An Examination of Meteorological and Soil Moisture Conditions in the Babocomari River Basin before the Flood Event of 2008

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ABSTRACT

The NOAA Hydrometeorology Testbed (HMT) program has deployed a soil moisture observing network in the Babocomari River basin located in southeastern Arizona. The Babocomari River is a major tributary of the San Pedro River. At 0000 UTC 23 July 2008, the second-highest flow during the period of record was measured just upstream of the location where the Babocomari River joins the main channel of the San Pedro River.

Upper-air and surface meteorological observations and Special Sensor Microwave Imager (SSM/I) satellite images of integrated water vapor were used to establish the synoptic and mesoscale conditions that existed before the flood occurred. The analysis indicates that a weak Gulf of California surge initiated by Hurricane Fausto transported a warm moist tropical air mass into the lower troposphere over southern Arizona, setting the stage for the intense, deep convection that initiated the flooding on the Babocomari River. Observations of soil moisture and precipitation at five locations in the basin and streamflow measured at two river gauging stations enabled the documentation of the hydrometeorological conditions that existed before the flooding occurred. The observations suggest that soil moisture conditions as a function of depth, the location of semi-impermeable layers of sedimentary rock known as caliche, and the spatial distribution of convective precipitation in the basin confined the flooding to the lower part of the basin. Finally, the HMT soil moisture observations are compared with soil moisture products from the NOAA/NWS/NCEP Noah land surface model.

1. Introduction

This paper presents an extensive look at the 23 July 2008 record flood in the Babocomari River basin located in southeastern Arizona (Fig. 1) from both a meteorological and hydrological perspective. The Babocomari River is a major tributary of the San Pedro River and drains an area of 792 km². The National Oceanic and Atmospheric Administration (NOAA) Hydrometeorology Testbed (HMT) program (Ralph et al. 2005) instrumented this river basin in May 2008 in collaboration with the National Weather Service (NWS) Colorado River Basin River Forecast Center (CBRFC) and the NWS Office of Hydrological Development (OHD).

The HMT program began deploying soil moisture observing stations in support of both hydrometeorological and air quality research studies in the year 2000 (Ralph et al. 2005; Zamora et al. 2003). These observing platforms have been designed to provide research-quality observations of soil moisture and temperature on time scales ranging from minutes to decades. Zamora et al.
(2011) outlined the observational strategies and instrumentation used by the HMT soil moisture observing networks and presented some preliminary research results obtained by the networks.

The Babocomari River basin does not contain flood control dams, and the climate conditions that exist in southeastern Arizona minimize the impact of snowpack or frozen soil in the basin. This makes the river basin attractive for validating meteorological and hydrological models that forecast streamflow, soil moisture, and soil temperature. There are two river gauge stations located in the upper and lower parts of the river channel (Fig. 1). Table 1 shows the historical flows measured during the period of record (2000–10); and that the Babocomari is an ephemeral river.

Studies that compare in situ soil moisture observations with either hydrological or meteorological models have been carried out by Clark and Hay (2004), Meng and Quiring (2008), and Godfrey and Stensrud (2008, 2010). Meng and Quiring compared U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Soil Climate Analysis Network (SCAN; Schaefer et al. 2007) average daily observations of soil moisture with forecast output from three hydrological models over an 8-yr period (1997–2005). The models they evaluated included the Variable Infiltration Capacity (VIC) hydrological model (Wood et al. 1992; Liang et al. 1994), the Decision Support System for Agrotechnology Transport (DSSAT) soil moisture model (Ritchie and Otter 1985), and the Climatic Water Budget (CWB) model (Thornthwaite 1948; Thornthwaite and Mather 1955). Godfrey and Stensrud (2008) utilized in situ soil moisture observations from the Oklahoma Mesonet (Illston et al. 2008) to show how errors in the initial soil state impact the accuracy of mesoscale meteorological forecasts made using the NOAA National Centers for Environmental Prediction (NCEP) North American Mesoscale Model (NAM–Eta model (NAM–Eta; Black 1994). Godfrey and Stensrud (2010) utilized the Oklahoma Mesonet soil moisture observations and NOAA Advanced Very High Resolution (AVHRR) satellite observations of leaf area index (LAI) to evaluate and refine an empirical latent heat flux parameterization they developed.

