

1. “I would just ask the authors to again address the question of saturation in the atmosphere. As I noted in my first revision, the atmosphere is simply not saturated from the surface to the “top” of the atmosphere. You have to emphasize that you are making this assumption (which is TOTALLY unrealistic). It may be a question of semantics, but the atmosphere cannot saturate from the surface upwards, it would be radically unstable, and would not last a minute in that configuration. I ask that you at least note this assumption directly in the text. You don’t have to change any of your calculations or figures, but just state explicitly that this is not a realistic assumption.”

We thank the reviewer for reminding us of this point. The sentence “Note that a fully saturated atmosphere is an unrealistic assumption for a real atmosphere, but can be used for a simplified comparison” was added to Lines 306-308 to clarify that our assumption was unrealistic.

General aspects of the manuscript:

- 1. The motivation of the paper are not suitable and should be improved. I do not agree that there are not previous work that examine the characteristics of the PW and precipitation, although the number of this works is not expressive, some work should be mentioned and the results most important should be discussed in the introduction. No previous work was discussed. By the way, the number of the works referred in the text is very low. There are several research groups in different parts of the globe involved in this theme.**

Lines 147-151 were changed to be more specific and add in the only source with similar research who we have any knowledge of. We would appreciate if the reviewer would provide examples of prior work and also be more specific on why they think “the motivation is not suitable.”

- 2. The climate change and relationship with severe precipitation are presented in introduction section out of context and a speculative discourse. This could be discussed in final section referring other papers for mention the of possible link between these themes.**

We do not agree with the reviewer’s comment that this was “out of context and a speculative discourse.” If extreme precipitation events such as the one studied here are rare, it might not be that important to study them. The point we were making by including this relationship is that as the climate is warming, we will see more of these events. Therefore, it is essential to study past events, understand physical processes, and improve the models to thus improve the prediction of such events in the future. As a result of improved understanding and prediction, more lives and properties can be saved.

- 3. The authors state (lines 160-162): “... better understand the contributions of PW to an extreme precipitation event with the objective to someday apply these results to future research incorporating a wider variety of events.” This statement can be the final aim of this research about GPS-PW. However, they are not clear how the GPS data can help in this aim, based on the results presented in this paper. GPS data are not suitable explored.**

This sentence was revised to make our points clearer. It is important to study one particular event that had high impacts, but it is also essential to understand whether the results are applicable to other events which occurred at other times or in other regions. With regard to how GPS data can help in this aim, see our replies below on the importance of the high temporal resolution of GPS PW data. Also, we do not understand what the reviewer meant by the comment, “GPS data are not suitable explored.”

4. **The aim of the work is examine the characteristics of PW during the precipitation event of 2013 and an analysis of the climatological series of PW is used. This analysis, presented in Fig. 2, is poor and the quality (the size or zoom selected) not make evident the abnormality of this event. In my opinion this climatological study (as organized in this figure) does not help the examine the characteristics of the event. Besides, the PW time series shows that there are many similar values to observed in September of 2013 and severe precipitation was not observed (for example, September of 2011).**

The main purpose of this figure was to show how we combined the data from five GPS sites to create a 10-year climatology and show no obvious discontinuity between stations at the adjoining boundaries. Figure 2 also serves as a preliminary comparison of PW in September of 2013 to previous Septembers. We have revised the plot to make it taller and show the September 2013 abnormal values more clearly. This figure also shows the seasonal variation observed in the Front Range region of Colorado. If the reviewer would once again examine this figure, they would see that high PW values extend into September only in 2013 (as was stated in Lines 279-280), and not in 2011.

5. **In this Special Issue, all details about the methods and options selected in the GPS data processing to obtain Zenithal Tropospheric Delay should be presented and discussed, as well as about the conversion in PW estimates. The current version of the manuscript discusses briefly the used methodology to obtain PW and only an paper is referred (Ware et al. 2000). Other more recent works should be used because the methodology employed in GPS data processing have been improved in the last years. There are many aspects and options that would be taken into consideration to obtain PW, which significantly impact in the quality and behavior of PW time series from GPS data. For example: what kind of products for orbit and clock for satellite was used and what is the sampling of these products? Elevation-Dependent Weighting used for GPS observations was used? Was tropospheric models used for ZWD time evolution constraint as a random walk process? Were tropospheric gradients estimated? If yes what are the constraints of temporal evolution of these two parameters? Several specific works should be referred to in this description.**

As PW processing techniques were not the focus of this particular study, an in-depth description would have brought the paper off-topic. Also, the processing details for each dataset have been thoroughly described in previous research. For SuomiNet data, which is processed by the COSMIC group at UCAR (and not the authors), the paper describing their processing technique is Ware et al. (2000) (Lines 192-196). The first two authors were, however, instrumental in processing the two-hourly, long-term PW dataset from IGS data (Lines 183-191). For this dataset, there are various papers cited within this manuscript which describe the processing techniques used in great detail (Lines 183-184). Any further description of the processing techniques would have been beyond the focus of this study.

6. **The list of GPS stations used in this paper is not suitably presented, which are used in several parts of manuscript (i. e. figures and text) but the GPS stations are not described with more important information presented. For example, the Figure 1 shows the geographic localization of the GPS stations, but they are not mentioned in the text. Line 211: “This region encompasses six SuomiNet stations and two IGS stations (Fig. 1a)”. Which stations were used? The figure 1a not present any station. A table with more relevant information about the list of used GPS stations in this study should be presented in the beginning of the section 2.**
Line 211 was changed to read “Fig. 1b” instead of “Fig. 1a.” A list of station data was also added as Table 2.

Analysis of data and interpretation of results:

7. **The precipitation time series should be better explored in this study. Although this information is crucial to characterize the GPS-PW variation before, during and after the precipitation severe event, the precipitation values are presented separately from PW values in a last figure of the manuscript (Figure 9). These data are critical for this study and should be better discussed in term of intensity and relationship with PW oscillations. Separating the time series of precipitation and GPS-PW the authors committed a serious mistake, which penalize the analysis of results and hinders to reach the proposed aims. The precipitation time series should be presented in Figs 3, 4 and 5, at least.**

As per the reviewer's request, Figures 3 and 9 were combined into the new Figure 3. A brief outline of the precipitation timeline during the flood was added.

8. **The Figure 2 shows PW values larger than the observed values in 2013 September (e. g. September of 2011) and it was not observed intense precipitation. This fact should be discussed.**

The seasonal oscillation observed in Figure 2 is discussed in Lines 273-276. The peaks represent Colorado's wet season. As was stated in response to Comment #4, the extension of moisture observed in September of 2013 is not observed in September of 2011. The peak you might be mistaking for being in September of 2011 was actually at the end of August. Fig. 2 has been improved in the revised manuscript and the new figure shows the abnormal values in September of 2013 more clearly.

9. **Lines 283-294: The description of the results presented by Fig. 3 is very poor, which describe the period where the PW decreases and increase. The precipitation time series in this analysis should be interesting and it would help the analysis of those results.**

Precipitation data was added to Figure 3 and description of this was added to the manuscript, as was stated in response to Comment #7.

- 10. Figure 4, I agree with David Adams that “fully saturated atmosphere, i.e. 100 relative humidity from the surface up to 300hPa.” can not be accepted and this analysis should be completely redone. I don’t understand why the GPS-PW values in high temporal resolution are not explored in this analysis, which could be very much rich.**

David Adams suggested that we alter the description of the graph slightly to state that our assumption was unrealistic. Redoing this entire section is not an option, as we have already finished two rounds of reviewer comments. Had the reviewer responded with this suggestion in the first round, there may have been time to devise a new research method for this particular graph.

- 11. In the analysis of results in Section 3.2 the authors try to demonstrate the abnormality of PW values during September of 2013, when precipitation severe event was observed. I can not understand the reasons why in this analysis monthly-averaged values are used (Figure 5). The reported values of the monthly-averaged for September 2013 is the largest, which is the expected result above of normal. However, this analysis using monthly-averaged is not able to characterize the PW oscillation before, during and after the severe precipitation, as is proposed in the introduction section.**

Monthly-averaged values were used because the usage of every point would have resulted in a noisy, indecipherable graph. The use of monthly-averaged values resulted in a more easily-deciphered graph that showed us just how abnormal the PW values during the flood were that they pushed the monthly average above the 99th percentile.

- 12. In section 3, GPS-PW in high temporal resolution are not explored before, during and after the severe event of precipitation, consequently the authors did not demonstrate the additional benefits obtained with GPS data than the usage of the other techniques of water vapor measurement. The same study can be carried out using the radiosonde data, which not justify the publication of this manuscript in this Special Edition about GNSS-PW estimates.**

The high resolution GPS-PW characteristics around the timing of the flooding event were discussed on Lines 283-297. Figures 3 and 8 showed the advantages of using GPS PW data for the detection of abnormal atmospheric moisture amounts which could lead to heavy precipitation events.

- 13. In the analysis of water vapor transport, a bibliographic revision of previous work is done and results are reported. A similar analysis is done in the current version of the manuscript, using reanalysis data and water vapor anomaly from SuomiNet. The reported results not make evidence about the contribution of GPS data to corroborate with the results reported by these previous works.**

We do not fully understand the reviewer’s points here. Standardized anomalies of GPS-PW data reflected the patterns of moisture flux shown with the reanalysis data. This can serve as the basis to overlay 750 hPa winds on the PW anomalies to determine moisture transport in future studies.

