# National Weather Service Forecasters Use GPS Precipitable Water Vapor for Enhanced Situational Awareness during the Southern California Summer Monsoon

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See the associated StoryMap


## Abstract

During the North American Monsoon (NAM), low-to-midlevel moisture is transported in surges from the Gulf of California and Eastern Pacific Ocean into Mexico and the American Southwest. As rising levels of precipitable water interact with the mountainous terrain, severe thunderstorms can develop, resulting in flash floods that threaten life and property. The rapid evolution of these storms, coupled with the relative lack of upper-air and surface weather observations in the region, make them difficult to predict and monitor, and guidance from numerical weather prediction models can vary greatly under these conditions. Precipitable water vapor (PW) estimates derived from continuously operating ground- based GPS receivers have been available for some time from NOAA's GPS-Met program, but these observations have been of limited utility to operational forecasters in part due to poor spatial resolution. Under a NASA Advanced Information Systems Technology (AIST) project, 37 real-time stations were added to NOAA's GPS-Met analysis providing 30-min PW estimates, reducing station spacing from approximately 150 km to 30 km in Southern California. An 18–22 July 2013 North American Monsoon event provided an opportunity to evaluate the utility of the additional upper-air moisture observations to enhance National Weather Service (NWS) forecaster situational awareness during the rapidly developing event. NWS forecasters used these additional data to detect rapid moisture increases at intervals between the available 1-6hr model updates and approximately twice-daily radiosonde observations, and these contributed tangibly to the issuance of timely flash flood watches and warnings in advance of flash floods, debris flows, and related road closures.

## Filling the Need for Observational Data

Most decisions about whether to issue flash flood watches and warnings are based on real-time data that give the forecaster confidence whether a threatening situation has developed or is about to develop. However, rapidly evolving low-to-midlevel regional moisture surges leading to flash flood conditions can be particularly difficult to detect using satellite, radar, and surface dewpoint observations. Further, moisture observations around the Gulf of California and inland locations in Mexico, where convection often initiates, have historically been sparse and/or irregularly monitored. Radiosonde sites in San Diego, Yuma, Phoenix, Tucson, and Las Vegas are crucial for detecting monsoonal moisture surges, but are too widely spaced to precisely locate the horizontal boundaries between moist and dry air, and have limited temporal resolution because most are launched at 12-h intervals. As a result, inadequate real-time atmospheric moisture information can hinder the accuracy of flash flood watches and warnings during NAM events, and new methods that measure PW with high temporal resolution are of considerable interest.

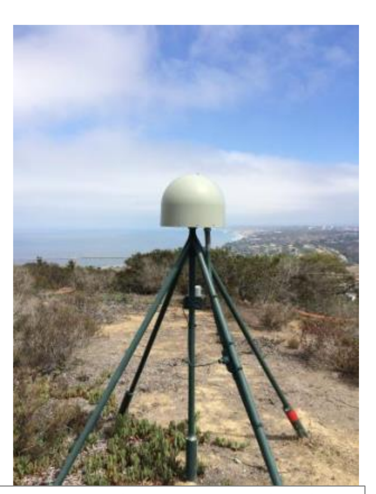

**Figure 1:** A typical GPS station in Southern California. [Photo Credit : D. Glen Offield, Scripps

## GPS Meteorology

Continuous GPS (CGPS) stations for observing crustal motion in the western United States now number more than 1,200. These stations are permanently mounted on bedrock (Fig. 1) or deeply anchored to improve stability. In Southern California, most stations are now part of the Plate Boundary Observatory, or the Southern California Integrated GPS Network operated by the U.S. Geological Survey and Scripps Institution of Oceanography. The GPS positioning technique is based upon measuring signal travel time from the GPS satellites to the receiving antenna to estimate the geometric distance between them. However, the signal is also subject to delays due to the total electron content in the ionosphere and the amount of moisture and total density of the troposphere. In estimating the position of the ground station to accuracy better than 2 mm, it is necessary to account for these atmospheric delays. Dual-frequency receivers allow the ionospheric delay to be determined, and the remaining tropospheric effects estimated from the residual delay are the foundation of GPS meteorology.

