Rapid Retrieval and Assimilation of Ground Based GPS Precipitable Water Observations at the NOAA Forecast Systems Laboratory: Impact on Weather Forecasts

Seth I. GUTMAN, Susan R. SAHM, Stanley G. BENJAMIN, Barry E. SCHWARTZ

NOAA Research-Forecast Systems Laboratory, Boulder, Colorado, USA

Kirk L. HOLUB, Jebb Q. STEWART

NOAA Research-Forecast Systems Laboratory, Boulder, Colorado [Contract with Systems Research Group, Inc. (SRG), Colorado Springs, Colorado, USA]

and

Tracy Lorraine SMITH

NOAA Research-Forecast Systems Laboratory, Boulder, Colorado [In collaboration with the Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University, Fort Collins, Colorado, USA]

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Abstract

Since 1994, the NOAA Research-Forecast Systems Laboratory (NOAA/FSL) has been evaluating the utility of ground-based Global Positioning System (GPS) remote sensing techniques for operational weather forecasting, climate monitoring, atmospheric research, and other applications such as satellite calibration and validation. Techniques have been developed to acquire, process, distribute GPS integrated precipitable water vapor (IPW) retrievals and ancillary surface meteorological observations every 30-minutes with less than 15 minute latency. Techniques to assimilate these observations into the research version of the Rapid Update Cycle (RUC) numerical weather prediction assimilation/model system running hourly at NOAA/FSL have been developed, and the impacts of these observations on short-range weather forecast accuracy have been evaluated since 1998 using a 60-km version of the system.

These assessments consist of data denial experiments (parallel runs with and without GPS water vapor observations) to determine the impact that GPS-derived integrated (or total column) precipitable water vapor (IPW) retrievals have on short-range moisture and precipitation forecasts. The experiments have been conducted over a portion of the central United States that, from a meteorological perspective, is one of the best-observed areas on Earth. While this greatly facilitates the impact assessments, it also presents a special challenge to a new observing system under evaluation, such as GPS-Met, since relatively few measurements have to "compete" with an enormous number of other (conventional and non-conventional) observations of similar and related parameters. Despite this, five years of experiments in-

Corresponding author: Seth I. Gutman, Chief, GPS-Met Observing Systems Branch, NOAA Forecast Systems Laboratory, 325 Broadway R/FS3, Boulder CO 80305-3328, USA
E-mail: Seth.I.Gutman@noaa.gov
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dicate more or less continuous improvements in 3-hour relative humidity forecasts at pressure levels below 500 hPa. The greatest skill is seen during the cold season when moisture changes are dominated by synoptic-scale weather systems. Perhaps the most significant result is that the impact in improved forecast skill from assimilation of GPS-IPW data has increased each year as the number of stations has increased, suggesting that further increases in the network density over the United States will result in further forecast improvement.

1. Introduction

In December 1992, the NOAA Forecast Systems Laboratory (NOAA/FSL) in Boulder, Colorado was actively looking for a way to make all-weather upper-air moisture observations to complement the thermodynamic measurements made with Doppler radar wind profilers equipped with radio acoustic sounding system (RASS) temperature sensors. Based on an article on the effects of the troposphere on GPS measurements (Brunner and Welsch 1993), FSL started to investigate the use of the satellite Global Positioning System (GPS) as an alternative to rawinsondes and surface-based microwave water vapor radiometers for this purpose. As described in Wolfe and Gutman (2000), FSL was approached by the University Corporation for Atmospheric Research (UCAR) and North Carolina State University (NCSU) for assistance in conducting the GPS-Storm experiment in the spring of 1993 (Rocken et al. 1995). Participation in this experiment gave FSL an opportunity to assess the ability of GPS to monitor warm season signal delays caused by water vapor in the atmosphere (Bevis et al. 1992) and relate them to weather phenomena in the central United States. Based on the results of this and another experiment conducted with UCAR during the winter months of 1993–1994, NOAA/FSL began a long-term scientific and engineering evaluation of the utility of ground-based GPS integrated precipitable water (IPW) retrievals for weather forecasting, climate monitoring, and other applications including satellite calibration and validation.

FSL 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).

