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The Role of Ground-Based GPS Meteorological Observations in Numerical Weather Prediction

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For lack of sufficient observations, the definition of atmospheric moisture fields (including water vapor and clouds) remains a difficult problem whose solution is essential for improved weather forecasts. Moisture fields are under-observed in time and space, primarily due to the high variability of water in the atmosphere. Because of the important role of water in weather and climate processes, a significant effort has been expended to develop new or improved remote sensing systems to mitigate this problem. One such system uses ground-based Global Positioning System (GPS) receivers to make accurate all-weather estimates of atmospheric refractivity at very low cost. This largely unanticipated application of GPS has led to a new and potentially significant upper-air observing system for meteorological agencies and researchers around the world (Wolfe and Gutman, 2000). The first and most mature use of GPS for this purpose is in the estimation of integrated (total column) precipitable water vapor above a fixed site (Duan et al., 1996, with improvements by Niell, 1996 and Fang et al., 1998). The techniques currently used by the National Oceanic and Atmospheric Administration's Forecast Systems Laboratory (NOAA/FSL) to collect, process, and distribute GPS water vapor observations are mature and almost ready for transition to operational use. NOAA/FSL has shown that GPS integrated water vapor data can be used effectively in objective (i.e. numerical weather prediction) and subjective weather forecasting. To understand the strengths and limitations of GPS for weather forecasting, it is essential to understand what types of information are currently available to forecasters and modelers, and how models use the data to describe the current and probable future state of the atmosphere. It is also important to understand the current trends in modern weather prediction to ensure that GPS observing systems play a significant role in the future.

WATER VAPOR OBSERVATIONS FOR OPERATIONAL WEATHER FORECASTING

An important goal in modern weather prediction is to improve short-term weather forecasts, especially of severe weather and precipitation, but the ability to do so is hindered by the lack of timely and accurate observations of atmospheric water vapor. This is primarily because of the high temporal and spatial variability of water vapor in the free atmosphere. The distribution of water vapor changes significantly in time and space, especially under conditions of active weather, making it difficult to observe with conventional upper-air observing systems.

Most of the information used by NOAA for operational weather forecasting comes from three sources. The majority of the information about the vertical distribution of water vapor in the atmosphere comes from radiosondes (i.e., weather balloons) that make *in-situ* measurements twice daily at widely spaced locations. This provides fairly good resolution of regional-scale features, but is inadequate to resolve many small-scale variations often associated with thunderstorms and severe weather. Many surface measurements of dew point temperature (convertible to relative humidity) are made frequently at land sites throughout the world, mostly at airports, but these tell us very little about moisture content in the atmosphere above the surface. Finally, information from satellite observations is also available, but this data also has limitations. In general, satellite-based water vapor estimates derived from upwelling infrared radiation have high horizontal resolution but coarse vertical resolution (although the use of satellite-based interferometers on the next generation of environmental satellites are expected to improve vertical resolution significantly) but are reliable only in cloud-free regions. Multispectral satellite data measured at various frequencies emitted by water vapor also provide additional information about water vapor approximately 5 km above the earth's surface (below ~550 hPa isobaric level), but again with coarse vertical resolution. Estimates derived from space-born microwave radiometers are valid in cloudy regions, but are generally reliable only over the ocean.

Estimates of total precipitable water vapor (commonly abbreviated as PWV or TPW) derived from GPS signal delays complement these other atmospheric moisture observation sources. One of the most valuable attributes of GPS PWV is its ability to provide accurate signal delay estimates under all weather conditions, including cloud cover and precipitation. From a forecasting perspective, GPS PWV observations are most valuable when satellites cannot obtain good radiance measurements, mainly in cloudy regions where the need for accurate measurements is greatest since, of course, areas of precipitation are also cloudy.

