THE NORTH AMERICAN MONSOON GPS TRANSECT EXPERIMENT 2013

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Expanding networks of all-weather, high-time-resolution GPS networks with surface meteorology throughout the southwestern United States and Mexico offers opportunities for improved understanding of the North American monsoon convection and forecasting of organized convective events and associated hazards.

The North American monsoon accounts for more than half of the total annual precipitation over northwestern Mexico (Adams and Comrie 1997) and is important to agriculture and water resources across the region (Brito-Castillo et al. 2003; Gochis et al. 2006). Monsoon convection typically forms as individual thunderstorms over the Sierra Madre Occidental (SMO) in the afternoon (Adams and Comrie 1997; Nesbitt et al. 2008). Sea-breeze circulations from the Gulf of California (GoC) contribute moist upslope flow supporting this convection (Johnson et al. 2007). Synoptic-scale forcing, often in the form of upper-level troughs (Adams and Comrie 1997; Pytlak et al. 2005; Bieda et al. 2009; Newman and Johnson 2012; Seastrand et al. 2015), can then organize the convective cells into mesoscale convective systems (MCSs) that propagate toward the lower elevations and the GoC throughout the evening and into the early morning hours (Nesbitt et al. 2008). Surges of moisture up the GoC, or gulf surges, which can result in convective outbreaks in the desert Southwest, can be triggered from MCS outflow over the northern portion of the gulf (Adams and Comrie 1997; Johnson et al. 2007; Rogers and Johnson 2007), or from the passage of a tropical disturbance at the mouth of the GoC (Ladwig and Stensrud 2009; Newman and Johnson 2013; Seastrand et al. 2015). The latter typically results in a more intense surge. While much progress has been made in understanding links between the synoptic-scale and associated convective outbreaks in the North American monsoon region and on the diurnal cycle of convection, processes associated with the initiation and growth of convection on the mesoscale, particularly over the highest elevations of the SMO, and the important regional sources of water vapor relevant to these processes, remain poorly understood. As a result of these deficiencies, both operational and high-resolution models have difficulty replicating the timing and subsequent propagation of deep convection over the SMO (e.g., Li et al. 2008; Castro et al. 2012; Pearson et al. 2014).

To better understand the initiation and upscale growth of convection over Mexico, observational networks with sufficient density, high temporal frequency, and preferably with all-weather capacity are needed. Long-term stability of the measurements is also a consideration in order to monitor the water cycle over seasonal and longer time periods. While there have been recent efforts to restore the radar and radiosonde networks throughout the country (Zavaleta and Vargas 2012), these methods of observation are costly, of low density, and, in the case of radar, are compromised by complex terrain leading to partial signal blockage (e.g., Minjarez-Sosa et al. 2012). In an effort to explore options for building a more complete observing network in Mexico, the National Science Foundation (NSF) in the United States and the National Council of Science and Technology [Consejo Nacional de Ciencia y Tecnología (CONACyT)] in Mexico funded a workshop in Puerto Vallarta, Mexico, in 2010 that brought together experts in the use of GPS technology. The outcome of this workshop was the Trans-Boundary, Land and Atmosphere Long-term Observational and Collaborative Network (TLALOCNet), a continuous GPS-Met (cGPS-Met) network for basic and hazards science research in Mexico funded by the NSF and the National Autonomous University of Mexico (UNAM) in late 2013.

GPS-Met observations provide all-weather, high-time-resolution precipitable water vapor (PWV) with accuracy comparable to that of radiosondes (e.g., Raja et al. 2008; Leblanc et al. 2011) for atmospheric applications (e.g., Bevis et al. 1992; Bengtsson et al. 2003; Gutman et al. 2004; Kursinski et al. 2008a,b; Hanesiak et al. 2010; Adams et al. 2011, 2013, 2014, 2015). Kursinski et al. (2008a) showed that precipitation in high-resolution modeling studies over the SMO was sensitive to PWV initialization. The changes to the PWV initial fields for these modeling sensitivity studies were shown to be realistic through comparisons of PWV from the North American Regional Reanalyses (NARR) with PWV from a network of GPS-Met stations installed as part of the North American Monsoon Experiment 2004 (NAME 2004; Higgins and Gochis 2007), as well as against more limited radiosonde PWV observations in the region. The temporal and spatial variability of the NAME 2004 PWV was also used to indicate the dominant scales of the dynamical forcing over the sensor network throughout the monsoon (Kursinski et al. 2008b). At even higher time scales, the rapid increase in PWV prior to rainfall events in association with water vapor convergence (Kursinski et al. 2008a,b; Adams et al. 2011, 2013, 2015) permits the time rate of change of PWV to be used as an indicator for convective activity, as well as representing an important aspect of the convection itself. Moreover, unlike variables associated with cloud or precipitation processes, PWV is not derived from complex physical parameterizations in numerical models. As such, its temporal evolution and spatial variability can provide target relationships for models to replicate outside of convective and microphysical parameterization schemes.

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Given the promising results of the limited NAME 2004 GPS-Met network and the upcoming installation of TLALOCNet, the North American Monsoon GPS Transect Experiment (Transect) 2013 in northwestern Mexico focused on exploring the short-term applications of GPS-Met for atmospheric science research on the mesoscale in a region with significant diurnally forced topographic deep convection. The more limited NAME 2004 network also crossed from east to west on the western side of the SMO (Kursinski et al. 2008b) but only collected a limited amount of data from the highest-elevation station (E. R. Kursinski 2015, personal communication) and did not include a north–south coastal transect. The Transect 2013 dataset also includes lightning, used to indicate convective intensity, which was not available during the 2004 NAME field campaign.

The main objectives of the Transect 2013 network are to investigate the impact of GPS PWV on high-resolution forecasts of North American monsoon organized convective events and to develop applications of GPS-Met to studies of convective initiation and life cycle over complex terrain. Here, we review the configuration of the network and the available data products, as well as some applications of these data to convective studies and operational forecasting. We conclude with a discussion of the future of GPS-Met in the North American monsoon region to address moisture variability on a wide range of time and space scales beyond what could be addressed by the 2013 network.

