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

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A Global Positioning System (GPS) network in Southern California, newly densified to an average station spacing of 30 km, enhanced situational awareness for local National Weather Service (NWS) forecasters during 2013 summer monsoon rainfall events. The North American Monsoon (NAM) occurs in summer due to strong heating of the Sierra Madre and Rocky Mountains driving a transition to mean low-level flow from the south (Adams and Comrie 1997). During this season, moisture associated with tropical easterly waves (Fuller and Stensrud 2000; Favors and Abatzoglou 2013) and remnant Pacific tropical cyclones (Corbosiero et al. 2009) is advected northward into the southwestern United States from the Gulf of California at low levels and westward from the Gulf of Mexico at midlevels. The origin and evolution of moisture surges from the Gulf of California into the southwestern United States have been investigated by Higgins et al. (2004), who identified a positive precipitation anomaly moving northward along the Mexican coastline that is correlated with the moisture surge. Favorable synoptic conditions for the surge generation and propagation along the Sierra Madre Occidental (SMO) include passage in the NAM region of tropical easterly waves (Ladwig and Stensrud 2009) or westerly moving mid-to-upper-level lows, termed "inverted troughs" (Bieda et al. 2009), that lead to moisture convergence over the SMO (Pytlak et al. 2005). It is thought that the development of mesoscale convective systems (MCS) and organized convection over the SMO produce cold outflow boundaries that contribute to surges of moist air into the southwestern United States (Douglas and Leal 2003; Finch and Johnson 2010; Schiffer and Nesbitt 2012).

In comparison to California, Arizona receives a greater amount of monsoon rainfall, and it also comprises a larger fraction of annual rainfall there (Means 2013). However, monsoonal moisture regularly reaches southern California and causes heavy rainfall, particularly when interacting with mountain ranges (Tubbs 1972). Orographic lift, channeling, lee-side convergence, and upslope convergence over the mountains all play a role (Whiteman 2000). Thunderstorms in Southern California tend to initially form along mountain ridges as upslope flow generates a convergence zone at or near the ridgeline. This typically oc-

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curs when a Gulf of California moisture surge provides sufficient precipitable water (PW), instability, and dynamic forcing to the region. Boundary interaction becomes very important as the sea breeze interacts with terrain-generated flows and outflow boundaries (Small and Maxwell 2014). Features such as easterly waves and upper-level lows can also destabilize the air mass enough to allow thunderstorms to develop, and potentially reach severe levels generating flash floods.

The mission of the NWS includes issuing weather watches and warnings to protect lives and property, and NWS forecasters use a variety of weather models and observations in making watch and warning decisions during monsoon events. Under rapidly changing conditions, model solutions and forecast guidance can vary greatly with respect to the timing, intensity, and duration of precipitation. Commonly cited factors include differences in model resolution, convective parameterizations, and cloud microphysics. Less commonly recognized is the need for more accurate and comprehensive initial conditions provided by upper-air observing systems at temporal and spatial resolutions consistent with the models assimilating them. This is especially true in regions of complex orography like Southern California. Given the incomplete or conflicting guidance that current model solutions often provide and their focus on longer-range (6–24 h) probabilistic predictions, 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 in this region 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 (Dixon 2005), 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. [At the U.S. Army Yuma Proving Ground (YPG), radiosondes are launched irregularly in support of the local mission, and many observations only become available to the NWS and WMO retrospectively and with a variable delay.] 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. Additional sites in the Peninsular Ranges west of the Colorado and Mojave deserts in the southwestern United States are now equipped to provide near-real-time PW information from GPS receivers. We describe in particular a July 2013 NAM event that resulted in flash floods in the mountainous desert regions of Southern California. The new GPS PW measurements provided forecast guidance and contributed tangibly to NWS forecasters issuing timely flash flood watches and warnings.