NUMERICAL WEATHER PREDICTION

To explain the potential value of GPS PWV observations for weather forecasting, we first present a brief summary concerning computer weather forecasting. Modern numerical weather prediction (NWP) is based upon a closed set of non-linear partial differential equations that describe the physical laws governing change of atmospheric conditions (e.g., temperature, moisture, wind, pressure) and a numerical solution (finite difference or spectral representation) to these equations. The problem treated, geophysical fluid dynamic flow on an unevenly heated rotating sphere, is an initial value problem (and boundary problem, for a non-global, limited-area model). For grid-point atmospheric models, the atmosphere over the area for which a forecast is to be made is resolved with a three-dimensional set of grid points at which the equation set will be solved. Typical resolutions for operational weather forecast models as of the year 2000 are 20-100 km, and 30-60 levels in the vertical. The partial differential equations describing the rate of change of various atmospheric variables are continuous in time, but are approximated with short, discrete solutions with time steps of approximately 30 seconds to 10 minutes, depending on the horizontal resolution of the model. A new prediction of the state of the atmosphere advanced a single time step is determined by solving each of the equations at each three-dimensional grid point. This process is repeated until the desired forecast duration (e.g., 12 hours, 72 hours…) has been obtained. Numerical weather forecasts require a significant number of computations, for example, with a total of almost 10^{14} floating-point operations for a 20-km regional forecast model covering the United States and surrounding areas for a 12-hour forecast. Additional, more detailed descriptions of NWP are available in various textbooks (e.g., Haltiner and Williams 1980, Durran 1999).

INITIALIZING A WEATHER PREDICTION MODEL

The process of defining the initial conditions for an atmospheric forecast model is called *data assimilation*. As an initial value problem, the accuracy of numerical weather forecasts is heavily dependent on the accuracy of the estimated initial state or *analysis* of the atmosphere, especially for short-range forecasts. Model errors also contribute to numerical forecast inaccuracy. The sources of information in data assimilation are the 4-dimensional set of observations, some of which were mentioned in the first section, and knowledge about atmospheric behavior as represented in the forecast models themselves. Atmospheric data assimilation usually combines 1) *a priori* gridded information: the most recent numerical forecast, including effects of previous observations through the "filter" of the model equations, and 2) a current set of observations, from which the error of the recent numerical forecast is estimated. The assimilation task is essentially a sophisticated interpolation problem requiring detailed knowledge about observation errors, forecast model errors, including expected spatial correlations of forecast error, and multivariate relationships based on the model equations themselves. In reality, observations are always imperfect since they sometimes contain gross errors, and are never completely adequate in coverage or information content. Sometimes what is actually ingested into a model is not an observation at all, but an indirect product or a highly processed retrieval that carries with it another set of errors or uncertainties. Numerical weather prediction models providing *a priori* information also have errors, but with the advantage of imposing some consistency between temperature, wind, and moisture fields and physical processes governing cloud behavior and precipitation (including water phase change), radiation, and sub-grid-scale mixing (e.g., turbulence and convection). Also, a model ensures the smooth evolution of atmospheric conditions (temporal continuity).

A major problem in optimally estimating an initial state for a numerical forecast comes from spatial and temporal aliasing when interpolating discrete observations into an "analysis increment" field. This field is the correction from the information in a "background" field, usually a recent forecast containing information from previous observations. The potential for aliasing always exists when performing atmospheric data assimilation, as in any system where sampling frequency is less than some of the frequencies present in the true spectrum. For any observation type, sampling error, or aliasing, can occasionally lead to a *poorer* result *even though the observation may be completely accurate* at the point where it is located. In understanding results from GPS PWV data impact tests presented later in this article, it must be recognized that GPS PWV observations are subject to two kinds of aliasing: horizontal and vertical. Horizontal aliasing for GPS PWV comes from interpolating total column water vapor between widely spaced stations. From observational studies, it is known that there is significant PWV variability over distances of 50 km or less in conditions of active weather, and that these differences may significantly impact storm-scale cloud and precipitation forecasts. Vertical aliasing occurs from assimilation of any vertically integrated quantity (including GPS PWV) in that the forecast background error at discrete vertical levels must be estimated from the difference between observed and forecast integrated quantities. The actual forecast error of total-column precipitable water is positively correlated with forecast error at individual levels in the lowest ~4000 m in a statistical sense over many forecasts, but this correlation will not hold in all individual cases.

GPS PWV IMPACT ON AN OPERATIONAL WEATHER PREDICTION MODEL

One trend in modern numerical weather prediction models is to initialize them more frequently and more rapidly to provide more timely forecast guidance for certain applications such as aviation and thunderstorm forecasting. For the U.S. National Weather Service, the Rapid Update Cycle (RUC, Benjamin et al., 1999) is the most frequently initialized of its suite of models. The RUC provides analyses (initial state estimates using data assimilation) and forecasts at *mesoscale* horizontal resolution (40 km in 2000, moving to 20 km in 2001) and short (hourly) temporal resolution. A mesoscale model describes weather phenomena at a size-scale smaller than synoptic or large-scale (on the order of several hundred kilometer) features, but larger than thunderstorm-scale systems that are typically less than 20 kilometers wide. The RUC runs hourly at the NWS National Centers for Environmental Prediction (NCEP), producing a new analysis using the latest observations combined with a previous 1-hour forecast. 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 hours in the future (Figure 1). As can be seen in Table 1, the state of the atmosphere is defined by a composite observing system with different data types, each providing partial information. Even with this composite observing system, the state of the atmosphere even over a relatively data-rich region such as the United States is still heavily underdetermined, with many fewer observations than the number of grid points where information is needed to constrain a solution.