NETWORK OF GPS-MET SENSORS IN NORTHWESTERN MEXICO. To capture North American monsoon moisture variability and its relationship to deep convective activity, 10 GPS-Met stations were installed over northwestern Mexico. The installation consisted of a coastal transect from Los Mochis (MOCH) to Puerto Peñasco (PSCO), to capture gulf surges, and two east–west transects, including one from Rayon (RAYN) to Chihuahua (CHIH) through the higher elevations of the SMO and a shorter one from Los Mochis to Badiraguato (BGTO), to capture the strong precipitation gradient (Fig. 1). Each station included a Trimble NetR9 GPS receiver for measuring PWV and a Vaisala WXT520 surface meteorological package for measuring wind speed and direction, air temperature, humidity, pressure, and precipitation. The geographic location, elevation, and data period for each station are provided in Table 1. The GPS receiver at Rayon failed on 16 July 2013, 21 days after installation. Data include 1-min surface meteorological variables, while the GPS PWV is calculated at 5-min intervals. In addition to the GPS-Met observations, the Transect 2013 dataset includes four-times-daily (0000, 0600, 1200, and 1800 UTC) radiosonde observations at Rayon. Vaisala also provided lightning data over all of Mexico from the Global Lightning Dataset (GLD360). These data have an event location accuracy of at least 2–5 km and 1-μs RMS event-timing accuracy.

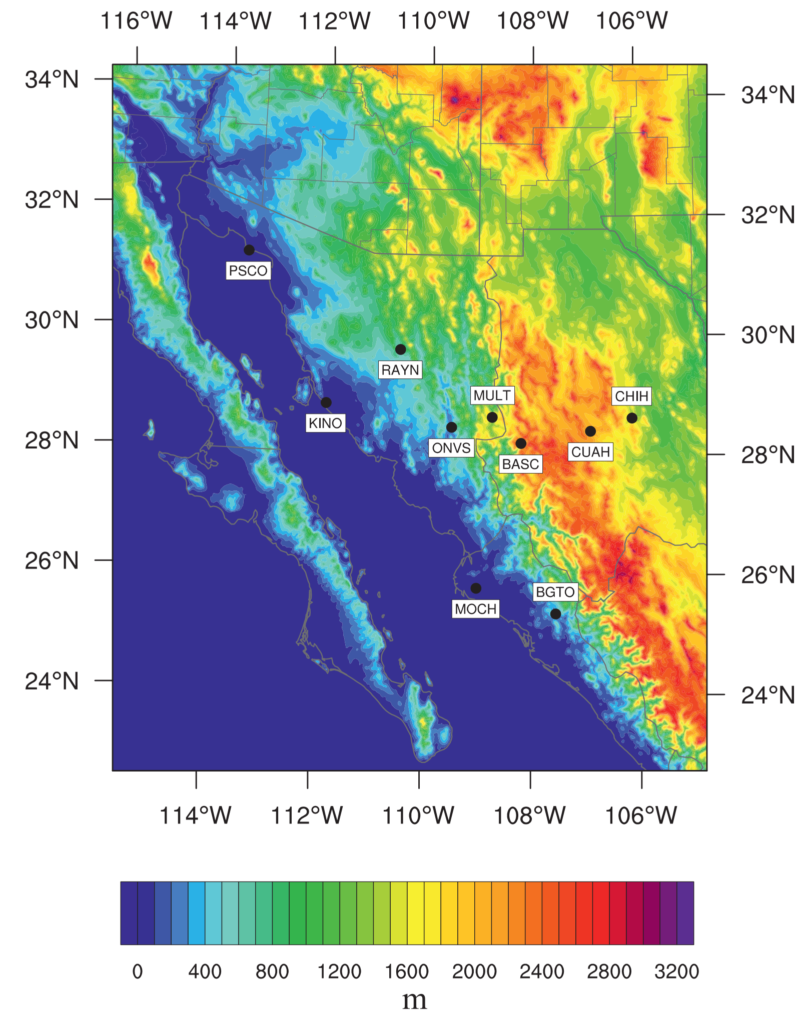

Fig. 1. Map of Transect 2013 GPS-Met sites in northwestern Mexico overlaid on contours of elevation.

The GPS data from this experiment have been processed using Global Navigation Satellite System (GNSS)-Inferred Positioning System and Orbit Analysis Simulation (GIPSY-OASIS) software with a cutoff elevation angle of 10°. This elevation angle results in a cone of observation of approximately 10–15-km radius, permitting it to capture the spatial and temporal scales at which the shallow-to-deep convective transition occurs and upscale convective growth begins. PWV results at Cuauhtemoc (CUAH) were also processed in real time using GAMIT software as part of the Earth System Research Laboratory (ESRL) GPS data archive. Comparison of the two processing methodologies yielded very similar results for PWV at CUAH (not shown), suggesting that differences in the choice of processing software and use of final orbit calculations as opposed to real-time orbits has little effect on the resulting PWV calculation in this region. This result is consistent with comparisons of GAMIT and GIPSY-OASIS PWV calculations in the Amazon (Adams et al. 2011).

PWV VARIABILITY AND MONSOON CONVECTION. A unique aspect of PWV, related to its all-weather capabilities and high-time-resolution sampling, is that the temporal evolution provides a proxy dynamical variable for the intensity of the diurnal cycle of convective activity. Given the topographic

Table 1. List of Transect stations, locations, elevations, and data records.