The hydrological model evaluation studies described previously used soil moisture observations averaged over 1-h periods or longer and attempted to address issues that were related to soil water forecasts on daily or monthly time scales. Godfrey and Stensrud (2010) focused on how soil moisture controls the partitioning of surface sensible and latent heating and how changes in these variables impact meteorological mesoscale numerical weather forecasts.

Extensive research has focused on the synoptic and mesoscale meteorological conditions that are conducive

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**Fig. 1.** Arizona HMT soil moisture network: (top) Arizona view and (bottom) zoom in on the area surrounding FHU with the Babocomari River basin boundary indicated by the heavy red line. Red crosses show the locations of the soil moisture observing stations and black circles denote the locations of the river gauge stations NWS UPBA3/USGS 09471380, NWS BABBA3/USGS 09471400, and NWS SPPA3/USGS 09470500, NYL, and TUS.
to severe convective activity and flash flooding in the western United States. Maddox et al. (1980) found that the convection tended to occur during the afternoon and evening hours. They identified moisture provided by the North American monsoon (Adams and Comrie 1997) atmospheric circulation as one of the key components associated with flash flood events.

Research conducted by Hales (1972, 1974) established that surges of low-level maritime tropical moisture originating in the Pacific Ocean can be channeled northward through the Gulf of California (GOC) into southern Arizona during the North American monsoon. Hales observed that these shallow surges could move up the GOC at speeds of up to 15 m s\(^{-1}\) even though the midtropospheric winds were light and variable. Hales (1974) suggested that the synoptic-scale pressure gradient that develops during the monsoon season between the cooler maritime tropical air in the GOC and the very warm continental air mass located over the Great Basin drives the GOC surges.

Numerical modeling studies carried out by Stensrud et al. (1997) using the fourth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM4; Anthes and Warner 1978; Anthes et al. 1987) found that GOC surges could be replicated by MM4. Strong surges occurred when a midlatitude trough passed the western United States a few days before the passage of a tropical easterly wave. Weak surges were associated with an easterly wave passage over the western coast of Mexico when the midlatitudes were either quiescent or not acting against the surge. The easterly waves found in the numerical simulations shared some of the characteristics of the westward-propagating Rossby wave solutions found in the linearized primitive equations model developed by Holton (1971).

However, not all GOC surges and heavy North American monsoon rainfall events are associated with tropical easterly waves. Higgins and Shi (2005) and Corbosiero et al. (2009) both show that GOC surges can be associated with tropical cyclones (TCs) that pass the mouth of the GOC. Higgins and Shi (2005) found that TCs that track past the GOC crossing 19.6°N, 110.4°W initiate stronger surges than TCs that track farther south, crossing 15.4°N, 111.5°W.

The study presented here has three objectives. The first objective is to determine the synoptic and mesoscale meteorological forcing that produced the precipitation in the basin. The second is to determine if the in situ soil moisture observations made in the Babocomari River basin can be used to understand how the soil moisture state modulated the hydrological response of the Babocomari River basin to the precipitation that fell before the flood. The third is to determine if the NCEP operational Noah land surface model (LSM; Chen and Dudhia 2001; Koren et al. 1999) can replicate that observed soil moisture state in the Babocomari River basin before the flood.

Section 2 provides a brief overview of the Arizona HMT soil moisture observing network deployment. Section 3 describes the synoptic and mesoscale meteorological conditions that existed prior to and during the flash flood event of 23 July 2008 in the lower Babocomari River basin. In section 4, the soil moisture and precipitation distribution in the basin are examined along with the hydrological response of the river. The comparisons between the HMT soil moisture observations and the Noah analyses are presented in section 5. The summary and conclusions are presented in sections 6 and 7.