TABLE 1
Observations used by the RUC.

Data Type	~Number	Freq.	In Use at
Rawinsonde (balloons)	85	/12 hour	NCEP and FSL
NOAA 405 MHz wind profilers	31	/ 1 hour	NCEP and FSL
VAD winds (WSR-88D radars)	110-130	/ 1 hour	NCEP and FSL
Aircraft (ACARS) (V,temp)	1000-3000	/ 1 hour	NCEP and FSL
Surface - (V,P_{sfc},T,T_d)	1500-2000	/ 1 hour	NCEP and FSL
GOES precipitable water	1000-2500	/ 1 hour	NCEP and FSL
GOES high-density cloud drift winds (IR, VIS, VW cloud top)	1000-2500	/ 3 hour	NCEP and FSL
SSM/I precipitable water	1000-4000	/2-6 hour	NCEP only

Despite these limitations, modern numerical weather prediction models such as RUC are able to do a fairly good job in describing the moisture field, even under conditions of moderately active weather. For example, Figure 2 illustrates variations in the total precipitable water vapor over North America estimated from the RUC at 40-km horizontal resolution. The time difference between Figures 2a and 2b is only 1 hour, but Figure 2b includes the assimilation of a new set of ~85 rawinsonde soundings, each with 20-40 levels of moisture observations in the vertical. Despite this considerable volume of new moisture

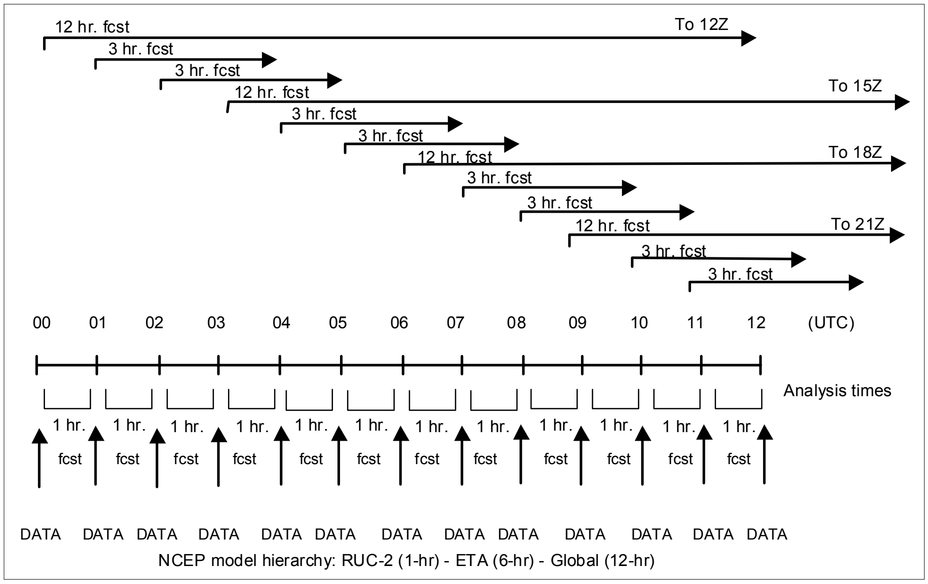

FIGURE 1. Data ingest, analysis, and forecast cycle for the Rapid Update Cycle (RUC-2) NWP Model.

