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The Climatological Relation Between Extreme Precipitable Water Vapor (PWV) and Precipitation for the September 2013 Colorado Flooding Event

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1. INTRODUCTION

The IPCC 5th assessment found that changes in extreme weather events have been observed since the 1950s and the additional warming of 1°C will increase the risk of extreme events such as droughts, heat waves, and floods. Precipitation events are predicted to become more intense and possibly more frequent. Recent climate-related extremes, like floods have shown the vulnerability of certain ecosystems and humans to climate variability, through impacts such as disruption of food production, mental health, damage to infrastructure, and water supply (IPCC 2013).

In September of 2013 an unusual rainfall event occurred along the Front Range in Colorado (CIRES 2013). Precipitation amounts exceeded 15 inches in some locations, an extremely rare amount of rain to occur in the area during September (Hydrometeorlogical Design Studies Center 2013). The heavy rainfall was due to an intense moisture flow from the Pacific Ocean and the Gulf of Mexico and a stationary weather pattern over the Great Basin (Lukas et al. 2013). The flood devastated the region, over 200 miles of state highways were destroyed, about 23,000 acres of crops were damaged, and over 18,000 homes were affected. The current estimate for damages is $1.9 billion (Harvey and Shields 2013). The Boulder, CO flooding event that occurred in September of 2013 is a prime example of the devastation extreme floods can create, and although the likelihood of this event to occur again is small, the societal exposure to flooding in the Front Range has increased creating a need for constant monitoring of the current atmospheric state (CIRES 2013).

Total moisture content of the atmosphere during the event was at record levels for the month of September, providing the moisture needed for a precipitation event to occur (CIRES 2013). This study will examine the observed relationship between Precipitable Water Vapor (PWV) and precipitation and the near-time predictive capabilities of observed PWV during the Boulder, CO flooding event.

2. DATA

2.1 Observations

Three types of observations will be used for this study. Total daily precipitation comes from the Earth System Research Laboratory and is available starting in 1948 for Boulder, CO. The precipitation data is from the NOAA/NWS Cooperative site. SuomiNet ground-based GPS provides 30-minute observations of PWV at the P041 site in Marshall Field, CO. The GPS data is averaged to create daily values and is available from 2009-2013. The NASA Atmospheric Infrared Sounder (AIRS) also provides PWV but for a longer period, 2003-2013. The daily L3 gridded product (1°x1° spatial resolution) was used and the closest grid box to Boulder, CO was selected, choosing the maximum value between the ascending and descending overpasses.

2.2 Reanalysis

The ECMWF ERA-Interim was used in this study. Daily PWV values from 1979-2013 were used; the first 20 years (1979-1999) were used to create a monthly climatology while the last 10 years (2003-2013) were used for the actual analysis. The native spatial resolution was interpolated to 1°x1° resolution and the closest grid box to Boulder, CO was selected.

3. METHODOLOGY

3.1 Derivative of the Cumulative Sum (DoCS)

The derivative of the cumulative sum describes the rate at which moisture is transported through a region (mm/day) and was calculated using the PWV observations from the SuomiNet GPS and AIRS L3. A monthly climatology was calculated using daily PWV values from the ERA-Interim from 1979-1999, shown in figure 1 (top panel). A daily PWV anomaly is calculated from the observations (SuomiNet GPS and AIRS L3), by subtracting the ERA Interim climatology from the observational PWV timeseries shown in figure 1 (middle and bottom panel). The cumulative sum of the PWV anomaly is calculated by adding up the daily PWV anomaly values sequentially. Periods of rapid increase in the cumulative sum represent intense moisture transport and the potential for precipitation events as seen in figure 2 (top panel). To quantify this rapid increase the derivative of the cumulative sum is calculated over a 3-day period (units of mm/day). By subtracting the cumulative sum value 3 days prior from the current cumulative sum value. This can also be thought of as an average of the PWV anomaly over 3 days and is shown in figure 2 (bottom panel). When the derivative of the cumulative sum is positive (negative) there is an above (below) average amount of moisture being transported into the area, relative to the ERA-Interim climatology.