Fig. 1. A typical continuous GPS station in Southern California. [Photo credit: D. Glen Offield, Scripps Institution of Oceanography]

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, the geodetic component of the National Science Foundation's EarthScope Program, operated by UNAVCO (http://unavco.org), or the Southern California Integrated GPS Network operated by the U.S. Geological Survey and Scripps Institution of Oceanography. The autonomous stations continuously record signals from the GPS satellites and transfer the data to a central facility, where position is estimated at cadences from daily to once per second to precisely identify ground motion during and between earthquakes. 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 (TEC) 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 (Davis et al. 1985). 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

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

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 (Bevis et al. 1994). 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. Typical modern receivers track 12 or more satellites simultaneously. The tropospheric delay observed for a given satellite at angle θ from vertical is modeled as

$$\mathrm{TD}\ (\theta) = \mathrm{ZHD} \times m_h(\theta) + \mathrm{ZWD} \times m_w(\theta)$$

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 (Böhm et al. 2006). 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 (Bevis et al. 1992). 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. Studies using the postprocessed estimates of PW from a dense geodetic network of GPS sites in California have examined monsoon conditions in great detail, but not with the timeliness necessary for operational use (Means 2013).

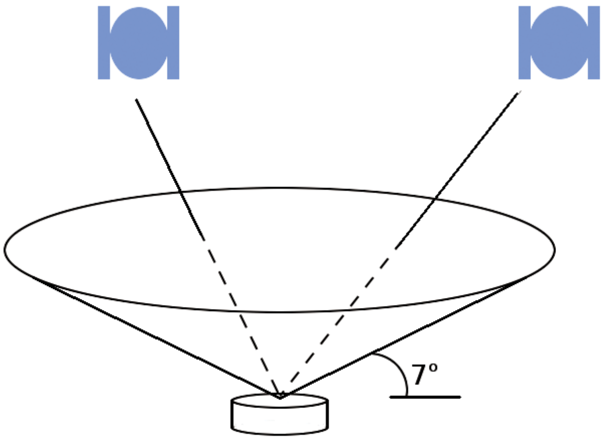


Fig. 2. All signals arriving at a GPS antenna with elevation angle greater than 7 degrees, within an inverted cone centered on the receiving antenna, are considered in determining the zenith tropospheric delay. Typical receivers track 12 or more satellites.

When initially installed in the early-to-mid-1990s, most stations only transferred data to central archives for processing on a daily basis. A collaboration between the Scripps Institution of Oceanography's Orbit and Permanent Array Center and the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) began in the mid-1990s to implement the GPS meteorology data analysis using available stations and establish its accuracy, beginning with a 40-station demonstration network (Duan et al. 1996; Fang et al. 1998; Wolfe and Gutman 2000). Gradually, communications were upgraded to allow timelier processing. By 2005, the NOAA GPS-Met program was routinely providing and disseminating half-hourly PW from approximately 300 stations nationwide for assimilation into National Centers for Environmental

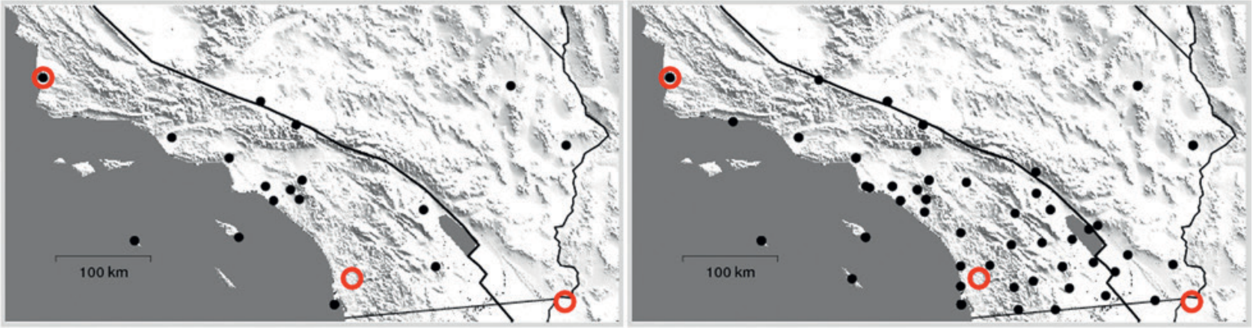


Fig. 3. (left) Southern California stations analyzed by the NOAA GPS-Met project prior to the start of this project. (right) The station set following the inclusion of 37 additional stations. Red circles indicate radiosonde sites at Vandenberg, San Diego, and Yuma. Heavy black line indicates the San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