The total tropospheric delay (TD) observed by GPS is the integrated refractivity of the atmosphere, N, over the signal ray path:

$$\mathrm{TD} = \int_{s=raypath} N ds = \int_{s=raypath} (k_1 \frac{P}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2})\, ds$$

where P is the atmospheric pressure, T is temperature, e is water vapor partial pressure, and the k's are empirically determined physical constants in an expression for N. Therefore, this estimated tropospheric signal delay provides information about the unknown moisture above the station. All GPS signals arriving at the site with an elevation angle greater than 7 degrees, within an inverted cone (**Fig. 2**) centered on the receiving antenna, are considered in determining the zenith (vertical) delay.

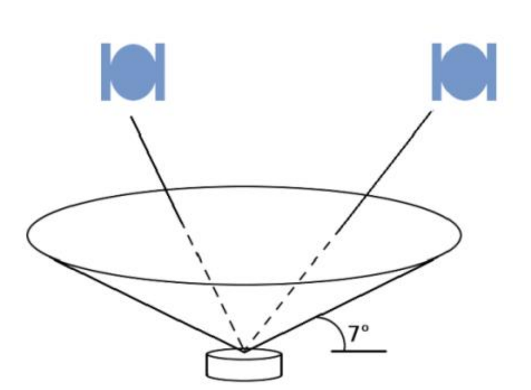


**Figure 2:** All signals arriving at a GPS antenna with elevation angle greater than 7 degrees, within an inverted cone centered on the receiving antenna, are considered in determining the zenith tropospheric delay. Typical receivers track 12 or more satellites.

**ACKNOWLEDGMENTS**

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The tropospheric delay observed for a given satellite at angle θ from vertical is modeled as

$$TD\,(\theta) = ZHD \times m_h(\theta) + ZWD \times m_w(\theta)$$

where ZHD is the zenith hydrostatic delay, ZWD is the zenith wet delay, and $m_h$ and $m_w$ are mapping functions that describe the variation of ZHD and ZWD with varying elevation angle. ZHD is a function of surface pressure, which is measured directly at the site, allowing ZWD to be isolated. Further, ZWD is proportional to PW, with the multiplier being a function of mean water vapor–weighted atmospheric temperature, which can be approximated as a linear function of surface air temperature derived from climatology. **Thus, given a zenith total delay estimate at the GPS station, along with surface pressure and temperature measurements, the PW parameter familiar to meteorologists can be calculated at high temporal resolution (intervals of 5 to 30 min) to track moisture-associated weather conditions**.

Under a NASA AIST project, 37 more Southern California stations were included in NOAA's GPS-Met analysis providing 30-min estimates of PW to forecasters and modelers, as a test bed for the regional use of GPS PW in operational weather forecasting during weather conditions involving moisture extremes, and in particular to study their value in improving forecasts of monsoon rainfall. **Figure 3** depicts the station sets before and after the additions.

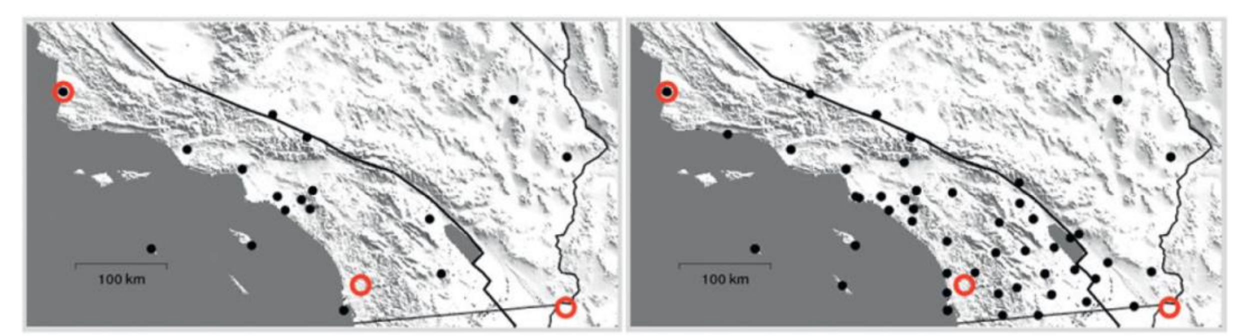


**Figure 3:** (left) Southern California stations analyzed by the NOAA GPS-Met project prior to the start of this project. (right) The station set following the inclusion of 37 additional stations. Red circles indicate radiosonde sites at Vandenberg, San Diego, and Yuma. *Heavy black line indicates the San Andreas fault.*

## GPS PW Improves Situational Awareness

An example highlighting the use of GPS PW is a North American Monsoon event that began to develop on July 18th 2013, when an upper-level low pressure system moved into northern Sonora, Mexico, and weak southerly winds in the Gulf of California transported significant amounts of moisture into the area of Yuma, Arizona (**Fig. 4**).