Station	Lat (°N)	Lon (°W)	Elevation (m MSL)	Data record
KINO	28.8149	111.9287	7	15 Jun–19 Sep
MOCH	25.7815	109.0264	15	18 Jun–18 Sep
PSCO	31.3004	113.5483	53	23 Jun–7 Sep
ONVS	28.4602	109.5288	189	15 Jun–20 Sep
BGTO	25.3625	107.5511	207	18 Jun–7 Sep
RAYN	29.7410	110.5366	641	26 Jun–16 Jul
CHIH	28.6224	106.1006	1463	25 Jun–30 Sep
MULT	28.6356	108.7595	1550	21 Jun–3 Sep
BASC	28.2035	108.2098	1999	22 Jun–30 Sep
CUAH	28.4079	106.8922	2058	24 Jun–30 Sep

range of the Transect 2013 data, the entire life cycle of deep propagating convection can be evaluated in terms of the PWV temporal and spatial evolution captured by the Transect, including the initiation phase at the highest elevations of the SMO. The temporal evolution of gulf surges, including the surge amplitude and propagation speed, is also captured by the Transect 2013 dataset by placing sites along the coast in the path of a typical gulf surge. These features within the Transect 2013 dataset are highlighted below.

The North American monsoon convective diurnal cycle revisited. The observed precipitation frequency and intensity as a function of topography over the North American monsoon region has been well identified through surface precipitation networks (Gochis et al. 2004; Nesbitt et al. 2008), radar studies (Lang et al. 2007; Rowe et al. 2008, 2011, 2012), satellite climatology (Wall et al. 2012), and using a combination of these sources (Gebremichael et al. 2007; Becker and Berbery 2008). However, the lack of in situ PWV measurements at the highest elevations of the SMO, as well as a lack of sufficiently dense PWV along the lower elevations, meant that the spatial and temporal variability in moisture associated with the observed complex pattern in rainfall (Gochis et al. 2004) could not be identified. This lack of high-elevation data strongly motivated the Transect 2013. In addition to providing critical observations for modeling efforts, these Transect 2013 data also lend new insights into water vapor convergence at the crest of the SMO and afternoon convection, which subsequently propagates westward and downslope into the late afternoon and early evening (e.g., Johnson et al. 2007; Nesbitt et al. 2008).

To characterize the convective diurnal cycle observed during the Transect 2013, we focus on afternoon and evening convection between 1200 and 2100 LT, which, for the western slope of the SMO [Basaseachic (BASC), Mulatos (MULT), and Ónavas (ONVS)], represents essentially all observed convective events. On the eastern slope (CUAH and CHIH), deep convective events are less frequent and are not clustered in time in this dataset. Note that while CUAH is at the highest elevation in this dataset, it is located to the east of the crest of the SMO, while BASC, the second highest site, is located just to the west of the crest, where higher precipitation is generally observed (Gochis et al. 2004). To identify the convective days, two criteria were employed: 1) an observed drop in cloud-top temperature (CTT) [*Geostationary Operational Environmental Satellite-13* (*GOES-13*) 10.7-μm channel] of at least 50 K and 2) the occurrence of at least 10 lightning strokes as measured by Vaisala's GDL360 dataset, both between 1200 and 2100 LT. Lightning strikes within an approximately 10-km radius of the site were used as a proxy for deep convection to match the GPS cone of observation. During the shallow-to-deep-convection transition, when cloud cover limits direct solar radiation at the surface, latent heat flux is relatively small (Zehnder et al. 2006). With this in mind, Adams et al. (2013, 2015) have argued that $\Delta(\mathrm{PWV})/\Delta t$ is a useful proxy for water vapor convergence and, hence, intensity of deep convection.

The convective diurnal cycle composites for PWV, CTT, and lightning frequency (LNG) for the east–west transect from CHIH to ONVS are shown in Fig. 2. East of the SMO crest (CUAH, CHIH), the less frequent and less intense convective events have a weak diurnal cycle, with CUAH, near the crest of the SMO, indicating a late afternoon peak. In contrast, west of the crest (BASC, MULT, ONVS), events are more intense, resulting in a larger diurnal amplitude and clearer diurnal phasing for precipitation than on the eastern slopes. Despite having a similar diurnal range in PWV, BASC has larger diurnal amplitude in rainfall than CUAH, suggesting more favorable conditions for convective organization along the western slope. The

