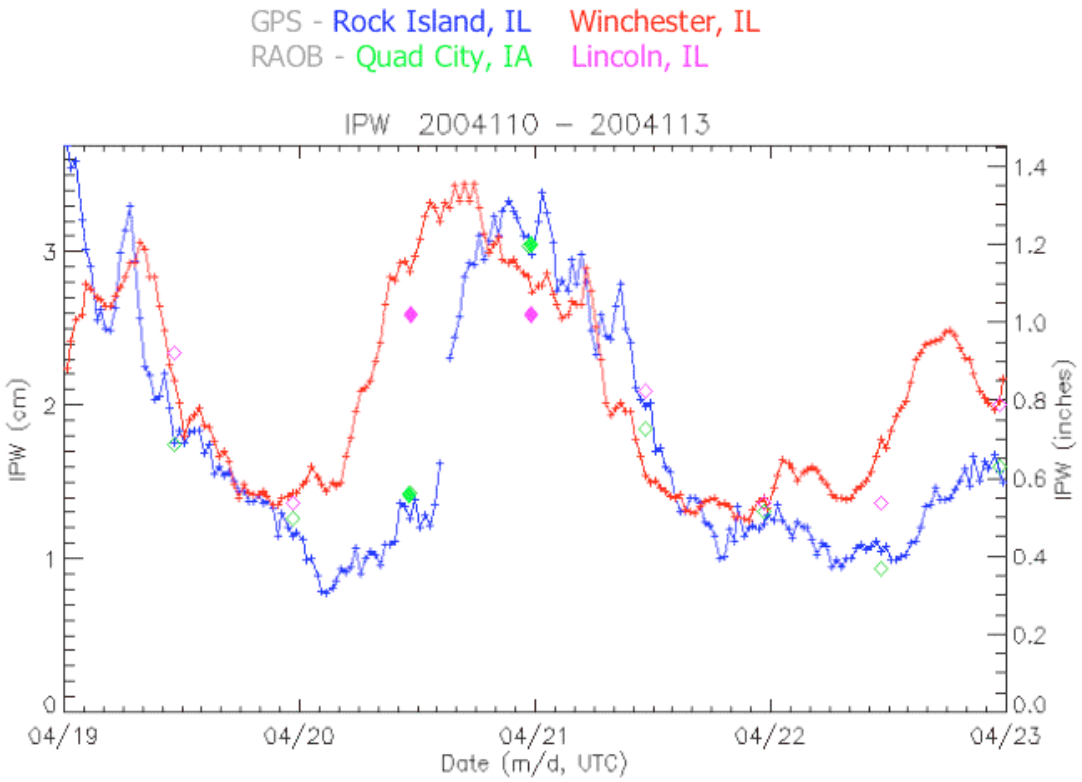

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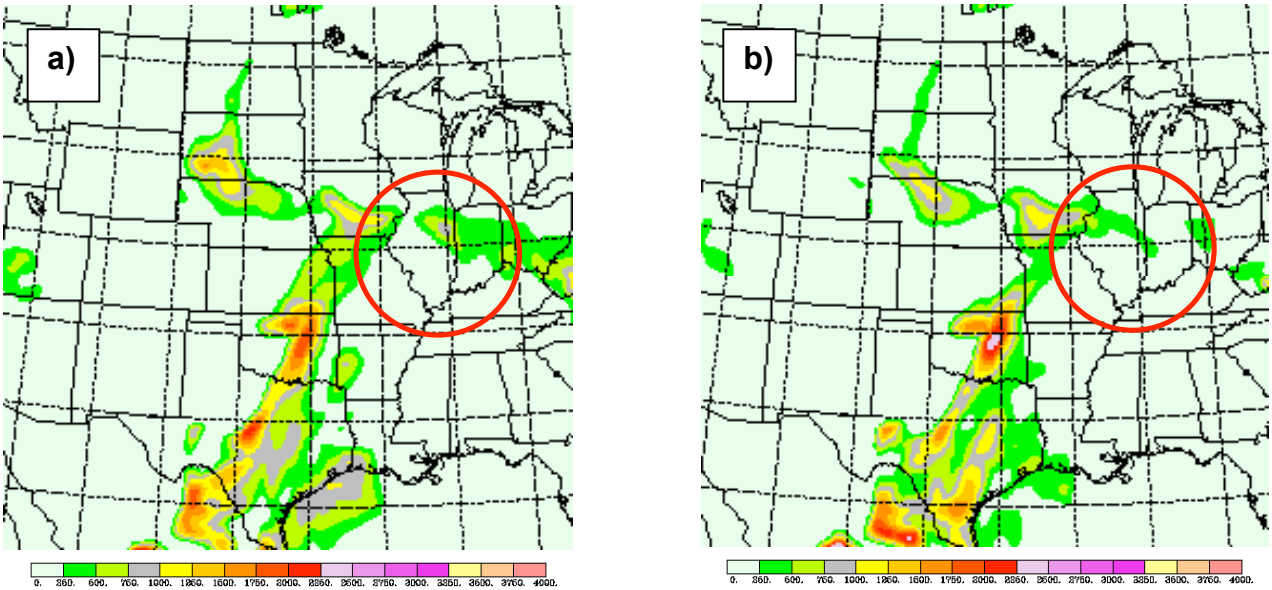