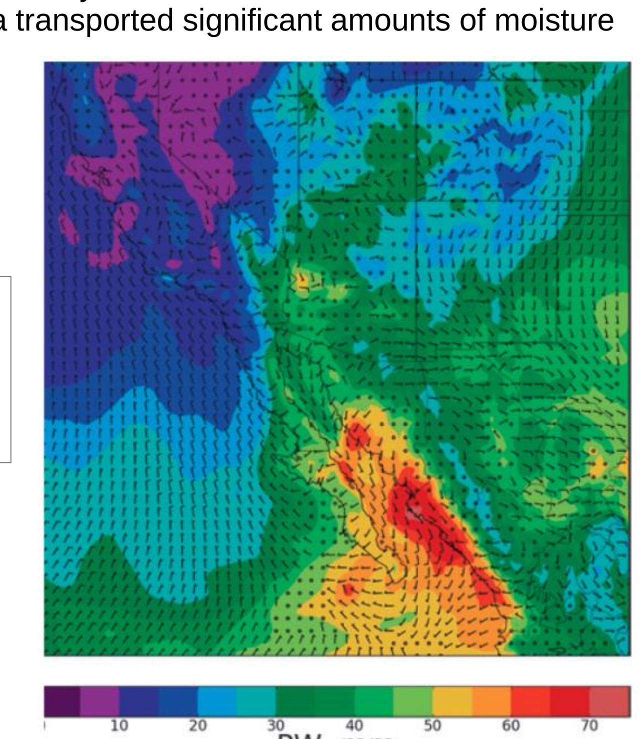


**Figure 4:** National Centers for Environmental Prediction Rapid Refresh (RAP) model precipitable water with 10-m winds at 0000 UTC 19 Jul 2013, illustrating the transport of moisture from the Gulf of California into the area of Southern California.

On 19 July, the upper low (manifesting itself as a wave) had moved west over the Gulf of California and the Baja Peninsula (**Fig. 5**).

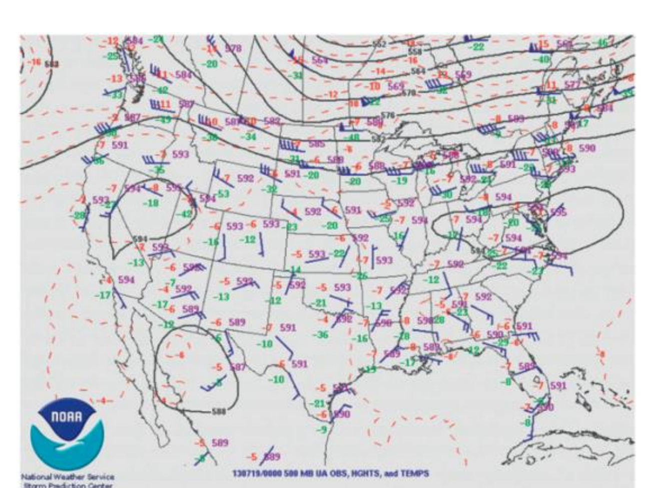

**Figure 5:** 500-mb upper-air analysis at 0000 UTC 22 Jul 2013, showing the location of the upper-level low in northern Mexico. [Image credit: NOAA NWS Storm Prediction Center]

A Mesoscale Convective System developed in central Arizona, and by July 21st it had moved northwestward toward the Southern California coast. Optimal atmospheric conditions involving high GPS PW along with the forcing provided by the wave resulted in heavy rainfall, flash flooding, and debris flows in Riverside and San Diego counties beginning at about 0400 Pacific Daylight Time (PDT) (1100 UTC) 21 July. Precipitation totals over 30 min and one hour exceeded the 1,000-yr recurrence levels on 22 July at Llano, California in the Antelope Valley, where vehicles became stuck due to flash flooding. This event presented an opportunity for NWS forecasters to utilize the expanded Southern California GPS PW dataset.

## Looking at the GPS PW

On the afternoon of July 18th, a sounding at Yuma indicated 44 mm of PW, sufficient monsoonal moisture to cause heavy rainfall (considered to be PW > 35 mm in the local area). Meanwhile, PW of 13 mm in the San Diego sounding indicated the moisture had not spread west to the coast.

