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A STATISTICAL EXAMINATION AND CASE STUDY OF INTEGRATED PRECIPITABLE WATER (IPW) IN NORTHERN NEW ENGLAND

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1. INTRODUCTION

The use of GPS measurements of atmospheric water vapor in the form of integrated precipitable water (IPW) continues to expand worldwide. In the United States, the National Oceanographic and Atmospheric Administration's (NOAA) Forecast Systems Laboratory (FSL) continues to provide real-time data from GPS sensors nationwide. The network currently consists of 324 sites, with two of these sites located in New Hampshire; Plymouth (SA06) and Bartlett (BARN). The Bartlett site is located 56 km northeast of the Plymouth site (Figure 1). The Bartlett GPS site is an FSL site located at the Mount Washington Observatory research facility. The Plymouth GPS site is part of the SuomiNet (Ware et al., 2000) Program of the University NAVSTAR Consortium (UNAVCO) and is located on the roof of the Boyd Science Center at Plymouth State University (PSU; formerly Plymouth State College). SuomiNet is a program designed to help advance university research through a GPS sensor network that will optimize student and faculty participation. SuomiNet currently manages 75 GPS sensors nationwide.

Bevis et al. (1992) envisioned many meteorological applications of GPS-derived water vapor data. Possible research topics include mesoscale modeling and data assimilation, storm system analysis, severe weather, cloud dynamics, climatology, hydrology, space and terrestrial weather, and sensing of the ionosphere (Ware et al., 2000). Past research using and applying GPS-derived IPW data has proven it as a precise and well-established technique. It agrees highly with precipitable water (PW) measurements from water vapor radiometers (WVR's) and radiosondes (Cucurull et al., 2000). In regards to the two sites in New Hampshire, past research by Dumont and Zabransky (2000) compared the first three months of IPW data from the Bartlett site with regional radiosonde stations, and found correlation coefficients of 0.92 for both 00Z and 12Z launch times. Brown et al. (2002) calculated a correlation coefficient of 0.89 for IPW data between the Plymouth and Bartlett GPS sites, while also finding occasional, short-term departures in the data that could be attributed to regional synoptic scale or mesoscale variations. The research was limited to the first seven weeks (11 July to 31 August 2001) of data collection from the Plymouth GPS site.

The purpose of this research is to continue the research started by Brown et al. using the past two years of data from both sites to calculate correlation coefficients. Seasonal and monthly variations in correlation coefficients and average IPW values are discussed. A case study of a strong cold frontal passage in the Northeast examines how these frontal systems affect regional IPW values and provide insight into the water vapor structure of these systems.

2. DATA COLLECTION AND ANALYSIS

2.1 Statistical Analysis

Two years of GPS-derived water vapor data and observed meteorological data from the meteorological package (metpack) included with both receivers were analyzed for the Plymouth and the Bartlett, NH sites. Datasets from each site included IPW, relative humidity, temperature, and pressure. Correlation coefficients for each variable were calculated for monthly and annual periods as well as for the entire time of observation from 1 August 2001 through 31 July 2003. In addition, average IPW values were also calculated for the same time periods.