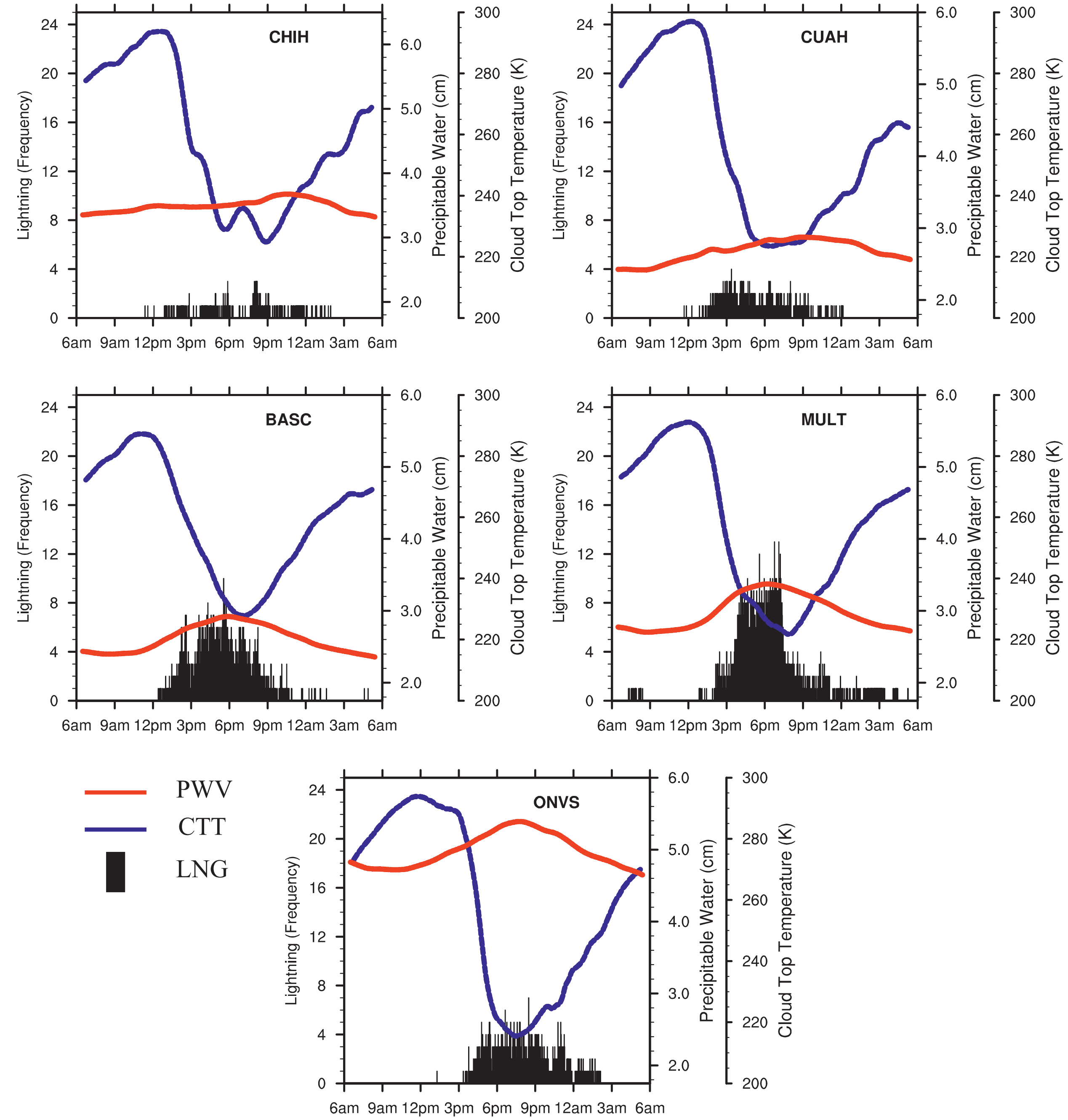

Fig. 2. Composite diurnal cycles in PWV (red), CTT (blue), and LNG (black) for east–west transect sites in order from east of SMO (CHIH) to the western slope (ONVS).

sharper peak in lightning occurrence and PWV along the western slope also reflects a stronger connection between diurnally driven topographic affects and convective activity west of the mountain crest. These results corroborate what was inferred from precipitation, cloud-top temperature, and radar retrievals (Gochis et al. 2004; Nesbitt et al. 2008; Rowe et al. 2008), that the convective PWV diurnal cycle intensifies along the western slope of the SMO and toward the foothills.

Table 2 contains information on the convective events used in the diurnal cycle composite, including the number of events observed, the magnitude of the change in PWV (ΔPWV), CTT (ΔCTT), minimum CTT, and $\Delta\mathrm{PWV}/\Delta t$, as a measure of convective intensity. To calculate ΔPWV, ΔCTT, and $\Delta\mathrm{PWV}/\Delta t$, the morning minimum (maximum) of PWV (CTT) is subtracted from the evening maximum (minimum) of PWV (CTT), where the time interval Δt

Table 2. Characteristics of the convective diurnal-cycle composite along the east–west transect (see text for details).

Station	No. of events	Δ(PWV) (mm)	Δ(CTT) (K)	Min CTT (K)	Δ(PWV)/Δt (mm h^{-1})
CHIH	9	3.2	72.0	222.0	0.20
CUAH	11	4.6	75.1	225.5	0.38
BASC	37	5.3	60.4	227.2	0.58
MULT	35	6.8	69.2	221.9	0.74
ONVS	19	6.8	79.5	214.6	0.74

depends upon the time of the diurnal extremes for each day. The intensification in convective activity from east to west across the SMO is apparent, with greater drops in CTT, minimum CTT, and stronger water vapor convergence $\Delta PWV/\Delta t$. In this respect, the time evolution of PWV provides a useful metric, not only for gauging convective intensity, but also for evaluating the diurnal cycle across the SMO in numerical models.

Gulf surges. The gulf surge is a key element of the North American monsoon (Hales 1972; Brenner 1974; Adams and Comrie 1997), contributing to a large portion of the summer precipitation in Arizona and southeastern California, primarily as a source of moisture at low levels (Berbery and Fox-Rabinovitz 2003; Higgins et al. 2004; Becker and Berbery 2008). On the other hand, PWV from gulf surges does not contribute significantly to monsoon precipitation in northwest Mexico (Douglas and Leal 2003; Higgins et al. 2004). Hypotheses for the physical mechanism of a gulf surge include a coastally trapped wave (Zehnder 2004) or an evolving internal bore under rotation (Newman and Johnson 2013). Determining the dynamical mechanisms of surges is difficult due to the lack of low-level wind and moisture data across the region at sufficient time and space scales either during NAME or from the existing observational surface network (Zehnder 2004; Rogers and Johnson 2007; Newman and Johnson 2013).

During the Transect 2013 experiment, nine gulf surges of varying intensity and duration were visually observed at the coastal GPS sites of MOCH, Bahia Kino (KINO), and PSCO. These surges were validated against an objective measure of a gulf surge using surface data at Yuma, Arizona (see next section for details). GPS observations from the SuomiNet also demonstrated that these surges penetrated into the southwestern United States. Figure 3 shows three of the more notable surges during the experiment. In each of the three cases shown, the perturbation in PWV is weakest at the southern station MOCH, where the daily mean PWV is highest. Likewise, the surface wind perturbation is least notable at MOCH. Using peak PWV to estimate the "propagation" speed of the PWV perturbation, all three cases propagate between 5 and 8 m s^{-1}. Clearly, it would be difficult to make direct mechanistic deductions as to the waveform responsible for the gulf surge with these data. However, these results can be employed to validate proposed mechanisms for the gulf surge in a modeling framework.

With the installation of TLALOCNet, PWV observations along the coast now offer forecasters a real-time alternative for tracking gulf surges to surface observations, which might be affected by local circulations associated with land–sea breezes or irrigation. As not all monsoon convection in Arizona results from a gulf surge, additional sources of tropospheric moisture must also play a role in the outbreak of convection in the southwestern United States. The newly installed TLALOCNet in northern Mexico with the SuomiNet GPS sites in the southwestern United States now provide a means of investigating this issue.