- 14. In the analysis of water vapor transport (Figure 8) the selection of the time steps are aleatory or opportune without objective justification for the definition of these time steps. Why are these time steps used in different hours of the day? A figure with GPS-PW and precipitation (unacceptable lack in this study) would be used to justify this choice.**

As was stated in Lines 384-386, the times were chosen based on their proximity to rapid fluctuations in PW. The precipitation data from the previous Fig. 9 have been added to the new Fig. 3.

- 15. In the analysis of results the anomaly fields of water vapor from SuomiNet data (Figure 8) are used to indicate more drought or wetter atmospheric condition. It is a mistake because negative anomaly can not indicate a drier condition, but lower values than the climatological average. This is done in the line 391 and other parts of this manuscript.**

When the authors refer to “drier conditions,” they are comparing the anomalies observed in the panels to one another. Therefore, when the anomaly is lower in one panel compared to the previous one, it can be assumed that the atmosphere is drier in that panel than the previous panel.

Technical corrections and imprecision:

- 16. Line 211: The Fig1.a is mentioned when the correct should be Fig. 1b, which it is the correct plot that shows the GPS stations.**

As was mentioned in reply to Comment #6, this was altered.

- 17. Lines 294-297: This comment about the humidity transport should be in the final subsection 3.2, before section 4.**

We do not agree with the reviewer. Section 3.1 is about the temporal variability of PW.

- 18. Line 313: 2013 PW monthly averages were consistently lower than climatology until June and not July. In July the PW monthly averages were larger than climatology.**

This is a question of semantics and misinterpretation. The phrasing “up until July” means “prior to July.”

- 19. Line 560: The NISU station is mentioned in the caption of the Figure 1, but I can not see this station in the plot of this figure. This station is used in others parts of the manuscript but: which are the information of this station? See item 6 above.**

This station is collocated with the station NIST and the label was mistakenly left out. This has been fixed in the latest version of the manuscript.

- 20. Line 490: The number of previous work referred in this manuscript is very low. There are many important papers about this theme that should be included in this study. No paper from AMT and EGU were mentioned here.**

We would be most appreciative if the reviewer could suggest some previous works for us to read through. We have included what was found through numerous literature searches and we did not intentionally leave out papers from AMT or EGU.

- 21. Line 550: The rain values presented in Table 1 are in inches, and should be converted to mm, because the PW is presented in mm and the comparison is more direct when the same unit are used.**

The rainfall total units in Table 1 were changed to mm.

- 22. Line 556: The Figure 1a shows the preliminary precipitation accumulation values for Colorado, but this field is not mentioned in the manuscript. The plot 1.b of this figure is terrible to see the geographic localization of the GPS stations and coordinates are not expressed in this map.**

This was added as Table 2.

- 23. Line 563: The Sept should not be in GPS station legend of the Figure 2.**

This was removed per the reviewer's request.

- 24. Line 563: The figure 2 is not suitable for analysis of the results about the PW oscillation during the 2013 September and to compare with other Septembers. This figure should be significantly improved. The results are confused and they turn an arduous task to affirm some conclusion.**

Fig. 2 is improved. We have also clarified the purpose of this figure in the responses above to help the reviewer understand it better.

- 25. Lines 573-587: The precipitation data should be in Figures 3, 4 and 5.**

Fig. 3 and 9 have been combined. This was addressed in Comments #7 and 9.

- 26. Line 574: The term "all times are in UTC" are not correct because the time in the figures is in Days. The same for the figures 3 4 and 9.**

These were removed per the reviewer's request.

- 27. Line 586: In the figure 5 it is mentioned the 95th (dashed red line) and 99th (dotted red line) percentiles for 10 years and these lines are not showed.**

This line was removed from the figure description as it had been accidentally left in from previous edits.

Precipitable Water Characteristics during the 2013 Colorado Flood using Ground-Based
GPS Measurements

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Abstract

During 9th-16th September 2013, the Front Range region of Colorado experienced heavy rainfall that resulted in severe flooding. Precipitation totals for the event exceeded 450 mm, damages to public and private properties were estimated to be over \$2 billion, and nine lives were lost. This study analyzes the characteristics of precipitable water (PW) surrounding the event using 10 years of high-resolution GPS PW data in Boulder, Colorado, which was located within the region of maximum rainfall. PW in Boulder is dominated by seasonal variability with an average summertime maximum of 36 mm. In 2013, the seasonal PW maximum extended into early September and the September monthly mean PW exceeded the 99th percentile of climatology with a value 25% higher than the 40 year climatology. Prior to the flood, around 18 UTC on 8 September, PW rapidly increased from 22 mm to 32 mm and remained around 30 mm for the entire event as a result of the nearly saturated atmosphere. The frequency distribution of September PW for Boulder is typically normal, but in 2013 the distribution was bimodal due to a combination of above average PW values from September 1st-15th and much drier conditions from 16th-30th September. The above normal, near saturation PW values during the flood were the result of large-scale moisture transport into Colorado from the eastern tropical Pacific and the Gulf of Mexico. This moisture transport was the product of a stagnating, cutoff low over the southwestern United States working in conjunction with an anticyclone located over the southeastern United States. A blocking ridge located over the Canadian Rocky Mountains kept both of the synoptic features in place over the course of several days, which helped to provide continuous moisture to the storm, thus enhancing the accumulated precipitation totals.

47 **Keywords**

48 Precipitable Water, GPS, 2013 Colorado Flood, Extreme Precipitation

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1. Introduction

During 9th-16th September 2013, multiple local and state precipitation records were broken when low-level, easterly flow interacted with an anomalous moisture pool over the Front Range region of Colorado to produce one of the largest floods in state history (Colorado Climate Center, 2013). The heaviest and most persistent rainfall occurred on the 11th and 12th of September, with a maximum centered over Boulder and Larimer counties (Fig. 1). In the hardest hit areas, total precipitation accumulation exceeded 450 mm (17.7 in) (Gochis et al. 2015). The city of Boulder set multiple records, observing 292.6 mm over the course of two days and 341.8 mm over the course of three days. The resultant flooding claimed nine lives and caused 1,100 documented landslides. Damages to public and private properties were estimated to be over \$2 billion (Gochis et al. 2015).

The following summary of the September 2013 event was first presented in Gochis et al. (2015). Surface temperatures were in the 16-18 °C (60-64 °F) range and precipitable water (PW) values were high. Periods of heavy precipitation exceeding 25 mm (1 in) per hour, along with flooding, began on the evening of 11th September, with the heaviest portions over the Front Range, the area outlined in Fig. 1. The mountainous region between Boulder and Estes Park experienced the heaviest rain rates, which ranged from 25-50 mm (1-2 in) per hour and resulted in an overnight total exceeding 200 mm (8 in). Somewhat lighter rainfall continued into the 12th, becoming intense once more during the afternoon hours and increasing rainfall totals to over 380 mm (15 in) in the Boulder to Estes Park region. By the 13th, precipitation had finally lessened to intermittent showers and widespread drizzle, finally clearing on the 14th. A final surge of moisture occurred on

the 15th and resulted in 25-50 mm (1-2 in) of widespread, moderate rainfall on soils that were already saturated, thus increasing the amount of runoff.

This event was uncharacteristic, not only because of its rainfall amounts but also because of the time of year in which it occurred. Petersen et al. (1999) examined the climatology of precipitation events over the Front Range region and found that, while a majority of events occur between April and October, the convective classification of the events differs depending on what time of year the [convectiony](#) occurs in. There are two peaks in the event distribution, the first of which occurs in late May to early June.

Precipitation events during this time are synoptic, or large, scale and quasi-stationary. The precipitation in these events is enhanced orographically and locally, and is typically widespread and of moderate intensity. The second peak in precipitation events occurs from late July into early September with a pronounced maximum frequency from late July into early August. The storms in these events generally have a small areal extent and are highly convective. The September 2013 event was quasi-stationary and synoptic with precipitation controlled by localized and orographic enhancements. The areal extent of the 2013 event was large and the rainfall was of moderate intensity. According to the climatology completed by Petersen et al. (1999), this type of event was more typical of storms which occur in late May to early June. However, this event occurred at a time of year when precipitation tends to be highly convective and of small areal extent, so the timing, as well as the amount of rainfall, was abnormal.

In another study which examined the climatology of rainfall events in Colorado, Mahoney et al. (2015) found that the region of Colorado east of the Continental Divide does not generally experience heavy precipitation events in the fall because it is during

this time of year that the region experiences seasonal atmospheric drying. They did note that there was enhanced climatological variability in September and October, making it difficult to place these months into the same category as the drier months (November-February). In general, east of the Continental Divide experiences most of its precipitation in the spring and summer months, with the Front Range receiving a majority of its moisture in the spring. However, extreme precipitation events are not limited to these seasons and can also occur in fall and winter months.