An increase to 25 mm was measured at San Diego in the 0500 PDT July 19th sounding, but no new sounding from Yuma was available. It was expected that the continued outflows from convection to the east and southeast, and moisture surges from the southeast into the deserts and mountains, would increase the low-level moisture and convective potential. Orographic lifting had the potential to cause heavy rainfall as this flow reached the Coast Ranges.

Forecasters were able to use the GPS PW to characterize the moisture distribution and content in the absence of a Yuma sounding. The expanded GPS dataset also provided moisture information at higher spatial and temporal resolutions. For example, as seen in **Fig. 6**, the PW increase at Durmid Hill, near the Salton Sea, began to accelerate early on July 19th, exceeding the PW at both San Diego and Glamis a few hours later.

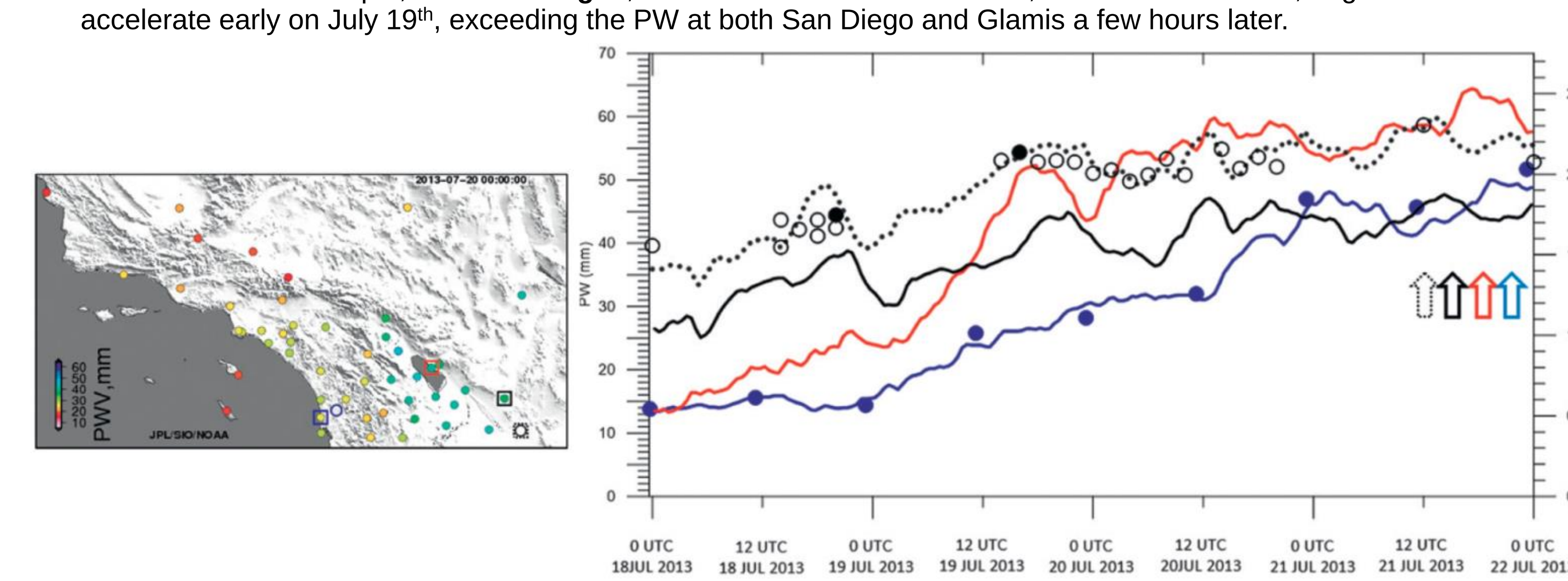


**Figure 6:** PW measurements during the evolution of the July event. Circles represent PW for radiosondes at San Diego, CA (blue), and Yuma, AZ (black). Solid black circles indicate those that were available to forecasters in AWIPS leading up to the flash flood watch and warning described in the text. Open circles represent additional Yuma soundings provided for retrospective insight into the event. Solid traces show GPS PW measurements at San Diego (blue), Durmid, CA (red), and Glamis, CA (black), about 60 km from Yuma. Dotted black trace is PW from a GPS station in Yuma that was not available to the forecasters at the time of this study, but was post-processed to compare with PW measured by the Yuma radiosondes during the passage of the inverted trough. Arrows indicate the times of passage of the wave at the identified GPS-Met sites. Map locates GPS stations with squares and radiosondes with circles, and shows PW in mm according to the color scale, at 1700 PDT 19 Jul (0000 UTC 20 Jul).