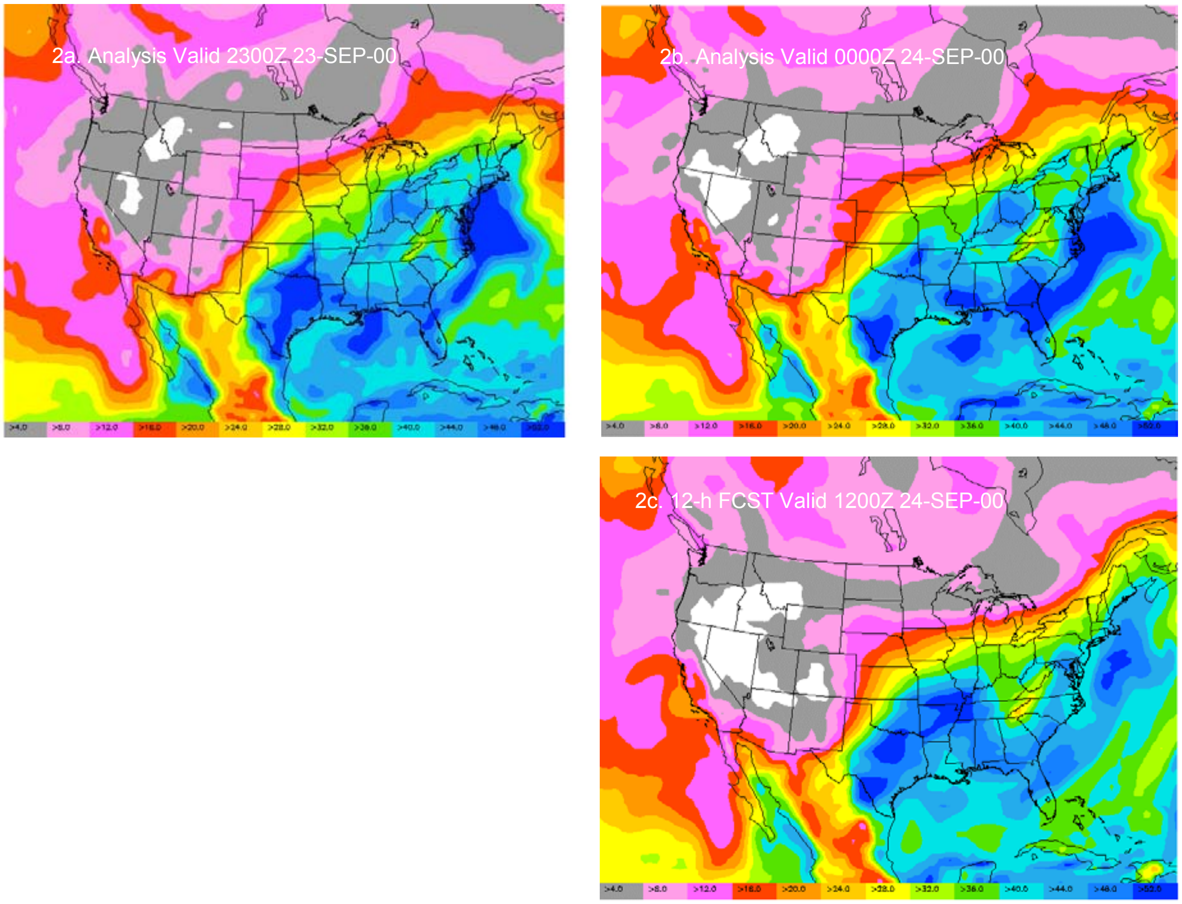

FIGURE 2. Rapid Update Cycle (RUC-2) total precipitable water vapor. Clockwise from upper left: 2a. Analysis valid 23 SEP 00 at 2300 UTC; 2b. Analysis valid 24 SEP 00 at 0000 UTC; and 2c. Forecast valid 24 SEP 00 at 0200 UTC. Contour interval is 2 mm.

observations, the change in the overall field is not substantial, and the main contrast zone along a front from western Texas northeastward through the Great Lakes appears similar in both figures. Finally, Figure 2c depicts a 12-hour forecast initialized at 0000 UTC and valid at 1200 UTC. This last panel gives the reader a sense of change in the total precipitable water field over a 12-hour period for a typical situation; more intense variations may occur in situations with strong storm development or rapidly moving fronts.

Evaluations of the moisture accuracy of NWP models have been carried out for several years as part of the evaluation of GPS as a possible next-generation weather observing system. We have found that NWP models are slightly more accurate in the winter than in the summer months, and more accurate in the interior of the continent than along the coasts. The root mean square (RMS) difference for total precipitable water between 3-h RUC forecasts and GPS observations was less than 3 mm for all but coastal stations (Benjamin et al. 1998). At coastal sites, this RMS difference, mostly due to forecast model inaccuracy, was 4-5 mm. These model PWV accuracy results for the RUC over the United States are in close agreement with those estimated with a regional mesoscale model in Europe (Yang et al. 1999). Generally, in order for observations to have a chance to produce improved forecasts, the observations must have an observational error somewhat less than that of the *a priori* information in the previous forecast. 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. Further discussion of the estimated required accuracy for GPS PWV is provided by Smith et al. (2001).