Flooding due to extreme precipitation events can occur at any time of the year because all elevations in all seasons are prone to experiencing heavy precipitation. This is partially represented by the dates in Table 1, which compares the September 2013 event to previous heavy precipitation events in Northern Colorado history that resulted in catastrophic flooding (Colorado Climate Center; Maddox et al. 1977; Petersen et al. 1999; Gochis et al. 2015). Prior to the September 2013 event, there were 5 events on record that were classified as comparable to the 2013 event by the Colorado Climate Center. However, all except one of these storms took place in the spring and summer months, as would be expected from the climatology of the rainfall events presented in earlier.

Out of the events listed in Table 1, the Colorado Climate Center noted that the event that occurred on 1st-12th September 1938 near Fort Collins, Colorado was the most similar in timing and magnitude to the September 2013 event. Observers recorded [203-254 mm \(8-10 inches\)](#) of rainfall and the surrounding region experienced severe flooding. However, there is not much else known about this event because the amount of recorded atmospheric data available from this time period is limited. Comparing the September

138 2013 event to the 5 previous events in Table 1, this event had the highest total rainfall and
139 caused the most damage, as is seen by the total cost of the event. This event also had a
140 vast areal coverage, with heavy precipitation occurring from Denver all the way into
141 southern Wyoming. Flooding took place as far to the east as Nebraska and caused a lot of
142 damage to infrastructure along the Front Range of Colorado.

143 The amount of precipitation that fell during the September 2013 event required a
144 large amount of moisture at a time of year when atmospheric moisture ~~was~~
145 ~~beginning~~climatologically begins to decrease from higher summer values to lower winter
146 values (Mahoney et al., 2015). This uncharacteric increase in moisture implies moisture
147 was transported into the region. When moisture converges at the surface, it is transported
148 to higher levels assuming there is sufficient atmospheric instability, which is usually
149 greater over orography (Graham et al. 2012). The interaction of low level moisture with
150 orography results in convection and the production of precipitation (Guerova et al. 2016).
151 Adams et al. (2013) found that water vapor convergence which results in heavy
152 precipitation generally occurs approximately an hour prior to the event. They also found
153 that the stronger the convergence, the more intense the precipitation. Sapucci et al. (2016)
154 found that after PW peaked, rainfall began and PW decreased.

155 ~~Moisture transport and quantity are important aspects to evaluate when investigating~~
156 ~~heavy precipitation events. However, there has not been a vast amount of research~~
157 ~~examining the characteristics of PW during heavy precipitation events.~~ Such
158 characteristics are important to understand because they could influence future weather
159 and climate trends. Kunkel et al. (2013) found an increasing trend in atmospheric PW
160 quantities associated with extreme precipitation events and suggested this trend could

lead to an increase in storm intensity. While Hoerling et al. (2014) noted that the September 2013 event was probably not connected to climate change, they did find that heavy precipitation events are becoming more frequent and Karl and Trenberth (2003) found evidence that the number of heavy precipitation events is expected to increase with increasing global temperatures, such as we are experiencing now. The observed and projected increase in the number of heavy precipitation events, combined with the uncertainty of how PW contributes to characteristics of these events, motivated an investigation of PW characteristics surrounding the 2013 event so as to better understand the contributions of PW to an extreme precipitation event with the objective to someday apply these results to future research incorporating a wider variety of events.

As the aim of this research was to examine the characteristics of atmospheric PW during the 2013 Colorado Flood, data with a high spatial and temporal resolution was needed to resolve features within the event. GPS receivers are much more densely spaced with a total of 236 stations over North America than the radiosonde network, which has a total of 92 stations. The higher density of observations in the GPS network results in a higher spatial resolution with which to analyze storm features and water vapor transport. GPS data also has a much higher temporal resolution of anywhere from 30 minutes to two hours, as compared to the standard, twice-daily launching of radiosondes.

The primary goal of this research was to investigate the magnitude and characteristics of PW over the Front Range region associated with the September 2013 event. The goal of this study was to answer the following scientific questions.

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(1) What were the characteristics of PW surrounding this event? This portion of research was focused on the examination of the temporal variability of PW, as well as a comparison with climatology, before, during, and after the event.

(2) Where did the moisture for the 2013 event originate? To answer this question, synoptic-scale dynamics and pre-existing conditions that led to large-scale, continuous moisture transport were evaluated.

2. Data and Methodology

2.1 Precipitable Water Datasets

Two datasets were used to analyze PW characteristics surrounding the 2013 event. The first of these was a two-hourly, long-term (1995-2015) PW dataset (Wang et al. 2007; Mears et al. 2015; Mears et al. 2016). The PW in this dataset is derived using 5-minute International Global Navigation Satellite System (GNSS) Service (IGS) Zenith Total Delay (ZTD) data. The analysis technique for the interpolation and conversion of ZTD to PW is summarized in Wang et al. (2007) and two key variables used in the conversion are water-vapor-weighted atmospheric temperature (T_m) and surface pressure (P_s). ZTD is represented as the sum of the Zenith Hydrostatic Delay (ZHD), which is a function of P_s , and the Zenith Wet Delay (ZWD), which is a function of PW and T_m . The 2-hourly PW data from Boulder became available starting in 2004.

The second PW dataset used in this study was the 30-minute SuomiNet dataset from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) group (Ware et al. 2000). The SuomiNet network currently consists of over 200 sites located around North America and the data are processed in near-real time from raw GPS data, the values of which do not differ greatly from post-processed GPS data.

For this research, the standardized anomalies of the SuomiNet data were calculated by subtracting PW at each time step from the mean and dividing this by the standard deviation (Grumm and Hart 2001). The standardized anomaly data were gridded and interpolated using a general kriging method to a grid box of $0.5^{\circ} \times 0.5^{\circ}$. Kriging is defined as optimized interpolation that is weighted by spatial covariance values and based on regression against observed values of surrounding data points (Bohling 2005). This method was chosen because of its simplicity and superior performance when compared with the inverse distance weighting (IDW) method (Zimmerman et al. 1999; Yasrebi et al. 2009).

2.2 Formulation of a GPS PW Climatological Dataset

PW data for Boulder, Colorado were chosen to evaluate the PW variability of this region over the course of 10 years and compare this variability with that of 2013 to improve the understanding of how the September 2013 event differed from climatology. This region encompasses six SuomiNet stations and two IGS stations (Fig. 1ba). To examine the anomalous nature of the flood, a dataset with a length of at least 10 years of observations was needed as a climatological standard for the analyzed region. While 10 years is not long enough for a standard climatology of 30 years as defined by the World Meteorological Organization (WMO), GPS PW data for Boulder has only been available since 2004. The PW time series of each GPS station was initially examined to determine which, if any, station had a long enough data record to serve as the climatological standard, and also to check for data outliers and data continuity. No stations were found to have more than seven years of data and datasets that contained discontinuities were

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discarded. A major issue that appeared during this analysis was that only one SuomiNet and one IGS station had data observations during the September 2013 event, and neither of them had a lengthy dataset. A decision was made to combine the data from different stations in the region and make a 10-year dataset that included observations from the flood.

The GPS PW data used to create the 10-year dataset were first quality-controlled by using several methods defined in Wang et al. (2007). The first method used was the range test in which the lower and upper limits of PW values were set as 0mm and 150mm, respectively. The second quality-control method used involved using the mean and standard deviation for each month to detect any outliers. This method required that at least one-quarter of the data be present in order to have an adequate amount of observations so that the statistical aspects could be deemed accurate. Individual PW values within each month were analyzed and any values that were more than 4 standard deviations away from the monthly mean were discarded (Wang et al. 2007). The quality control removed 0.1% of the total data points for the station SA00 and less than 0.1% of the total data points for the rest of the stations.

The next step in the creation of the 10-year dataset was to compare PW data among the stations. PW is strongly dependent on elevation so any station that had an elevation above 1,800 m was eliminated because these receivers were located too far above the elevation of Boulder (1655 m). To remain consistent, the remaining stations were compared to the station with the longest dataset and elevation closest to that of Boulder (DSRC). Five stations were chosen for the merged 10-year PW dataset (Fig. 2) because their averaged PW differences were not statistically significant from one another and the

elevation differences between all stations were less than 50 m. A more thorough analysis of the complete dataset and its comparison with 2013 is described in Sect. 3. The SuomiNet station, P041, also passed the statistical significance test, but did not have a complete record of data for 2013 so could not be included in the 10-year dataset. Instead, the 2013 PW data from P041 was used to analyze small-scale variability leading up to, and during, the flood period because it has a higher temporal resolution (30 minutes) than NIST (two-hourly), which was chosen for the 10-year dataset.

2.3 Additional Datasets

The data used as a long-term PW climatology dataset were twice-daily radiosonde data from the Stapleton airport in Denver, Colorado extracted from the homogenized radiosonde dataset created by Dai et al. (2011) (Fig. 2b). This PW dataset was created by integrating specific humidity from the surface to 100hPa, is available from 1979 to 2013, and was homogenized using an advanced statistical approach that is more thoroughly described in Dai et al. (2011).

The primary dataset used to evaluate moisture transport was the North American Regional Reanalysis (NARR) dataset, which is available from 1979 to the present (Mesinger et al. 2006). The domain for NARR is North America and the horizontal resolution is 32 km with 45 vertical layers. The NARR variables chosen for the evaluation of moisture transport surrounding the event were the 500 hPa geopotential height and the vertically integrated moisture flux.