2. Data acquisition

Operational weather agencies have begun to implement numerical weather prediction (NWP) models with higher horizontal and vertical resolution, and initialize them more frequently to support applications such as transportation and severe weather forecasts. Higher frequency data assimilation drives the need for more timely observations within and upstream of the forecast area of concern. Data must also be available with minimal latency to be useful for other applications including diagnostic algorithms (Mazany et al. 2002), data fusion (Keighton et al. 2003), model verification, and general subjective forecasting.

At this time, the most frequently initialized U.S. NWS model is the Rapid Update Cycle, or RUC (Benjamin et al. 2003). The RUC cur-

rently provides analyses (i.e., initial state estimates using data assimilation) and forecasts every hour at a 20-km horizontal resolution and 50 vertical levels. Mesoscale models such as the RUC20 describe weather phenomena at a size-scale somewhat larger than most thunderstorm-scale systems, but smaller than synoptic features such as tropical storms. The RUC20 generates a new analysis using the latest observations combined with a previous 1-h forecast (Fig. 1). Each hour, the RUC ingests data from a large number of observing systems (Table 1) and uses them to forecast the weather up to 12 h in the future.

Table 1 shows that the state of the atmosphere over North America is actually defined by a composite observing system, with each system providing only partial information. Even with this composite observing system, the state of the atmosphere in the data-rich United States is still heavily underdetermined (the number of observations is much smaller than the number of grid points). As of late 2003, FSL acquires GPS and ancillary meteorological observations in near real time from more than 200 GPS meteorological sites belonging to U.S. federal, state, and local government agencies, universities, and private companies (Fig. 2). These GPS meteorological (GPS-Met) observations are assimilated into experimental versions of the RUC and Local Analysis and Prediction System (LAPS) models run at FSL every hour.

The GPS sites are partitioned into two categories of continuously operating reference stations (CORS): backbone sites and infill sites. Backbone sites provide an assured source of high quality GPS-Met observations to NOAA. They are operated by (or on behalf of) various U.S. federal government agencies, are monitored and maintained as operational systems, have dedicated communications, and all have collocated surface meteorological sensors. Infill sites provide the essential network densification. They belong to other agencies or organizations, and are not generally maintained as operational systems. Infill sites may or may not have collocated meteorological sensors. Those that do not have nearby automated surface weather stations from which pressure and temperature measurements can be acquired in real time, interpolated to the horizontal and vertical location of the GPS antenna, and used to parse the GPS tropospheric signal delays into their wet and dry components as described by Gutman et al. (2003).

The ability to acquire GPS and ancillary meteorological observations from diverse GPS re-

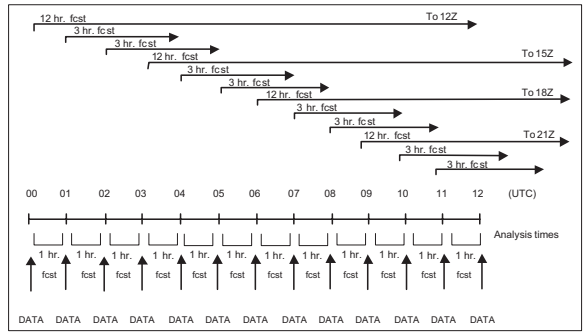

Fig. 1. Data ingest, analysis, and forecast cycle for the Rapid Update Cycle (RUC) used operationally at the National Centers for Atmospheric Prediction (NCEP) as of 2003. The 60-km version of the RUC used in experiments described in this paper used a 3-h cycle.

Table 1. Observations currently used by the Rapid Update Cycle (RUC) numerical weather prediction model.

Observing System	~Number	Freq.	In Use At
Rawinsonde (including special obs)	80	12 h	NCEP & FSL
NOAA 405 MHz wind profilers	31	1 h	NCEP & FSL
Boundary-layer 915 MHz wind profilers	24	1 h	NCEP & FSL
RASS virtual temperatures	10	1 h	NCEP & FSL
VAD winds (WSR-88D radars)	110–130	1 h	NCEP & FSL
ACARS (wind/temp)	1400–4500	1 h	NCEP & FSL
Surface METAR reports	1500–1700	1 h	NCEP & FSL
Surface mesonet reports	2500–4000	1 h	NCEP & FSL
Buoys	100–150	1 h	NCEP & FSL
GOES precipitable water	1500–3000	1 h	NCEP & FSL
GOES cloud drift winds	1000–2500	1 h	NCEP & FSL
GOES cloud top pres/temp	~10 km res.	1 h	NCEP & FSL
SSM/I precipitable water	1000–4000	1 h	NCEP Only
GPS precipitable water	200	1 h	FSL, NCEP by 03/03