Observation sensitivity experiments on the impact of GPS PWV observations have been carried out with the RUC over the last 3 years (Smith et al. 2001). In these experiments, parallel versions of the RUC with a 60-km horizontal resolution were run in ongoing 3-hour assimilation cycles, one with all observations assimilated (Table 1) including GPS PWV, and one with GPS PWV excluded. Until late 1999, data from only 18 GPS sites was available to these experiments. For these experiments, forecasts from the two cycles were verified against different independent observations, including rawinsonde observations of relative humidity (RH).

Relative humidity forecasts of 3-hour duration were found to show more sensitivity than other forecast variables to assimilation of GPS PWV. As shown in the second column of Table 2, the percentage improvement when data from 18 GPS PWV stations was available was 1.0% at the lowest pressure level where verification was performed (850 hPa, about 1500 m above sea level). This improvement was considered to be very modest, but positive nonetheless, especially considering that the result was obtained over thousands of cases (14 rawinsonde sites twice daily used in the verification over a 500-day period). In the majority of these cases, the RUC data was already quite accurate, so the GPS PWV data had no impact. However, as shown by Smith et al. (2001), the changes made by GPS PWV were much more substantial when the atmosphere was more active and producing rapid changes.

As of November 1999, the number of GPS PWV stations providing data over the lower 48 United States had increased to 58 stations, with plans to expand the network to about 100 sites in 2001. With the larger amount of data available, now including more stations near United States coastlines where PWV forecast accuracy was lower, the impact of the GPS PWV data was somewhat higher, now at 4.5% reduction of error for relative humidity at 850 hPa and 700 hPa (Table 2, column 3). The day-to-day impact on 3-hour RUC relative humidity from GPS PWV assimilation is shown in Figure 3 for two different pressure levels. The improvement in RH forecasts was found to be as high as 6% RH (40% reduction of forecast error) for individual verification times, each with 14 rawinsonde observations. Some verification times occurred with an increase of error of 1% RH, due to the aliasing issues discussed earlier. It is also notable that the times with peak positive impact from GPS PWV at either 850 hPa or 700 hPa do not coincide. This is another indication of how the forecast error in total precipitable water at a particular time may correspond very well to the forecast error at one vertical level, but not necessarily to another. More results from the RUC parallel cycle testing for GPS PWV forecast impact are presented by Smith et al. (2001).

TABLE 2

Improvement in 3-h relative humidity forecasts from the RUC with assimilation of GPS PWV observations in parallel cycles (equivalent to reduction in forecast error). Percent improvement is relative to standard deviation total forecast-minus-rawinsonde difference.

Improvement in RH Forecasts by pressure level	**18-station tests**	**55-station tests**
850 hPa	+ 1.0 %	+ 4.5%
700 hPa	+ 0.7%	+ 4.5%
500 hPa	+ 0.5%	+ 2.0%
400 hPa	+ 0.2%	+ 0.5%
300 hPa	+ 0.1%	- 0.5%
Period of parallel test statistics	Mar 98 – Sep 99	Feb 00 – Apr 00

