Summary of Global Positioning System (GPS) Integrated Precipitable Water (IPW)

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Abstract

Decision-makers are increasingly reliant on public and private forecasts for daily planning, hurricane evacuations, fuel distribution, agriculture pricing policy, positioning fire weather assets, and applying road chemicals for winter storms. They can benefit from better forecasts resulting from measurements of atmospheric water vapor from ground-based Global Positioning System (GPS) Integrated Precipitable Water (IPW) retrievals. These GPS-IPW data are being used in weather prediction models and by operational weather forecasters to help produce more accurate analyses and forecasts of the atmospheric moisture patterns over the United States, leading to a wide range of improved forecast applications including severe weather. This paper presents a brief history of the GPS-IPW network along with a summary of recent studies on validations and forecast impacts of these data. Examples of impact in operational forecast scenarios are also presented.

1. Introduction

Global Positioning System (GPS) satellite radio signals are slowed as they pass through the Earth's atmosphere. This delays the arrival time of the transmitted signal from what is expected if there was no atmosphere. The delay in the signal as it travels through the atmosphere originates from both the ionosphere and the neutral atmosphere. The ionospheric-caused delays can be corrected for by using dual-frequency GPS receivers as they are frequency dependent. The delays from the neutral atmosphere, however, are not frequency dependent as they depend on its constituents, which are a mixture of dry gases and water vapor. Using the techniques first described by Bevis et al. (1992, 1994) and Duan et al. (1996), the signal delays caused by water vapor in the troposphere can be estimated and used to retrieve the total column water vapor or integrated precipitable water (IPW). This new technology opened the door for the development of a ground based GPS-IPW network in the 1990s led by the National Oceanic and Atmospheric Administration (NOAA) Earth Systems Research Laboratory (ESRL) Global Systems Division (GSD) (Wolfe and Gutman 2000; Gutman et al. 2004). As of June 2007 the network has grown to nearly 400 sites across the United States, Canada, Mexico, and the Caribbean (Fig. 1).

GPS-IPW complements other systems capable of measuring atmospheric moisture such as radiosondes, surface-based radiometers, satellite-based infrared and microwave sensors, research aircraft, and commercial aircraft [e.g., Aircraft Communication Addressing and Reporting System (ACARS)]. However, it is not a substitute as it does not provide information about moisture profiles. Radiosondes provide tropospheric moisture profiles, but have limited spatial coverage and are only launched twice-daily—in some countries only once per day. Surface-based radiometers are capable of high temporal resolution but are costly, require frequent calibration, and their performance is adversely affected by the presence of rain. Satellite-based infrared (IR) and microwave sensors offer planetary scale coverage, but IR sensors are reliable only in cloud-free regions, and microwave sensor-based retrievals, although valid in cloudy regions, are most reliable over oceans (less reliable over land) and have limited temporal resolution. Aircraft measurements are beginning to provide moisture observations using the Water Vapor Sounding Systems (WVSS) or Tropospheric Airborne Meteorological Data Reports (TAMDAR). However, these observations are limited to commercial operational locations and flight times, and are generally less continuous than GPS-IPW observations. In fact, aircraft observations other than TAMDAR are generally limited to hub airport areas below 15 kft. The GPS-IPW network provides unattended, continuous, independent, frequent, and accurate observations of IPW that are unaffected by weather conditions or time of day. And the cost of each station is very low; installation cost is usually less than $7,000 if collocated with a surface meteorological observation station, or around $10,000 otherwise with an approximate $500 annual operating cost[2]. The main limitations of the GPS-IPW network are that the IPW retrievals do not provide information about the vertical distribution of water vapor, and the spatial resolution is limited (although this is becoming somewhat alleviated by the fast expansion of the network). *It also meets essential water vapor monitoring requirements not met by all other sensors, most significantly its ability to monitor water vapor under all weather conditions which is critical during potential severe weather events (*United States Weather Research Program Prospectus Development Team Report; Emanuel et al. 1995). In addition, GPS-IPW accuracy of 1 to 2 mm (Deblonde et al. 2005) is equal to or better than integrated radiosonde moisture soundings at a fraction of the cost (Gutman et al. 2005).

But why bother measuring atmospheric water vapor? Water vapor is one of the most significant constituents of the atmosphere because it is the means by which moisture and latent heat are transported in the atmosphere. Water vapor is also a greenhouse gas that plays a critical role in the global climate system. This role is not restricted to absorbing and radiating energy traveling through the atmosphere, but includes the effect it has on the formation of clouds and aerosols and the chemistry of the lower atmosphere. Despite its importance to atmospheric processes over a wide range of spatial and temporal scales, water vapor is one of the least understood and poorly described components of the Earth's atmosphere. Water vapor moves rapidly through the atmosphere, redistributing energy through evaporation and condensation. This can occur abruptly over extremely short distances. For this reason, water vapor is under-observed in time and space, especially during severe weather. This conclusion is supported by multiple scientific publications, among them a special report on water vapor in the climate system (1995)[3] published by the American Geophysical Union (AGU), which states that although the Earth's "*basic operation of the hydrologic cycle is well known…some details are poorly understood, mainly because we do not have sufficiently good observations of water vapor.*" The first United States Weather Research Program Prospectus Development Team Report by Emanuel et al. (1995) made as one of its key recommendations "*the support of research seeking to determine optimal combinations of satellite and* ***ground-based remote sensing****, aircraft, balloon, and surface observations as well as the support of key technological developments such as satellite-borne active sensing techniques,* ***near-field remote sensing of atmospheric water vapor****, and observations from commercial and, perhaps, pilotless aircraft*" as a condition to achieve forecasts improvements "*at the 2-7-day range*" which "*could have enormous potential economic benefits but will require greatly improved data over the oceans* *and other data sparse areas.*" The Global Climate Observation System (GCOS) workshop report (2006)[4] on the Upper-Air Network includes recommendations concerning GPS-IPW. The GPS-IPW network makes it possible to make observations of IPW with high horizontal resolution (provided the network is dense enough), high temporal resolution, high accuracy, long-term measurement stability, and high reliability under all weather conditions. Although at first glance the applicability of GPS-IPW measurements over oceans is limited, its deployment across island environments and on platforms such as oil rigs, buoys, and ships—representative of the oceanic environment in which they are embedded—has been proposed since they would undoubtedly yield significant benefits (Chadwell and Bock 2001; Rocken et al. 2005).

The next two sections include brief summaries taken from various published articles on GPS-IPW data validation studies (section 2) and GPS-IPW impacts on forecasts (section 3).

2. Validation

The errors associated with GPS-IPW estimates are usually determined from comparisons with other moisture sensing systems, especially radiosondes and microwave water vapor radiometers (MWR). NOAA-sponsored 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; Revercomb et al. 2003). As illustrated in Figs. 2 and 3, comparisons between GPS-IPW and radiosonde-derived IPW indicate a 2.0-mm IPW standard deviation difference at the ARM CART site between 1996 and 1999 and a 1.5-mm IPW difference for the International H2O Project (IHOP – 2002) (Birkenheuer and Gutman 2005). These differences include both GPS and RAOB measurement errors (Birkenheuer and Gutman 2005). Tregoning et al. (1998) also demonstrated similar results when comparing GPS-IPW to both radiosondes and MWR (Fig. 4). Comparisons at other facilities around the world are consistent with these results (e.g., Emardson et al. 2000; Haas et al. 2001; Guerova et al. 2003; Basili et al. 2004). They 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.