Fig. 12. 3h forecast of CAPE (convective available potential energy) initialized 2100 UTC 20 April 2004 valid at 0000 UTC 21 April. Contours are in 250 J kg^{-1} increments. a) from Exp. 2 (20-km RUC with GPS-IPW) b) for Exp. 1. (20-km RUC without assimilation of GPS-IPW).

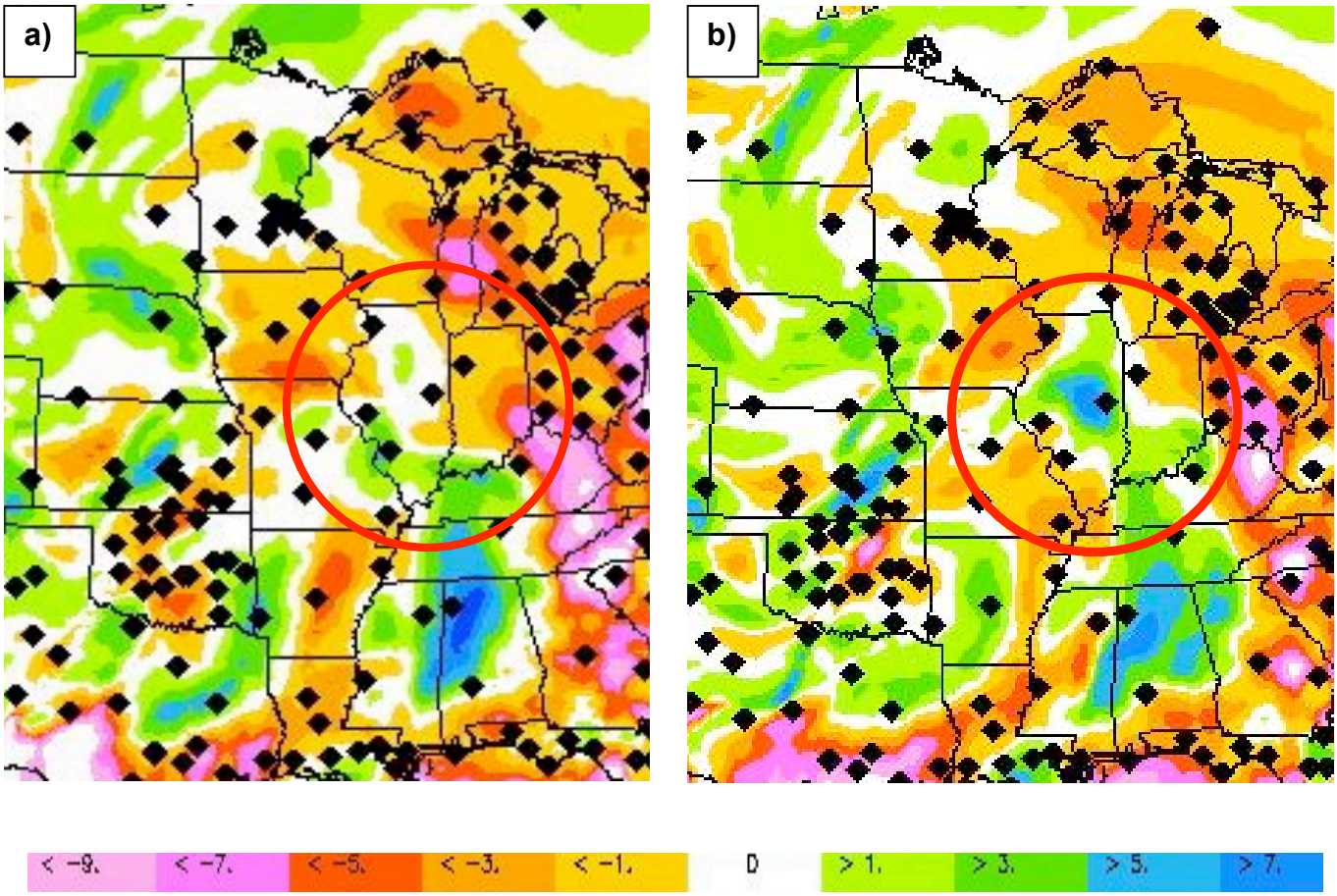

Fig. 13. IPW difference (mm) between Exp. 2 (20-km RUC with GPS) and Exp. 1 (without GPS). Difference is defined as (Exp. 2 – Exp. 1). a) Analysis valid at 2100 UTC 20 April 2004 and b) 3-h forecast valid at 