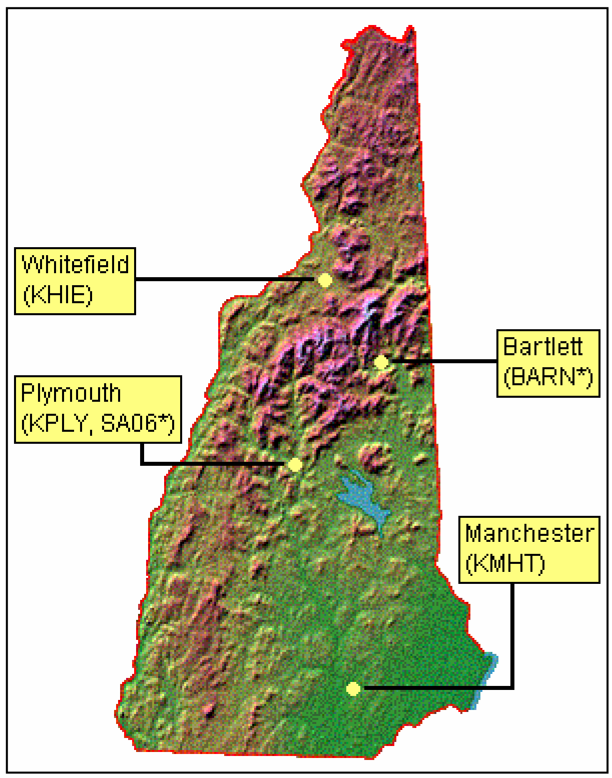

FIGURE 1. Relief map of New Hampshire showing the four locations where meteorological data are observed and used in this study. (* represents GPS-IPW station identifiers, all others are surface meteorological stations)

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Data from both GPS sites are downloaded as half-hourly averages from the NOAA/FSL Ground Based GPS Meteorology (GPS-MET) website as unformatted text, which are then converted onto a spreadsheet. The data were downloaded in monthly intervals. The Plymouth GPS data available on the FSL site goes back to 25 October 2002, with data available back to 11 July 2001 on the local server at PSU. These datasets contain quality controlled and half-hourly averaged data collected through the SoumiNet server at UNAVCO. The files are of the same format as the FSL files and include the same variables, but are separated by day.

There were time periods during the two years of observation when data were not available for one of the sites. For these situations, the other station's data were also removed from the spreadsheet to avoid any skewness of the data. Sometimes the data were missing and other times specific observations were not available. These events lasted anywhere from an hour to four days and did not occur very frequently.

2.2 Case Study

A case study of a strong cold front passage from 16-17 April 2003 is presented. Surface observations, like sea-level pressure and dewpoint temperature, are not available through the GPS data. Pressure data are available, but in order to compare the stations, sea-level pressure values were necessary. Surface observations from Whitefield (KHIE), Plymouth (KPLY)†, and Manchester (KMHT) helped determine surface frontal passage from north to south across the state of New Hampshire (Figure 1). Surface analyses from the National Centers for Environmental Prediction (NCEP) at 09Z, 12Z, and 15Z on 16 April also aided in confirming the location and movement of the surface front. NCEP charts of the 850-hPa, 500-hPa, and 250-hPa levels helped identify troughs or ridges, jet streaks, and regions of cold or warm advection associated with the surface front. A series of three maps from 12Z April 16 to 12Z April 17 were used. Radiosonde soundings from Gray, Maine (KGYX) at the same times helped determine the moisture characteristics of the upper atmosphere.

† Not a formal NOAA designator

	Correlation Coefficients			
Year	**IPW**	**Press.**	**Temp.**	**RH**
8/01 - 7/02	0.9758	0.9940	0.9882	0.9053
8/02 - 7/03	0.9840	0.9941	0.9916	0.8843
TOTAL	0.9801	0.9941	0.9903	0.8939

TABLE 1. Correlation Coefficients from a comparison of IPW, pressure, temperature and relative humidity (RH) for two annual periods and the entire time period at Bartlett and Plymouth, NH.

3. RESULTS AND DISCUSSION

3.1 Statistical analysis

Correlation coefficients between the two sites for the entire time period of study and each annual period are shown in Table 1. The two-year correlation coefficient for IPW between the two sites is 0.98. Brown et al. (2002) calculated a correlation coefficient of 0.89 between IPW values for the initial seven weeks of data collection. For this study, the data from 11 July through 31 July 2001 were excluded in order to calculate averages and correlation values on a monthly basis.