FORECAST EVALUATION OVER NORTHWESTERN MEXICO USING HIGH-RESOLUTION MODELING. A primary objective of the North American Monsoon GPS Transect Experiment 2013 was to assess the sensitivity of a high-resolution forecasting system to initial conditions of PWV over northwestern Mexico and the southwestern United States. This work was in part motivated by the need to design an effective operational network for Mexico considering the financial, technological, and human resource limitations of the country at this time, as discussed at the Puerto Vallarta meeting in 2010. GPS-Met offers a low-cost measurement of PWV with little maintenance or human resources. Thus, we seek to test the value added by these measurements to forecasts over the region, as well as identify sites for which the model forecasts have particular sensitivity.

The Advanced Research version of the Weather Research and Forecasting (ARW) Model (Skamarock et al. 2008) is used to provide daily convective simulations of the 2013 North American monsoon

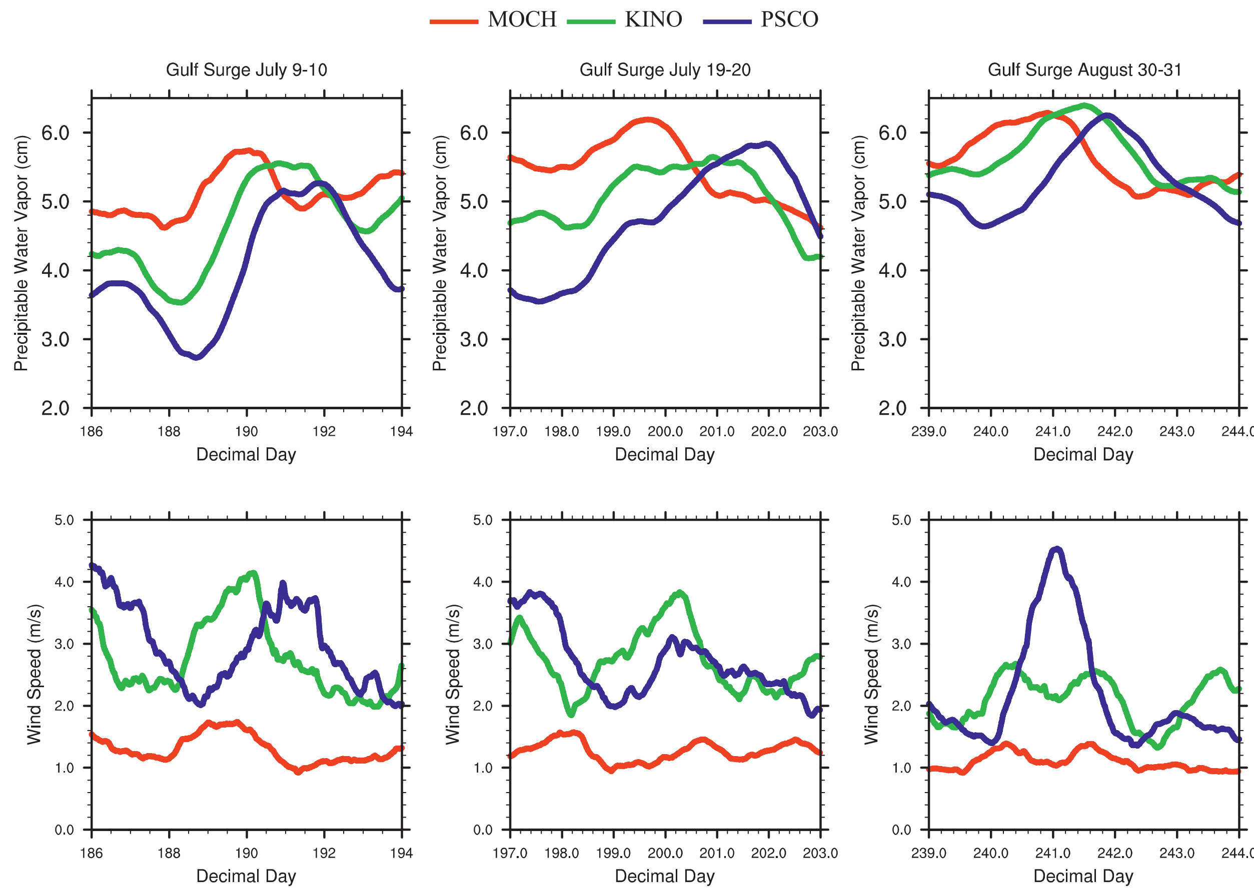

Fig. 3. Gulf surges as seen along the south–north coastal transect from MOCH to PSCO for the events during (left) 9–10 Jul, (middle) 19–20 Jul, and (right) 30–31 Aug 2013.

season. The model basic setup consisted of the WRF single-moment 6-class microphysics scheme (Hong and Lim 2006), the Kain–Fritsch convective scheme (Kain 2004), the Yonsei University planetary boundary layer scheme (Hong et al. 2006), the Rapid Radiative Transfer Model for GCM (RRTMG) longwave (Iacono et al. 2008) and Goddard shortwave (Chou and Suarez 1999; Chou et al. 2001) radiation schemes, and the unified National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction (NCEP)–Oregon State University–Air Force Research Laboratory–NOAA/Office of Hydrology land surface model (Noah) land surface model (Tewari et al. 2004). The model configuration uses 29 vertical levels and three one-way nested domains, with the innermost 2.5-km domain capable of explicitly resolving convective cloud systems. Hindcasts were run for 24 hours from 26 June to 12 September 2013, starting at 1200 UTC (0500 LT). Initial conditions and 6-hourly updated boundary conditions were derived from the North American Mesoscale Forecast System (NAM) 32-km and the Global Forecast System (GFS) 0.5° × 0.5° products. The Rapid Refresh (RAP) 32-km hourly forecast product, version 1, was used for the soil moisture and temperature initial conditions.