### 2. The Arizona HMT soil moisture network

The Arizona HMT soil moisture observational network consists of six stations located in the Babocomari tributary of the San Pedro River basin (Fig. 1, Table 2). The stations are located at Canelo (CNL), Black Oak Cemetery (BOC), Freeman Spring (FMS), Elgin (ELG), WSE, and FEBRUARY 2014 ZAMORA ET AL. 245

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Elevation (m)</th>
<th>Probe depths (cm)</th>
<th>Depth to caliche (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOC</td>
<td>31.556</td>
<td>110.542</td>
<td>1556</td>
<td>5, 10</td>
<td>10</td>
</tr>
<tr>
<td>CNL</td>
<td>31.552</td>
<td>110.516</td>
<td>1505</td>
<td>5, 10, 20, 50, 70</td>
<td>70</td>
</tr>
<tr>
<td>ELG</td>
<td>31.590</td>
<td>110.809</td>
<td>1470</td>
<td>5, 10, 20, 30, 50</td>
<td>52</td>
</tr>
<tr>
<td>FMS</td>
<td>31.565</td>
<td>110.546</td>
<td>1537</td>
<td>5, 10, 20, 50, 100</td>
<td>100</td>
</tr>
<tr>
<td>WSE</td>
<td>31.684</td>
<td>110.281</td>
<td>1277</td>
<td>5, 10, 15, 20, 50</td>
<td>50</td>
</tr>
</tbody>
</table>
Whetstone (WSE), and Fairbank (FBK). Observations were not available at the Fairbank station because the deployment of the instrumentation at that location was delayed until 5 February 2011. The San Pedro River supplies a large portion of the agricultural water used in southeastern Arizona and is a major recharger of the aquifers that provide Ft. Huachuca (FHU) and Sierra Vista, Arizona, with drinking water. In addition, during the North American monsoon, heavy precipitation events in the San Pedro River and tributaries can cause significant flooding along the river.

One of the objectives of the Arizona HMT soil moisture network is to provide an observational dataset that can be used in the evaluation and refinement of the hydrological models used operationally by the NWS River Forecast Centers. Stations were placed from the headwaters of the Babocomari River down to the location where it joins the main channel of the San Pedro River.

**Table 3. SSURGO soil data for HMT soil moisture station locations.**

<table>
<thead>
<tr>
<th>ID</th>
<th>Soil classification</th>
<th>Clay (%)</th>
<th>Depth to restrictive layer (cm)</th>
<th>Water content 1.5 MPa (%)</th>
<th>Water content 33.3 kPa (%)</th>
<th>Soil group</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOC</td>
<td>White House gravelly loam station, 0%–10% slopes</td>
<td>29.5</td>
<td>&gt;200.0</td>
<td>15.0</td>
<td>27.0</td>
<td>C</td>
</tr>
<tr>
<td>CNL</td>
<td>White House gravelly loam, 10%–35% slopes</td>
<td>45.0</td>
<td>&gt;200.0</td>
<td>22.0</td>
<td>35.0</td>
<td>C</td>
</tr>
<tr>
<td>ELG</td>
<td>White House gravelly loam, 0%–10% slopes</td>
<td>43.9</td>
<td>&gt;200.0</td>
<td>22.0</td>
<td>34.0</td>
<td>C</td>
</tr>
<tr>
<td>FMS</td>
<td>Bernardino–Hathaway association, rolling</td>
<td>20.0</td>
<td>&gt;200.0</td>
<td>15.0</td>
<td>18.0</td>
<td>C</td>
</tr>
<tr>
<td>WSE</td>
<td>Nolam–Libby–Buntline complex, 1%–10% slopes</td>
<td>26.0</td>
<td>&gt;200.0</td>
<td>7.4</td>
<td>11.0</td>
<td>B</td>
</tr>
</tbody>
</table>

Fig. 2. The 500-hPa geopotential height (dam; blue solid lines) and absolute vorticity (s\(^{-1}\); red dashed lines) analysis for 1200 UTC 22 Jul 2008. Shaded areas indicate absolute vorticity exceeding 16 \(\times 10^{-5}\) s\(^{-1}\).
The soils in southeastern Arizona are dominated by alluvial fan material, volcanic debris, and extensive layers of limestone conglomerate known as caliche. In this region, caliche can be found anywhere between the surface of the Earth and 1.0 m below the surface. Table 3 contains a summary of the basic soil properties assigned to each HMT soil moisture station by the USDA NRCS Soil Survey Geographic database (SSURGO). The SSURGO soil surveys do not indicate the presence of restrictive layers in the Babocomari basin.