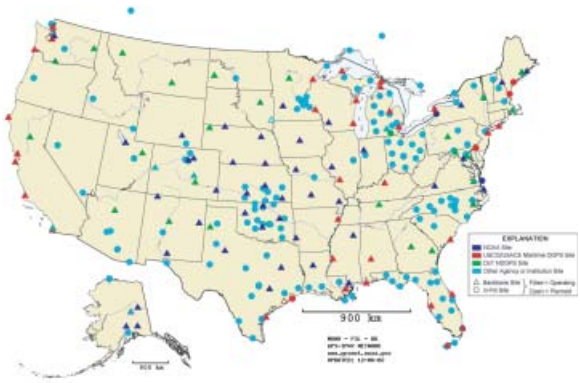

Fig. 2. NOAA/FSL GPS-Met network as of 6 December 2002.

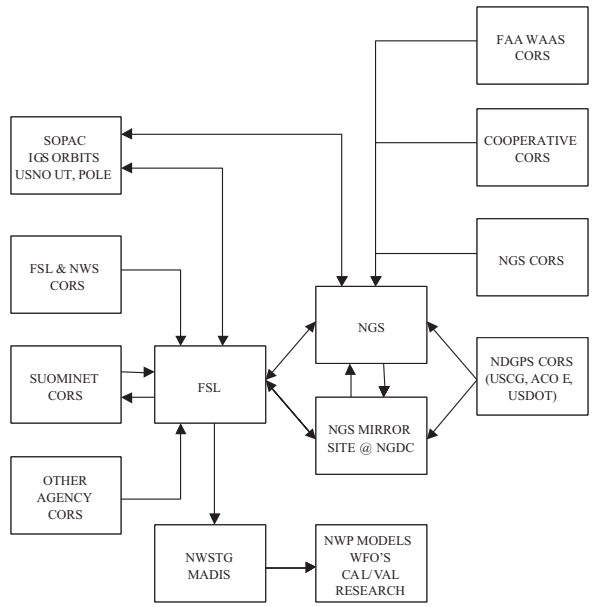

Fig. 3. Schematic GPS-Met data flow diagram.

ceivers and antennas belonging to numerous organizations was incorporated into the redesign of the GPS-Met data acquisition and processing system in 2000. An attribute of the redesigned system is that the data distribution methods and file naming conventions of disparate organizations can be accommodated without requiring these organizations to make any changes to their existing system architectures. Typically, organizations need only configure firewalls to have their data acquired integrated into the GPS-Met network. A schematic GPS-Met data flow diagram is presented in Fig. 3.

GPS data acquisition begins at 2 and 32 min after the hour and is normally completed within 3 to 4 min using media ranging from dedicated land-lines at NOAA and NDGPS CORS, to the internet using HTTP, FTP, and SCP protocols. Once the GPS and surface meteorological observations are received, they are decimated to 30-s epochs for GPS, 5-min averages for meteorological data, and written into RINEX2 format files using the International GPS Service file name convention. These files are then shipped to the processing system via an export NFS file system.

3. Data processing

GPS-Met data processing involves three distinct steps: estimating the zenith-scaled tropospheric delay (ZTD) and gradient; computing the wet-delay mapping function (using surface temperature and the technique described by Bevis et al. (1992)), or the mean temperature estimated from a NWP model as described in Gutman et al. (2003) and retrieving IPW; and evaluating the IPW retrieval using physical quality control metrics.

Determination of ZTD and its gradient is accomplished using GAMIT software developed by the Massachusetts Institute of Technology (MIT) in collaboration with the Scripps Institution of Oceanography. The input data required by GAMIT are the raw GPS observations, earth orientation parameters, and two-hour orbit predictions from the hourly GPS satellite orbit product generated by the Scripps Orbit and Permanent Array Center (SOPAC). The number of calculations required to estimate signal delays is proportional to the square of the number of sites being processed. Therefore, for the purposes of data processing, the GPS-Met network is logically divided into "sub-networks" each consisting of four IGS fiducial sites located at the far corners of the U.S. and 15 to 25 sites, depending on the speed of the processing node.