Prediction (NCEP) models, and delivering continuous time series via the NOAA web page at http://gpsmet.noaa.gov. The results showed positive impact in winter, increasing as the number of sites increased in the central and eastern United States (Gutman et al. 2004); however, it was more difficult to confirm improvement in summertime precipitation, which is dominated by thermodynamic processes and greater spatial moisture variability. This was especially true in the southwestern United States due to a relative absence of independent observations needed for verification (Smith et al. 2007). Preliminary experiments assimilating GPS PW in convective-permitting models are attempting to address several of these issues (Kawabata et al. 2007). Several studies of moisture enhancements in cold-season heavy precipitation events along the west coast of North America followed (Marcus et al. 2007; Ralph et al. 2010; Neiman et al. 2013) and the California Department of Water Resources Hydrometeorology Testbed Legacy project (HMT-Legacy) added several stations to the California GPS-Met station set in this time frame (White et al. 2013). Communications improvements have continued, and approximately 600 stations in the western United States now stream raw GPS data with latency of less than a second (http://sopac.ucsd.edu/readi.shtml). Under a National Aeronautics and Space Administration (NASA) Advanced Information Systems Technology (AIST) project beginning in 2012, 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. West of the San Andreas fault, typical station spacing is now 20–40 km. NWS Weather Forecast Offices (WFOs) in San Diego and Los Angeles/Oxnard are participating as technology infusion partners in the project to examine the utility of this dataset in their routine forecasting activities.

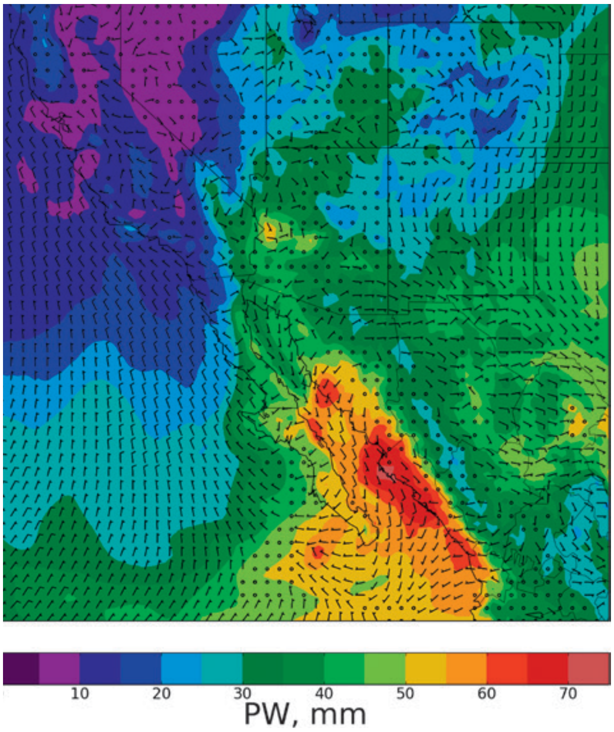


Fig. 4. National Centers for Environmental Prediction (NCEP) Rapid Refresh (RAP) model precipitable water with 10-m winds at 0000 UTC 19 Jul 2013, illustrating the transport of moisture from the Gulf of California into the area of Southern California. The NCEP models assimilate available scatterometer winds in the Gulf region.