3.2 Cross-Correlation

Cross-correlation measures the degree to which two time-series are correlated as a function of time lag and was used to understand the relationship between extreme PWV and precipitation. Correlation coefficients were computed between the daily precipitation and the DoCS of PWV. For this analysis, different thresholds were used. For the precipitation, four different monthly thresholds were used that were calculated from the daily precipitation observations over the period 1979-1999. They were

1. Precipitation >0.01 inches
2. Precipitation > 50th Percentile
3. Precipitation > 95th Percentile
4. Precipitation > 99th Percentile

Only two monthly thresholds were used for the DoCS of PWV and were calculated from the DoCS of daily ERA-Interim PWV over the period 1979-1999. The thresholds are:

1. DoCS of PWV > 95th Percentile
2. DoCS of PWV > 99th Percentile

The cross correlation was calculated based on whether the variables surpassed the thresholds, not on the magnitude of which they surpassed.

3.3 Probability Analysis

Conditional probabilities describe the probability of an event given another event has occurred and were used in this study to examine the ability to predict rain events. The conditional probability is defined as:

$$P(A|B) = \frac{P(AB)}{P(B)}$$

where A is precipitation and B is the DoCS of PWV; the probability of precipitation given the DoCS of PWV. The analysis was only applied to data before 2013 and during the months of May-September. Furthermore the same thresholds used in the cross-correlation analysis were used, meaning there were 8 different conditional probabilities computed:

1. P(A>0.01 inches | B > 95th Percentile)
2. P(A > 50th Percentile | B > 95th Percentile)
3. P(A > 95th Percentile | B > 95th Percentile)
4. P(A > 99th Percentile | B > 95th Percentile)
5. P(A>0.01 inches | B > 99th Percentile)
6. P(A > 50th Percentile | B > 99th Percentile)
7. P(A > 95th Percentile | B > 99th Percentile)
8. P(A > 99th Percentile | B > 99th Percentile)

In addition to the conditional probabilities, the probability of a missed rain event and the probability of a false alarm using this method were computed.

4. RESULTS

4.1 Correlation-Coefficients

Figure 3 shows the cross-correlation coefficients for the SuomiNet GPS, AIRS L3, and ERA-Interim for a max lag of 10 days using a 95th Percentile threshold on the DoCS of PWV and a 50th percentile threshold on the precipitation. The max correlation coefficient occurs at 0 lag but all correlation coefficients are statistically significant to the 95% confidence interval. Table 1 shows the correlation coefficients at lag 0 for the observations and the reanalysis using different thresholds. For all of the threshold cases, the max correlation coefficient occurred at lag 0. As the precipitation threshold becomes more restrained, the correlation coefficient decreases, potentially due to the decrease in the number of events used in determining the correlation. Overall, the observations and the reanalysis show similar correlations coefficients suggesting that a relationship between PWV and precipitation exists and is not an artifact of a particular dataset.

4.2 Near Time Capabilities

Table 2 shows the probability of precipitation, the probability of a missed event, and the probability of a false alarm for the different thresholds. The probability of precipitation is larger, 5-10% greater chance of rain, when the threshold for PWV is higher (threshold < 99th percentile). Generally, the observations and the reanalysis agree suggesting the relationship between PWV and precipitation is real and not an artifact in the data set or the model. Figure 4 shows the average probabilities of the SuomiNet GPS, AIRS L3, and the ERA-Interim. As the threshold on precipitation increases, i.e. more extreme precipitation cases, the probability of precipitation decreases. Similar to the correlation coefficient, this is probably due to the reduction in the number of precipitation events used in the statistical analysis. The probability of a missed event, however, reduces as the precipitation threshold increases while the probability of a false alarm increases. Even though the false alarm increases, the false alarm rates are relatively small, ranging from 1-5% (for the 99th percentile threshold), suggesting this analysis could be used simultaneously with current forecasting methods to potentially capture extreme precipitation events that are missed and provide high certainty that a precipitation event will occur.

