P5.14 THE USE OF GPS INTEGRATED PRECIPITABLE WATER MEASUREMENTS TO SUPPLEMENT WSR-88D PARAMETERS IN DETERMINING THE POTENTIAL FOR FLASH FLOOD PRODUCING RAINFALL

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1. INTRODUCTION

The Appalachian mountain region in the eastern United States has always been prone to flash flooding, particularly in the warm season. The area is susceptible to moisture feed from both the Atlantic Ocean and Gulf of Mexico, and the terrain induces enhanced upslope vertical motion as well as rapid runoff. Clearly, many different factors play a role in determining the potential for a flash flood-producing rain event, such as overall moisture in the environment, instability, lift, movement and evolution of storms once they form, intensity of rainfall within any storm, antecedent soil moisture conditions, steepness of terrain, urban vs. rural areas, vegetation, and many others. Short term forecasting of flash flooding depends on observing or anticipating many of the above factors, especially in terms of both the mesoscale environment and convective storm evolution.

Forecasters at the National Weather Service (NWS) in Blacksburg have responsibility for issuing flash flood forecasts and warnings for the southern Appalachian region of southwest Virginia, southeast West Virginia, and northwest North Carolina. Among the most important tools utilized for flash flood forecasting by the staff are the WSR-88D radar located near the Blue Ridge south of Roanoke, which provides important reflectivity-based data every five or six minutes, as well as approximately 150 automated rain gages that report in 15 minute increments. Recently, forecasters have been able to merge radar precipitation estimates with rain gages measurements in the form of “Stage II” output, and compare this directly with flash flood guidance generated by NWS River Forecast Centers. However, to supplement radar and rain gage information, forecasters at Blacksburg and throughout the NWS also use a variety of other data and tools to assess short term, mesoscale changes that might influence the evolution of convection and intensity of rainfall. Recently, thanks to coordinated efforts between nearby Virginia Polytechnic Institute and State University (VA Tech), the NWS in Blacksburg, and especially the NOAA Forecast Systems Laboratory (FSL) in Boulder, forecasters have a new tool to detect potentially important short term trends associated with an impending heavy rain or flash flood threat.

NOAA FSL has been involved with developing Global Positioning System (GPS) technology to measure integrated water vapor or precipitable water (IPW) in the atmosphere since the mid-1990’s, and currently maintains a network of sensors across the county, mainly in the central U.S. (a map is available on the web at *www-dd.fsl.noaa.gov/gpsimages/net_now.jpg*). In the summer of 1999, due to interest on behalf of VA Tech and NWS Blacksburg, FSL agreed to co-locate a sensor with the NWS Blacksburg upper air radiosonde site. The data is available to forecasters via the world wide web in near real-time (15 to 20 minute latency), and is calculated at 30 minute intervals. Data for the purposes of this study were primarily collected during the summer of 2000, although some more recent data has been used as well. For an example of the output available on the web, visit *gpsmet.fsl.noaa.gov/realtime/jsp/rti.jsp*.

The motivation behind installing, collecting, and studying these GPS IPW measurements at Blacksburg was to determine whether short term trends in these data could be correlated with observed trends in radar parameters and actual rain gage measurements within an assumed radius of influence of the sensor, in hopes of ultimately providing some additional lead time before heavy flash flood-producing rainfall begins,

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or at least before flash flooding begins. Some preliminary results of this research are provided here.

2. GPS IPW vs. RADIOSONDE PW

While the details of the techniques to extract IPW measurements from GPS signals are left to the reader to examine further in Bevis et al (1992), Rocken et al (1995), and Businger et al (1996), the fundamental differences between GPS and radiosonde measurements will be reviewed here. A single GPS receiver collects signals from four to eight GPS satellites (depending on any line-of-site obstructions that may occur at low angles to the horizon). The “zenith tropospheric delay” of the signal from each satellite is averaged. Furthermore, this signal delay is composed of a dry delay component and a wet delay component, and it is the wet delay that can be attributed to the amount of water vapor in the atmosphere. Using other known atmospheric quantities (including mean temperature and surface pressure) the total water vapor, which is assumed to be directly above the site even though the satellites are technically not, can be calculated in terms of the IPW (units typically are in mm or cm). To obtain accurate measurements in near real-time, precise predictions of the satellite orbits are required, but the final calculations are still available within about 15 to 20 minutes of each measurement.