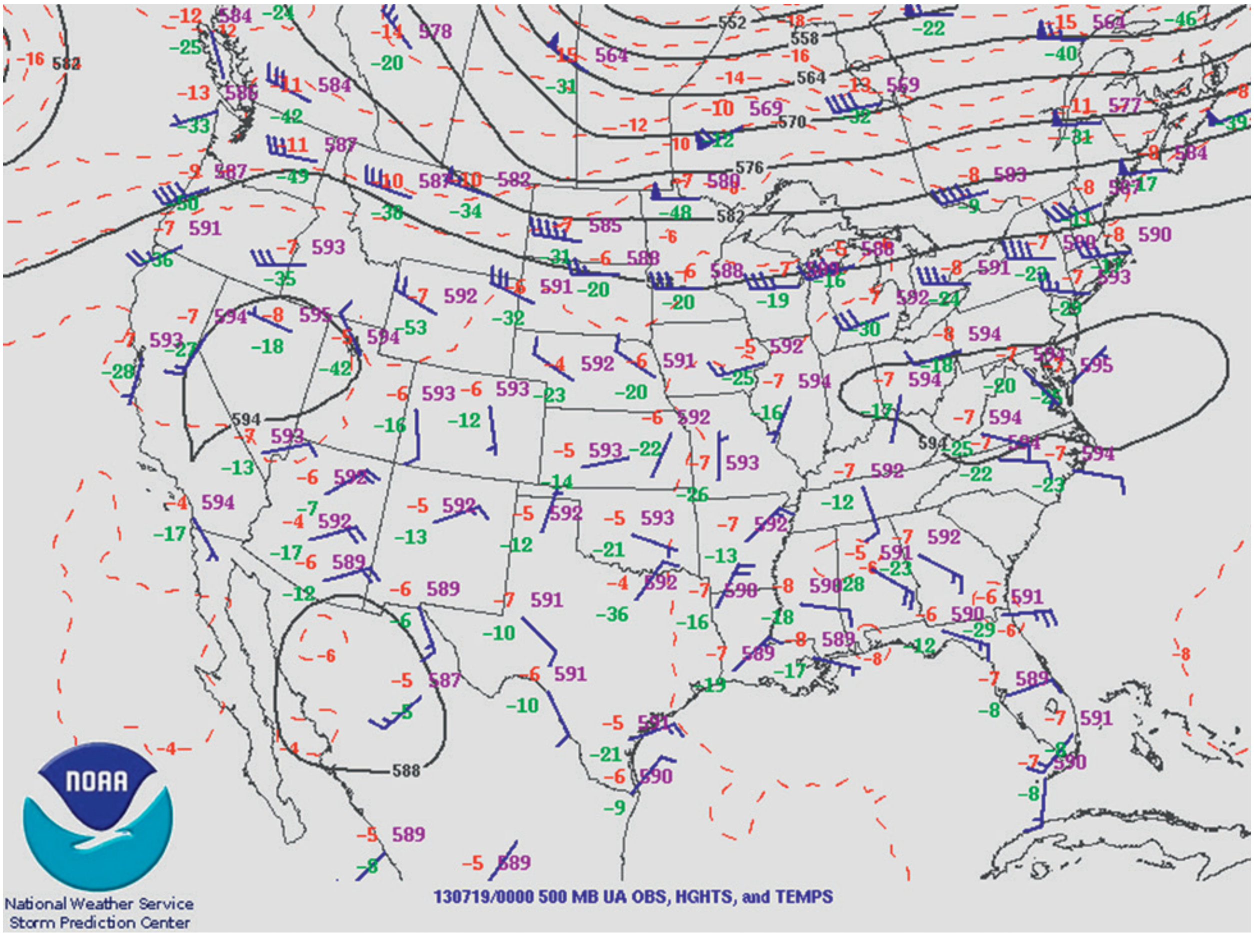


Fig. 5. 500-mb upper-air analysis at 0000 UTC 22 Jul 2013, showing the location of the upper-level low in northern Mexico. [Image credit: NOAA NWS Storm Prediction Center]

GPS PW IMPROVES SITUATIONAL AWARENESS IN A JULY 2013 EVENT. An example highlighting the use of GPS PW is a North American Monsoon event that began to develop on 18 July 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 (Arellano et al. 2013) (Fig. 4). 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). An MCS developed in central Arizona, and by 21 July it had moved northwestward toward the Southern California coast. Figure 6 shows the progression of the wave that moved through Southern California on 21 July as seen by the 500-hPa heights and the 300-hPa equivalent potential vorticity (EPV) from the 12-km North American Mesoscale model (NAM12) between 0600 UTC 21 July 2013 and 0000 UTC 22 July 2013. During the period of maximum heating, a high EPV feature rotated around the upper low and moved through Southern California, likely enhancing the convection generated over the region. The low-level forcing mechanism for the convection was probably the convergence near the ridgelines of the mountains. Optimal atmospheric conditions indicated by 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. The southernmost observations available to detect low-to-midlevel moisture arriving into the forecast areas from the Gulf of California