3. Impact on Forecasts

a. Forecast Models

Assimilation of GPS-IPW data into mesoscale numerical weather prediction (NWP) models has been proven to reduce model 3-h IPW errors by 25% on average over a 3-month period (Smith et al. 2007). This has resulted in increasing improvements in 3-h relative humidity (RH) forecasts below 500 hPa in the south-central United States (Fig. 5) as the GPS-IPW network has increased from 2000-2004. Smith et al. (2007) showed an 8% improvement in 3-h RH forecasts over the entire year, with 10-15% improvement in transition seasons (Fig. 6), and substantial reductions in root-mean–square (RMS) errors of model IPW forecasts across the CONUS region (Fig. 7). Significant improvements in model 3-h Convective Available Potential Energy (CAPE) forecasts, skill scores (ETS) for heavy precipitation events (Benjamin et al. 1998; Deblonde et al. 2005; Smith et al. 2007), and even slight improvements in land-falling hurricane forecast tracks (Fig. 8) have been documented (Macpherson et al. 2007). This overall improvement in NWP performance has resulted in the incorporation of the GPS-IPW data into two models at the National Centers for Environmental Prediction (NCEP), namely, the Rapid Update Cycle (RUC) in June 2005 and the North American Mesoscale (NAM) model in June 2006 (Smith et al. 2007). Fig. 9 illustrates the impact in the operational RUC model of the assimilation of these data starting during the summer of 2005.

These improvements are essential to help NOAA meet its strategic goals[5] of improving severe weather forecasts, aviation forecasts, hydro-meteorological forecasts, and climate forecasts. Additionally, the ability to retrieve atmospheric water vapor content from GPS signals has enabled up to 19% improvement in real time kinematic positioning from GPS signals widely used in surveying techniques (Ahn et al. 2006), with positioning accuracies on the order of centimeters (Bisnath and Dodd 2004). This suggests the development of the GPS-IPW technology has benefited the society at large beyond the weather enterprise. This goes to the core of NOAA's mission in support of the nation's commerce.

Additional benefits of the GPS-IPW network include: 1) quality control of moisture for global radiosonde observations, which leads to detection of bad soundings and results in improved moisture observations for NWP, climate statistics, satellite calibration and validation, and research [Gutman et al. 2005; McMillin et al. 2007; Rama Varma Raja et al. 2007; see also R. Maddox's blog (http://www.madweather.blogspot.com) regarding moisture measurements from the Radiosonde Replacement System (RRS)]; 2) verification of satellite and other moisture sensing systems which provides an independent check on the quality of remotely sensed measurements from satellites and/or *in situ* measurements from radiosondes (Birkenheuer and Gutman 2005); and 3) improved situational awareness to forecasters leading to better short-term regional warnings and forecast services that could save life and property [personal communications with Science and Operations Officers at National Weather Service (NWS) field offices].

b. Operational Forecasts

As suggested in the previous section, the use of the GPS-IPW data has resulted in both better performances of operational NWP models during severe weather events and better situational awareness leading to such events in the field. The next three examples illustrate this. Fig. 10a depicts the severe weather reports associated with an outbreak across northern Illinois and Indiana on 20 April 2004. Fig. 11 shows the impact of assimilating the GPS-IPW data on the 20-km RUC 3-h forecast CAPE. In this case, the 3-h forecast CAPE was improved by as much as 50% to nearly 100% (Smith et al. 2007) in the experiment with GPS-IPW assimilation in the area hardest hit by the severe weather. This was also confirmed via personal communication with Steve Weiss, the Storm Prediction Center (SPC) Science and Operations Officer (SOO).

On 15 May 2006, severe thunderstorms developed across South Florida resulting in numerous reports of penny-sized to golf-ball-sized hail covering roadways and occasionally breaking through wind shields in cars. Reports of wind gusts in excess of 60 mph were also common (Fig. 10b). Excerpts from the Area Forecast Discussion issued at 951 AM EDT by the NWS in Miami that morning read as follows:

".UPDATE…CONVECTIVE PARAMETERS CALCULATED WITH MORNING SOUNDING DATA LOOKING VERY IMPRESSIVE. STEEP MID-LEVEL LAPSE RATE WITH AN AFTERNOON LIFTED INDEX OF -11C...CAPE OVER 5000 J/KG...ELEVATED DRY

*LAYER...****RAPIDLY INCREASING LOW-LEVEL MOISTURE*****...GOOD SURFACE HEATING AND SEABREEZE DEVELOPMENT JUST SOME OF THE MORE PROMINENT FEATURES THAT WILL SET US UP FOR SOME STRONG STORMS THIS AFTERNOON. WILL UPDATE HAZARDOUS WEATHER OUTLOOK TO RAMP UP SEVERITY POTENTIAL JUST A TAD*."

Although not specifically mentioned, the comment in bold was also based on the time series plot of GPS-IPW shown in Fig. 12. IPW increased through the morning hours from around 1 inch around 1200 UTC in the Miami and Naples area to over 2 inches by late afternoon and early evening. Notice that this increase occurred between sounding observation periods. The forecasters were able to catch up to it based on the fact that the area was under warm and moist air advection from the south as illustrated by the rate of increase in the moisture field by the Key West GPS-IPW data. Monitoring of observed and diagnostic sounding data demonstrated that the observed increase in IPW was associated with moistening at low levels/boundary layer (with discernable increases in surface dew points along the sea breeze front, which also provided the forcing for convective development). Increases in surface dew points will result in increasing surface based CAPE, assuming temperature profiles remain the same. However, on this date, the warming and moistening at low levels contributed to steeper lapse rates and increased instability (Fig. 13). All together this led to an increased situational awareness and updated forecast products in excess of 4 hours prior to the beginning of severe weather across the area.

The third example illustrates the impact of assimilating the GPS-IPW data on the Japan Meteorological Agency mesoscale model precipitation forecast for a heavy precipitation event that occurred on 27 Aug 1998 in the main island of Japan (taken from Nakamura et al. 2004).

Fig. 14 illustrates the radar observed precipitation (top), the model 3-h precipitation forecast valid at the 9th hour without GPS-IPW data (middle), and the forecast with the GPS-IPW data (bottom). Clearly, the assimilation of the data resulted in the model forecasting the heavy precipitation event in the northern sections of the main island of Japan. This kind of performance improvement is critical for forecasters to issuing life-saving warnings during flash flood events, particularly in mountainous regions.

4. Summary

Drawing upon previous work, this paper summarizes how the GPS-IPW data have become very important for more accurate analysis of the moisture field in the atmosphere. Its accuracy compares exceedingly well to other more conventional platforms, and is even used as a tool for quality controlling/cross-calibrating radiosonde IPW data. It is well documented that the data have a substantial positive impact on NWP models resulting in better forecasts of severe weather events and heightened situational awareness in the field, leading to better forecast and warning services. These data, with their high temporal and increasing spatial resolution, complement rather than supplant radiosondes and other devices capable of measuring moisture profiles. The co-existence of this wide array of sensors and associated networks clearly supports the recommendation made by the first United States Weather Research Program Prospectus Development Team over a decade ago, namely, to support research seeking the optimal combination of space and ground based sensors for better monitoring of moisture fields and their evolution.