0000 UTC 21 April 2004. Green/blue areas indicate moister conditions in Exp. 2 from assimilation of GPS-IPW data; orange/pink areas indicate drier conditions. Contours are in 2-mm increments starting at 1 mm. Black diamonds are the location of the GPS sites.

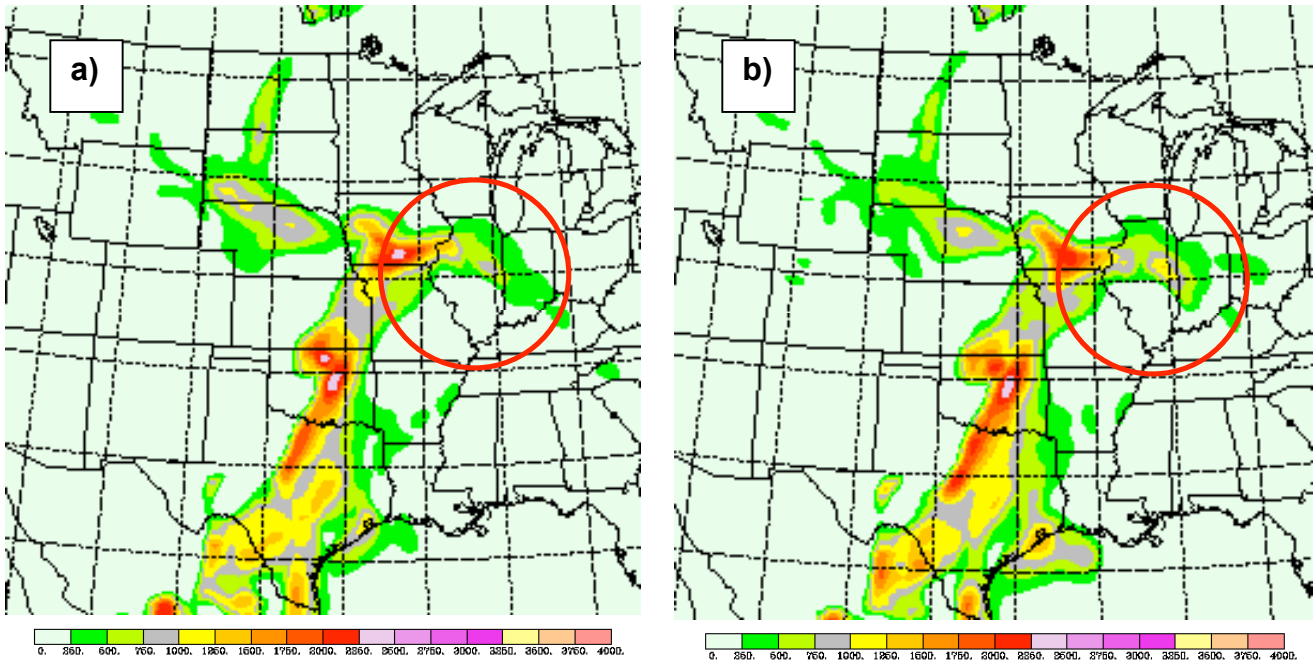

Fig. 14. a) Same as Fig. 12 but for Exp. 3 (with the PBL-based surface assimilation and without GPS-IPW data). b) Same as Fig. 12 but for Exp. 4 (with both the PBL-based surface assimilation scheme and GPS-IPW assimilation).