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The probability analysis can be applied to the Boulder, CO flooding event. Figure 5 shows the DoCS of PWV for the SuomiNet GPS, AIRS L3, and ERA-Interim with daily precipitation overlaid. The red dotted line represents the 99th percentile threshold that the observations would have needed to exceed in September for the probability of precipitation to be what is shown in Table 2 (top panel). The observations, SuomiNet GPS and AIRS L3, exceed the threshold continuously two weeks prior to event, showcasing the difference in the model and observations and suggesting a need to utilize observations more. For two weeks prior to the event, this probability analysis would have suggested the following:

- 57% probability of rain each day
- 36% probability of rain > 50th percentile each day
- 16% probability of rain > 95th percentile each day
- 8% probability of rain > 99th percentile each day

Future work will examine the frequency of extreme DoCS of PWV and how having several days of extreme PWV transport effects the probability of rain. In addition, the analysis will be extended beyond the Boulder, CO case study by using TRMM datasets for precipitation.

5. REFERENCES

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6. TABLES and FIGURES

Table 1: Correlation Coefficients at lag 0 for the 99th percentile threshold on the DoCS PWV (top table) and the 95th Percentile threshold on the DoCS PWV (bottom panel)

Precipitation Threshold	SuomiNet GPS	ERA Interim	AIRS L3
> 0	0.10	0.13	0.12
> 50th Percentile	0.10	0.14	0.12
> 95th Percentile	0.07	0.16	0.11
> 99th Percentile	0.10	0.09	0.05
Number of Samples	1284	3653	3617

Precipitation Threshold	SuomiNet GPS	ERA Interim	AIRS L3
> 0	0.18	0.21	0.22
> 50th Percentile	0.19	0.23	0.24
> 95th Percentile	0.16	0.20	0.19
> 99th Percentile	0.09	0.13	0.10
Number of Samples	1284	3653	3617

Table 2: Conditional probabilities for the different observations and reanalysis using the 99th percentile threshold on the DoCS of PWV (top) and the 95th percentile threshold on the DoCS of PWV (bottom)

Precipitation Threshold	Observation/Model	Probability of Precipitation	Probability of Missed Event	Probability of False Alarm
> 0	SuomiNet GPS	0.54	0.46	0.01
	ERA Interim	0.61	0.48	0.01
	AIRS L3	0.57	0.46	0.02
> 50th Percentile	SuomiNet GPS	0.33	0.34	0.02
	ERA Interim	0.48	0.34	0.01
	AIRS L3	0.28	0.33	0.03
> 95th Percentile	SuomiNet GPS	0.17	0.23	0.03
	ERA Interim	0.22	0.24	0.01
	AIRS L3	0.08	0.24	0.05
> 99th Percentile	SuomiNet GPS	0.13	0.20	0.03
	ERA Interim	0.09	0.21	0.01
	AIRS L3	0.02	0.21	0.05

Precipitation Threshold	Observation/Model	Probability of Precipitation	Probability of Missed Event	Probability of False Alarm
> 0	SuomiNet GPS	0.46	0.42	0.04
	ERA Interim	0.59	0.45	0.02
	AIRS L3	0.47	0.40	0.07
> 50th Percentile	SuomiNet GPS	0.29	0.32	0.07
	ERA Interim	0.36	0.33	0.03
	AIRS L3	0.26	0.30	0.11
> 95th Percentile	SuomiNet GPS	0.13	0.22	0.09
	ERA Interim	0.17	0.23	0.05
	AIRS L3	0.09	0.23	0.14
> 99th Percentile	SuomiNet GPS	0.06	0.20	0.10
	ERA Interim	0.08	0.21	0.05
	AIRS L3	0.03	0.21	0.15