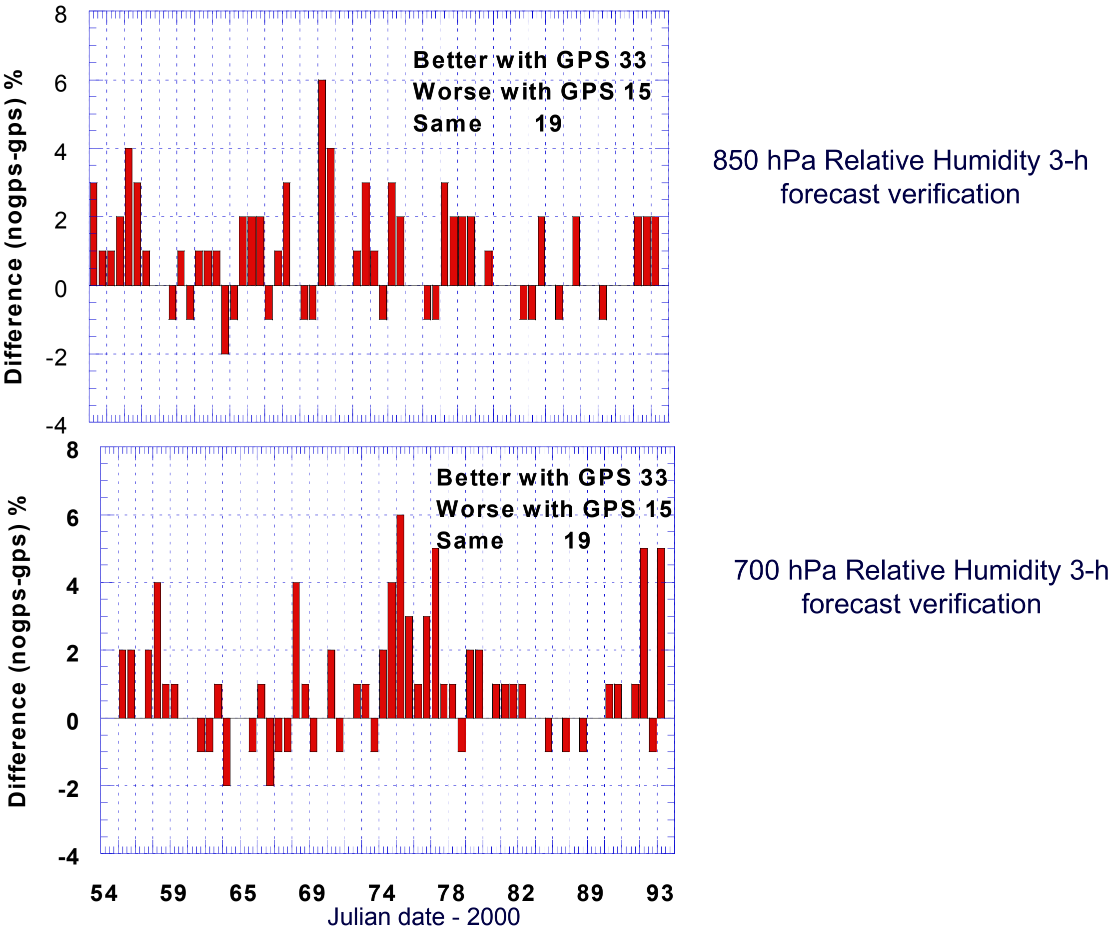

FIGURE 3. Time series of 3-h relative humidity forecast verification improvement from GPS PWV assimilation. For period from Julian date 54-94 in 2000 and for two isobaric levels, 850 hPa and 700 hPa.

The improvement in humidity forecasts is determined by the difference in forecast verification against rawinsonde RH observations for RUC parallel cycles with and without GPS PWV assimilation. A positive number means an improved forecast when assimilating GPS PWV data, while a negative number indicates a less accurate forecast.

Beyond the issues of aliasing and adequate number of GPS PWV stations, improvements also can be made to the techniques for assimilation of the GPS PWV data. Statistics on the correlation between forecast error of total precipitable water and that at individual levels would help to minimize the vertical aliasing problem. Variational assimilation approaches which simultaneously take into account surface moisture observations as well as total precipitable water values will also help to resolve some of the vertical ambiguity. Further in the future, if accurate line-of-sight (or slant-path) signal delays could be made from a network of closely spaced GPS receivers, a still more detailed diagnosis of the three-dimensional moisture field could be made using variational techniques, as demonstrated by MacDonald and Xie (2000).

PROVIDING GPS-MET OBSERVATIONS TO FORECASTERS AND MODELERS

Based on the initial evaluation of its utility for improved forecasting, accuracy under all weather conditions, and cost effectiveness, FSL believes that ground-based GPS-Met will be an integral component of the next generation composite upper-air observing system for NOAA. An essential attribute of such a composite observing system is that the individual systems provide complementary information with a minimum of unnecessary redundancy. For example, a "division of labor" among GPS, satellites, and radiosondes may evolve something like this. A reasonably dense (~100 km spacing) network of ground-based GPS receivers will contribute moisture information when satellite data is unavailable due to cloud cover, an independent calibration and validation of satellite retrievals from different sensors and platforms, and an independent quality assessment for radiosonde moisture profiles. Approximately 40 km station spacing will probably be required for slant-path measurements. Satellites will provide, among other things, images and high resolution soundings in cloud-free areas, while radiosondes will continue to tie the system together by providing essential in-situ observations of atmospheric parameters at all levels. How best to do this is currently under review at meteorological agencies and universities around the world.