Data processing is event driven. It begins about 6 and 36 minutes after the hour, depending on the time that data acquisition is completed. Data from each subnetwork is processed on a different node (consisting of a PC with a single Intel Pentium 4 processor), and

signal delay estimates are typically available 6–9 minutes after processing begins. This large variation of the completion times depends on the characteristics of the PC being used and the number of sites in the subnetwork.

The use of any geodetic processing software for operational GPS meteorology requires a certain amount of tailoring, and GAMIT is no exception. The end products of geodetic processing software are site position and velocity. Processing is normally carried out in daily solutions, where tropospheric, ionospheric, and multipath errors are modeled and/or generally average out. In GPS meteorology, zenith-scaled tropospheric signal delays (ZTDs) that are normally estimated as nuisance parameters and removed are retained as the end product(s). The high temporal resolution of near real-time GPS virtually guarantees that these parameters will not average out in a short period (30-min or less) and will therefore appear as biases in the ZTD or its gradient. As a consequence, care must be given to identify and remove errors as described in Fang et al. (1998b), but it is also possible to "overprocess" these data and remove atmospherically valid signals imbedded in modeled noise such as multipath. We have found that an 8-h "sliding window" (comprised of 16 30-minute sessions) using the technique described by Fang and Bock (1998a) is adequate to produce a solution of comparable or slightly better accuracy than a single daily solution as described in Gutman et al. (2000).

The implementation of the sliding window technique is straightforward in practice. The average ZTD for every 30 minute session in the 8-h sliding window is estimated independently and assigned a time-tag midway between the start and end time of the session. For example, the *first* time a 0745 ZTD estimate is made occurs when the 8-h window starts at 0000 UTC and ends at 0800 UTC and the *last* time a 0745 ZTD estimate is made is when the window runs between 0730 UTC and 1530 UTC. The question then is what happens to the values of ZTD at a point in time as the window progresses? The first estimate is the *near real-time value* and is made available to forecasters and modelers by 0815; a latency of less than 15 minutes after the end of the most current session. The second estimate is replaced with the mean of the first two. The third through sixteenth estimates are replaced with the median value in each case as the window moves along. Eight-hours after the end of the day, a complete set of (48 half-hour) median ZTD solutions are archived as a daily product.

After ZTD has been estimated, IPW is calculated using observations of surface pressure and temperature and the algorithms developed by Saastamoinen (1972) and Bevis et al. (1992). Once an IPW estimate has been made, its validity is determined by applying quality control (QC) techniques. The validity of an IPW estimate is based on three factors: were there a sufficient number of epochs observed in the current session; is the ZTD estimate physically realistic; is the estimate consistent with prior estimates; and is the RMS scatter in the estimates lower than the minimum acceptable IPW retrieval error. All geodetic processing software estimating time varying parameters such as ZTD will estimate a parameter at a particular time, whether or not there is an observation to support it. Such data dropouts often occur due to communication problems. If there are no observations made during a given time period, the ZTD estimate for this period will not be used to calculate the median solution.

Assuming that sufficient data are available during a given time period, and GAMIT estimated a physically realistic ZTD value, the precision of the estimate is checked by examining the "formal error" (FERR) value. For the purposes of GPS-Met at FSL, the FERR constraint is established as 1.2 cm in the conterminous U.S., a value that corresponds to approximately 2 mm of IPW. If a ZTD FERR value exceeds this, the corresponding IPW is identified as questionable, and will not be distributed or displayed unless the user specifically requests it.

4. Data delivery

Data delivery is one of the most critical components of any meteorological observing system. Unless GPS-IPW retrievals and surface meteorological observations are available to modelers and forecasters in a timely fashion, they have very limited utility in operational weather forecasting. Currently, we provide GPS-IPW retrievals every 30-min to experimental real-time versions of the 20-km Rapid Update Cycle (RUC20) and 13-km Local Analy-

sis and Prediction System (LAPS) running at FSL in Boulder, Colorado. Assimilation into operational models running at the National Centers for Environmental Prediction (NCEP) in Camp Springs, Maryland is scheduled to start in late 2003 or early 2004. GPS retrievals are available to operational forecasters via the NOAAPORT in the form of "ISTX40 KBOU" messages, the Meteorological Assimilation Data Ingest System (MADIS), as delimited ASCII files available for ingest via the Local Data Acquisition and Dissemination (LDAD) system at each NWS forecast office, and from the internet at http://gpsmet.noaa.gov.