3. Precipitable Water Characteristics

Gochis et al. (2015) noted that the atmosphere over Northern Colorado was abnormally moist from 9th-16th September. Radiosondes captured PW values above 30

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mm, an abnormal value for a semi-arid climate. Gochis et al. (2015) also noted that the raindrop distribution during the event consisted of numerous small raindrops, which is more commonly observed in a tropical climate. To better understand how abnormal the atmospheric moisture was during this event, the magnitude, distributions, and variability of PW over Boulder were evaluated and compared to climatology.

3.1 Temporal Variability of Precipitable Water

First, the temporal characteristics of September of 2013 were compared with the 10-year GPS PW dataset described in Sect. 2.2. Figure 2 shows the time series of the merged 10-year PW dataset discussed in Sect. 2. The strongest PW variation is seasonal with a mean seasonality of 18mm and the summer peaks are coincident with the annual occurrence of the wet season in Colorado. Also note that the belted appearance of this time series represents synoptic and diurnal PW variability, the latter of which has an average magnitude of 8 mm. The maximum value of PW for 2013 was 33.5 mm on September 12th. Note the extension of high PW values from the summer months into early September of 2013. This extension is not observed in any of the other years contained in this dataset and is an indication that the atmosphere was anomalously moist for the time of year in which the flood occurred.

Figure 3 zooms in on the extension of high PW values observed in September of 2013, giving a clearer view of the temporal variability of PW [and precipitation](#) surrounding the flood event. The high PW values ~~from 28th August~~ [up until](#) 5th September represent moisture associated with the end of the North American Monsoon. These high values begin to decrease around 6th September before quickly rising on September 9th into the 10th, with values spiking to above 30 mm. PW decreases slightly

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to 26 mm until the 11th, when it once again increases to above 30 mm where it remains until the 13th. After this, PW decreases to values closer to the September climatological average of 15 mm.

PW peaks approximately one hour before rainfall begins, which is consistent with the findings of Adams et al. (2013) and Sapucci et al. (2016), both of which found that PW peaks between 32 and 64 minutes prior to the start of rainfall. Also consistent with their findings is the decrease of PW after it peaks. This is associated with the condensation of PW as it makes the transition into precipitation (Van Baelen et al. 2011). Another point to take note of is precipitation begins after PW rises between 2 and 3 standard deviations above the PW long term median, which was found in Foster et al. (2003).

An interesting point to take note of is that PW values stay relatively constant during the event despite the fact that continuous, and sometimes heavy, precipitation is occurring. For PW to remain at high values over multiple days, as was seen here, moisture needed to be continuously transported into the region (Gimeno et al. 2012). Had there not been a constant transport of moisture, PW would have decreased as atmospheric moisture condensed and formed precipitation. The examination of the moisture transport that fueled this event is presented in Sect. 4.

3.2 Precipitable Water Abnormality During the 2013 Flood

The consistently high values of PW during the time of heaviest precipitation in Fig. 3 led to an investigation to discern if the atmosphere over Boulder was fully saturated during the September 2013 event. To evaluate this, observed radiosonde PW data were compared with PW values that were calculated assuming a fully saturated atmosphere,

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i.e. 100% relative humidity from the surface up to 300 hPa. Note that a fully saturated atmosphere is an unrealistic assumption for a real atmosphere, but can be used for simplified comparison. Figure 4 shows the comparison between these two variables from 6th - 28th September 2013. Starting on 10th September observed and fully saturated PW values were within 5 mm of each other, indicating an atmosphere that was very near to saturation during the course of the September 2013 event. Except for a period of time on 14th September when the atmosphere began to dry, observed PW stayed relatively close in value to the fully saturated PW until 16th September.

Figure 5 compares monthly-averaged 2013 GPS data and radiosonde data to 40 and 10 years of monthly-averaged radiosonde and GPS data, respectively. 2013 PW monthly averages were consistently lower than climatology until July while ~~Up until July,~~ the Front Range was still under drought conditions according to the National Climatic Data Center (NCDC) North American Drought Monitor. The monthly average for September of 2013 was around 20 mm, approximately 25% higher than the long-term climatological monthly average for September. Also note that the monthly average for September of 2013 is above the 95th and 99th percentiles, which were calculated from 40 years of monthly averaged radiosonde data. McKee and Doesken (1997) evaluated extreme precipitation events for Colorado from the late 1800's up until 1996 and found that, for these events, PW never exceeded the 95th percentile. That the monthly averaged PW for September of 2013 exceeded the 99th percentile when compared to 40 years of data shows just how anomalous the event was in terms of PW magnitude and timing.

Another tool used to evaluate how anomalous the 2013 Event was in terms of PW was to examine the PW frequency distributions. Foster et al. (2006) examined the

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monthly and annual frequency distributions of PW data for various stations and found that there were three main types of distributions for PW data: lognormal, which is the most common distribution around the world; reverse-lognormal, which represents an atmosphere near saturation; and bimodal, which occurs in regions with strong seasonal variability such as monsoonal zones.

To analyze PW frequency for this event, monthly distributions were created for June through September of 2004-2013 (Fig. 6). The skewness of each distribution was then calculated and these values, along with visual analysis, were used to determine if each distribution was normal, lognormal, reverse-lognormal, or bimodal. Bulmer (1979) provided guidelines for interpreting the skewness of a distribution that were employed when evaluating the distributions in this study. A normal distribution has a skewness from -0.5 to 0.5, while a positive (negative) skewness with its absolute values within 0.5 to 1 represents a lognormal (reverse-lognormal) distribution (Bulmer 1979; Foster et al. 2006).

Upon analyzing the distributions in Fig. 6, June through September primarily have normal distributions with September being, on average, slightly more positively skewed than the other months with a value of 0.32, although the distribution is still considered normal according to the conditions for skewness defined in Bulmer (1979). However, the seasonal variation in PW is still evident as July and August distributions tend to have their highest frequencies over higher values of PW than either June or September. Also, despite most months having a normal distribution, there are four distributions which were labeled as lognormal because they have skewness values larger than 0.5: July 2005, September 2008, September 2010, and June 2013.

The distribution that shows the largest shift in distribution from the other years is that of September of 2013, which had a bimodal distribution. Figure 7 shows a more detailed comparison of September of 2013 PW data with 10 years of GPS PW data and 40 years of radiosonde PW data. September of 2013 PW data were split up into two categories: “Flood”, which represents 1st-15th September; and “Post-Flood”, which represents 16th-30th September. Fig. 7 shows how different September of 2013 is from climatology and also how the atmosphere during the “Flood” differed from the “Post-Flood” atmosphere. The atmosphere during the “Flood” was highly saturated, with a peak frequency around 25 mm and PW values as high as 35 mm. The frequency distribution during this time was normal with a skewness value of 0.175. The “Post-Flood” atmosphere had a distinct lognormal distribution indicated by visual analysis and also by a skewness of 0.6838. The atmosphere at this time was considerably drier, with frequency peaking at 0.9 around 7 mm of PW.

4. Water Vapor Transport

The occurrence of heavy precipitation such as was observed during the September 2013 event requires sufficient moisture supply to fuel it. In Sect. 3, PW was shown to spike rapidly prior to the flood and remain at highly anomalous values for the duration of the event. In order to more completely understand the PW characteristics of this event, it was important to investigate where the moisture originated and what mechanisms were controlling the moisture transport that kept the atmosphere very near to saturation for seven consecutive days.

The moisture source and transport for the September 2013 event was briefly investigated in previous literature. Gochis et al. (2015) noted that the sources of moisture

for the event were the Gulf of Mexico and the eastern tropical Pacific Ocean, both of which had 1-3 °C above normal sea surface temperature (SST) anomalies. They stated that the moisture from these regions was transported into the Front Range by a cutoff low over the southwestern United States working in conjunction with an anticyclone over the southeastern United States. Both of these features were kept in place for multiple days by a blocking ridge located over the Canadian Rockies (Gochis et al. 2015). Trenberth et al. (2015) stated that the source of moisture for the September 2013 event was only from the eastern tropical Pacific Ocean, while Mahoney et al. (2015) claimed the moisture for the event came primarily from the Gulf of Mexico.

Due to the slight variation of opinion on which body of water was the source of moisture for the event, this study further investigates moisture source and transport by examining NARR 500 hPa geopotential height and integrated water vapor flux in conjunction with the standardized anomaly of gridded SuomiNet PW data. Five times surrounding the event were chosen for analysis based on their proximity to rapid fluctuations in PW (Fig. 3). The three variables listed above are plotted in Fig. 8 at each of the five time steps.

Figure 8a-c shows the atmospheric conditions on 6th September at 9 UTC, prior to the start of the event. There was a large ridge with 500 hPa geopotential heights above 596 gpm over the western half of the United States (US) (Fig. 8a) which contributed to higher temperatures and dried the atmosphere over Boulder as seen in Figs. 3 and 8c. At that point, there was no direct water vapor transport from either the Gulf of Mexico or the eastern Pacific (Fig. 8b).