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Figures

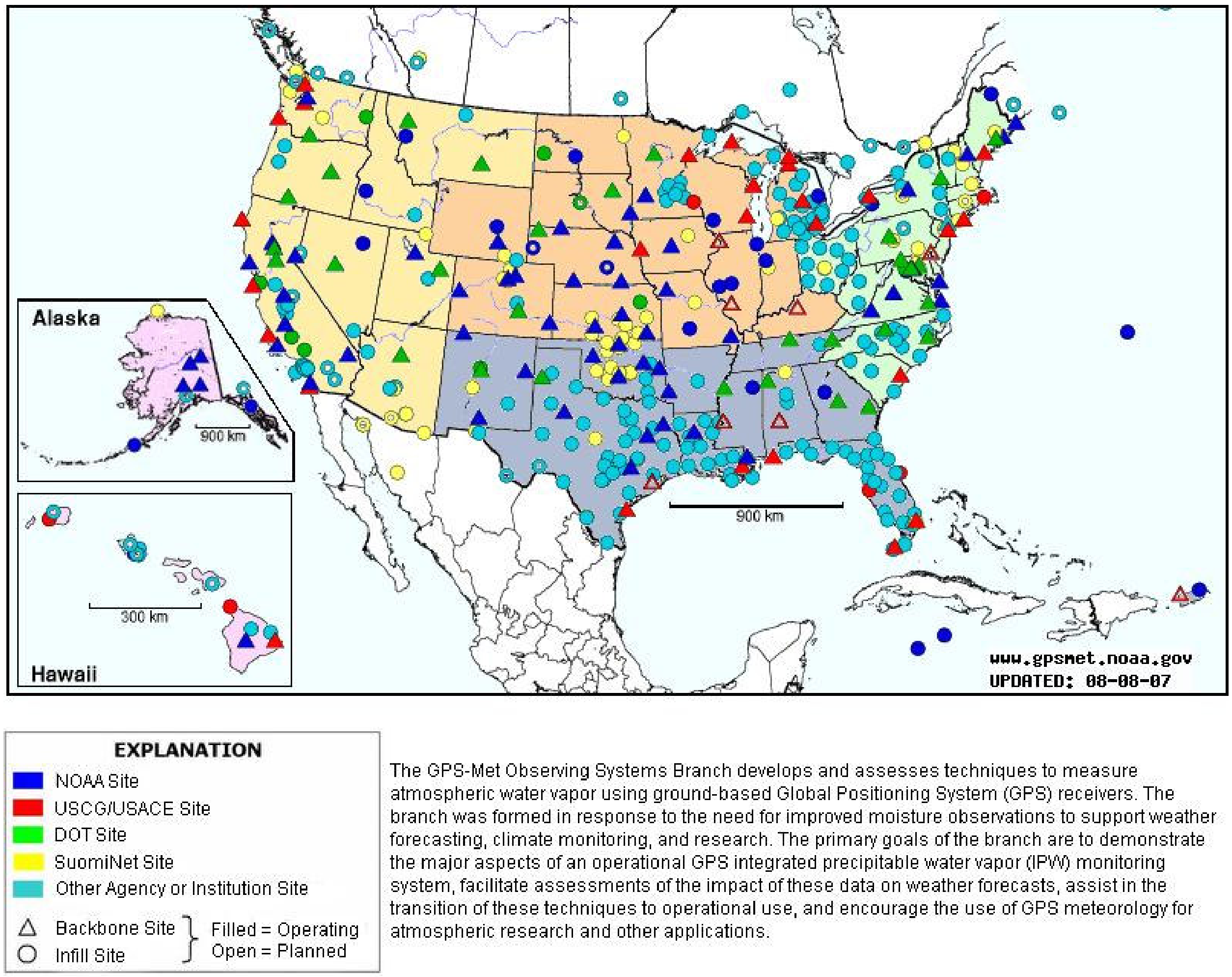


Figure 1. NOAA GSD GPS-IPW network as of August 2007 (http://gpsmet.noaa.gov).

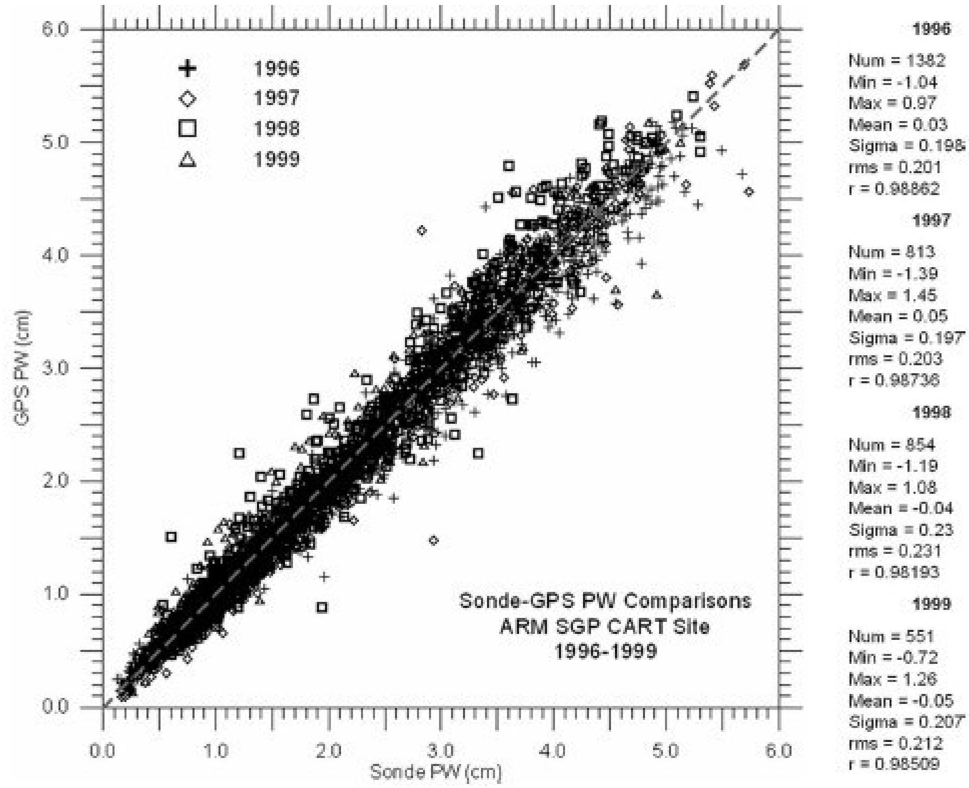


Figure 2. Comparison of 3600 GPS-IPW retrievals and radiosonde IPW over 3 years at the ARM CART facilities near Lamont, OK. From Birkenheuer and Gutman (2005).

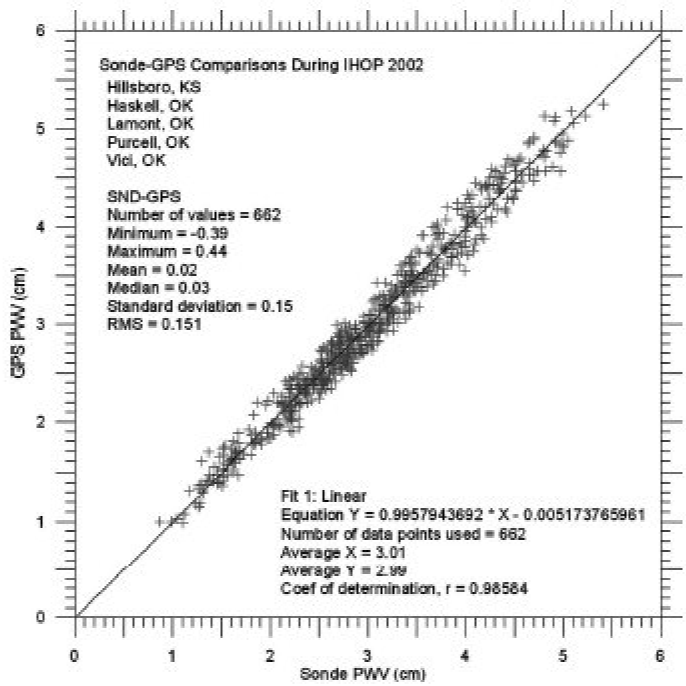


Figure 3. Comparison of collocated radiosonde and GPS-IPW measurements during IHOP-2002. From Birkenheuer and Gutman (2005).