In contrast, radiosondes collect temperature, humidity, and pressure measurements at specific intervals in time as the balloon carries the instrument upward and laterally to some extent (depending on the winds throughout the atmosphere). While the instrument may travel a couple hundred kilometers downstream during it’s 60-90 minute flight, the data collected is assumed to be directly overhead and instantaneous at observation time (which is near the end of the flight time) for the purposes of PW calculation. Furthermore, since dew point data are generally only made available up to about 300 hPA, the integration to calculate PW does not always include the entire troposphere. Systematic errors associated with the sensing equipment used in each system can also be responsible for potential differences in the values of PW between the two.

Despite the obvious difference in the two methods, comparisons have shown a minimal bias between them. Data collected from several of the first experimental sites in the central U.S. show that during the spring months the GPS measurements have a slight dry bias compared to the radiosonde, while the opposite is true during the autumn months, however these differences are only around 2 mm or less (Wolfe and Gutman 2000). In preliminary analyses comparing the Blacksburg GPS IPW with the co-located radiosonde measurements, a slight GPS wet bias of 1-2 mm was found (Gutman, personal communication).

3. METHODOLOGY

A radius of influence centered on the GPS site at Blacksburg was arbitrarily selected to be roughly 80 km for the analysis of radar and rain gage data (actually, 40 km was also used but proved to be too small to include enough events of more than an hour or so duration). In reality, the area of influence should be considered mainly downstream in the direction of the mean wind (and the radius might change depending on the magnitude of the wind), but the symmetric radius was chosen for simplicity.

The WSR-88D (KFCX) is located about 25 km from the GPS sensor. In terms of radar data considered, both the 0.5 degree elevation slice of base reflectivity was used (since this is the primary slice used by the KFCX precipitation processing system algorithms), and the vertically integrated liquid (VIL) product were examined within this 80 km radius of the GPS sensor. A wedge was defined within approximately 20 km of the radar where VIL would not be examined since it can be significantly underestimated within those ranges due to incomplete sampling of the upper portions of many storms. One of the reasons the 80 km range was chosen was because of how radar beam sampling can affect VIL estimates beyond that range, and the reduction in accurate rainfall estimates from the base reflectivity due to beam height above the ground and greater beam averaging. Within the range limits defined, and for each event that was examined, the maximum reflectivity and VIL values were recorded for each volume scan (usually every five minutes) over a sufficient period of time starting before and after the flash flood event or peak in rainfall or radar-observed maximum rainfall rates.

Within this 80 km circle, there are 112 automated rain gages that were examined for each 15 minute value. These were initially all averaged together every 15 minute period, but this proved to have little value as widespread light rainfall rates could produce higher averages than isolated intense rainfall falling over only one gage. It was determined that grouping gages by county had much more utility.

Not only were the trends in the above data compared to the GPS IPW trends, but a relationship to climatological PW normals and extremes (based on six years of radiosonde measurements at Blacksburg) was examined. Some promising but preliminary findings from this analysis are also presented below.

4. RESULTS OF IPW TREND ANALYSES

The first full warm season that GPS IPW data for Blacksburg were available on-line in near real-time was the Summer of 2000. An operational survey was conducted among forecasters in the Blacksburg office to get a subjective sense of how the IPW trends correlated with significant convective activity observed in the local area. Forecasters commented that there was a clear peak in the IPW very close to the time of peak convective activity, and sometimes this peak corresponded more with the initiation of convection or movement into the local area. Usually any lead time in the IPW peak was minimal, or not observed at all. While there was usually an upward trend in the IPW at the time convection developed or peaked, the survey did not ask them to assess when certain IPW thresholds were met, or when troughs in the IPW trend occurred relative to convective development or intensity. However, the objective analyses (still underway at the time of this writing), which are focusing on several specific events, are addressing these questions.

First, these analyses show that there is indeed a general correlation between peaks in GPS IPW and peaks in convective activity as measured by maximum reflectivity and VIL from the WSR-88D. So far, in the events analyzed, there was no obvious lead time observed when considering the peak in IPW. In one event, where the strongest convection generally occurred within a few miles of the GPS site but moved in from upstream, the maximum reflectivity and VIL (in the 80 km range) occurred slightly before the peak in the IPW at Blacksburg. Figure 1 and 2 show that on 27 August 2000 (extending into August 28 on the UTC clock) the peak in IPW occurred 5 minutes after the peak in VIL, as well as 5 minutes after the peak in base reflectivity in the lowest slice. However, note the smaller initial peak in the IPW followed by a trough that occurred before the highest peak in convective intensity. Heavy rain and some severe weather occurred on this evening (lightning actually cancelled the VA Tech football team's season-opening came), however no flash flooding was actually reported.