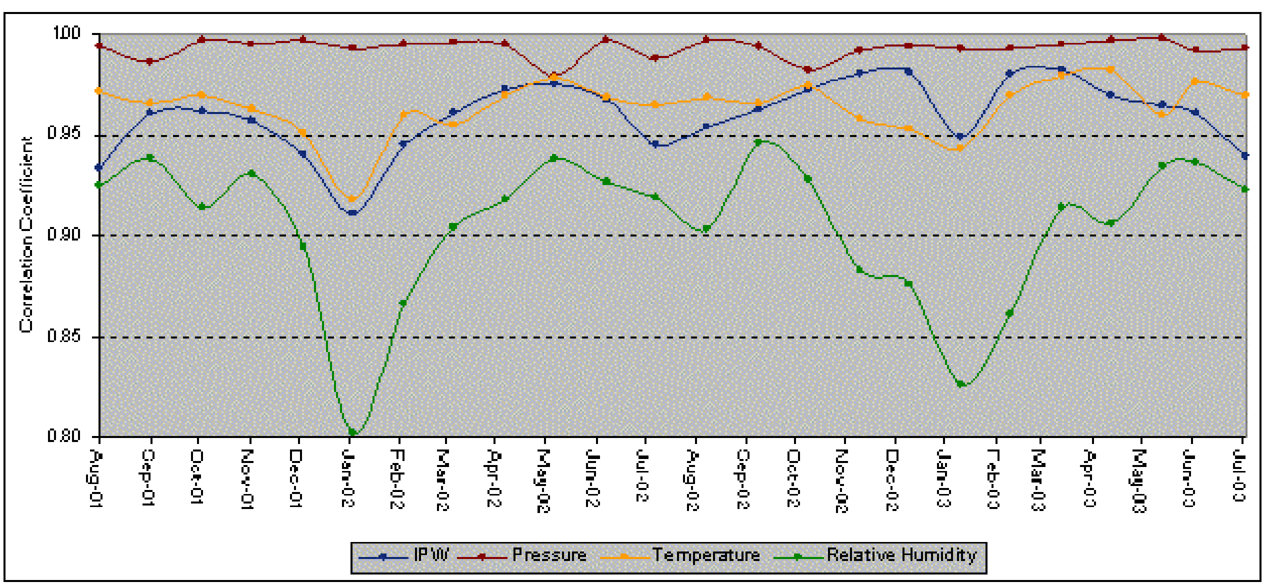

FIGURE 2. Monthly correlation coefficients of IPW, pressure, temperature and relative humidity for Plymouth and Bartlett, NH from August 2001 through July 2003.

	Average IPW (cm)	
Year	**Plymouth**	**Bartlett**
08/01 - 07/02	1.63	1.64
08/02 - 07/03	1.53	1.51
TOTAL	**1.58**	**1.57**

TABLE 2. Average IPW (cm) for two annual periods and the entire time period at Bartlett and Plymouth, NH.

Seasonal and monthly variations of weather patterns and moisture distribution may have also caused the lower correlation. Examples of these variations can be seen in Figure 2. Notice the relative minimum values of IPW, temperature and relative humidity correlation coefficients for each month of January during the two years of observation. Also notice the relative decreases in IPW correlation coefficients for each May to July time period. Two possible reasons for both the summer and winter situations are topography and wind direction. The role of the White Mountains in keeping cold, dry air to the north during the winter, and warm, moist air to the south during the summer is a probable cause. Other situations, such as synoptic scale patterns and mesoscale differences may have also played a role.

Average IPW values were calculated for several time periods (Table 2, Figure 3). Differences in annual IPW averages of 0.10 and 0.13 cm at Plymouth and Bartlett respectively, reveal how the amount of moisture in the atmosphere can vary on a seasonal basis.

The average monthly IPW values (Figure 3) indicate that the atmosphere was much drier during the winter of 2002-2003 than during the previous winter of 2001-2002. Average IPW values in January 2003 are 0.45 and 0.46 cm lower than January 2002 for Plymouth and Bartlett.

There is also a very sharp difference in average IPW from September to October of 2002, with differences of 1.07 and 1.09 cm for Plymouth and Bartlett. This is the largest change (from one month to the next) in average IPW during the entire time period. A major shift in the weather pattern occurred during the month of October. This change was a shift in the location of the subtropical high, which originally extended into the eastern US. A mean trough over the eastern US brought cooler, drier air in from Canada.

3.2 Case study

During the early morning hours of 16 April 2003, a stationary boundary was draped across northern New Hampshire. A dome of building high pressure, centered over northeast Manitoba, moved southeastward by 12Z, pushing that boundary towards central New Hampshire. The 15Z NCEP surface analysis shows that the front has moved through Plymouth, and continues to work its way southward across the state. Evidence of the cold front is found in the New Hampshire observations as shown in Table 3.