Required Accuracy of GPS Met Data

The accuracy requirement for any observation is determined by its intended use. In general, climate applications place the most stringent accuracy requirements on meteorological observations because they are intended for long-term statistical analysis and the determination of sometimes very subtle trends. One reason why it is so difficult to unambiguously define trends in global climate change is because of the accuracy and precision of the measurements. A comprehensive review of the accuracy requirements for water vapor observations can be found in Weckwerth, et al. (1999).

The required accuracy of GPS PWV is determined by the accuracy with which current NWP models can analyze the moisture field without the benefit of this data. As previously cited, NWP models are capable of analyzing the moisture field and defining the total quantity of precipitable water vapor in the atmosphere with an accuracy of about 3 mm in winter in regions such as the United States or Europe with rawinsonde data coverage. As a consequence, GPS PWV estimate errors should never be larger than 3 mm, and preferably never greater than half this value. The accuracy of GPS PWV estimates is continually evaluated by comparing them with PWV observations from other moisture observing systems, especially radiosondes. The Department of Energy's Atmospheric Radiation Monitoring facility near Lamont, Oklahoma has conducted periodic water vapor intensive observing periods (WVIOPs) in 1996, 1997, and 2000. The results from the 1997 WVIOP are summarized in Figure 4, which compares PWV from 6 different observing systems. It can be seen that GPS-derived PWV measurements have an error of less than 5% (or about 1 mm). According to the estimates of model PWV errors, this accuracy should be sufficient to positively impact weather forecast models regardless of the conditions, time of year, or location. This level of accuracy is also adequate for most climate monitoring applications. For more information about IOPs conducted by the ARM program, see http://www.arm.gov/docs/iops.html.

Required Timeliness of GPS Met Data

The timeliness requirement for an observation is also determined by its intended use. By far, the most stringent timing requirement comes from the use of GPS PWV data for subjective forecasting. In this case, a forecaster looks for GPS PWV data and expects it to be "current". The definition of "current" or "real time" is not precise, in that it depends both on what is needed and what is expected. In times of relatively stable weather conditions, a forecaster may look for new information infrequently and still consider it to be "real-time." During active weather conditions however, a forecaster may look for changes or trends every few minutes. If the data is only refreshed every half-hour, the updated information may still be useful, but it can only be considered "near real-time". If the data is available after it is needed, it will be considered "late" and is essentially useless except perhaps for retrospective study.

In numerical weather forecasting applications, a GPS PWV estimate is considered "real-time" if it is available to be ingested during the current assimilation cycle (see Figure 1). Otherwise, it will be considered late, not used, and not make any contribution to the forecast. The RUC, for instance, requires data to be available within 20-30 minutes.