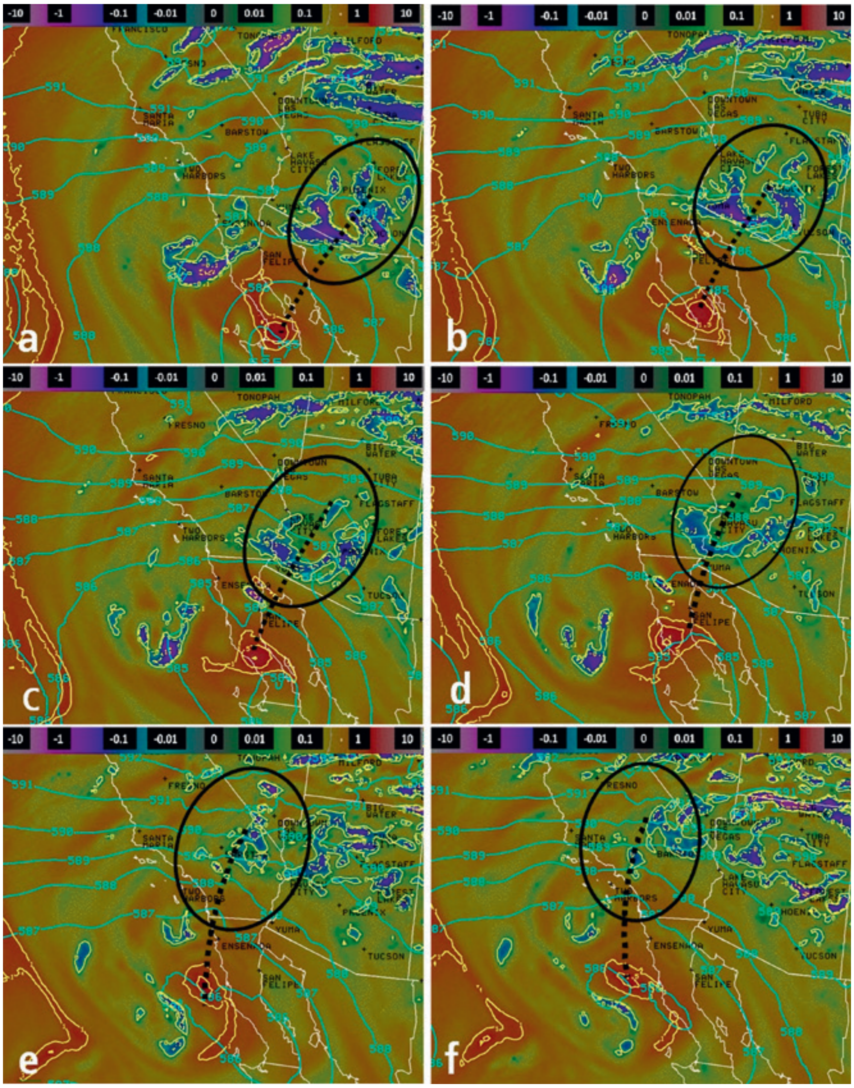
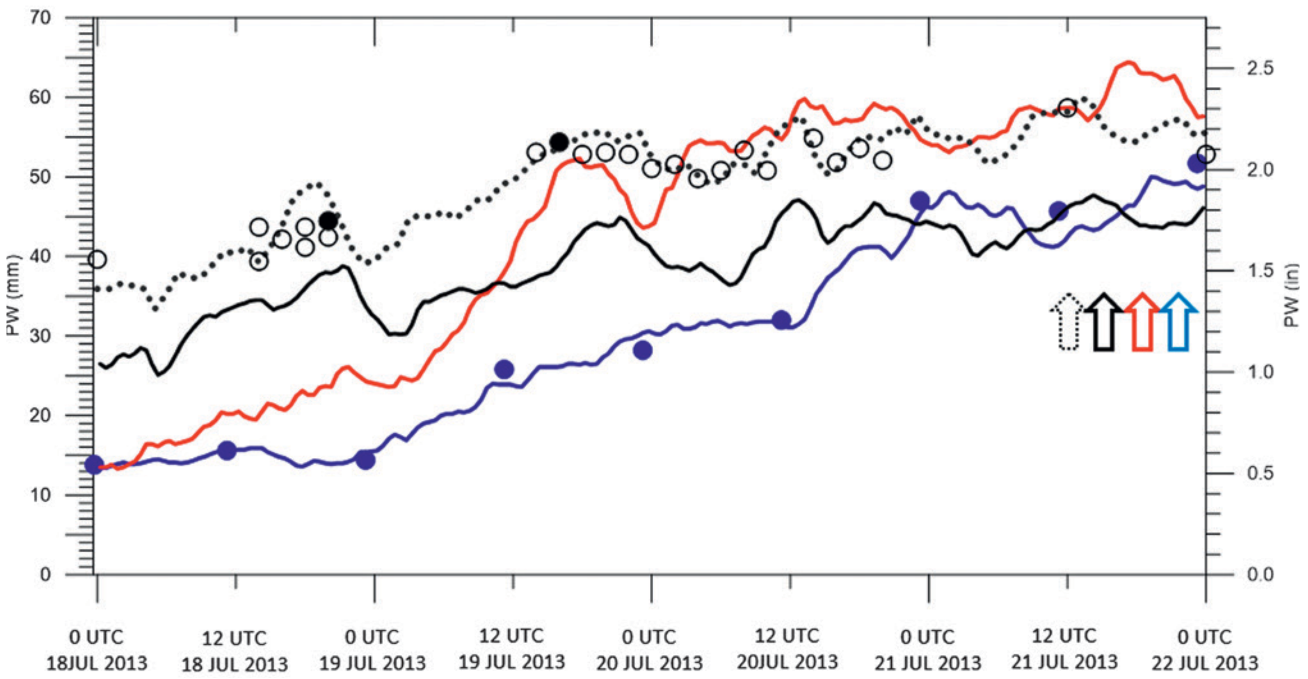