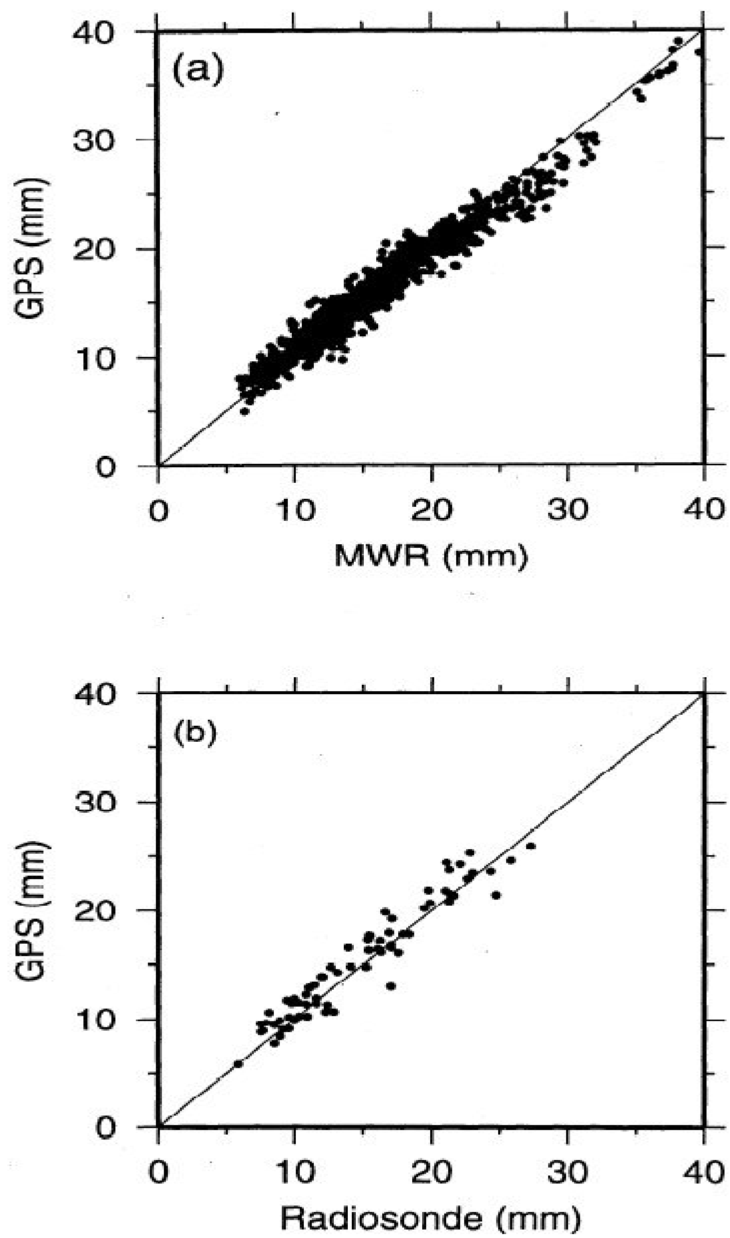


Figure 4. Comparison of GPS-IPW to microwave water vapor radiometer (MWR; top) and radiosonde (bottom) measurements taken from Tregoning et al. (1998) for different networks across Australia. Standard deviations between GPS and MWR ranged from 1.3 to 2.4 mm and between GPS and radiosondes standard deviations ranged from 1.5 to 2.7 mm; the average was ~ 2 mm in both cases.

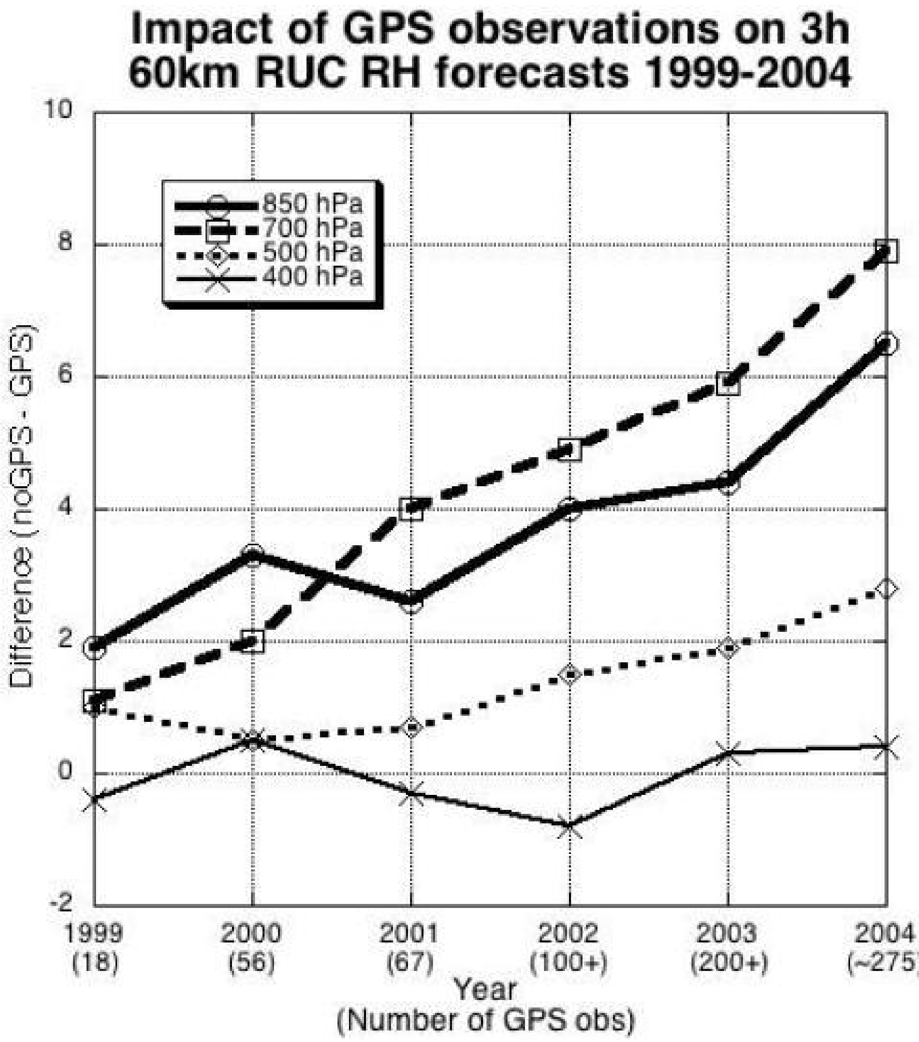


Figure 5. Normalized forecast impact for the 3-h relative humidity (RH) forecast error (using RUC60) from assimilation of GPS-IPW data (from Smith et al. 2007). Impacts at 850, 700, 500, and 400 hPa averaged by year for 1999-2004 are shown. Forecast error is assessed by computing forecast minus observed RH difference with radiosonde observations at 17 stations in the south-central United States. Normalized forecast impact is proportional to the ratio of the difference between the root-mean-square (RMS) error (mm) of the forecast with no GPS and the forecast with GPS to the difference between the forecast with no GPS and the verifying analysis.