5. Impact on weather forecasts

Despite the limitations identified in the introduction to this paper, modern numerical weather prediction models in observation-rich regions do fairly well in describing the moisture field, even under conditions of moderately active weather. For example, Fig. 4 illustrates typical variations in total precipitable water vapor over North America as estimated by the RUC running at 40-km horizontal resolution with a 1-h intermittent assimilation cycle (not assimilating GPS-IPW observations). The time difference between Figs. 4a (valid 2300 UTC) and 4b (valid 0000 UTC) is only 1 h. The analysis shown in Fig. 4b includes assimilation of observations from approximately 85 raw-insonde soundings including full moisture profiles that were not available the previous hour. Despite the considerable volume of new moisture observations assimilated at 0000 UTC (Fig. 4b), the 1-h changes in the overall field are not substantial. Note the similar appearance between Figs. 4a and 4b in the main contrast zone along a front that runs from western Texas northeastward through the Great Lakes. A 12-h forecast (Fig. 4c) initialized at 0000 UTC depicts how the total precipitable water field was expected to change over the next 12 h. Large forecast errors in precipitable water and relative humidity are usually associated with areas of rapid change associated with storm systems of various scales (e.g., frontal systems, convective systems).

In general, NWP relative humidity forecasts are slightly more accurate in the winter than in summer months, and more accurate in the interior of the continent than along the coasts

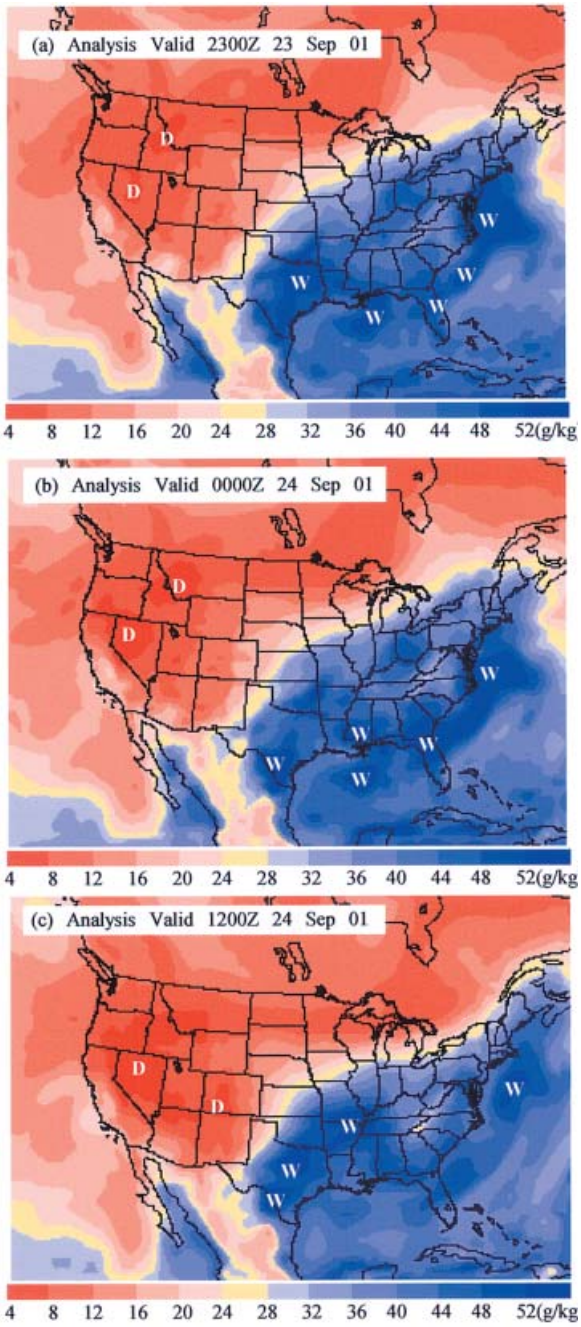

Fig. 4. Total precipitable water vapor fields generated by the Rapid Update Cycle (RUC) numerical weather prediction model running at 40-km horizontal resolution. From top to bottom: 4a) analysis valid 2300 UTC 23 Sept 2001; 4b) analysis valid 0000 UTC 24 Sept 2001; 4c) 12-hour forecast valid at 1200 UTC 24 SEP 2001. Contour interval is 2 mm.