Fig. 6. Progression of the 12-km resolution North American Mesoscale model (NAM12) 300-hPa equivalent potential vorticity (EPV) [shaded and yellow contours, in PVU (1 × 10^{-6} $m^2 K s^{-1} kg^{-1}$)], along with 500-hPa heights (cyan contours), as the wave moved through Southern California on 21 Jul 2013. Darker blue/purple shading indicates EPV<0. The dashed line indicates an inverted trough, and the ovals indicate a feature rotating around the upper low and moving through Southern California. The first flash flood was reported at about 1100 UTC (0400 PDT) 21 Jul 2013. Multiple areas of flash flooding were reported the following afternoon at around 0000 UTC 22 Jul 2013. Images are the 1800 UTC 20 Jul 2013 NAM forecast valid at (a) 0600 UTC 21 Jul 2013, (b) 0900 UTC 21 Jul 2013, (c) 1200 UTC 21 Jul 2013, (d) 1500 UTC 21 Jul 2013, (e) 2100 UTC 21 Jul 2013, and (f) 0000 UTC 22 Jul 2013.

included radiosonde observations at Yuma (Arizona) and San Diego, as well as about 20 California GPS-Met stations in the 100 km north of the Mexican border. On the afternoon of 18 July, a sounding at Yuma indicated 44 mm of PW, sufficient monsoonal moisture to cause heavy rainfall (considered to be PW exceeding 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 19 July 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. 7, the PW increase at Durmid Hill, near the Salton Sea, began to accelerate early on 19 July, exceeding the PW at both San Diego and Glamis a few hours later. By 0700 PDT, 45 mm of PW was observed at GPS stations in the deserts near the mountain slopes. The 0800 PDT aviation routine weather report (METAR) data included dewpoint temperatures at three desert locations exceeding 21°C, indicating increased low-level (boundary layer) moisture. The increase was confirmed when a 0900 PDT Yuma sounding eventually arrived, indicating PW of 53 mm. Note that there is a delay of roughly 2 h before a Yuma sounding is visible in forecasters' Advanced Weather Interactive Process-