Soil moisture observations in the Babocomari River basin are made using Campbell Scientific Inc. (CSI) CS616 soil water content reflectometers or Stevens Hydra Probes. A detailed description of the soil moisture instrumentation and calibration methods can be found in Zamora et al. (2011).

Attempts were made to locate the soil moisture and temperature probes used in the Arizona observational network at the standard USDA/SCAN observing depths (5, 10, 20, 50, and 100 cm). However, caliche layers located at depths shallower than 100 cm were encountered at all but the Freeman Spring site. Probe placements at the remaining locations started at 5.0 cm and continued downward until the first caliche layer was encountered. The deepest probe was then placed in the soil adjacent the observed restrictive layer (Table 2). All soil probes are placed horizontally in the soil. Volumetric water content (VWC) is defined as

\[
VWC = \frac{V_w}{V_t} \times 100, \quad (1)
\]

where \(V_w\) is the volume of water and \(V_t\) is the total (bulk) soil volume. The soil volumetric wetness fraction used in this paper is simply VWC/100.

Soil temperature observations are taken at each probe depth using Campbell T-107 temperature probes. All of the soil moisture stations deployed by NOAA/ESRL measure air temperature and relative humidity at 2.0 m using Vaisala HMP-45C probes. Precipitation...
measurements are made using Texas Electronics tipping-bucket rain gauges. The data loggers used at each site are programmed to store 2-min averages of each variable measured at that location.

3. Synoptic and mesoscale meteorological conditions

The Babocomari River flood of 23 July 2008 was the second-highest flow event recorded at the U.S. Geological Survey (USGS) river gauge station USGS 09471400/NWS BABA3 (Fig. 1, Table 1) during the period of record (2000–10). NWS Automated Surface Observing System (ASOS) observations; NWS constant pressure analyses; NWS 88D radar; NWS upper-air sounding data taken at Tucson, Arizona (TUS; Fig. 1); Special Sensor Microwave Imager (SSM/I) satellite imagery; and rainfall measured at the Arizona HMT stations and the USDA Agricultural Research Service (ARS) Walnut Gulch Watershed (Renard et al. 1993) were used to determine if the precipitation event associated with the flood was of a quasi-stationary nature (Bosart and Sanders 1981), for example, mesoscale convective system (MCS; Maddox 1980), atmospheric river (AR; Ralph et al. 2006), or diurnally forced deep convection fed by monsoonal moisture.

The 500-hPa geopotential and vorticity analyses at 1200 UTC 22 July and 0000 UTC 23 July (Figs. 2 and 3) show that southeastern Arizona was under the influence of a synoptic-scale, high-pressure ridge typically associated with the North American monsoon. A weak, short wave moved from Northern California up into Idaho. Geopotential height changes in the center of the ridge axis during the 12-h period are within the range of values that one would expect if the 500-hPa geopotential tendency was driven entirely by the diurnal heating cycle (~10 m). Changes in absolute vorticity advection and the position of the ridge axis were also negligible over southeastern Arizona. The SSM/I satellite image of integrated water vapor (IWV) derived for 22 July (Fig. 4) does not indicate that a strong source of Pacific moisture indicative of an AR event existed over northern Mexico or southern Arizona. NOAA Geostationary Operational Environmental Satellite (GOES) visible and IR images for the period (not shown) do not show the existence of any MCS type of convection.

These analyses suggest that mesoscale or synoptic-scale vertical motion forcing did not play a role in initiating the convective event responsible for the flooding. However, the IWV image (Fig. 4) shows the water vapor signature of Hurricane Fausto (EP072008; 17.5°N,
120.0°W) and IWV values > 4.0 g cm⁻² located in the central GOC.