Date: 04/16/03 17 UTC							
ID	TIME	T	TD	RH	DIR	SPD	GST
KPLY	1658	48	37	66			
KHIE	1652	36	22	56	10	8	
KMHT	1653	81	45	28	300	15	22

TABLE 3. Surface observations at 17Z from 16 April 2003 for Plymouth (KPLY), Whitefield (KHIE), and Manchester (KMHT).

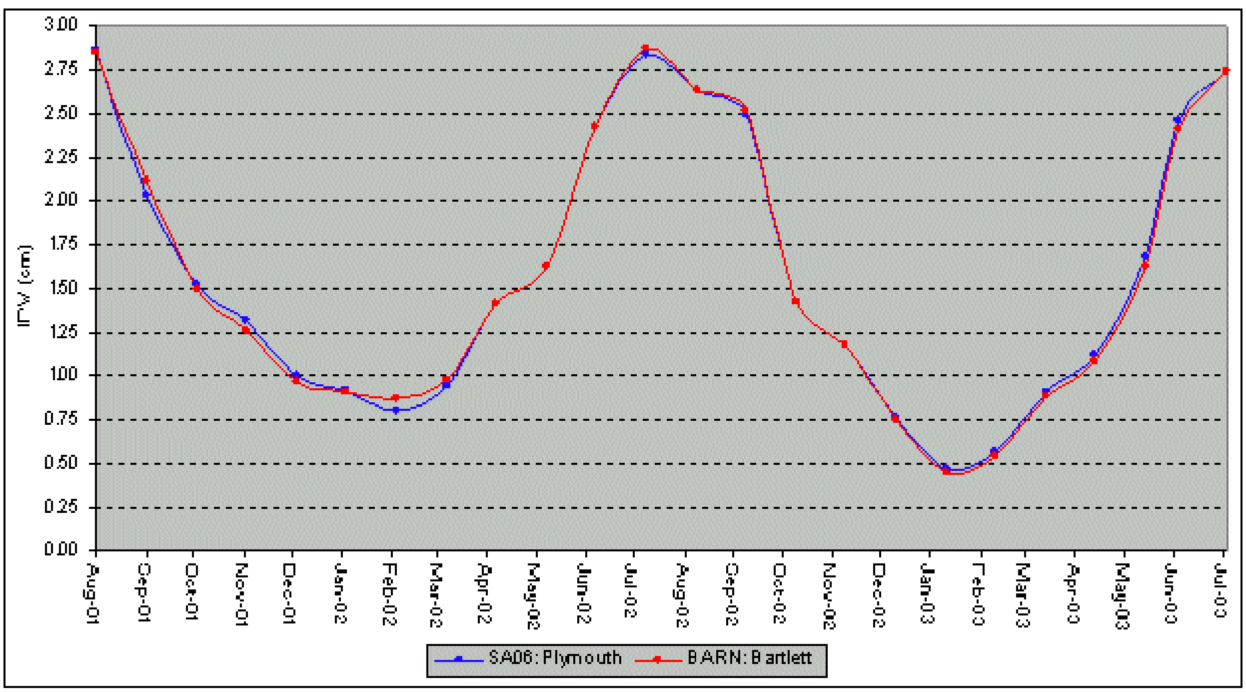

FIGURE 3. Monthly averages of IPW (cm) at Plymouth and Bartlett, NH from August 2001 through July 2003.