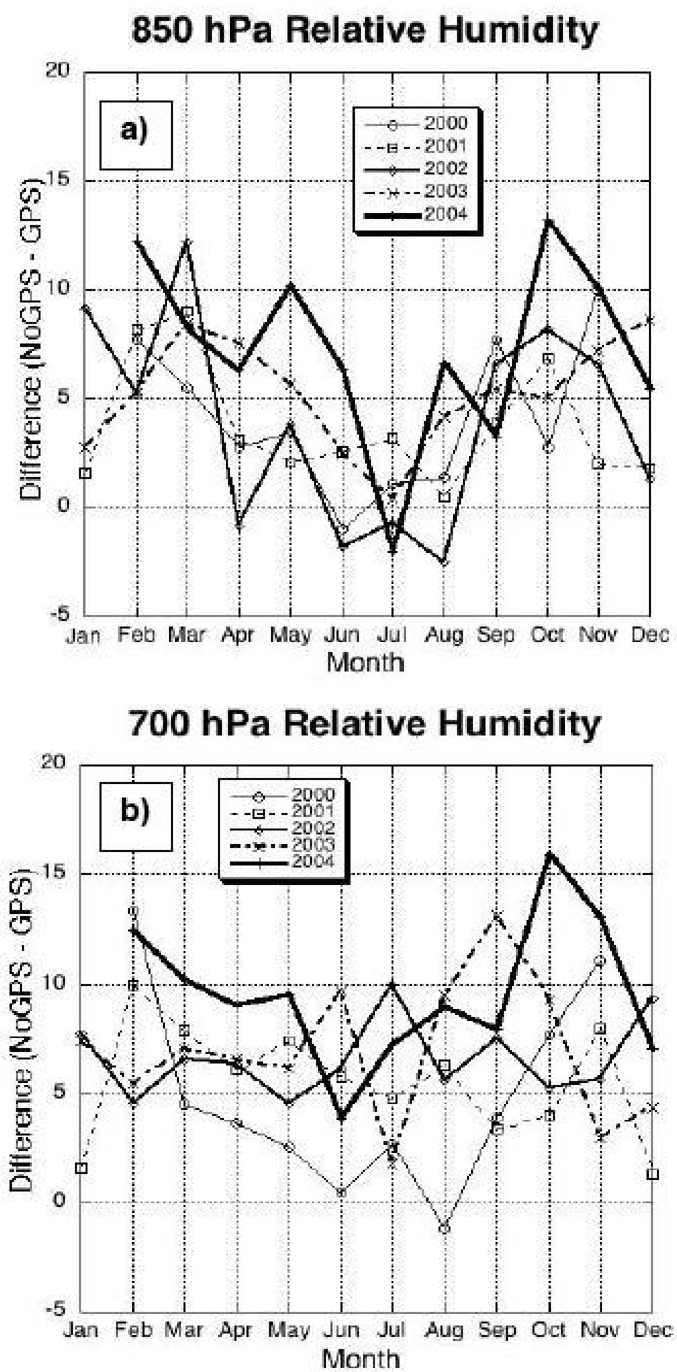


Figure 6. As in Fig. 5 except by month for the years 2000–2004 using (a) 850 hPa and (b) 700 hPa (from Smith et al. 2007).

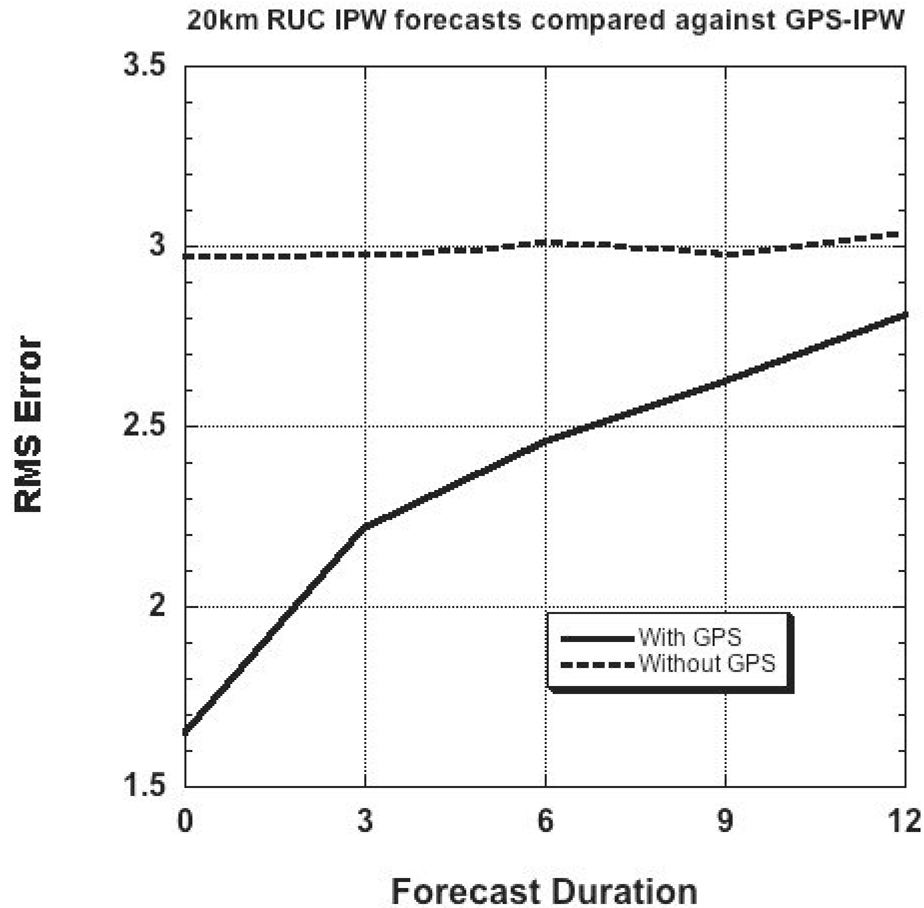


Figure 7. RMS error (mm) for RUC20 IPW forecast grids against GPS-IPW observations using 275 GPS sites across the CONUS for the March to May 2004 period (from Smith et al. 2007).