The best track position of Hurricane Fausto provided by the National Hurricane Center (NHC) for 1200 UTC 20 July located Fausto at approximately 15.0°N, −109.5°W (Fig. 5). Higgins and Shi (2005) have shown that TCs associated with indirect or weak GOC surges observed at Yuma, Arizona (NYL), are typically located at 15.4°N, 111.5°W on the day the surge is observed at Yuma. Surface dewpoint observations taken at NYL and TUS show a significant increase at both locations after 0000 UTC 19 July (Fig. 6), exceeding the 15.6°C threshold used by Fuller and Stensrud (2000) to establish the presence of GOC maritime tropical air. The surface dewpoints observed after that time at TUS and FHU remained above 15.6°C (Fig. 7) through 23 July. Upper-air dewpoint observations taken at TUS show a similar behavior, indicating the depth and the longevity of the maritime tropical air over southeastern Arizona (Fig. 7). Hybrid Single-Particle Lagrangian Integrated Trajectory (HY-SPLIT; Draxler 1992) 96-h back trajectories computed for 1200 UTC 22 July at 500, 2500, and 5000 m (Fig. 8) and the IWV image for 19 July (Fig. 9) also indicate that the air found over the Babocomari River basin at 1200 UTC 22 July originated in the GOC.

The 1200 UTC 23 July rawinsonde observation taken by the NWS at TUS (Fig. 10) indicated that the potential for severe convection existed in southeastern Arizona. Analysis of the sounding gave a convective available potential energy (CAPE) value of 2768 J kg⁻¹, a lifted index (LI) of −4.8, a parcel equilibrium level of 135.3 hPa, and 52.5 mm of precipitable water.

Documenting the areal extent of the precipitation that developed later over the lower Babocomari and Walnut Gulch basins using the NWS 88D Doppler radar located near TUS was limited by a gap in the radar coverage over those areas. The NWS 88D radar is located at an elevation of 1621 m MSL, and the radar coverage map confirms that the beam is blocked over the basins in question at 0.5° and 1.0° elevation angles by the Whetstone...
Mountains (Fig. 11). In fact, the Whetstone soil moisture observing station is situated 344 m below the TUS 88D at 1277 m MSL (Table 2).

The best indication of the areal extent of the heavy precipitation can be inferred from the storm total precipitation measured by the HMT and Walnut Gulch ARS rain gauges. They indicate that the region of heavy precipitation (>30 mm) was confined to the lower Babocomari and Walnut Gulch basins (Fig. 12). At Whetstone, 42 mm of precipitation fell in less than an hour (Fig. 13). A deep moist adiabatic layer and 52 mm of precipitable water were observed in the TUS sounding. These conditions ensured that convection forming in the vicinity of Tucson would be efficient.

It is also interesting to note that on each of the 2 days prior to 23 July and on the day after, precipitation began falling at Whetstone at almost exactly 0000 UTC (0500 LST; Fig. 13). This suggests that diurnally forced deep monsoonal convection triggered the flash flood of 23 July 2008. It appears that Hurricane Fausto initiated a weak GOC surge that provided the moisture source for the convection.

4. Soil moisture observations and streamflow

The evolution of the soil moisture volumetric wetness fraction measured at Whetstone (Fig. 13) showed that earlier monsoonal precipitation had brought the soil between 10.0 and 20.0 cm close to field capacity (0.42), while the soil below 20.0 cm stayed considerably drier. Field capacities in this paper are estimated by examining the way a soil layer dries in the days following a significant precipitation event (Veihmeyer and Hendrickson 1931; Hillel 1998). The water from the earlier precipitation events had been drawn into the deeper soil layers by gravity, and surface evaporation had managed to keep the shallower near-surface layers drier. The stage for the flooding event on the Babocomari River was set by two monsoonal rainfall events occurring on 21 and 22 July.