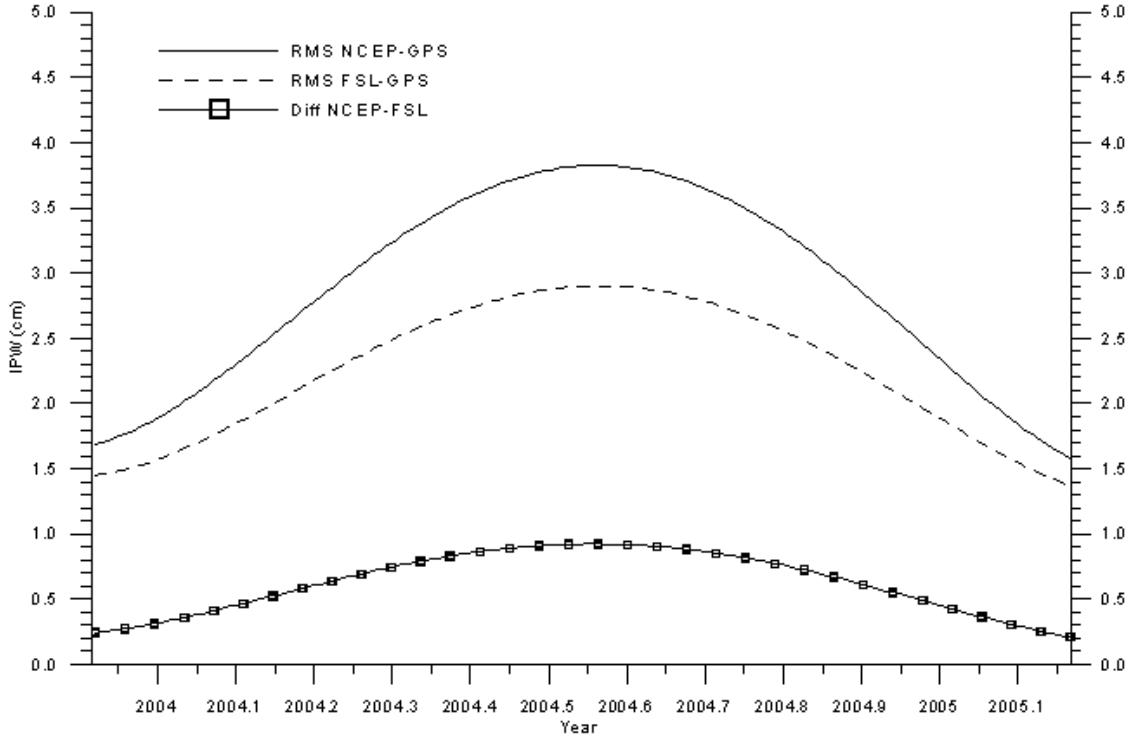

Fig. 15. RMS error for RUC 3-h forecasts IPW against all GPS-IPW observations in RUC domain (including lower 48 United States) with 30-day running average from Dec 2003 to Jan 2005. Shown are RUC without GPS-IPW assimilation (solid), RUC with GPS-IPW assimilation (dashed), and difference (boxes- RUC-noGPS minus RUC-GPS).