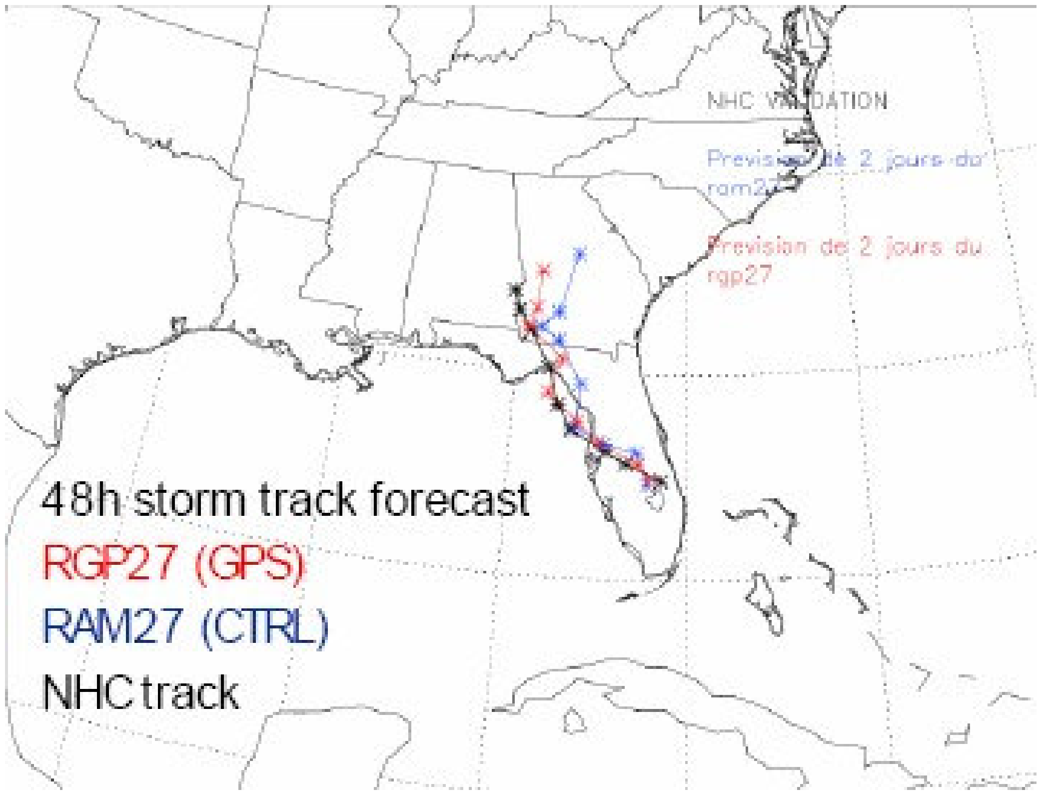


Figure 8. Two-day storm tracks for Hurricane Frances [from Macpherson et al. (2007)]. The 6-h positions are plotted from 1200 UTC 5 Sep 2004 to 1200 UTC 7 Sep 2004 (black asterisks). Red (blue) asterisks represent the experiment with (without) GPS-IPW.

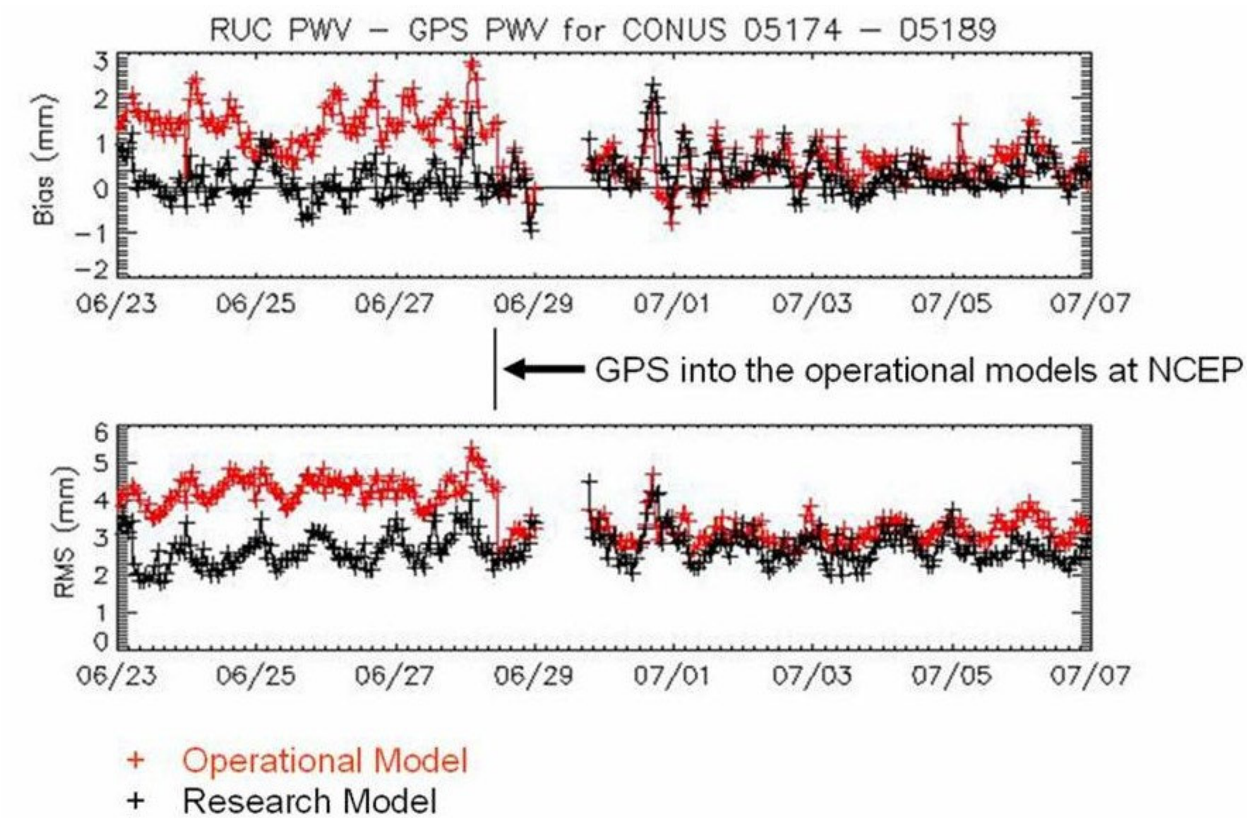
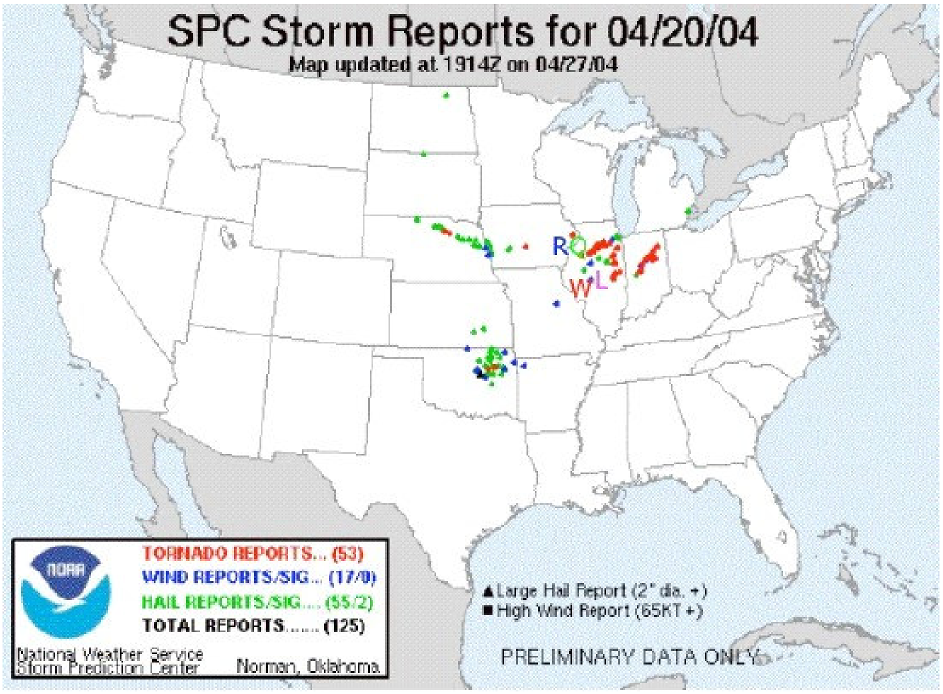
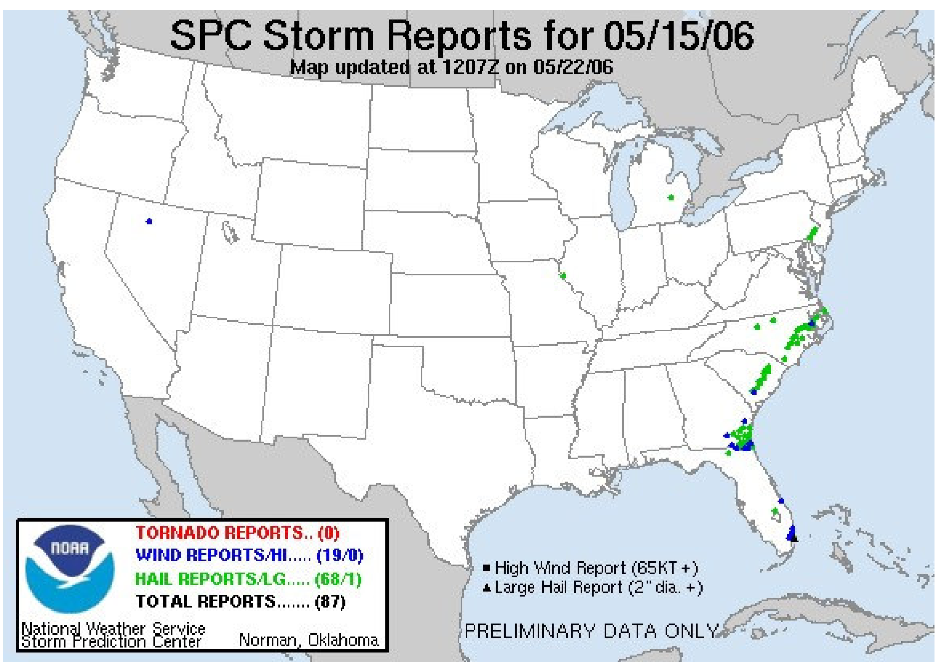