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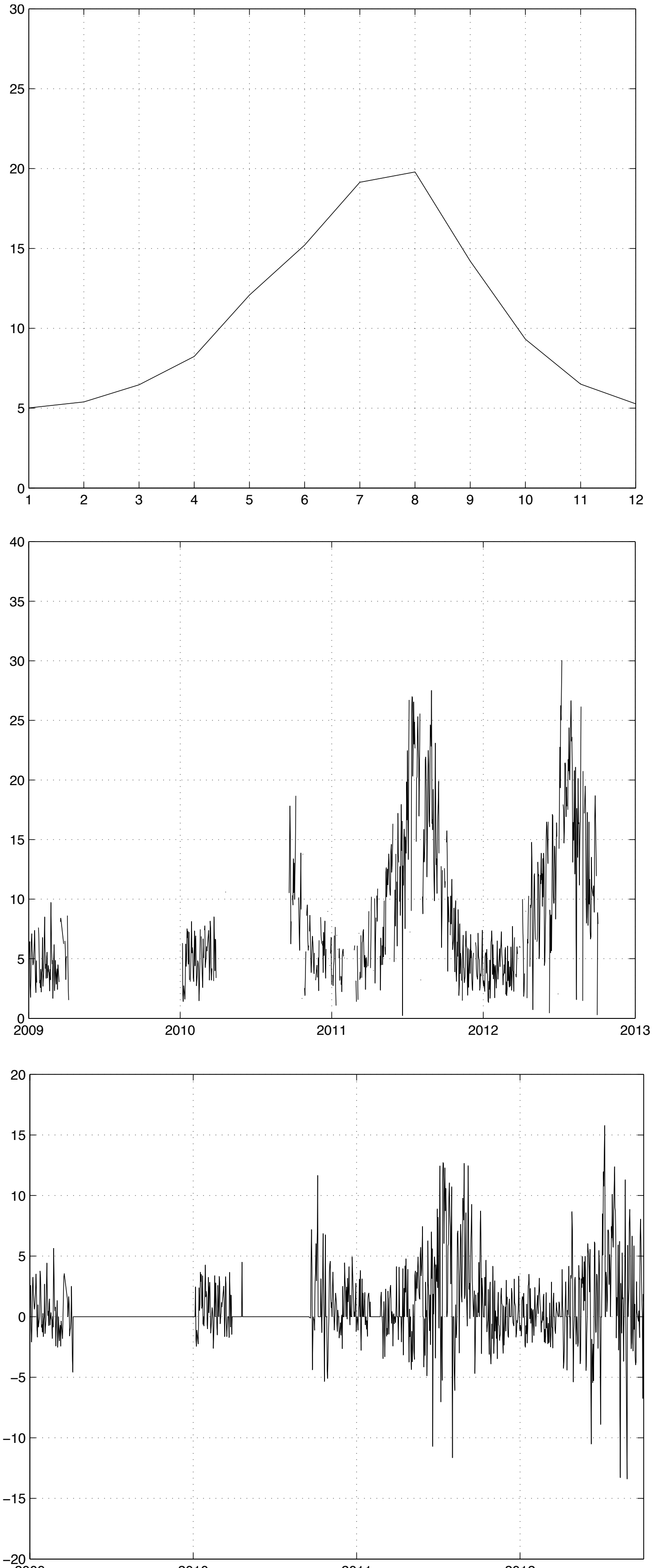

Figure 1: ERA Interim Mean Climatological PWV (mm) for Boulder, CO (top panel), SuomiNet GPS Daily PWV (mm) for Boulder, CO (middle panel), SuomiNet GPS Daily PWV Anomaly (mm) for Boulder, CO (bottom panel)