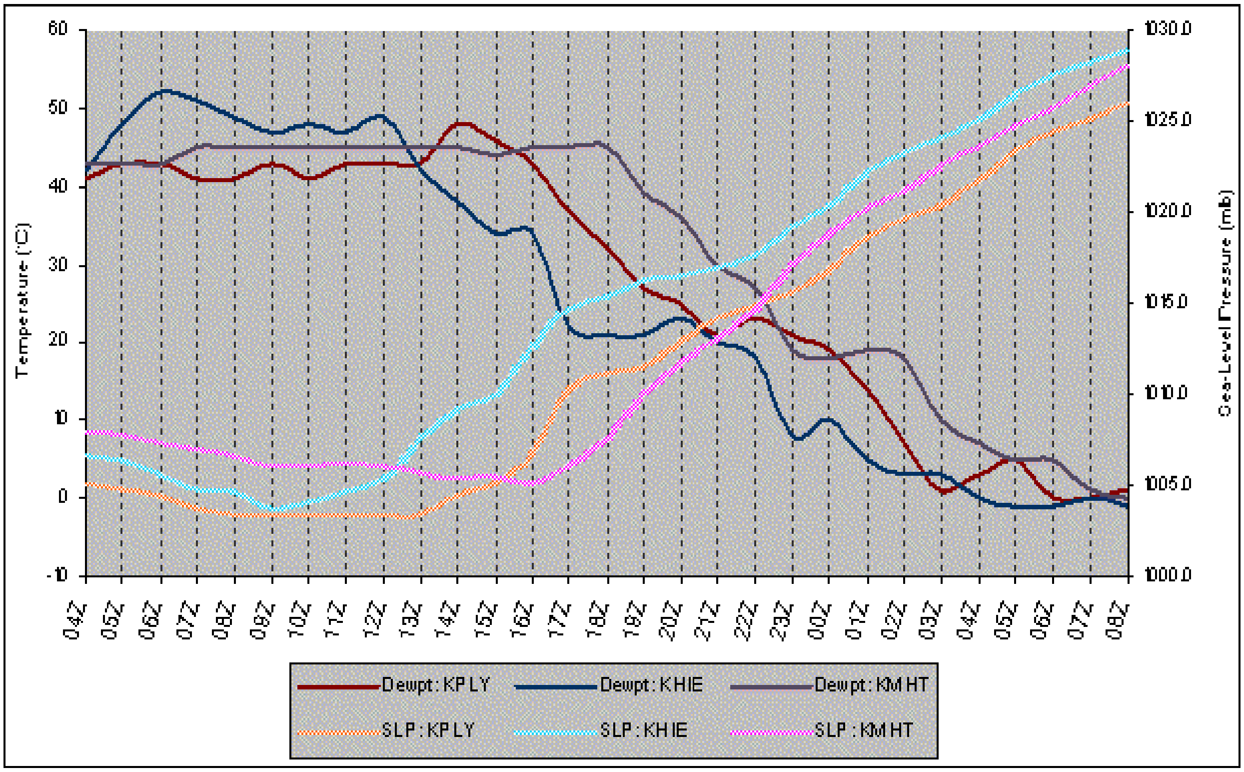

FIGURE 4. Dewpoint temperatures (°C) and sea-level pressure (hPa) at Plymouth (KPLY), Whitefield (KHIE), and Manchester (KMHT) for the time period of 04Z April 16 to 08Z April 17, 2003.

Notice the extreme differences in the characteristics of the air masses on each side of the surface front. West-northwest winds in Manchester imply that the surface front is approaching as there is a more northerly component to the winds. Changes in the dewpoint temperatures and sea-level pressure observations across the state confirm the NCEP analysis of the surface front location (Figure 4). The dewpoint temperatures begin to decrease first in Whitefield at 12Z, then Plymouth at 14Z, and finally Manchester at 18Z. Looking at pressure rises, which are expected after frontal passage, Whitefield begins to rise at 09Z, but not rapidly until 12Z. Pressure rises in Plymouth begin at 13Z and in Manchester, the rises begin at 16Z. It can be concluded then that the front passed through Whitefield at 12Z, Plymouth at 14Z, and Manchester at 17Z.

At 12Z April 16, the 850-hPa level featured strong cold air advection in southern Quebec and Ontario, which helps to build the high pressure system at the surface. There is a short wave trough extending through western New York with a strong temperature gradient on the west side of the trough. Height falls of 30 and 40 m were common in the northeast ahead of the approaching trough. By 00Z April 17, the trough moves through northern New England bringing strong cold air advection into the region with it. Finally by 12Z April 17, height rises of 70 m or more are occurring as a ridge slides in behind the trough.

The 500-hPa level features a broad trough axis over the western Great Lakes at 12Z April 16. Because low-level cold air advection is associated with height falls at the mid levels, this trough strengthens and moves eastward. By 12Z April 17, the 500-hPa trough axis is offshore and the winds over northern New England had shifted from west to northwest.