(FSL results not shown here). The root mean square (RMS) difference in total precipitable water between 3-h RUC forecasts and GPS observations is typically less than 3 mm for all but coastal stations (Benjamin et al. 1998). At coastal sites, the RMS difference was 4–5 mm, likely caused by forecast model inaccuracy associated with the paucity of observations offshore. The RUC model PWV accuracy results over the United States are in close agreement with those estimated with a regional mesoscale model in Europe (Yang et al. 1999).

Even though analysis error is decreased at least slightly by assimilation of observations with random error of any magnitude, in practice, improved weather model forecasts do not generally result from assimilation of an additional observation type unless the random error of those observations is less than that of *a priori* information in the background forecast (Benjamin, personal communication). This suggests that the required accuracy for GPS PWV observations is 1.0–1.5 mm for the interior United States, and perhaps 2.0–2.5 mm for coastal locations where forecast error is typically higher. See Smith et al. (2000) for a further discussion of the required accuracy for GPS-IPW retrievals.

Observation sensitivity experiments on the impact of GPS PWV observations have been carried out with the RUC over the last five years. The data denial experiments used parallel versions of the RUC at 60-km horizontal resolution with 3-h assimilation cycles. One cycle used all available observations identified in Table 1, and the other excluded GPS-IPW. To look for a a first-order effect from assimilation of GPS-IPW observations in very short-range RUC forecasts, 3-h forecasts initialized at 0900 and 2100 UTC (see Fig. 1) from the two cycles were verified against independent rawinsonde observations of relative humidity at five isobaric levels: 850, 700, 500, 450, and 300 hPa. The number of GPS-Met stations used in the experiment remained constant at 18 between 1998 and 1999, and then increased to 56 in 2000, 70 in 2001, and to more than 100 in 2002.

Table 2 summarizes the results from a large number of verification times (857 for 1998–1999, 421 for 2000, 427 for 2001, and 592 for 2002 out of a possible 730 per year) analyzed over the last five years. In each of these cases, 16–18 rawinsonde stations provided data at each isobaric level. All days with a successful verification contributed to the arithmetic average, no matter what the weather regime. Averaging over all cases mutes the magnitude of statistical impact from assimilating GPS data, since under quiet weather conditions, the model tends to be quite accurate and the differences between the observations and forecasts are smaller. Nevertheless, the reduction of forecast error from assimilation of GPS data has increased each year for the 5-year period of this experiment. We attribute this to the increased number of stations, since the RUC60 assimilation and model code was not changed over the period of the experiment.

Table 2. Normalized improvement in 3-h RH forecasts using 60-km RUC weather prediction model from assimilation of GPS-IPW for period 1998–2002. Numbers are difference in error (RMS difference from rawinsonde observations) between experiments with and without GPS-IPW normalized by error in experiment without GPS-IPW. Shown for isobaric levels at 850, 700, and 500 hPa. Units in percent.

Level	1998–9	2000	2001	2002
850	1.5	3.8	3.9	5.0
700	1.1	4.1	6.3	6.5
500	0.7	2.1	2.0	2.4

An alternate way of looking at the results presented in Table 2 is shown in Table 3, where statistics from the GPS experiment at each 12-h verification time are binned according to whether they were better, worse, or the same from the experiment without GPS data. Table 3 shows that the percentage of events (as defined in previous sentence) with positive impact from GPS at 850 and 700 hPa has also increased each year, as well as the mean statistics shown in Table 2.

The optimum interpolation (OI) assimilation scheme used for assimilating precipitable water observations from GPS, GOES, rawinsondes, or other sources, involves three steps:

(1) Determine PW background field (PW_o) from previous forecast valid at analysis time;

Table 3. Verification of results presented in Table 2 for the 850 and 700 hPa levels, binned by whether they were better, worse, or the same with GPS IPW retrievals. In this table, an event is the RMS verification score over ∼18 rawinsonde stations at a given level. The precision of this score for each event is 1% relative humidity, so better/worse signifies at least a 1% difference in this RMS error score for the event.