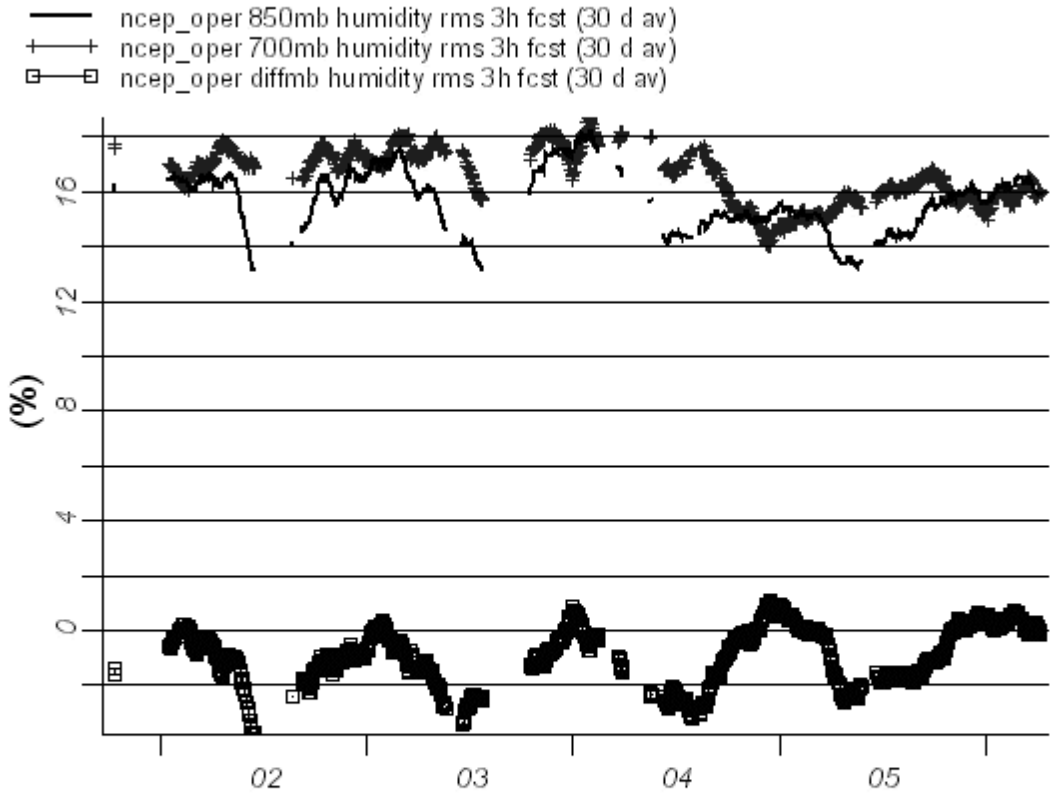

Fig. 16. 3-h relative humidity forecast error from the operational RUC model at 850 hPa (top, solid), 700 hPa (top, crosses), and 700-850 hPa error difference (bottom, boxes) from January 2002 through April 2006 for full national RUC domain. A 30-day running mean was applied to verification every 12 h at RAOB launch times, and missing values are caused by missing data in the ESRL/GSD verification archive.

TABLE CAPTIONS

Table 1. Relevant assimilation/model differences between 60-km and 20-km versions of RUC used in long-term experiments.

Table 2. Experiment differences between long-term RUC60 and RUC20 studies.

Table 3. 3-h, 6-h, and 12-h normalized forecast impact (as in Fig. 2) from assimilation of GPS-IPW data for RUC60 forecasts for 2004 verified over the full domain verification area against RAOBs for three levels, 850 hPa, 700 hPa, and 500 hPa.

a) Forecasts valid at both 0000 and 1200 UTC

b) Forecasts valid at 0000 UTC only

c) Forecasts valid at 1200 UTC only

Table 4. Data assimilation variations for RUC experiments for 20 April 2004 case study.

Table 5. Improvement (% RH, not normalized) from incorporation of GPS-IPW data for RUC20 forecasts (Exp.1 minus Exp.2) valid 0000 UTC 21 April 2004 as verified with the 17 RAOBs in the south central U.S. (Fig. 1).

Table 6. IPW differences (RMS and bias, units - mm) between RUC gridded IPW data and GPS-IPW observations over 12-month period from Dec 2003 to Nov 2004 broken down into winter (DJF), spring (MAM), summer (JJA), and fall (SON) 3-month periods. These differences are shown for analysis (top) and 3-h forecasts (bottom). The difference between RMS scores (ΔRMS) is also shown for (RUC-noGPS minus RUC-GPS). Number of verification times going into the averages is in parentheses.