Figure 9. Impact on operational RUC IPW forecasts across the CONUS since ingesting GPS-IPW data during the summer of 2005 when they started to assimilate the data into the model (NOAA ESRL GSD 2005 GPS-Met Technical Review online report at: http://gpsmet.noaa.gov).



(a)



(b)

Figure 10. Severe weather reports for (a) 20 Apr 2004 and (b) 15 May 2006.

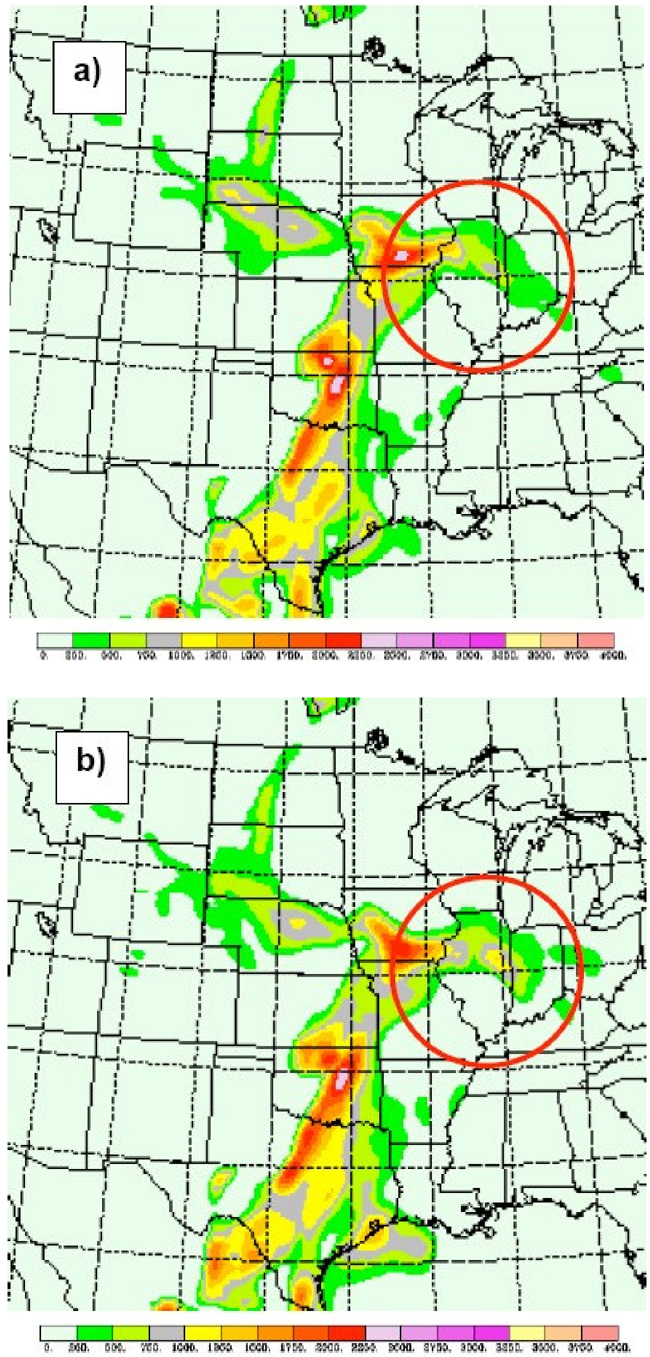


Figure 11. (a) 3-h forecast CAPE valid 0000 UTC 21 Apr 2004 from the 20-km RUC without GPS-IPW and (b) with GPS-IPW. Intervals in color legend are 250 J kg^{-1} (from Smith et al. 2007).

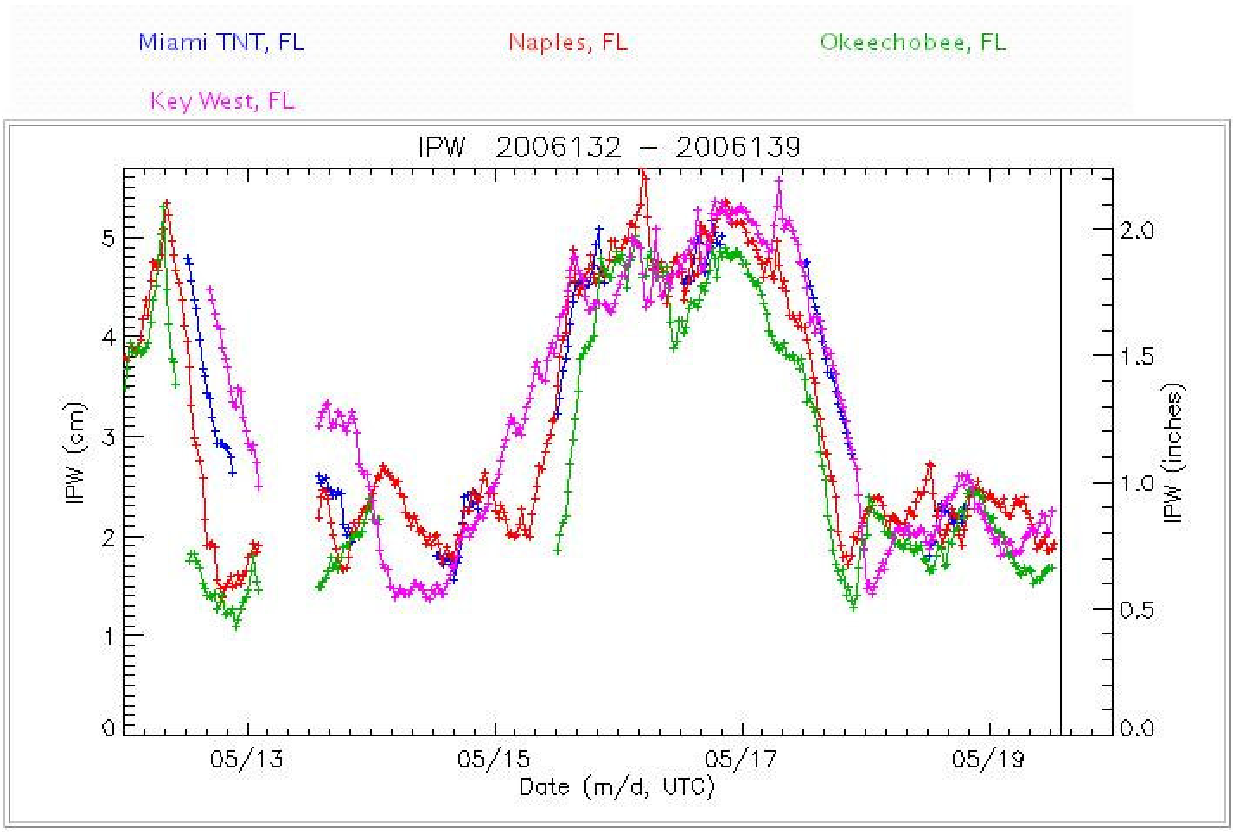


Figure 12. Time series plot of GPS-IPW across selected sites in South Florida covering the period from 12 May to 19 May 2006. Notice the rapid increase in moisture across the area beginning early on 15 May.