At jet-level (250-hPa), the entrance region of a jet streak is located over Manitoba at 12Z April 16. Divergence at the surface below the entrance region helped build the high pressure system at the surface. Winds in the vicinity of this jet streak were 70 to 90 knots. The polar jet runs south of a trough over Ontario and follows the US-Canada border to the Atlantic. By 12Z April 17, the trough is over the Canadian Maritimes and the southern edge of the jet is over northern New

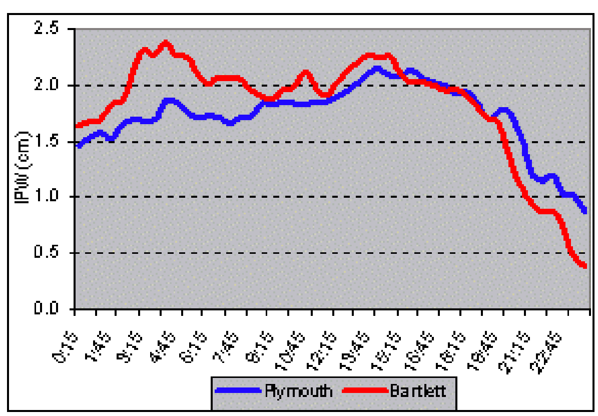

FIGURE 5. IPW(cm) for Plymouth and Bartlett, NH during April 16, 2003. (Time in EDT)

England. All of these factors helped build the high at the surface and move the stationary front southward across New England.

IPW values did not decrease with the surface frontal passage (Figure 5). IPW values did not begin to drop off until some time after 8PM (00Z on 17 April). This is about the time when the 850-hPa trough passed through and the mid- and upper-level jets shifted from westerly to northwesterly flow bringing much dryer air from mainland Canada to these levels in the atmosphere over New England. Looking at soundings from Gray, Maine (KGYX), observed precipitable water (PW) also agreed with the IPW readings from the GPS-IPW sites. PW was observed at 0.75 in (1.91 cm) for 12Z April 16 and 0.35 in (0.89 cm) for 00Z April 17. The 00Z April 17 sounding also showed strong backing of the winds at low levels and a cold frontal inversion near the surface. The atmosphere is very dry below 700 hPa, but remains moist above that level as expected.

5. CONCLUSIONS

A statistical analysis of GPS-derived IPW values between Plymouth and Bartlett, New Hampshire shows that the two stations correlate very well. One exception is the occasional case where synoptic scale or mesoscale phenomena affect the regional moisture field. Metpack data from Plymouth were also in agreement with the Bartlett datasets. Seasonal and monthly variations in weather patterns caused minimum correlation coefficients (except pressure) each winter on record. Average IPW calculations showed that the winter of 2002-2003 was drier that the previous winter.

Analyses of the surface, upper-air, and GPS data used in the case study of a cold frontal passage over the two sites, gave two main results. First, IPW values did not decrease initially with surface frontal passage, mainly because the moist air at the surface should be wedged aloft by the surface front, leaving the atmosphere relatively moist above the surface frontal inversion. Secondly, IPW values did not begin to decrease steadily until all upper-level features passed. For the April 16, 2003 case, once the surface front passed, IPW values at each site did not decrease steadily until about ten hours later. At this time, the 850-hPa trough and associated cold air advection had moved east and the mid and upper-level jets had shifted to northwesterly. Observed PW from radiosonde launches at Gray, Maine followed a similar trend as Plymouth and Bartlett for this case.

With multiple uses of GPS in the field of meteorology, the research possibilities are endless. Topics include storm and frontal system analysis, global climate change, air chemistry, and integration into forecast models. While there has been much research proving the value of GPS-derived IPW among other atmospheric water vapor measuring techniques, further research into the behavior of IPW with frontal passage and other weather phenomena is needed.

GPS-derived IPW has a very promising future in helping meteorologists understand the hydrologic cycle and analysis of water vapor in our atmosphere. With continued expansion of the SuomiNet program, the tremendous potential of GPS will be optimized.

6. ACKNOWLEDGEMENT

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