Control simulations were performed in which no PWV data were assimilated in order to evaluate the model baseline performance. The Transect 2013 observations were not reported to the Global Transmission System (GTS), and so are independent observations for comparing with the model PWV. Biases in PWV were calculated by comparing the observation with an interpolated value in the WRF Model using an inverse-distance-squared weighting scheme. The model grid elevation over each station is within 100 m of the station elevation. Differences of this magnitude translate to an estimated 1–2-mm error in PWV depending on the station elevation. Model gulf surge statistics were also compared with those at Yuma, where a gulf surge was defined on a per-day basis beginning at 1200 UTC with 3-hourly surface observations (to match the models' output) in a sliding 12-h window with 10-m winds originating from between 140° and 200° inclusive and a 2-m dewpoint of 18°C or greater. Precipitation validation was performed by scaling up the convective-permitting grid (at 2.5-km horizontal resolution) in the models to match that of Tropical Rainfall Measuring Mission (TRMM; at 0.25° horizontal resolution) using an inverse-distance-squared weighting scheme and performing statistical analysis on a pixel-by-pixel basis.

An evaluation of the initial conditions (1200 UTC) in PWV at the Transect sites and at SuomiNet sites for 20 organized mesoscale convective events aided by synoptic-scale forcing of transient inverted troughs during the 2013 monsoon suggests that the model control simulations tend to be too moist (Figs. 4a,b). The models' moist bias, along with errors in 10-m wind direction at the top of the Gulf of California (not shown), contributed to an overestimation of gulf surges in the WRF-NAM and WRF-GFS, with both models having over a 60% false-alarm rate for the gulf surge index at Yuma over the season compared to the GPS-Met observations. The errors in the initial PWV conditions and low-level moisture transport are consistent with the excess precipitation observed in the 9-h forecast of 3-h accumulated rainfall (Figs. 4c,d). The spatial correlation of the model initial conditions at the GPS sites with TRMM are higher in the WRF-GFS (0.40) than the WRF-NAM (0.32), but both increase to a maximum of ~0.65 by the 12- and 15-h forecasts of 3-h rainfall before dropping for later forecast periods. The overall bias in the 9-h forecast is 0.47 and 0.25 mm for WRF-NAM and WRF-GFS, respectively. The bias follows a similar pattern as the spatial correlations, increasing from the 9- to the 12-h forecast before decreasing for the 15-h forecast. Beyond the 15-h forecast, the biases become negative for both models. The smaller rainfall accumulation biases seen for WRF-GFS are consistent with the smaller biases in PWV initial conditions for this model, though a more complete analysis of the model hindcasts for these cases is necessary to fully understand the rainfall biases shown here.

The Transect PWV has also been assimilated in WRF-GFS for the 8 July hindcast using an ensemble adjustment Kalman filter scheme of the Data Assimilation Research Testbed (DART) software (Anderson et al. 2009). The model PWV for each site was calculated as a column integral of bilinearly interpolated model water vapor mixing ratios weighted by the thickness of each model layer starting from the model surface to the top of the atmosphere. Differences between model and site elevation, as well as the spatial gradients in terrain between neighboring model grids, are found to be smaller than 100 m, which produces errors within the expected accuracy of GPS PWV measurements. We carried out hourly assimilation of the 5-min Transect 2013 data across all sites for six consecutive hours prior to the 1200 UTC initialization using a 40-member ensemble. The ensemble covariance statistics were used to adjust the 3D modeled meteorological states in WRF-GFS, which were then tapered within about a 300-km horizontal radius away from the site location and within about 1 km above the model surface.

The resulting ensemble analyses show an overall reduced bias (2.4 vs 1.3 mm) and rmse (4.1 vs 2.3 mm) relative to GPS PWV that is close to the assumed GPS measurement error of about 1–2 mm (Figs. 5a,b). The impact of improved PWV initial conditions on the 24-h ensemble forecast of accumulated precipitation for WRF-GFS is shown in Figs. 5c–e. The ensemble mean with assimilation compares significantly better than that without assimilation relative to TRMM-observed rainfall in northwestern Mexico, where MCSs typically organize and propagate off the western slopes of the SMO. On the other hand, the high WRF-GFS bias at the high elevations in the central SMO is only slightly reduced with the assimilation. This is expected given the limited PWV constraints in this area of the domain. Our ongoing work will continue to refine and evaluate the assimilation of GPS PWV in the region on hindcasts of organized convection and will also examine the sensitivity of the model hindcasts to assimilation of PWV at particular sites to better inform decisions on future GPS PWV network configurations in Mexico. In particular, PSCO, BGTO, and CUAH have been made a part of TLALOCNet given their importance for either gulf surges or high-elevation moisture conditions.

SUMMARY AND FUTURE OPPORTUNITIES FOR NORTH AMERICAN MONSOON GPS-MET NETWORKS. The North American Monsoon GPS Transect Experiment 2013 has been a successful experiment in many ways. It has provided a unique and valuable time series of water vapor observations along the GoC and along east–west transects from the coast up into the highest elevations of the SMO, where convection initiates during the monsoon and strong gradients in precipitation occur. The high quality, ease of installation, and relatively low cost of these observations served as a proof of concept for the newly funded GPS-Met network covering all of Mexico, TLALOCNet. Currently, TLALOCNet is configured with seven GPS-Met sites in northwestern Mexico, including the northern Baja Peninsula. The Transect 2013 observations, together with ongoing studies of high-resolution model sensitivity to the location of PWV observations for data assimilation,