Characteristic	RUC60	RUC20
Assimilation cycle	3 h	1 h
Observation time window	-1 h to +0.5 h	-1 h to 0 h
Horizontal resolution	60 km	20 km
Number of vertical levels	25	50
Moisture observations assimilated	RAOB METAR dewpoint GOES IPW GPS IPW	RAOB METAR dewpoint GOES IPW GPS IPW GOES cloud-top data
Moisture analysis variable	Condensation pressure	Log (water vapor mixing ratio)
IPW assimilation technique	OI adjustment at all levels	OI adjustment up to 450 hPa
Steps in moisture analysis	1) IPW assimilation (OI) 2) In situ assimilation (OI)	1) IPW assimilation (OI) 2) Cloud assimilation 3) In situ assimilation (3DVAR)
Model treatment for resolved clouds	Supersaturation removal	Bulk mixed-phase cloud microphysics
Model treatment for parameterized clouds	Grell (1993)	Grell-Devenyi (2002)

Table 1. Relevant assimilation/model differences between 60-km and 20-km versions of RUC used in long-term experiments.

	RUC60	RUC20
Experiment duration	1999-2004	Mar-May 2004 (some comparisons for Jan-Dec 2004)
GPS-IPW retrieval	Used precise satellite orbit data processed 24 h after observation time.	Used satellite orbit prediction processed 30 min after observation time.
Primary Verifying Observations	Relative humidity from RAOBs at mandatory levels	Integrated precipitable water from GPS retrievals

Table 2. Experiment differences between long-term RUC60 and RUC20 studies.

Level	03h	06h	12h
850 hPa	6.6	4.7	0.9
700 hPa	4.2	2.8	0.6
500 hPa	0.2	0.8	0.1

a) Valid at 0000 UTC and 1200 UTC combined

Level	03h	06h	12h
850 hPa	5.1	3.6	1.0
700 hPa	3.8	2.4	0.1
500 hPa	-0.2	0.2	0.1

b) Valid at 0000 UTC only

Level	03h	06h	12h
850 hPa	8.2	5.9	0.8
700 hPa	4.6	3.2	1.2
500 hPa	0.6	1.3	-0.4

c) Valid at 1200 UTC only

Table 3. 3-h, 6-h, and 12-h normalized forecast impact (as in Fig. 2) from assimilation of GPS-IPW data for RUC60 forecasts for 2004 verified over the full domain verification area against RAOBs for three levels, 850 hPa, 700 hPa, and 500 hPa.

Experiment	Assimilation of GPS-IPW	Modified assimilation of Surface observations using PBL depth
1	N	N
2	Y	N
3	N	Y
4	Y	Y

Table 4. Data assimilation variations for RUC experiments for 20 April 2004 case study.

Level	03h	06h	09h	12h
850 hPa	1	0	-1	0
700 hPa	6	3	7	6
500 hPa	-1	4	2	1

Table 5. Improvement (% RH, not normalized) from incorporation of GPS-IPW data for RUC20 forecasts (Exp.1 minus Exp.2) valid 0000 UTC 21 April 2004 as verified with the 17 RAOBs in the south central U.S. (Fig. 1)

Analysis	RMS, RUC with GPS	RMS, RUC w/o GPS	∆RMS (col 2 – col 1)	Bias, RUC with GPS	Bias, RUC w/o GPS
DJF (2101)	1.335	2.045	0.71	-0.062	-0.096
MAM (2029)	1.667	2.973	1.31	0.017	0.489
JJA (2159)	2.252	4.031	1.78	0.138	0.882
SON (2031)	1.842	3.259	1.42	0.0625	0.8984

3h forecast	RMS, RUC with GPS	RMS, RUC w/o GPS	∆RMS (col 2 – col 1)	Bias, RUC with GPS	Bias, RUC w/o GPS
DJF (2062)	1.729	2.055	0.33	-0.060	-0.007
MAM (2008)	2.257	2.975	0.72	0.019	0.401
JJA (2136)	3.096	4.025	0.93	0.015	0.603
SON (1958)	2.525	3.338	0.81	0.116	0.869

Table 6. IPW differences (RMS and bias, units - mm) between RUC gridded IPW data and GPS-IPW observations over 12-month period from Dec 2003 through Nov 2004 broken down into winter (DJF), spring (MAM), summer (JJA), and fall (SON) 3-month periods. These differences are shown for analysis (top) and 3-h forecasts (bottom). The difference between RMS scores (∆RMS) is also shown for (RUC-noGPS minus RUC-GPS). Number of verification times going into the averages is in parentheses.