Moving on to 9th September at 18 UTC (Fig. 8d-f), a trough started to form over the western United States and an anticyclone shifted over the southeastern US (Fig. 8d). Together, these began transporting water vapor towards the northeast along the eastern flank of the trough from the eastern Pacific (Fig. 8e). This transport contributed to a belt of PW anomalies with magnitudes of 1.5 to 2.5 standard deviations over the southwestern and western US (Fig. 8f). The PW anomaly over Boulder at that point was between 1-1.5 standard deviations and precipitation had not yet begun (Fig. 39). [At this point, PW values started to rise at a fairly quick rate \(Fig. 3\). This coincided with Adams et al. \(2013\) who found that water vapor increases by low-level moisture convergence due to large scale or other forcings.](#) Water vapor appeared to travel to Colorado from the eastern Tropical Pacific at that time (Fig 8e).

By 11th September at 6 UTC (Fig. 8g-i), the low pressure over the western US deepened and formed into a cut-off low (Fig. 8g). The low stagnated over the western US due to the influence of the blocking ridge under which it resided. The anticyclone over the eastern US also strengthened. Working in conjunction, the strengthening of the low and the high increased the southerly water vapor transport and there was a corridor of flux convergence over New Mexico and the direction of the flux over Northern Colorado was toward the Rocky Mountains (Fig. 8h). This resulted in a corridor of PW anomalies that stretched from the Mexican border to southern Wyoming (Fig. 8i). The magnitude of the PW anomaly over Boulder rose to between 2.5 to 3 standard deviations as the moisture pooled against the Rocky Mountains due to easterly water vapor transport. Light, orographically enhanced precipitation began and Boulder experienced rain rates

around 5mm h^{-1} (Fig. 39). Water vapor was being transported into Colorado from the eastern Tropical Pacific and the Gulf of Mexico at this time (Fig 8h).

By 12th September at 6 UTC (Fig. 8j-l), the anticyclone began to break down but the cutoff low deepened even further (Fig. 8j). Water vapor was still being transported into the region from the Gulf of Mexico by the synoptic conditions with an easterly component of the flux continuing to pool water vapor against the Rocky Mountains (Fig. 8k). However, the transport of moisture into Colorado appeared to have weakened substantially and the eastern Tropical Pacific was no longer a source of moisture. There was still a corridor of PW anomalies coinciding with the regions of strong water vapor flux and the magnitude of the anomaly over Boulder was still between 2.5 to 3 standard deviations (Fig. 8l). Precipitation intensified over the past 24 hours and Boulder experienced up to 35mm h^{-1} of rainfall (Fig. 39). While a majority of the rainfall was orographically-enhanced, the occasional intense periods of rainfall were a result of mesoscale circulations, as was noted by Gochis et al. (2015).

By 14th September at 21 UTC (Fig. 8m-o), the blocking ridge broke down, which allowed synoptic conditions to shift eastward, and the cutoff low once again became a trough (Fig. 8m). This resulted in the water vapor flux also shifting eastward (Fig. 8n). The PW anomaly over Boulder decreased to between 1 to 2 standard deviations (Fig. 8o). Rainfall for the event ended at this point, excluding a peak that occurred during the afternoon of 15th September (Fig. 39).

Upon comparing NARR integrated moisture flux with 500 hPa geopotential height and observed standardized PW anomalies, it was found that the strength and location of moisture transport varied over the course of the event. Prior to the event, on 9th

September, moisture from the eastern tropical Pacific appears to have been transported up to Colorado by a stagnating cutoff low over the southwestern US. Starting on 10th September, the cutoff low and subtropical anticyclone promoted southerly flow into Colorado from the eastern tropical Pacific and the Gulf of Mexico. As of the 12th September, the eastern tropical Pacific no longer provided moisture for the event and the Gulf of Mexico was the sole source of moisture. By the 14th September, the transport of moisture into Colorado had significantly weakened due to the eastward shift of the synoptic pattern. The moisture transport was dependent on the strength and location of the dominant synoptic features, and based on the analysis shown in Fig. 8 the moisture has been transported into Colorado from both the Eastern Tropical Pacific and the Gulf of Mexico. These results are most consistent with the findings of Gochis et al. (2015), but do not discount the results found in Trenberth et al. (2015) and Mahoney et al. (2015).

5. Conclusions

The aim of this research was to analyze PW characteristics surrounding the September 2013 event and compare them to climatology. [Precipitation began approximately an hour after PW rose to between 2 and 3 standard deviations above the PW long-term median. This result was consistent with past literature that examined the relationship between PW and precipitation.](#) Monthly averaged PW values in the GPS dataset for September of 2013 was above the 99th percentile when compared to the climatological data as well as around 25% higher than the monthly-averaged climatological mean value for September. That the monthly average for September of 2013 was so far above the climatology for 10 and 40 years of data indicates how anomalous the atmospheric moisture content was during the event. The frequency

distribution of PW for September of 2013 was bimodal, which was much different than the typical normal distribution observed in September of other years. Upon further analysis, it was noted that the highly saturated portion of the bimodal distribution was solely the result of the September 2013 event, which had a nearly saturated atmosphere. The second half of September had a lognormal distribution, representing a much drier atmosphere for the rest of the month. The moisture for the event originated from the eastern tropical Pacific at the beginning of the event 9th September, came from this source and the Gulf of Mexico during the heaviest precipitation (10th – 12th September), and then from only the Gulf of Mexico towards the end (12th-14th September).

Code Availability

Code is available from the lead author upon request.

Data Availability

Two-hourly GPS PW data is available upon request from the first and second authors. 30 minute SuomiNet GPS PW data is available for download in ASCII and NetCDF format from the COSMIC group website (suominet.ucar.edu). The twice daily, homogenized radiosonde data is available upon request from the second author. NARR data is available for download on the National Oceanic and Atmospheric Administration (NOAA) website (nomads.ncdc.noaa.gov/data/narr). The 1-hourly rain gauge data is available upon request from the National Center for Atmospheric Research (NCAR) Research Applications Laboratory (RAL).

Appendix A – List of Figures

Fig. A1. (a) Map of accumulated precipitation over Colorado from 8-15 September 2013 (image courtesy of the Colorado Climate Center) with the area depicted in (b) outlined in

the black box; and (b) the locations of the primary GPS (blue circles), rain gauge (green circle), and radiosonde (red circle) observations used in this study. NISU and NIST are the only IGS GPS stations plotted on this map. All of the other GPS stations are from the SuomiNet network.

Fig. A2. A time series of the GPS PW data for Boulder, Colorado from 2004-2013 with each station denoted by a different color, the monthly means denoted by the solid, black line, and ± 1 standard deviation denoted by the horizontal, black, dashed lines.

September of each year is represented by the vertical black, ~~dashed~~ lines.

Fig. A3. A time series of 30-minute ~~GPS PW~~ (station P041) and 2-hourly (station NIST) GPS PW compared with precipitation (rain gauge UDFCD4840) from 1-28 September 2013. The inserted graph compares the same variables from 9-14 September 2013 with the addition of lines indicating 1, 2, and 3 standard deviations above the PW long-term median. All times are in UTC.

Fig. A4. A time series comparison of observed radiosonde PW (black line) and saturated PW (green line) for 1-28 September 2013 over Denver, Colorado. ~~All times are in UTC.~~

Fig. A5. Monthly-averaged GPS PW (solid black line) and Radiosonde data (dashed black line) for 2013 with the 10-year merged GPS PW dataset (solid red line) and the 40-year averaged Radiosonde PW dataset (solid blue line). Additionally, there are the 95th (dashed red line) and 99th (dotted red line) percentiles for 10 years of GPS data and the 95th (dashed blue line) and 99th (dotted blue line) percentiles for 40 years of Radiosonde data.

Fig. A6. Statistical frequency distributions of GPS PW for June- September of 2004-2013 with the 95th percentile for 10 years of each month of data denoted by the left-most

dashed line and the 99th percentile for 10 years of each month of data denoted by the right-most dashed line.

Fig. A7. Statistical frequency distributions for the month of September with 2013 GPS PW data over Boulder (black line), 40 years of climatologically-averaged radiosonde PW data over Denver (dark grey line), and 10 years of climatologically-averaged GPS PW data over Boulder (light grey line). September of 2013 GPS PW data was split into two halves: 1-15 September 2013 (Flood; green line), and 16-30 September 2013 (Post-Flood; blue line).

Fig. A8. A comparison of NARR 3-hourly averaged 500hPa geopotential height (left column), NARR 3-hourly averaged integrated water vapor flux (center column), and SuomiNet gridded standardized PW anomalies. Each row represents a different time surrounding the 2013 Event.

~~**Fig. A9.** A time series of observed precipitation data from the rain gauge UDFCD_4840 for 9-17 September 2013. All times are in UTC.~~

Appendix B – List of Tables

Table B1. A comparison of the September 2013 event to previous flood inducing, heavy precipitation events in Northern Colorado history. All monetary values were calibrated to 2013 values.

Table B2. The geographic and topographic information of the primary GPS, rain gauge, and radiosonde stations used in this study.

Author Contribution

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The first author was the primary researcher with constant assistance and guidance from the second author. The third author was the PI on the grant and a contributing editor. The fourth author served as an editor.