During the excavation phase of the Whetstone soil probe installation, NOAA scientists noted the presence of a layer of caliche 52.0 cm below the surface (Table 2). At Whetstone, this layer acts as a barrier that inhibits the ability of gravity to pull water deeper into the ground on
time scales shorter than those of aquifer recharge. According to the SSURGO soil surveys, the Whetstone soil has a low water storage capacity and low clay content and has been assigned a soil group B classification (Table 3). Group B soils tend to have moderate infiltration rates. Given the infiltration characteristics, shallow soil column, and low clay content, it is not surprising that the diurnal precipitation events managed to saturate the entire depth of the soil column (Fig. 13) just before the 22–23 July 42.0-mm precipitation event. Soil wetness fractions observed higher in the basin at Elgin (Fig. 14) and Freeman Spring (Fig. 15) at 50.0 cm were considerably lower in the days following the 22 July precipitation event observed at Whetstone. Freeman Spring and Elgin received light precipitation (<14.0 mm) on 22 July. The soil between 10.0 and 20.0 cm at both Freeman Spring and Whetstone was wetter than the same region at Elgin. This is not surprising given that the precipitation measured at Elgin was nearly a factor of 2 lower than either Freeman Spring or Whetstone during the period. In addition, Elgin has a rather shallow soil depth but high clay content. Freeman Spring has a deeper soil column that should help offset the reduced water storage capacity implied by its lower clay content (Table 3). In addition, little precipitation fell at Freeman Spring before the flood. Soil conditions through the depth of the soil column were the wettest at Whetstone.

If we assume that the Whetstone soil wetness observations characterized the soil conditions in the lower Babocomari, then it is safe to conclude that most of the rain that fell during the afternoon of 23 July became surface runoff. This implies that the flood was a saturation event. The peak discharge at the river gauge station closest to Whetstone (USGS 09471400, NWS BABA3; Fig. 2) occurred at 0000 UTC 23 July (Fig. 16a). The discharge increased from 0.0 to 114.4 m$^3$ s$^{-1}$ in less than 15 min. During the same time period, the river gauge located upstream (USGS 09471380, NWS UPBA3; Fig. 1) recorded less than 1.0 m$^3$ s$^{-1}$ (Fig. 16b).

After summing the observed flow at the Whetstone river gage during the period and subtracting the base flow, we estimated the total volume of the flow associated
with the flood to be $448,145 \text{ m}^3$. A simple water balance calculation was made using the total precipitation observed at Whetstone (42 mm). The basin area needed for balance is $10.67 \text{ km}^2$. This area is less than 2% of the total basin, which qualitatively agrees with the area in the basin that received precipitation (Figs. 1 and 12). Uncertainty in the areal extent of the heavy precipitation, the actual amount of precipitation that fell during the time period, and the simplicity of the calculation limits the conclusions that can be drawn from this simple calculation. However, the analysis is consistent with the idea that a large amount of runoff was generated from a relatively small fraction of the basin.

The analysis shows that soil wetness fractions as a function of depth and precipitation amounts varied considerably in the river basin before the river flooded. The heaviest rain fell in the lower basin on a soil column that was at or near saturation. Table 2 indicates the caliche depth found at each of the HMT soil monitoring locations during the installation of the soil probes. One can see that the heaviest precipitation occurred in a region of relatively shallow soil that was near saturation.

5. Comparing the Noah LSM forecast soil moisture with observations

The results presented in the previous section indicate that soil moisture content as a function of depth played an important role in the hydrological response of the lower Babocomari River basin to the precipitation that fell in that location. Unfortunately, point observations of soil moisture and temperature are limited in their ability to uniquely characterize soil conditions in a basin because of vegetative cover and soil type heterogeneity (Marshall et al. 2003; Brotzge and Crawford 2003). In principle, remote sensing techniques and LSMs can be used to overcome this limitation. Perhaps the greatest value of the in situ observations is not their ability to characterize conditions in a basin but is their ability to validate both models and remote sensing technology and provide background information for data assimilation into the LSMs.

The earlier referenced NCEP NAM–Eta mesoscale model–Noah LSM validation study conducted by Godfrey and Stensrud (2008) showed that in the region of the
Oklahoma Mesonet, strong biases existed in both the soil moisture and temperature fields at all depths when the model analyses were compared with the observations. Godfrey and Stensrud also found a pronounced dry bias at all levels in the NAM–Eta soil moisture fields.

After the work done by Godfrey and Stensrud (2008), the NCEP NAM was changed to the Nonhydrostatic Mesoscale Model (NMM) (Janjic 2003). The NMM is a fully compressible, nonhydrostatic, hybrid (sigma pressure) vertical-coordinate mesoscale model that continues to use the Noah LSM (Ek et al. 2003). The Noah LSM predicts soil moisture for four soil layers representing depths of 0–10, 10–40, 40–100, and 100–200 cm.