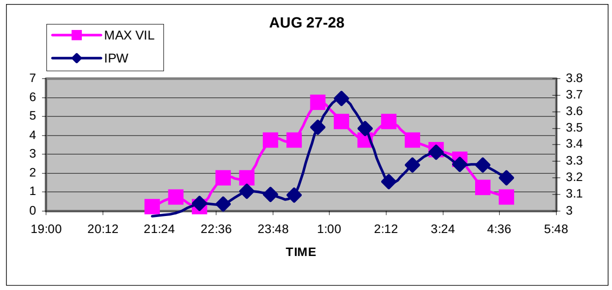

Figure 1. GPS IPW (scale on right in cm) vs. maximum VIL within 80 km of GPS sensor (scale on left in tens of kg m^{-2}. Times are in UTC.

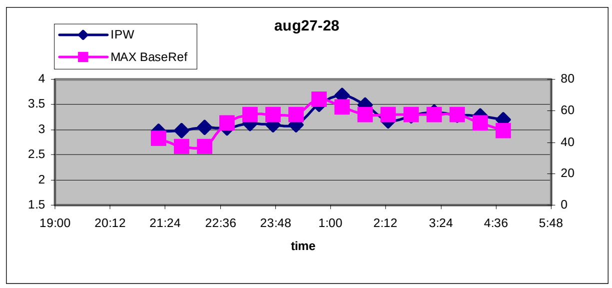

Figure 2. GPS IPW (scale on left in cm) vs. maximum base reflectivity (lowest slice) within 80 km of GPS sensor (scale on right in dBZ). Times are in UTC.

In this event and others analyzed, it was determined that a correlation also existed with troughs in the IPW trends and peaks in the convective intensity and rainfall data, yet with a negative lag (in other words, with lead time). The question was, by the time forecasters realize this trough has occurred (when the IPW trend begins to increase again) would this signal alone reliably foretell a heavy rain or flash flood event? To enhance this idea, we turned to historical PW data from the six years of radiosonde data in Blacksburg (RNK). Figure 3 shows a plot of average PW values for each month of the year at Blacksburg, with the 50th percentile plotted (representing the statistical "normal"), the 25th and 75th percentile also plotted, the "two standard deviation" (or 98th percentile) plot, and finally, daily extremes occurring in each month are plotted as well. All PW values in Figure 3 are shown in inches. Comparing the GPS IPW trends with these climatological values leads to some interesting results.

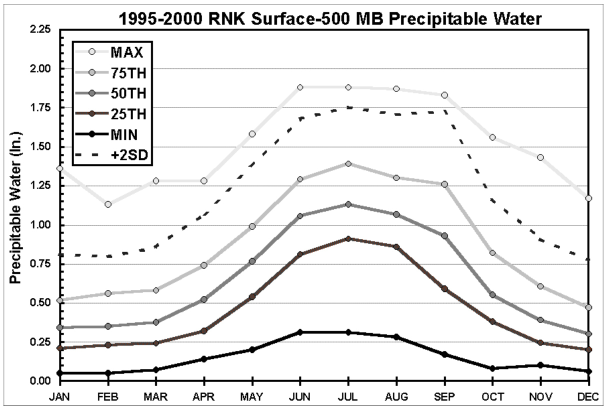

Figure 3. Monthly climatology of PW at Blacksburg (RNK) based on six years of radiosonde measurements. 50th percentile indicates statistical mean, +2SD indicates two standard deviations from the mean, and MAX and MIN refer to the extremes observed in each month. Courtesy of Matthew Bunkers, NWS Rapid City SD. Note: values are plotted in inches.