Competing Interests

There are no competing interests from any of the authors.

Disclaimer

There is no disclaimer regarding the research completed in this paper.

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Date	Location Most Affected	Total Rainfall (inches)	Deaths	Cost
September 1-12, 1938	Fort Collins	8-10	N/A	N/A
May 4-9, 1969	West of Denver	6-9	0	\$136.5 million
July 31-August 1, 1976	Estes Park	12-14	144	\$348.5 million
July 27-August 4, 1997	Fort Collins	14.5	5	\$290 million
April 29-30, 1999	Northern Colorado	8-10	0	\$140 million
September 9-16, 2013	Boulder	16	8	\$2 billion

Table 1. A comparison of the September 2013 Event to previous flood inducing, heavy precipitation events in Northern Colorado history. All monetary values were calibrated to 2013 values.

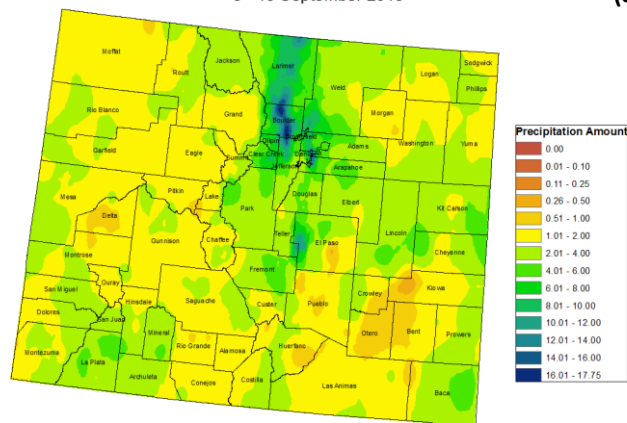
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<u>Station Name</u>	<u>Latitude (°N)</u>	<u>Longitude (°W)</u>	<u>Altitude (m)</u>	<u>Type of Station</u>
<u>72469</u>	<u>39.77</u>	<u>-104.87</u>	<u>1625</u>	<u>Radiosonde</u>
<u>DSRC</u>	<u>39.991431</u>	<u>-105.26103</u>	<u>1668.87</u>	<u>GPS</u>
<u>NISU/NIST</u>	<u>39.995</u>	<u>-105.2626</u>	<u>1648.488</u>	<u>GPS</u>
<u>P041</u>	<u>39.949492</u>	<u>-105.19427</u>	<u>1743.19</u>	<u>GPS</u>
<u>SA00</u>	<u>40.03516</u>	<u>-105.24327</u>	<u>1623.23</u>	<u>GPS</u>
<u>SA67</u>	<u>40.037568</u>	<u>-105.24086</u>	<u>1622.66</u>	<u>GPS</u>
<u>UDFCD 4840</u>	<u>39.9724</u>	<u>-105.2229</u>	<u>1645.92</u>	<u>Rain Gauge</u>

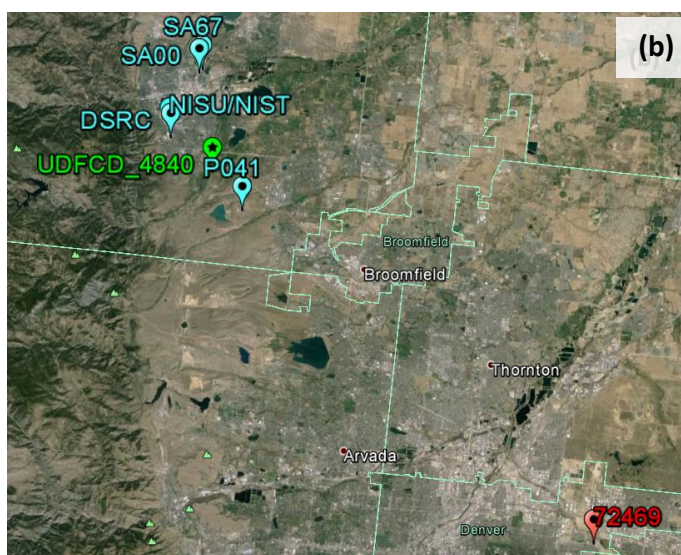
660 [**Table 2.** The geographic and topographic information of the primary GPS, rain gauge,](#)
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Preliminary Precipitation Accumulation for Colorado (inches)
8 - 15 September 2013

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(b)

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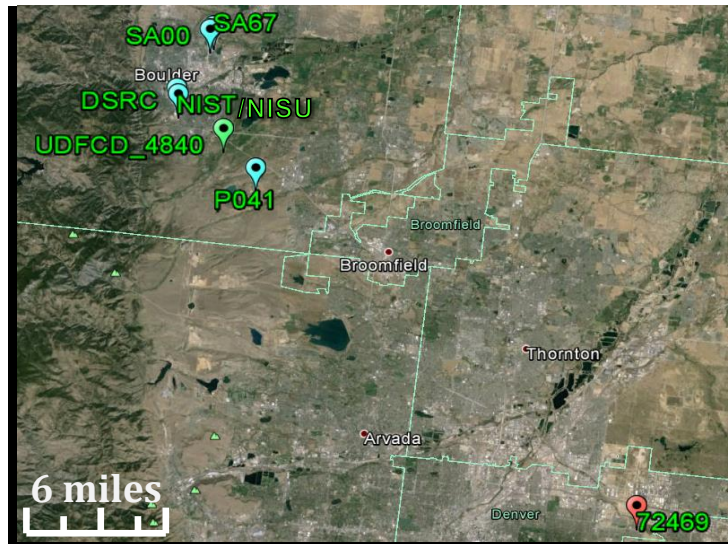


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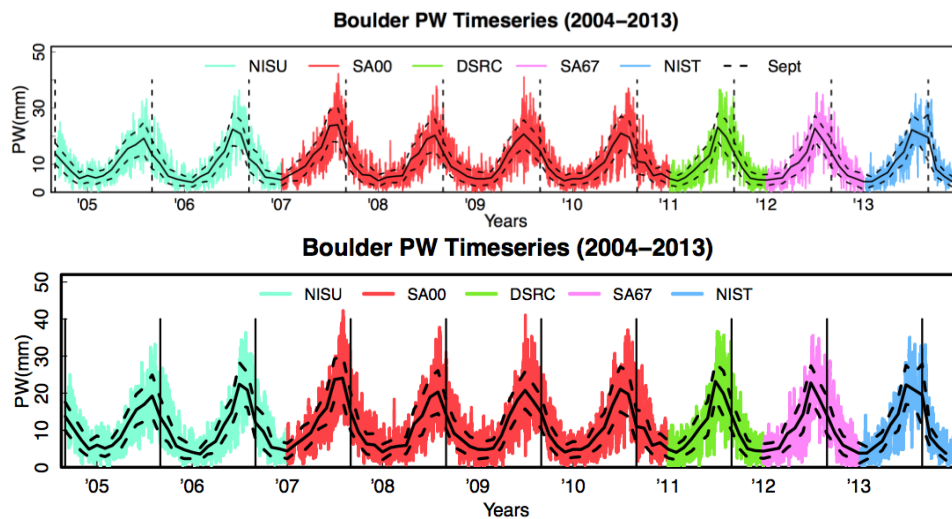