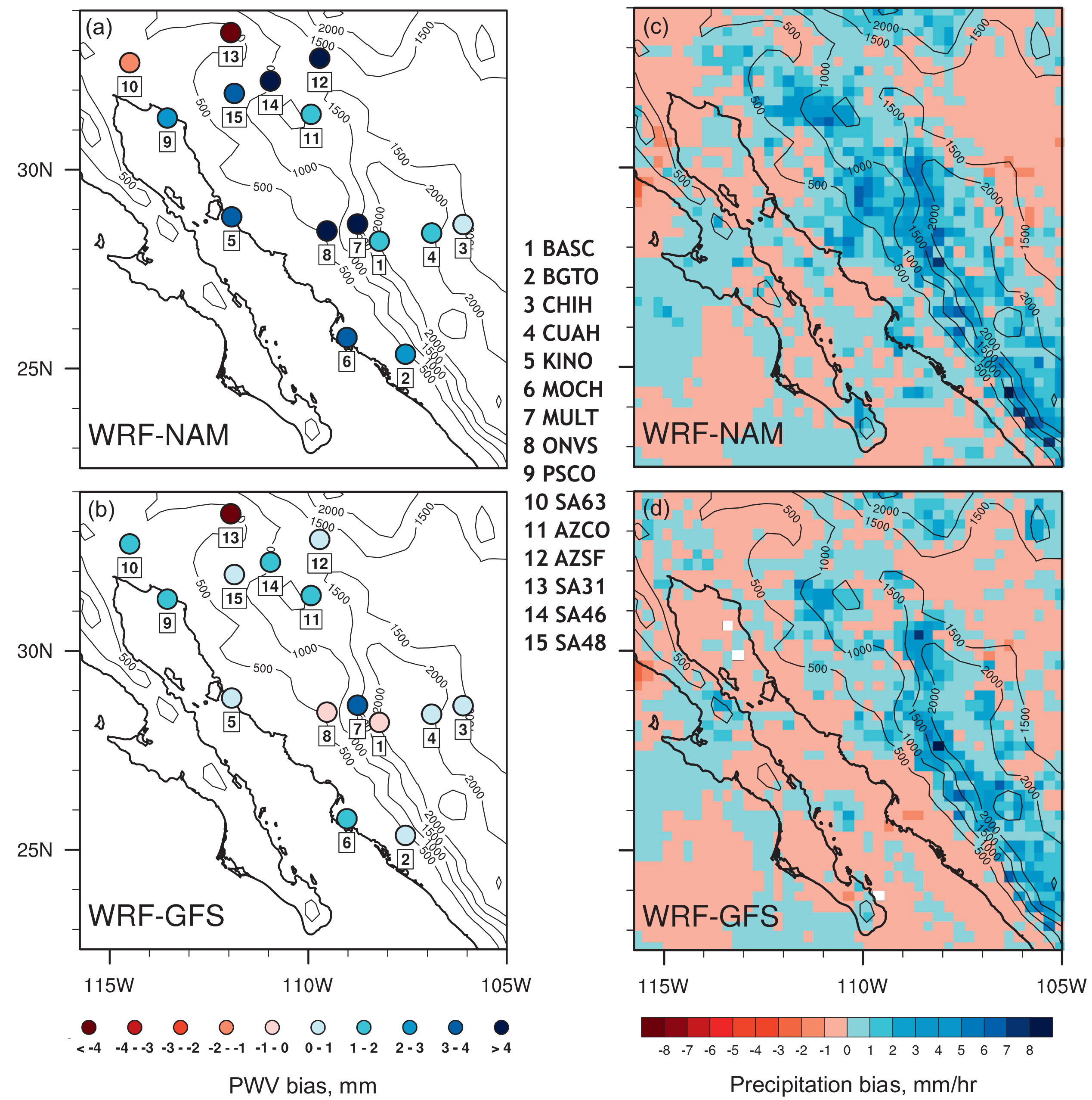

Fig. 4. Mean model bias in the PWV initialization at the Transect 2013 (stations 1–9) and SuomiNet (stations 10–15) GPS sites indicated for (a) WRF-NAM and (b) WRF-GFS days when there was organized convection. Biases in the 3-hourly accumulated precipitation for the 9-h forecasts (2100 UTC) for (c) WRF-NAM and (d) WRF-GFS organized convective days with respect to TRMM (model minus observations). WRF values have been scaled up to the 0.25° TRMM grid prior to the bias calculation.

provide valuable information for the configuration of TLALOCNet and any future expansion of GPS-Met in Mexico.

While the Transect 2013 included PWV time series at the highest elevations of the SMO, the closest spatial distance between stations was roughly 70 km, too far to examine meaningful spatial variability in PWV on convective or even daily time scales. The representativeness of a point measurement, particularly in an area of complex topography, is of great interest for improving data assimilation of point measurements. The Continuously Operating Caribbean GPS Observational Network (COCONet), capturing both high-frequency (30 min) variability and long-term variability of water vapor across the Caribbean, northern South America, Central America, and