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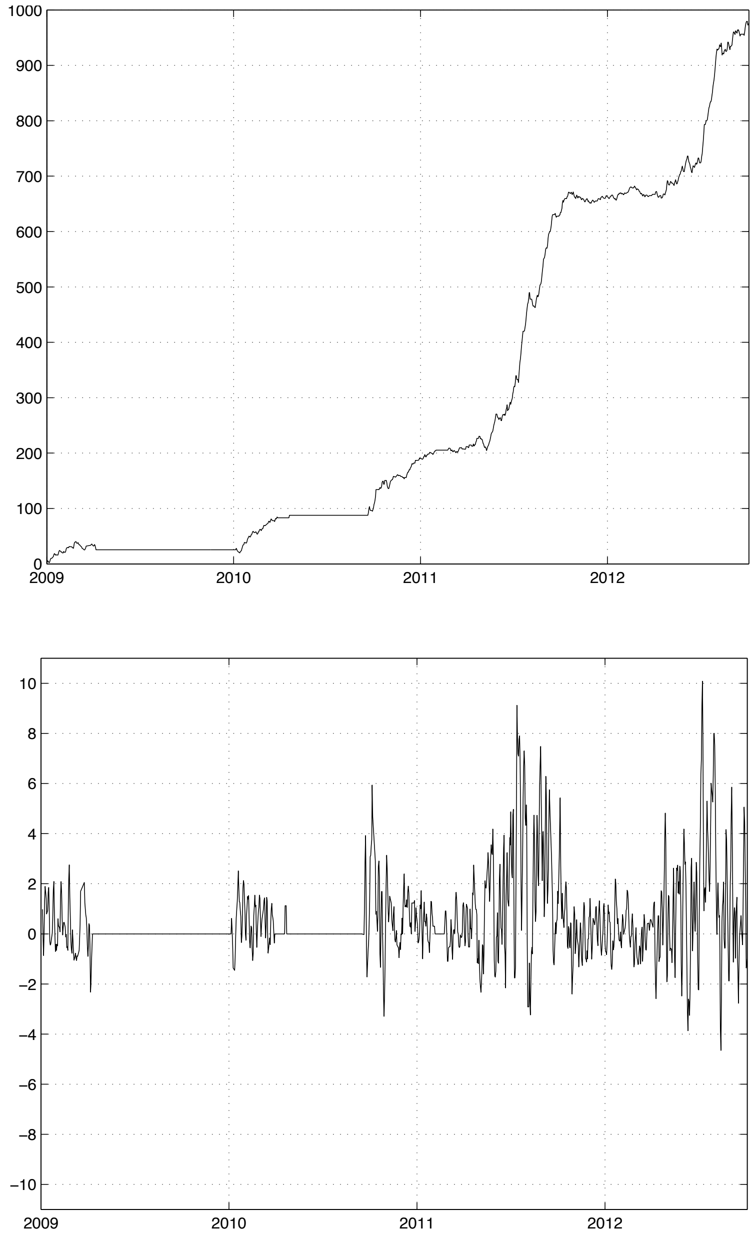

Figure 2: SuomiNet GPS Cumulative Sum of the PWV Anomaly (mm) for Boulder, CO (top panel), SuomiNet GPS Derivative of the Cumulative Sum (mm/day) for Boulder, CO (bottom panel)

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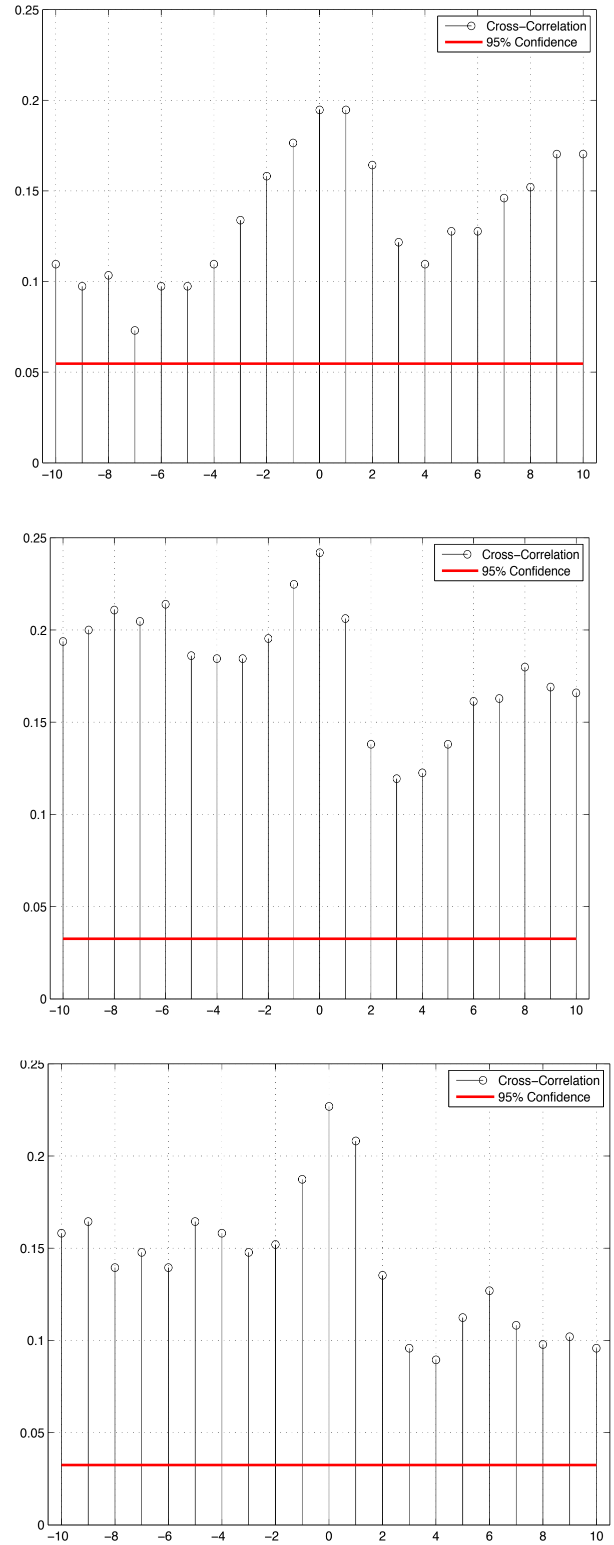