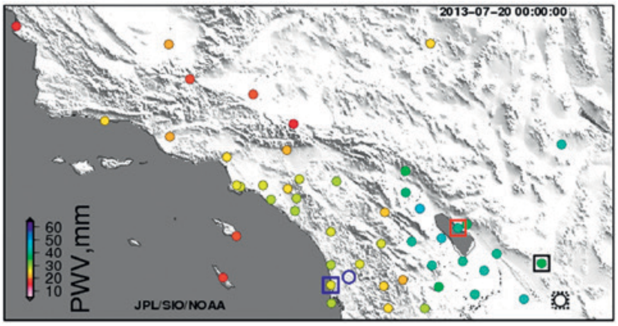


Fig. 7. PW measurements during the evolution of the July event. Circles represent PW (cm) for radiosondes at San Diego, California (blue), and Yuma, Arizona (black). At the U.S. Army Yuma Proving Ground (YPG), radiosondes are launched irregularly in support of the local mission, and many observations only become available to the NWS and WMO retrospectively and with a variable delay. 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, California (blue), Durmid, California (red), and Glamis, California (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 postprocessed 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 illustrated in Fig. 6 at the identified GPS-Met sites. Map locates GPS stations with squares at San Diego (blue), Durmid (red), Glamis (black), and Yuma (dotted black), and radiosondes with circles at San Diego (blue) and Yuma (black). PW in mm at the GPS stations is shown, according to the color scale, at 1700 PDT 19 Jul (0000 UTC 20 Jul).

ing System (AWIPS) terminals. In Fig. 7, we show the two Yuma soundings that were available to the forecasters during this period in solid black; other Yuma soundings are shown as open circles for retrospective context. Animations of the GPS PW during this event, alongside weather model PW, radar reflectivity, and rainfall data, are available as supplemental material.

At 2115 PDT on 19 July 2013, forecasters issued an Area Forecast Discussion (AFD) 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 20 July 2013, about 26 h and 26 min prior to the first report of flash flooding at 0400 PDT on 21 July 2013, 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

FIG. 8. Flooding across Highway 78 in San Diego County, California, 22 Jul 2013. [Photo credit: NOAA]

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. 8), and bowling ball–sized rocks and 1-m deep flood deposits covering about 24 m of a road in Riverside county.

DISCUSSION OF THE VALUE OF GPS PW TO THE WATCH/WARNING PROCESS. GPS PW gives forecasters confidence about whether a watch or warning is needed, and if so, how soon it will likely be needed and in which area. The GPS-PW data improves the watch/warning process 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 related to the upper-level low, 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 (Alpert 1986; Neiman et al. 2002; Neiman et al. 2009). The empirical relationship between upslope moisture flux and mean wind can be exploited on nowcasting time scales to directly evaluate the change in integrated water vapor as indicating potentially elevated risk of flooding in the regions downslope of the mountains within the forecast area.

FUTURE PLANS. In the 2014 NAM season, several events affecting Southern California caused roadway flooding, stranded hikers and bicyclists, and even one fatality. The products provided by NOAA GPS-Met had comparable impact on forecasts and the watch/warning process. 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.

The primary goals of this continuing NASA-sponsored project are to 1) make these tools and techniques available to NWS forecasters, and 2) 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. Since the initial results are very encouraging, the next steps are to install low-cost micro electro-mechanical systems (MEMS) pressure and temperature sensors at a greater number of real-time GPS sites, to take full advantage of the GPS infrastructure and provide very timely (seconds to a few minutes latency) water vapor estimates at even better spatial and temporal resolution and over a larger area. Ultimately, inclusion in AWIPS will allow enhanced interactive use of the high temporal resolution data.