850 mb	1998	1999	2000	2001	2002	(# cases/2002)
Better	25%	28%	37%	38%	45%	(266)
Worse	21%	19%	23%	24%	26%	(152)
Same	54%	53%	40%	38%	29%	(174)
700 mb	1998	1999	2000	2001	2002	(# cases/2002)
Better	23%	27%	39%	49%	52%	(310)
Worse	21%	21%	21%	18%	20%	(119)
Same	56%	52%	40%	33%	28%	(163)

(2) Calculate the differences between the PW observations and the model background at each observation point (observation residuals);
(3) Perform optimal interpolation analysis of IPW observation residuals to the background to obtain PW analysis increment. The analysis increment to 3-d water vapor mixing ratio is determined as follows:
   – IPW% (2-d field) = PW analysis increment (from step 3)/PW_o (as shown in Fig. 5)
   – $q_{adj}(k) = q_o(k) * (1 + \text{IPW\%})$ where $q(k)$ = water vapor mixing ratio at each vertical level k and q_o is the background water vapor mixing ratio
   – Eliminate supersaturation in q_{adj} found at any level and adjust q at other levels to compensate.
(4) The rest of moisture analysis is performed with in situ observations, now using $q_{adj}(k)$ after PW analysis as new water vapor mixing ratio background field.

This technique, described in Smith et al. (2000) and similar to that shown previously by Kuo et al. (1993), assumes that the shape of the background forecast profile (or shape) of water vapor mixing ratio is basically correct, but is in error by a constant percentage. The negative impact occurring in some cases (Table 3) comes from aliasing incurred when assimilating the single (integrated) value of the IPW observation into a 3-dimensional domain. If the assumption stated above is not correct, then applying this technique will moisten or dry out levels incorrectly, resulting in a negative impact on forecast accuracy. Since the impact of the optimally interpolated GPS-IPW observations above 500 hPa is negligible or slightly negative, the assumption appears to be less valid higher in the atmosphere.

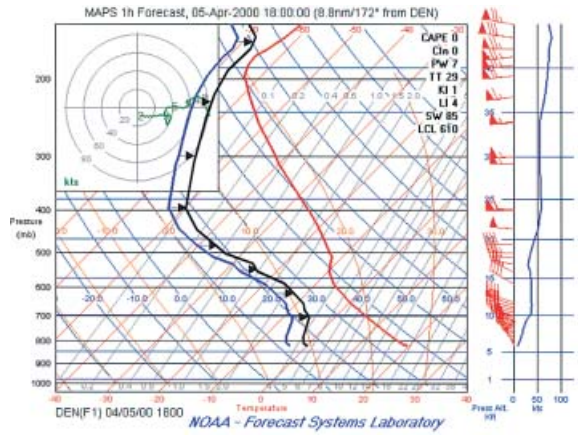

Fig. 5. Adjustment of RUC moisture field using optimal interpolation (OI).

Figure 6 presents the RH impact results for 850 hPa through 300 hPa for the years 2000–2002, respectively. Percent improvement is defined as:

$$100\frac{\sigma_f(\text{GPS}) - \sigma_f(\text{no GPS})}{\sigma_f(\text{no GPS})}$$

where σ_f is the 3-h RH forecast error from forecasts with or without assimilation of GPS observations. The forecast error is determined as an RMS difference between rawinsonde observations and forecasts interpolated to observation locations. The denominator of this expression is added to normalize the GPS—no GPS error difference by the full error from the no-GPS experiment. Improvement in RH forecasts at 850 and 700 hPa is, on the average, stronger during cold-season months, when moisture