The feedback loop between the Noah LSM and the NMM is highly nonlinear. Changes in evapotranspiration produced by the model-predicted surface temperature, surface specific humidity, boundary layer wind shear, and net radiation, along with the precipitation input, drive the LSM, which produces the soil moisture profile. The updated soil moisture distribution then provides boundary conditions for the fluxes calculated in the next model time step. Thus, changes in atmospheric model physics and advection schemes can completely change the performance of the meteorological model globally or in a specific region and, hence, the response of the LSM. Given that both the meteorological model and the region of interest changed from Eta to NMM and to the semiarid climate of Arizona, this work focuses on a limited comparison for a single case study. No attempt is being made to address systematic biases or a statistical analysis of NMM or Noah LSM performance. Our goal is to determine whether or not the NCEP operational Noah LSM analyses captured the simple upper/lower basin contrast in soil moisture found observationally that in part determined the hydrological response of the basin during the flood.

Analyses of 12-km resolution Noah LSM soil moisture at the model initialization times of 0000, 0600, 1200, and 1800 UTC for the period 18–27 July were obtained from NCEP. The Noah LSM grid points located in and around the HMT soil moisture observing sites are shown in Fig. 17. Using operational Noah LSM analyses avoids the problems associated with so-called model spinup (Cosgrove et al. 2003). Typically, hydrological models are forced externally and cycled for long time periods in an effort to minimize the effects of the initial conditions on the simulations. The operational analyses of soil moisture provided by the Noah LSM running operationally...
have been updated every 6 h for the entire time the model has been running at NCEP.

There are only five soil moisture observing sites and NMM grid points in the Babocomari River basin for this case study. Such a limited dataset creates numerous problems if one decides to place the observations and model output on a common grid using objective analysis. These problems include singular matrices caused by the locations of the observing locations, clusters of stations creating delta-function-like inputs into successive correction schemes, and the lack of first-guess fields or small statistical populations. Gridding that would match the Noah LSM depths with the HMT observational depths by interpolation was also rejected in this study. In this study, the nearest soil moisture observations to Noah LSM grid points at 5 and 20 cm were compared to the 0–10- and 10–40-cm Noah LSM estimates, respectively.

Noah LSM grid points 3 and 7 are in the upper basin and grid point 9 is in the roughly lower basin. For this comparison, we chose Freeman Spring and Elgin as the observing sites that characterized the upper basin. The Whetstone observing site characterized the lower basin. We compared the Elgin observations with grid point 7 rather than the closer grid point 3 because the soil characteristics derived for the Noah LSM using the SSURGO data at that grid point showed better agreement with the soil properties actually observed at Elgin. Grid point 2 lies outside the Babocomari basin in the Santa Cruz River basin. Hourly averages of the observed soil moisture at 5- and 20-cm depth were computed for all three stations. The difference between the observation and the model at each location and depth was calculated for each Noah LSM analysis time.

In the lower basin the differences between the observations and Noah LSM values varied from nearly zero to approximately 10% VWC in the upper soil layer (Fig. 18). A distinct wet bias existed in the upper basin where both Noah LSM VWC values were almost 20%
higher than the observations at Freeman Spring and Elgin (Fig. 18).

The differences between the Noah LSM VWC estimates and the observations for the lower soil layer (10–40 cm) are shown in Fig. 19. The comparison between the 10–40-cm Noah LSM layer and the Whetstone 20-cm observations showed a significant dry bias on the order of 20% VWC. The sign and magnitude of the bias stayed nearly the same at Freeman Spring as the bias found in the upper soil layer.

For this case, the basin gradient in soil moisture estimated by the Noah LSM and the gradient observed by the HMT network near 20-cm depth are reversed. The observations show a nearly saturated lower basin and a drier upper basin. The model has a wetter upper basin and drier lower basin. Given this reversed gradient, it appears unlikely that a streamflow model driven by the output of the Noah LSM would have produced high streamflow values in the lower basin because the model soil state in that region would have had the ability to absorb more of the heavy precipitation.