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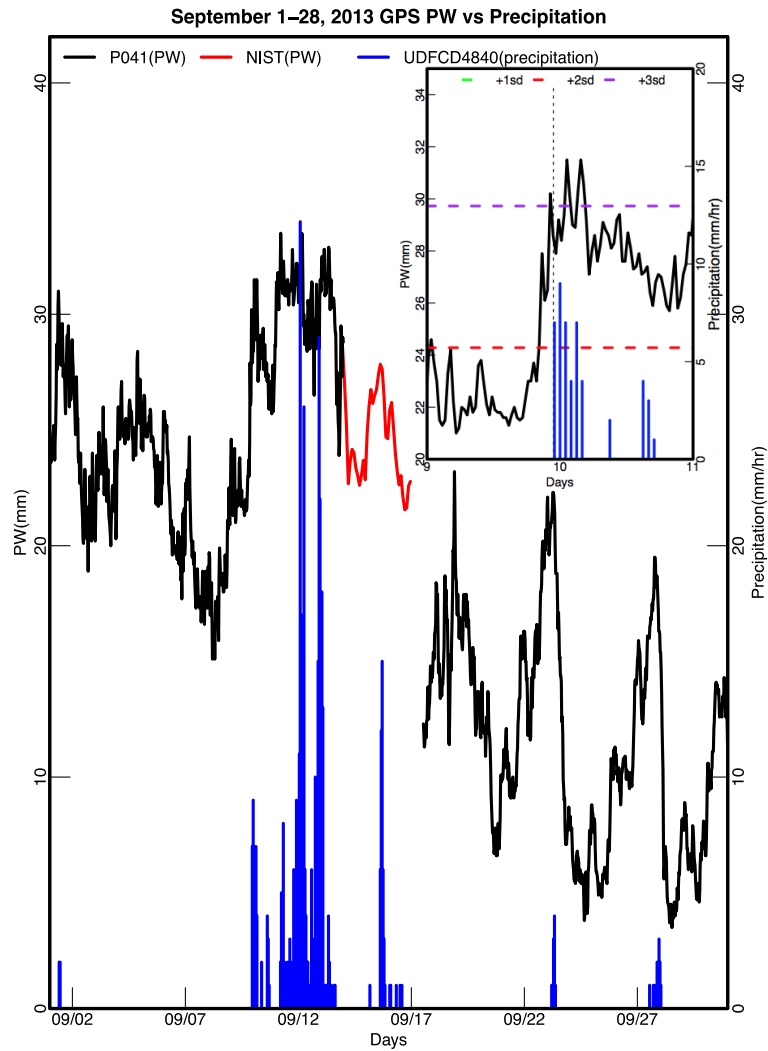
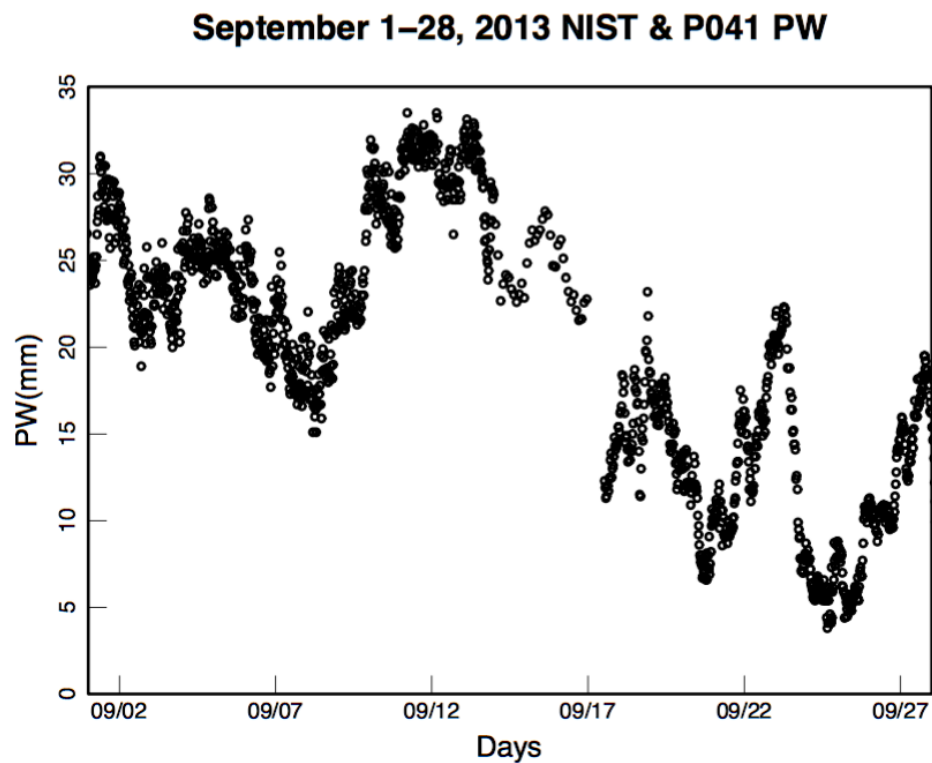


Figure 3. A time series of 30-minute (station P041) and 2-hourly (station NIST) GPS PW compared with precipitation (rain gauge UDFCD4840) from 1 – 28 September 2013. The inserted graph compares the same variables from 9 – 14 September 2013 with the addition of lines indicating 1, 2, and 3 standard deviations above the PW long-term median.

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Figure 3. A time series of 30 minute GPS PW (station P041) from 28 August – 28

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September 2013. All times are in UTC.

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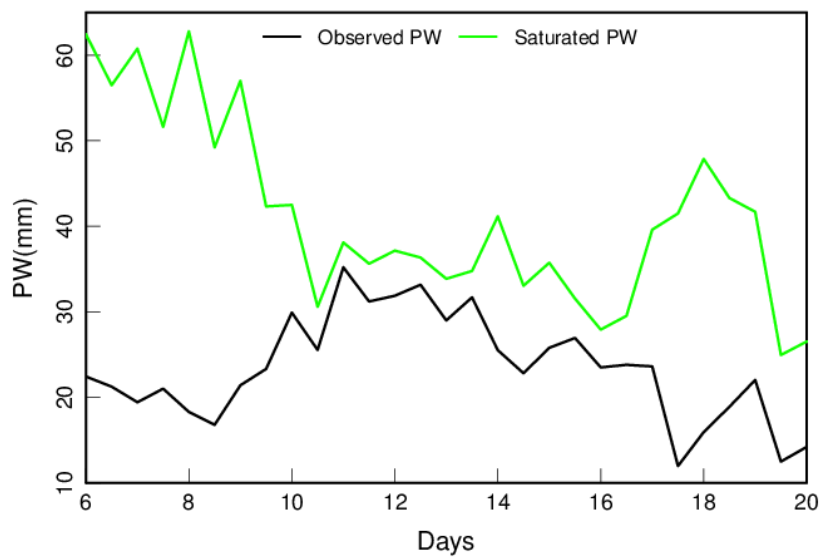


Figure 4. A time series comparison of observed radiosonde PW (black line) and saturated PW (green line) for 6-20 September 2013 over Denver, Colorado. [All times are in UTC.](#)

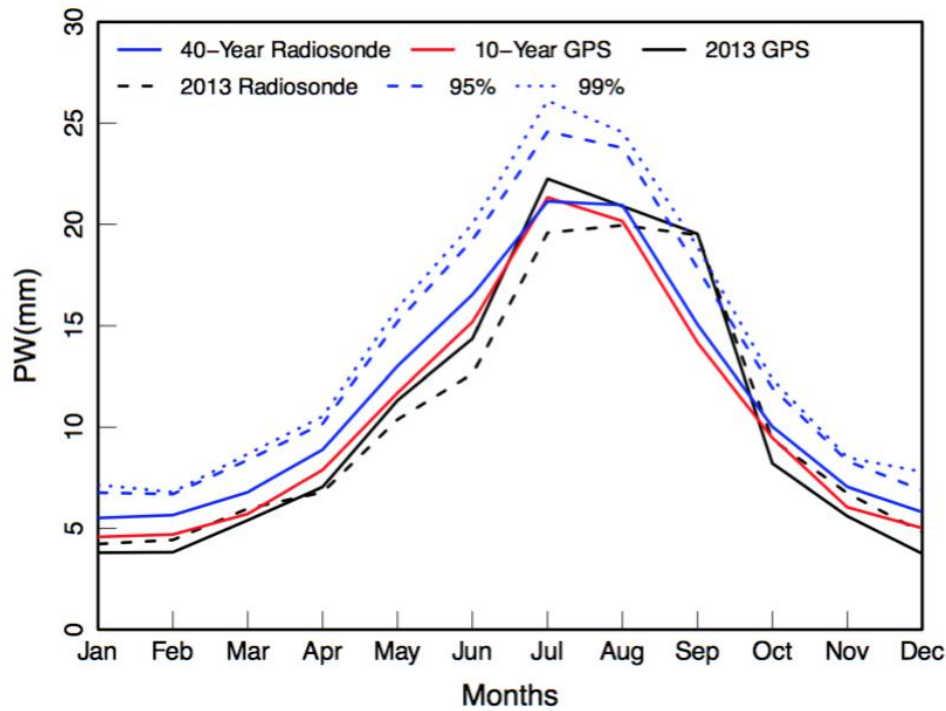


Figure 5. Monthly-averaged GPS PW (solid black line) and Radiosonde data (dashed black line) for 2013 with the 10-year merged GPS PW dataset (solid red line) and the 40-year averaged Radiosonde PW dataset (solid blue line). Additionally, there are the 95th (dashed red line) and 99th (dotted red line) percentiles for 10 years of GPS data and the 95th (dashed blue line) and 99th (dotted blue line) percentiles for 40 years of Radiosonde data.

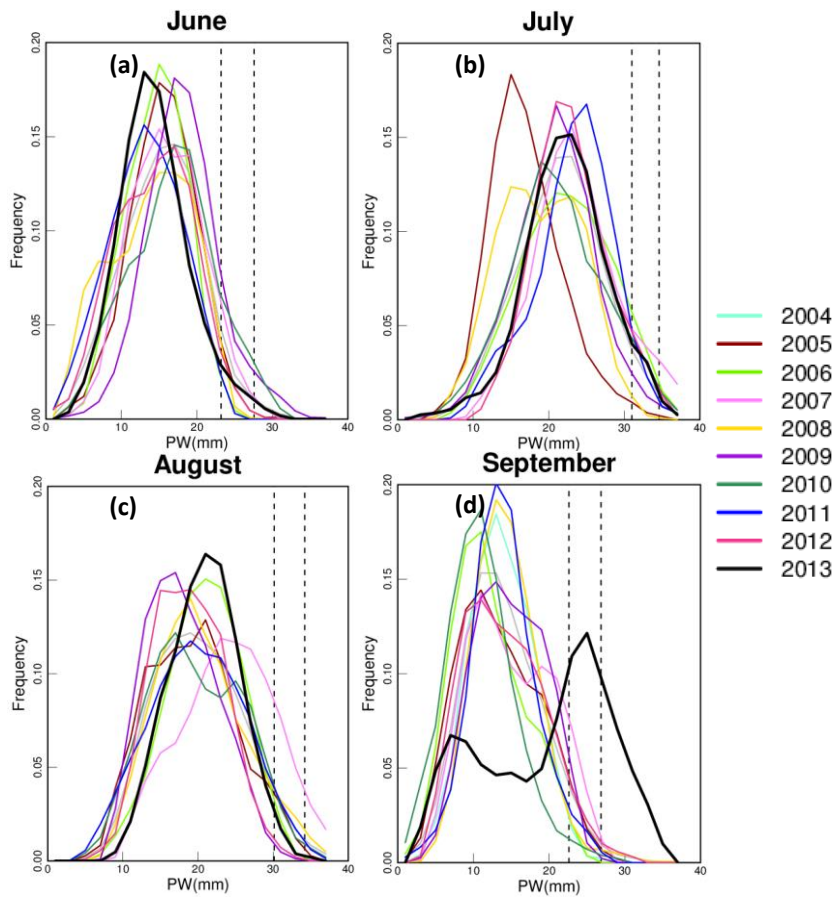


Figure 6. Statistical frequency distributions of GPS PW for June- September of 2004-2013 with the 95th percentile for 10 years of each month of data denoted by the left-most dashed line and the 99th percentile for 10 years of each month of data denoted by the right-most dashed line.