Figure 4 shows IPW plotted in comparison with the 75th percentile and two standard deviation (Mean +2SD) thresholds for the month of March, along with the average rainfall from all the gages in Montgomery County (for every 15 minutes period) on 29 March 2001. This rainfall was

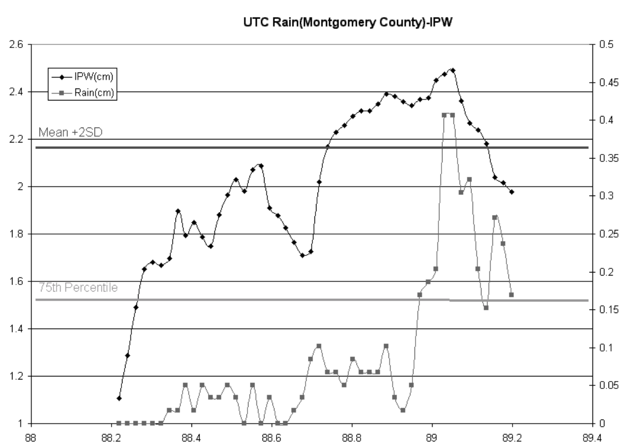

Figure 4. GPS IPW (scale in cm on left) vs. rainfall averaged from all gages in Montgomery County (scale in inches on right). X-axis is Julian day (88 = 03/29/01); each increment is just under 5 hours. Also indicated are the 75th percentile and Mean +2SD for March (from Fig. 3).

enough to produce some minor flash flooding mainly on small creeks and streams late in the day and early on the 30th. The initial climb above the 75th percentile occurs about 20 hours before the heaviest rainfall, but this is followed by a clear trough about 10 hours before the heavy rain, then the upward trend surpasses the value of the first peak about 5 hours before the heaviest rain (the flooding actually was reported another couple hours after the heaviest rainfall). The IPW values actually crossed the 2SD threshold in this case, however since this event was almost in April (when the 2SD threshold is considerably higher) this is not as extreme a case as it may first appear.

In a case from 29-30 July 2000, Figure 5 shows the IPW curve crossing the 75th percentile threshold for July at around 1700 UTC, followed by a very small scale trough, and then rising above the initial peak again at around 2100 UTC. While rainfall plots and radar parameter trends were not yet available at the time of this article, the maximum VIL was coincident with this secondary IPW peak, and flash flooding was observed an hour later. The IPW trend then dropped again, before rising above the initial peak a third time around 0000 UTC (and peaking at 0300 UTC). 0300 UTC was the time of additional flash flooding in the next county downstream (Roanoke). In other words, while the main peak did not provide any lead time before the most intense convection (as measured by VIL in this case) or flash flooding, a secondary rise surpassing an initial peak above the 75th percentile appears to offer some lead time in this and a few other cases examined so far.

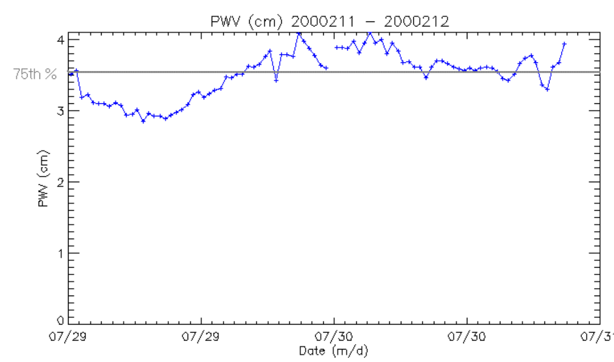

Figure 5. GPS IPW for 29-30 July 2000 compared to 75th percentile of PW for July (from Fig. 3)

5. FUTURE STUDY

We believe there is some promise in using the initial peak above the 75th percentile, followed by a trough and a secondary rise above the initial peak in providing some amount of lead time before flash flood-producing rain occurs within this radius of influence. However, more events from the summer of 2000 will continue to be examined, and some of these results should be available by the time of the conference. We also need to examine similar trends on non-event days to see what kind of a false alarm rate this method produces. Even so, when used with other mesoscale data sources, these kinds of trends show a mesoscale signal of some kind that seems to indicate heavy rain potential. We also plan to fine tune our criteria for the definition of an "event" by looking for any occurrence at a single rain gage with a 15 minute rainfall of 0.50 inches (which would result in 2 inches of rain in an hour if the storm maintained it's intensity for one hour). Whether or not this amount of rainfall would actually result in flash flooding, this kind of rainfall rate would at least suggest a flash flood threat, depending on storm movement, soil moisture, and specific location of the rainfall. Better anticipation of this potential should result in quicker warnings. Finally, we plan to do some similar comparisons with GOES satellite PW data for a small period of time during 2000 when we were able to access archived data for the Blacksburg vicinity, and examine any bias between the GPS IPW and GOES PW at the same time. The disadvantage in the GOES PW is that it cannot be calculated when there is cloud cover over the area, while GPS IPW still can.

6. ACKNOWLEDGEMENTS

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