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FOR FURTHER READING

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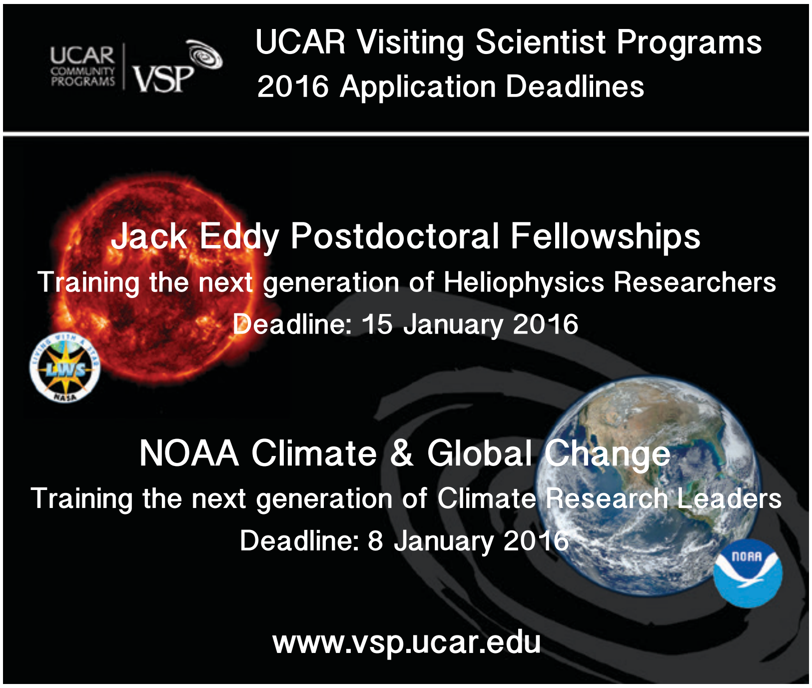

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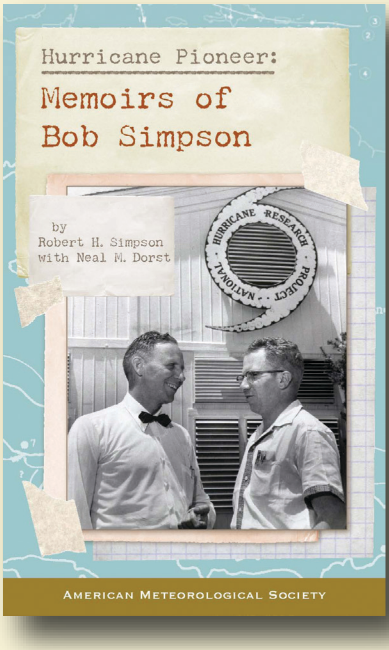

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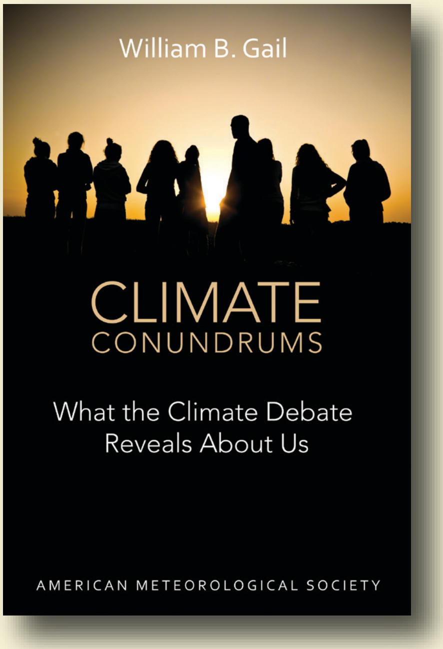

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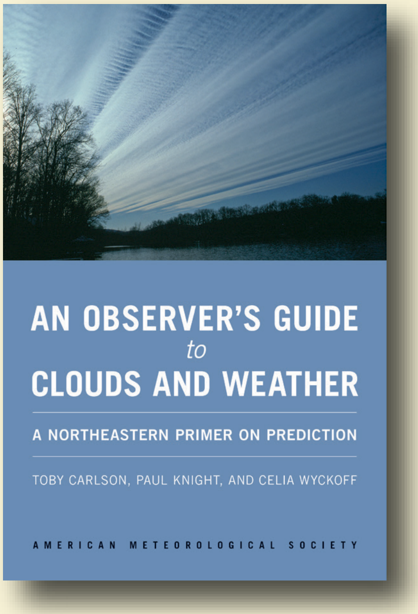

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