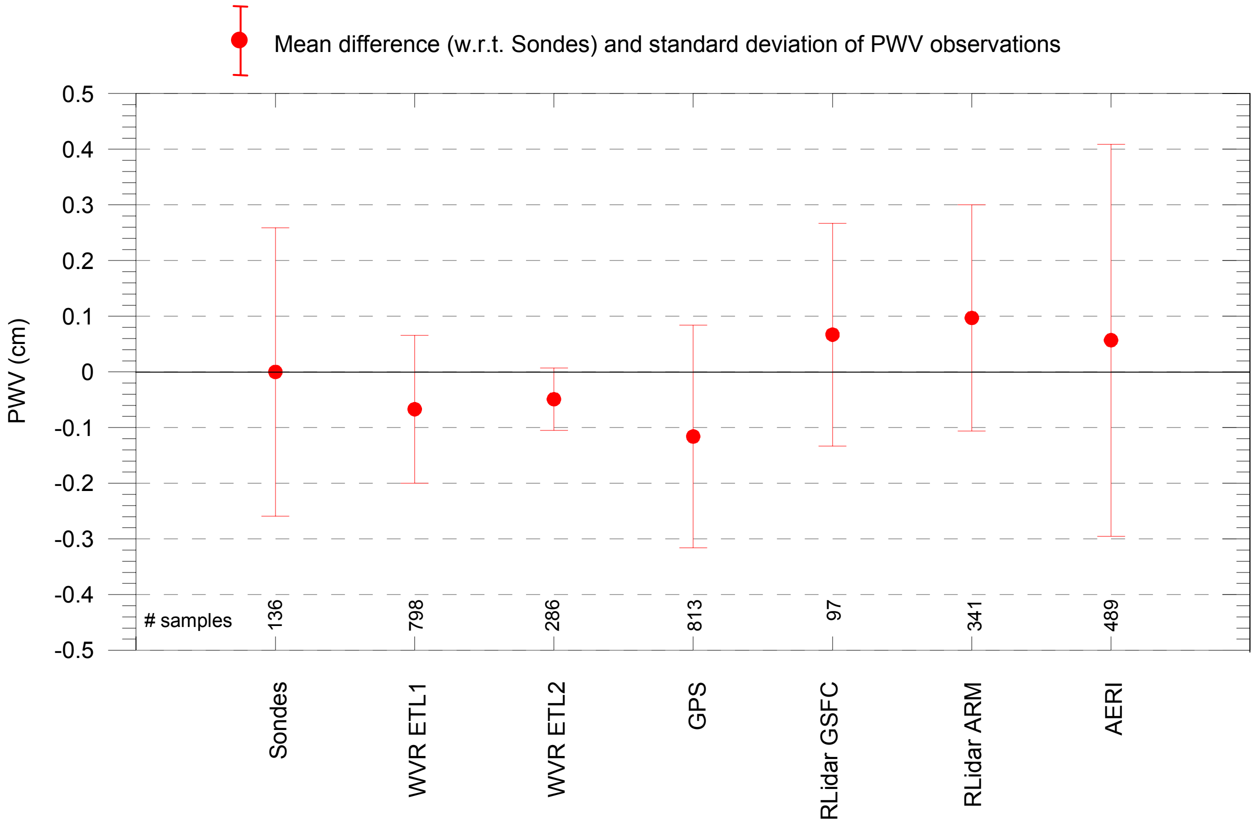

FIGURE 4. Comparison of different water vapor observing systems during the 1997 water vapor intensive observing period indicates that all measurements are within 5% (~1 mm PWV). Plot derived from information provided by Wayne Feltz and Hank Revercomb of UW-Madison SSEC/CIMSS.

The major factor that determines if a GPS PWV estimate is available when it is needed is the availability of sufficiently accurate GPS satellite orbits. In the case of the NOAA/FSL GPS data processing system, short-term (two-hour) predictions derived from hourly orbits generated at the Scripps Orbit and Permanent Array Center (SOPAC) allow PWV estimates every 30 minutes with no significant loss of accuracy compared with static (i.e. 24-hour) estimates made using an International GPS Service Rapid (IGSR) orbit. This permits FSL to generate two PWV estimates every hour for assimilation into the RUC, and anticipates an increase in RUC analysis frequency from the current 1-hour forecast cycle to a 30-minute cycle in the next few years.

It has been shown that predictions from rapid orbits (with an average age of about 36-hours) are perfectly suitable for real-time data processing once they have been retrospectively edited to eliminate satellites with unacceptable large orbit errors (more than 25 cm RMS). NOAA/FSL believes that if techniques can be developed by the IGS community to perform continuous real-time quality control of these predicted orbits, then it should be unnecessary for any operational meteorological agency without an in-house capability to generate them (such as NOAA possesses through its National Geodetic Survey) to acquire or implement its own. In addition, the ability to use longer-term predictions will mitigate the problem of an insufficient number of tracking stations report in a timely fashion resulting in hourly orbits and predictions of poor quality.

SUMMARY

In parallel tests of a weather prediction model called the Rapid Update Cycle, GPS PWV data was found to have a modest positive impact on 3h forecasts of relative humidity and precipitation (not shown) over the United States. This result is over a relatively data-rich region, where *a priori* knowledge of atmospheric precipitable water is high. The improvement from tests using a 55-station GPS PWV network, while modest, was higher than that evident from other types of moisture observations in previous tests. The improvement was evident despite using a "simple" method of assimilating the data and despite also assimilating satellite PWV observations into both cycles. The improvement was most evident in 3-hour forecasts, and was more pronounced in situations of large changes associated with weather events such as frontal passages.

Future plans are to conduct new parallel cycle experiments with hourly assimilation (instead of 3-hourly) using an advanced version of the RUC forecast model with higher spatial resolution and improved precipitation physical parameterizations. The future RUC experiments will also use a new three-dimensional variational assimilation method that will allow simultaneous assimilation of GPS PWV and surface moisture observations to decrease vertical aliasing.

Techniques have been developed to acquire, process, and distribute GPS PWV estimates every 30 minutes to forecasters and modelers. These estimates have almost the same level of accuracy as achieved using an IGS rapid orbit, but with 20-minute rather than 36-hour latency. If techniques can be developed to perform real-time quality control of predicted orbits, then it should be possible to acquire, process, and distribute GPS PWV data with arbitrary temporal resolution for future meteorological applications.

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