Figure 3: Correlation Coefficients for SuomiNet GPS (top panel), AIRS L3 (middle panel), and ERA Interim (bottom panel) using the 95th percentile threshold on the DoCS of PWV and the 50th percentile threshold on the precipitation

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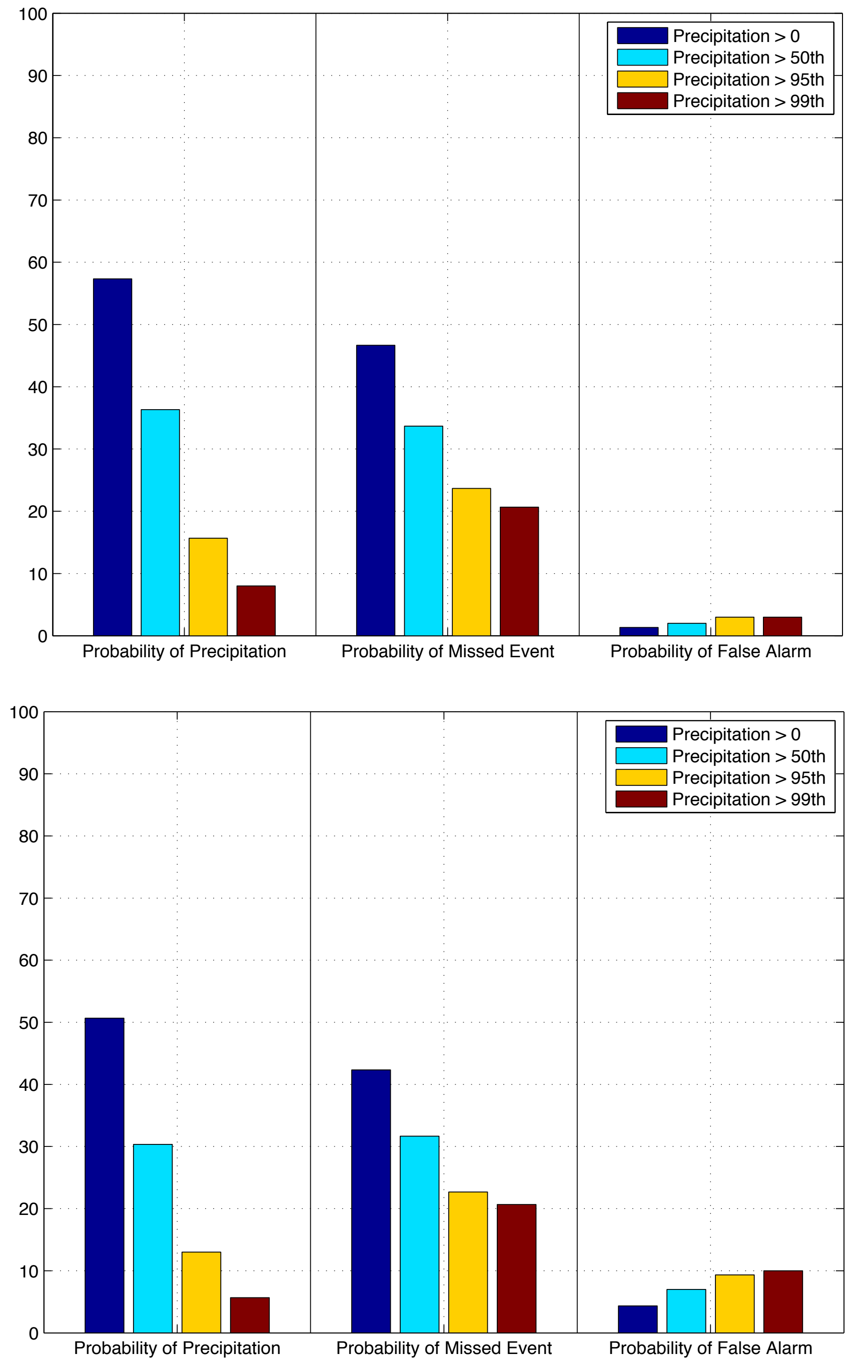