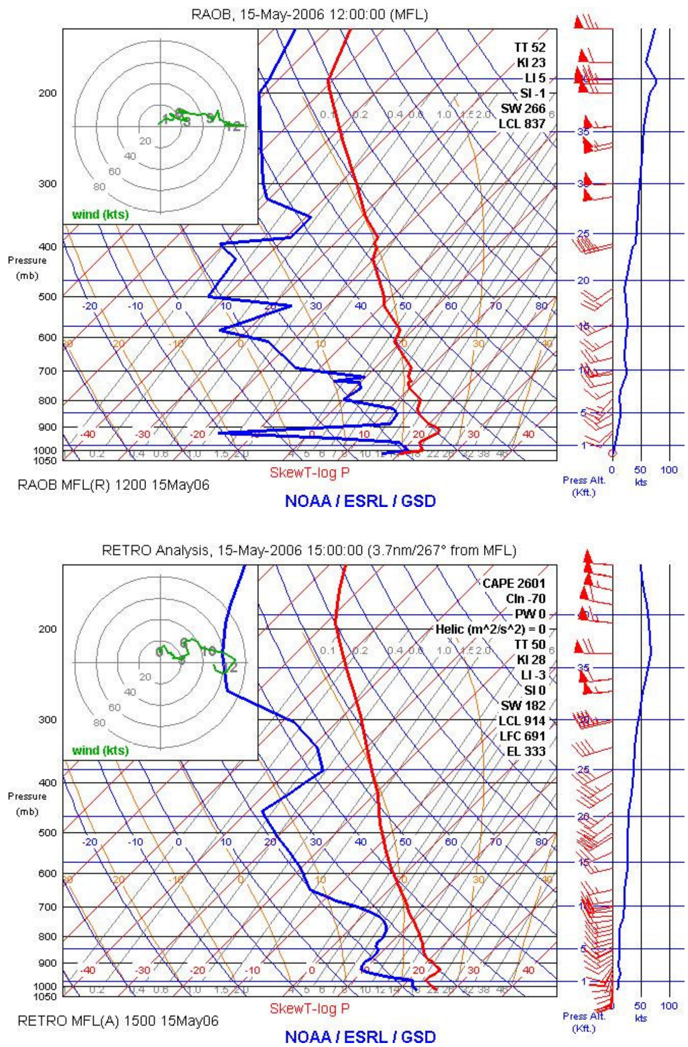


Figure 13. Observed RAOB (top) at Miami, FL valid at 1200 UTC 15 May 2006 and RUC13 diagnostic sounding (bottom) valid at 1500 UTC 15 May 2006 (from http://rucsoundings.noaa.gov). Notice moistening and warming (wind veering with height) at low levels with lapse rates becoming steeper during the period. In fact from the 1200 UTC RAOB the 850mb - 500mb temperature index was 27.7C and from the diagnostic sounding valid at 1500 UTC the same index was 29C. Also, mid level temperatures went down from -11C to around -12 through the period. As it is, these numbers represent 5 to 6 degrees below normal for 500mb temperatures across South Florida for this time of the year.

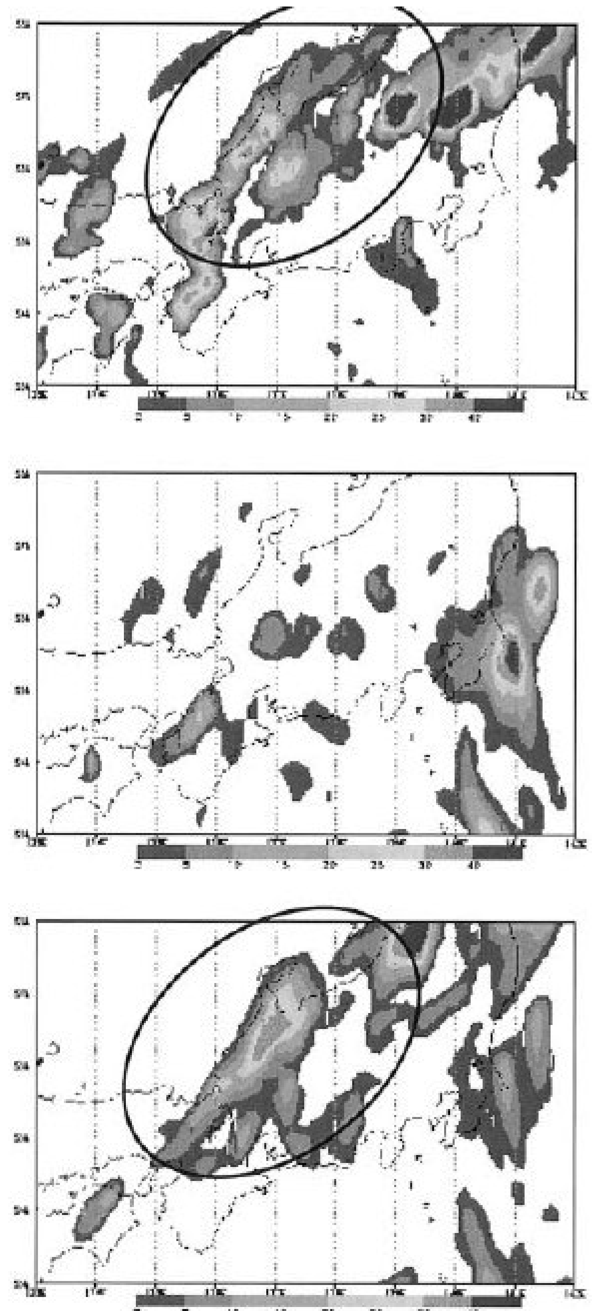


Figure 14. Radar observed 3 hours precipitation on the main island of Japan on 27 Aug 1998 (top); Japan Meteorological Agency (JMA) mesoscale model 3 hours precipitation forecast without the assimilation of the GPS-IPW data for the same period (middle); and the model's precipitation forecast with the GPS-IPW data assimilated (from Nakamura et al. 2004).

[1] The views expressed herein are those of the author and do not necessarily reflect the position of the National Weather Service.

[2] Per verbal communication with Seth Gutman from NOAA ESRL GSD.

[3] Special report on water vapor in the climate system located at: http://www.agu.org/sci_soc/mockler.html.

[4] The Global Climate Observation System (GCOS) workshop report on the Upper-Air Network available at: http://www.oco.noaa.gov (2006).

[5] NOAA Strategic Planning Office Website located at: http://www.ppi.noaa.gov/spo.htm.