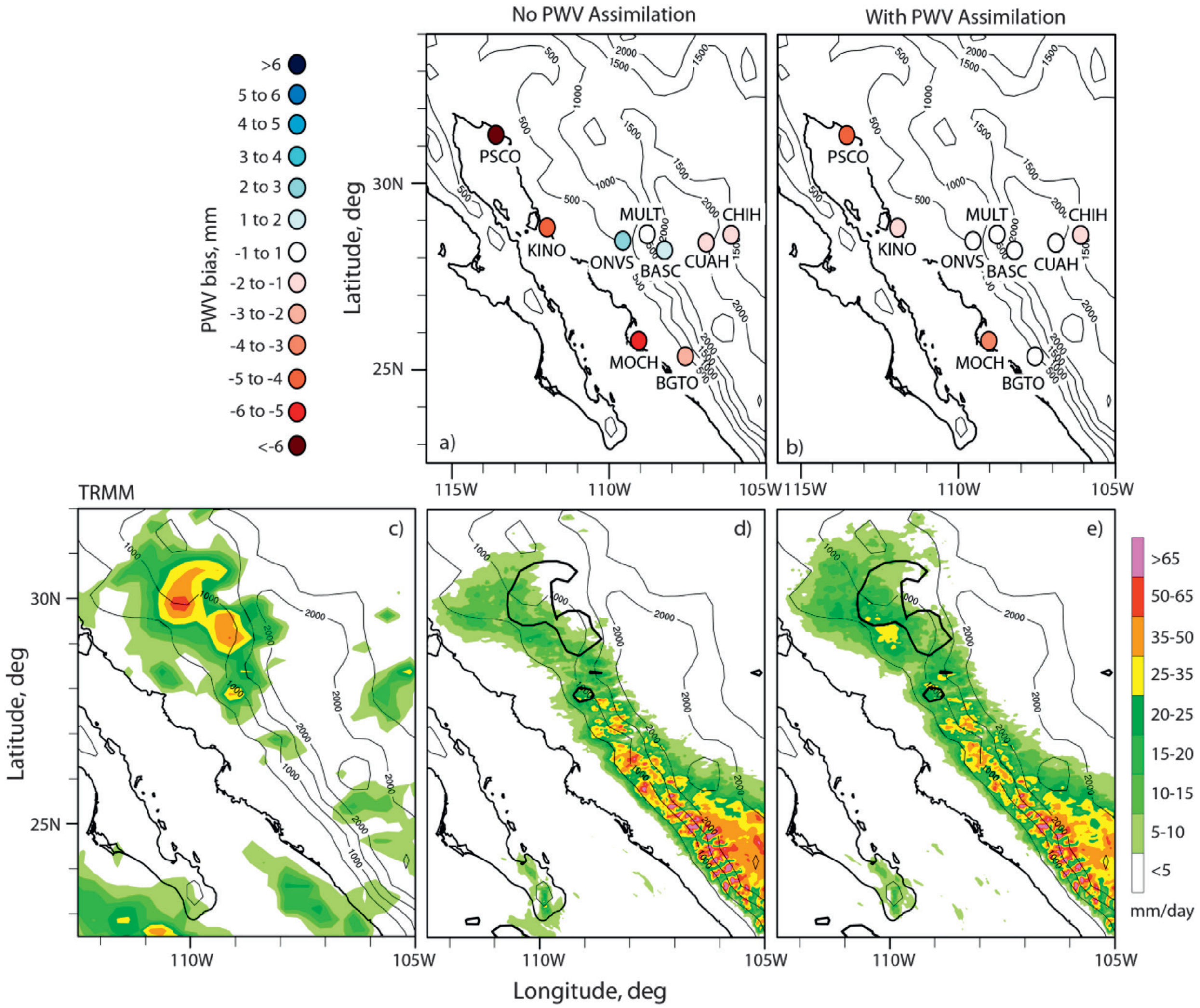

Fig. 5. GPS PWV data assimilation diagnostics. Bias in PWV initialization (1200 UTC 8 Jul 2013) for the WRF-GFS ensemble mean at the Transect 2013 sites is shown (a) without GPS PWV assimilation and (b) with GPS PWV hourly assimilation for six consecutive hours prior to initialization. The impact of PWV assimilation on the ensemble forecast of 24-h rainfall (1200 UTC 8 Jul–1200 UTC 9 Jul) is shown for (c) 24-h TRMM precipitation accumulation, (d) 24-h ensemble mean of rainfall without assimilation, and (e) 24-h ensemble mean of rainfall with assimilation. The thick black contour in (d) and (e) corresponds to the extent of the 25 mm day^{-1} TRMM isohyet.

southern Mexico (Braun et al. 2012), also offers limited opportunities for mesoscale studies of tropical deep convection due to the broad spatial distribution of the stations. The Amazon Dense GNSS Meteorological Network experiment in Brazil (Adams et al. 2015), where GNSS refers to all navigational satellites including GPS, was designed to examine water vapor and deep convection relationships in the tropics at the mesoscale, but because of its location in the Amazon, it does not offer an opportunity to examine the added role of mountainous topography in the initiation and organization of tropical deep convection. Despite the use of an isentropic, tapered nudging within about a 300-km horizontal radius away from the site location and within about 1 km above the model surface for our data assimilation approach, we found measurable improvements to the forecast rainfall. Installation of a dense GPS-Met network in northwestern Mexico like that in the Amazon would further improve model PWV initial conditions through more accurate and likely nonisentropic corrections to model fields away from the observation point.

In combination with SuomiNet GPS-Met stations in the United States and COCONet stations in the Caribbean, these data also have the unique potential to examine the tropospheric moisture sources important to convective outbreaks in northern Mexico and the southwestern United States. Gulf surges are the most studied of these sources; however, their nature remains poorly understood. Mesoscale convective outflow boundaries, regions of strong gradients in temperature and moisture at low levels, have also been suggested as an important mechanism for convective outbreaks north of the border. Deep layers of subtropical moisture can additionally contribute to these outbreaks. The continuing development of GPS-Met across the North American monsoon region, including a new permanent installation of GPS-Met in the Tucson, Arizona, region in 2015 and a temporary network of sensors near Rayon, Mexico, for the 2015 monsoon, is well poised, alone or in combination with other measurements, to address these issues.

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ABSTRACT

Northwestern Mexico experiences large variations in water vapor on seasonal time scales in association with the North American monsoon, as well as during the monsoon associated with upper-tropospheric troughs, mesoscale convective systems, tropical easterly waves, and tropical cyclones. Together these events provide more than half of the annual rainfall to the region. A sufficient density of meteorological observations is required to properly observe, understand, and forecast the important processes contributing to the development of organized convection over northwestern Mexico. The stability of observations over long time periods is also of interest to monitor seasonal and longer-time-scale variability in the water cycle. For more than a decade, the U.S. Global Positioning System (GPS) has been used to obtain tropospheric precipitable water vapor (PWV) for applications in the atmospheric sciences. There is particular interest in establishing these systems where conventional operational meteorological networks are not possible due to the lack of financial or human resources to support the network. Here, we provide an overview of the North American Monsoon GPS Transect Experiment 2013 in northwestern Mexico for the study of mesoscale processes and the impact of PWV observations on high-resolution model forecasts of organized convective events during the 2013 monsoon. Some highlights are presented, as well as a look forward at GPS networks with surface meteorology (GPS-Met) planned for the region that will be capable of capturing a wider range of water vapor variability in both space and time across Mexico and into the southwestern United States.