Figure 4: Average probability of SuomiNet GPS, AIRS L3, and the ERA-Interim using the 99th percentile threshold on the DoCS of PWV (top panel), and the 95th percentile threshold on the DoCS of PWV (bottom panel)

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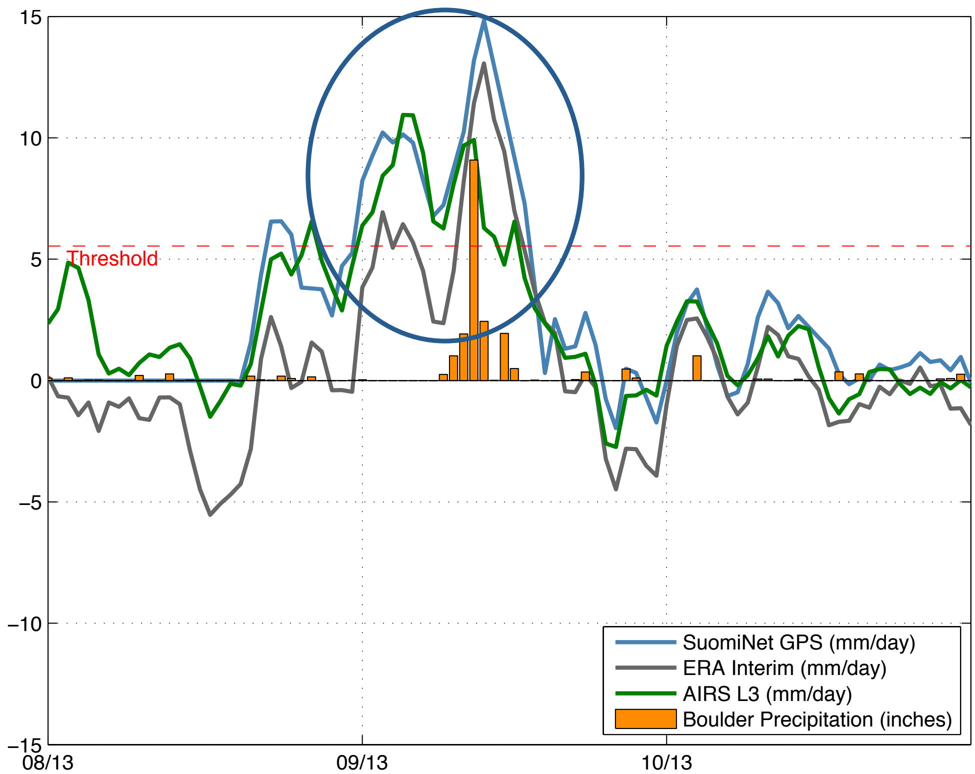

Figure 5: DoCS of PWV (mm/day) and Daily Precipitation (inches) for Boulder, CO from August - October 2013