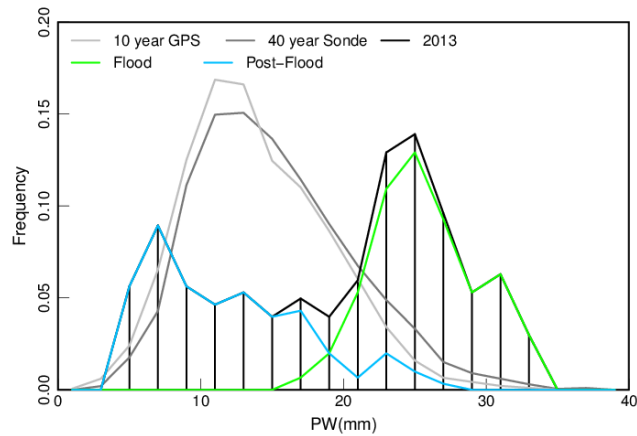


Figure 7. Statistical frequency distributions for the month of September with 2013 GPS PW data over Boulder (black line), 40 years of climatologically-averaged radiosonde PW data over Denver (dark grey line), and 10 years of climatologically-averaged GPS PW data over Boulder (light grey line). September of 2013 GPS PW data was split into two halves: 1-15 September 2013 (Flood; green line), and 16-30 September 2013 (Post-Flood; blue line).

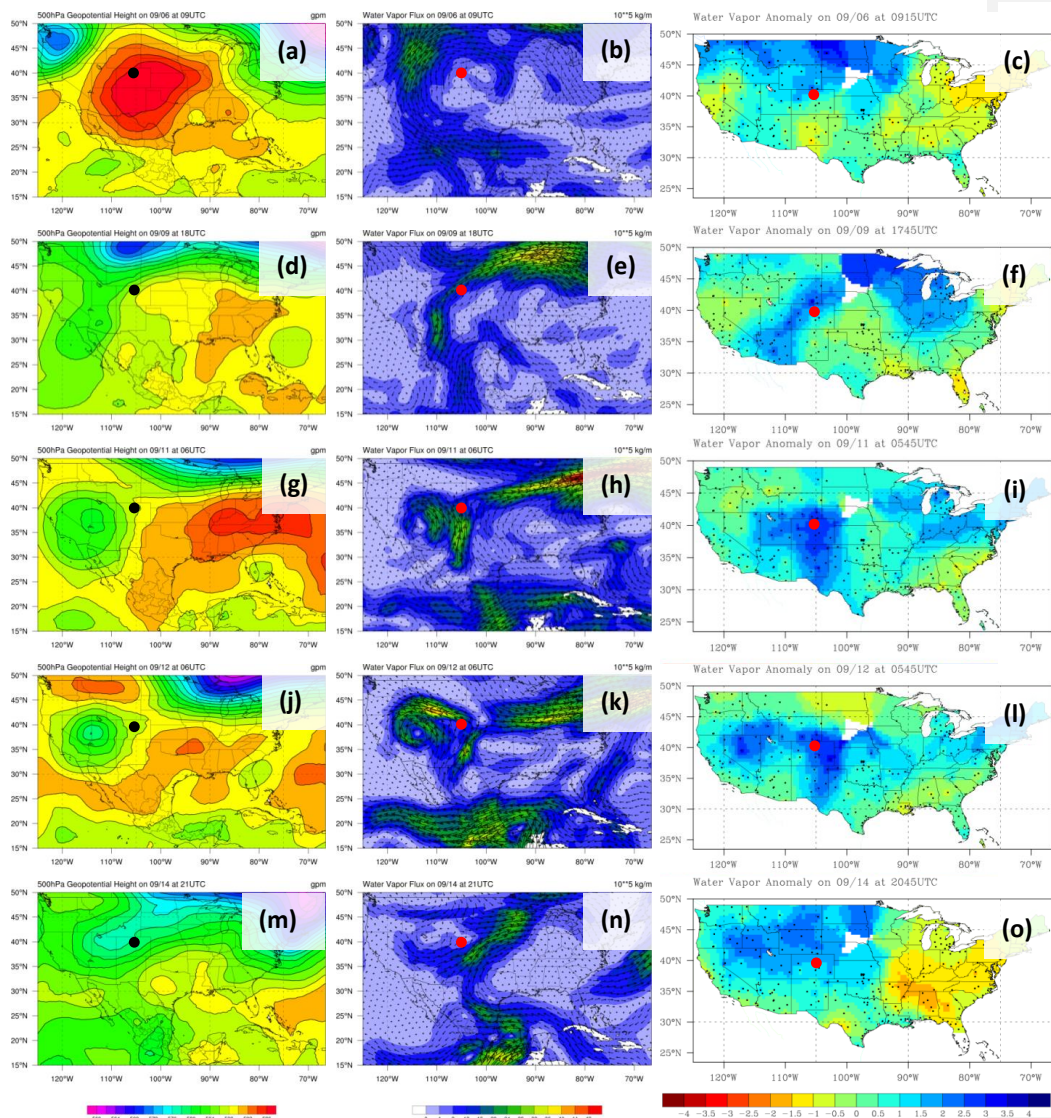


Figure 8. A comparison of NARR 3-hourly averaged 500 hPa geopotential height

(left column), NARR 3-hourly averaged integrated water vapor flux (center column), and SuomiNet gridded standardized PW anomalies. Each row represents a different time surrounding the 2013 Event.

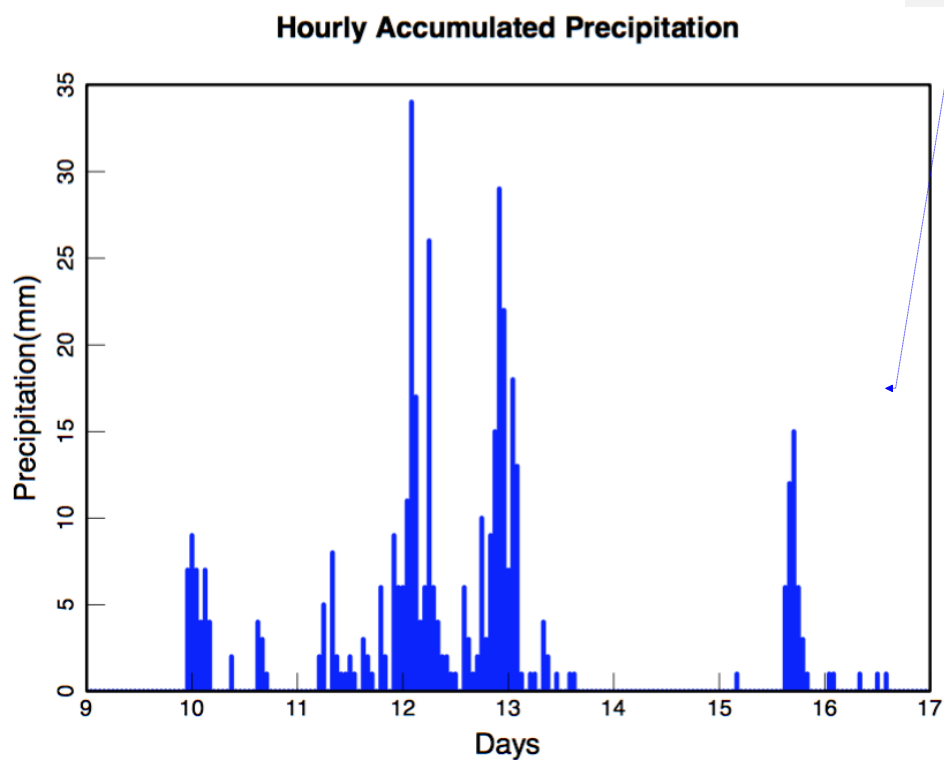


Figure 9. A time series of observed precipitation data from the rain gauge UDFCD_4840 for 9-17 September 2013. All times are in UTC.

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