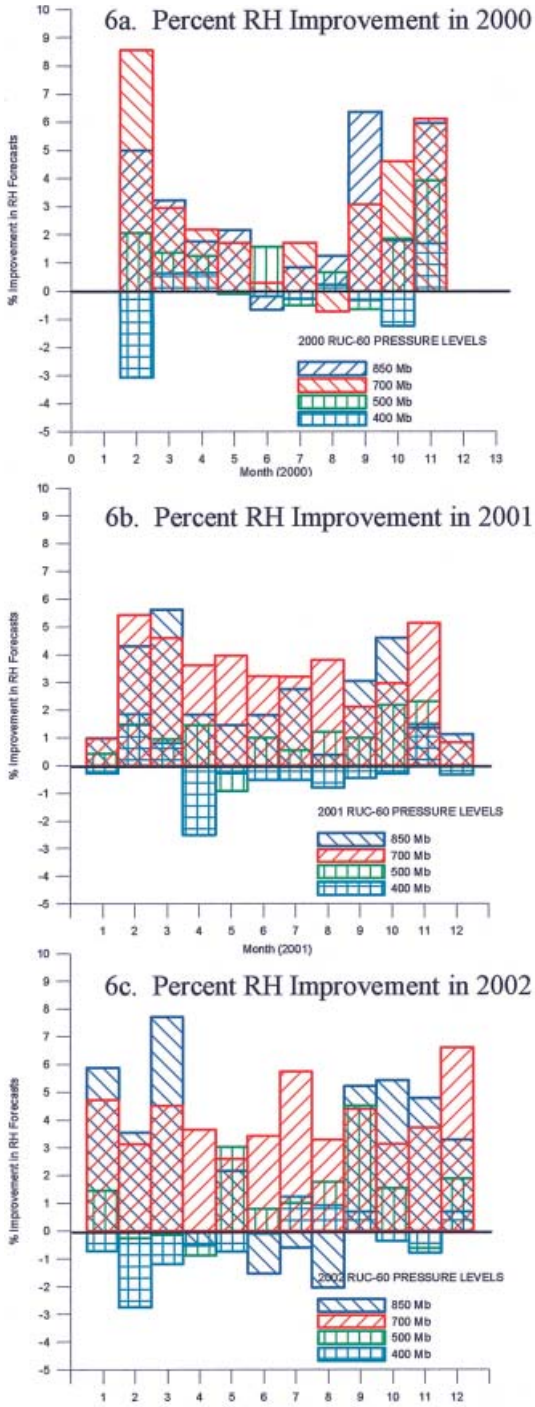

Fig. 6. Improvement (normalized by percent error) in 3-hour RUC relative humidity forecasts from assimilation of GPS IPW retrievals for 2000–2002. Four different isobaric levels are shown.

variability is driven more strongly by larger-scale weather disturbances, than it is in warm-season months.

6. Conclusions

The assimilation of GPS integrated precipitable water vapor retrievals into a numerical weather prediction model such as the RUC generally improves the 3-h prediction of the vertical moisture field at all levels at and below 500 hPa. The magnitude of the percentage-wise reduction of forecast error is modest (5–7% in 2002). However, it must be remembered that this is an average of a large number of cases (thousands of station events over each year). Many of these cases show no difference between GPS and no-GPS experiments because the forecast error is already fairly low in the no-GPS experiment. When the state of the atmosphere is well determined, little or no improvement in forecast accuracy is expected or observed by adding more observations. Although the greatest impact from assimilation of GPS is found during active weather conditions, the mean improvement is relatively small because these large-error events are in the minority. From this perspective, we consider the relative improvement in RH forecast skill of 5–7% shown for 2002 to be notable. More importantly, the improvement from GPS assimilation has increased each year as the number of GPS stations over the United States has increased. This suggests strongly that further improvement may be expected as the number of stations in the U.S. GPS network continues to increase.

The number of satellite-derived moisture estimates assimilated into the RUC exceeds the number of GPS retrievals by about an order of magnitude under cloud-free conditions, yet assimilation of GPS PW clearly provides added accuracy in RH forecasts. GPS-IPW observations complement satellite-based IPW retrievals since they are available in cloudy and even precipitating conditions, unlike satellite estimates. This all-weather availability for GPS-IPW is an advantage both for data assimilation into numerical weather prediction models as well as for subjective use by forecasters. The all-weather high temporal frequency capability of GPS appears to make the difference in the experiments shown in this paper.

The data assimilation experiments described in this paper use an older version of the Rapid Update Cycle system. Future work will focus on investigating GPS impact using a much-improved version of the RUC assimilation system and model, some of which is described by Smith et al. (2003).

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