By 0700 PDT on the 19th, 45 mm of PW was observed at GPS stations in the deserts near the mountain slopes. The increase was confirmed when a 0900 PDT Yuma sounding eventually arrived, indicating PW of 53 mm.

At 2115 PDT on July 19th, forecasters issued an Area Forecast Discussion noting that the upward trend in GPS PW indicated the need for a flash flood watch for the afternoon of 20 July. The watch was issued on the next shift at 0134 PDT on July 20th, about 26 hr prior to the first report of flash flooding - which is a significant amount of lead time for this type of event.

A flash flood warning was issued at 0343 PDT on 21 July 2013, giving 17 min of lead time between the issuance of the warning and the first report of flash flooding. As noted by Ivory Small, Science and Operations Officer at the San Diego WFO, "the absence of sounding data at Yuma, AZ, resulted in the GPS-MET PW data being very valuable to the forecaster in order to determine how the moisture distribution and content was changing in Southern California. The high temporal resolution of the GPS-MET PW data . . . eventually led to the issuance of a flash flood watch prior to significant flash flooding in southwest California." Local storm reports indicated debris flows from recent fire activity, vehicles trapped on a roadway between two flooded locations on Highway 78 (**Fig. 7**), and bowling ball–sized rocks and 1-m deep flood deposits covering about 24 m of a road in Riverside county.

**Figure 7:** Flooding across Highway 78 in San Diego County, California, 22 Jul 2013. [Photo credit: NOAA]

## The Value of GPS PW to the Watch/Warn Process

GPS PW gives forecasters confidence about whether a watch or warning is needed for several reasons, including the high temporal resolution compared with other observations and the rough correlation between high PW and heavy rainfall. In general, if a model indicates an upward PW trend, but the GPS PW does not, forecasters would tend to hold off on the watch and question the model, but if the trend continues or accelerates, the watch would be issued even sooner. Although many factors are considered by forecasters, including wind, stability, orographic lifting, and dynamic conditions, flash flood warnings would likely be issued sooner with very high GPS-PW values versus events with "typical" or marginal values of GPS-PW. **GPS PW can also be particularly useful in the case of atmospheric river events**, when moisture is concentrated in a band associated with the low-level jet, rain rate is minimally impacted by evaporation, orographically forced ascent is appreciably larger than synoptic ascent, and hydrometeor generation is instantaneous and 100% efficient. In this case, there is a correlation between upslope moisture flux, empirically described by PW and mean wind at ~1 km, and the triggering of heavy precipitation. will allow enhanced interactive use of the high temporal resolution data.

## Future Plans.

Monitoring the GPS PW dataset has become a routine part of operations at the NWS Oxnard and San Diego WFOs. As discussed above, we also anticipate utility in winter season events involving landfalling atmospheric rivers. Primary goals include making these tools and techniques available to all NWS forecasters, and to assess the impact of higher temporal and spatial resolution estimates of PW on local and regional predictions and warnings of heavy precipitation events in flash flood-prone regions of Southern California. Ultimately, inclusion in AWIPS will allow enhanced interactive use of the high temporal resolution data (**Fig 8**).

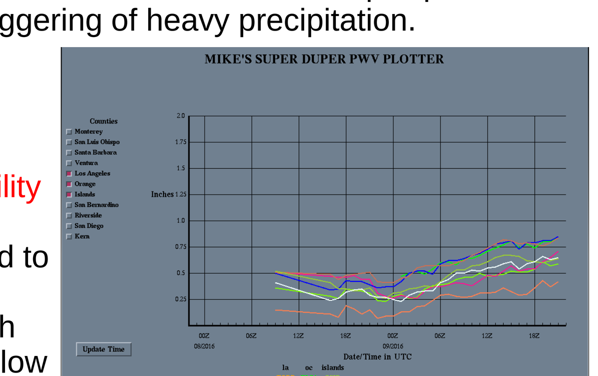


**Figure 8:** Initial GPS-PW Plotter in AWIPS