Quantifying this conjecture using Noah LSM runoff estimates was not attempted because the runoff estimates from the LSM are set to zero by the NCEP NAM Data Assimilation System (NDAS) at each analysis time used in the intercomparison. The most accurate estimates of runoff would be the NDAS 3-h forecast values valid at the analysis times we chose. Unfortunately, the NDAS system does not output 3-h forecast runoff values on the 12-km NAM grid. Runoff values are only output for the 6-h forecasts on the NAM grid, and as we have shown, the entire precipitation event occurred between 2300 UTC 22 July and 0000 UTC 23 July.

The findings in section 4 suggest that variations in the depth of the soil columns in the basin play an important role in the hydrological response of the Babocomari River. Soil properties such as depth of the soil column, composition, hydraulic conductivity, thermal conductivity, and available water capacity are specified in the Noah LSM using the USDA NRCS State Soil Geographic database (STATSGO). The higher-quality SSURGO soil surveys have been completed in Cochise and Santa Cruz Counties and are used here to evaluate the Noah LSM.

Examination of the SSURGO data for each of the HMT soil observing sites indicated soil depths of 200 cm or more at all locations (Table 3). As previously shown, only one site in the basin had a soil depth of 100 cm, and at one location (Black Oak Cemetery) the soil was only 10 cm deep. The Noah LSM assumes a soil depth of 200 cm in its design, and the available SSURGO data for the Babocomari basin confirm this depth. The reverse gradient shown earlier in the Noah LSM could be a result of the erroneous specification of the soil depth in the model. Infiltration calculated using a soil depth of 200 cm instead of 50 cm could have profound effects on the model soil moisture analyses in the lower Babocomari where a thinner soil layer exists. For example, a 200-cm volume of soil at 40% porosity can hold 80 cm of water. In contrast, a 50-cm volume of soil at 40% porosity can only hold 20 cm of water.

6. Summary

This paper describes a detailed case study of the role soil moisture played in controlling the hydrological response of the Babocomari River basin during a flooding event. Synoptic and mesoscale analysis has shown that the heavy precipitation that initiated the flood was diurnally forced convection fed by a maritime tropical air mass. A weak GOC monsoon surge triggered by Hurricane Fausto drove this air mass up the GOC into southeastern Arizona. Sounding analysis indicated that the atmosphere over southeastern Arizona was extremely moist and unstable. Precipitation amounts in excess of 40 mm h\(^{-1}\) fell on nearly saturated soil and produced the second-highest flow observed in the lower Babocomari River basin.

Important variations in the soil moisture distribution in the basin were documented along with information...
about the depth of the soil column in the basin. The antecedent precipitation in the basin saturated the thinner soil column in the lower basin, while soil moisture values higher in the basin remained lower.

Comparison of NCEP Noah LSM analyses at 0000, 0600, 1200, and 1800 UTC with observations found significant biases in the Noah LSM soil moisture analyses. Higher in the basin, a wet bias existed in both the 0–10- and 10–40-cm layers. A much stronger bias (>20% VWC) was found when comparing the lower basin observations with the Noah LSM.

The results of this study suggest that the depth of the soil column in the Babocomari River basin plays a crucial role in its hydrological response to precipitation. It seems plausible that the soil survey data and the depth of the simulated soil in the Noah LSM contribute to the differences between the Noah LSM simulated soil moisture and observations noted in this study. It is important to recall that the objectives of the study were to explore how the soil moisture state before the convective outbreak modulated the hydrological response of the Babocomari River. A single case study of this type cannot establish the existence of systematic biases in Noah LSM performance nor discount the role of other physical processes that influence the hydrological response of the river basin such as evapotranspiration, aquifer recharge, heterogeneity in canopy, and vegetative cover. In addition, the Noah LSM configured in the NMM is incapable of moving water laterally. This physical redistribution wets the valleys and dries the higher terrain. The presence of restrictive layers in the soil column is also not represented in the current NMM model. Clearly, these missing physical processes could help explain the results found in the intercomparison we have shown.

This study also shows that the meteorological situation in the tropical eastern Pacific can play an important role in supporting even isolated deep convention in southern Arizona. Understanding the antecedent soil moisture conditions in river basins along with the ability to determine regions primed for deep convection could be used to improve forecasts of saturation excess flooding.

7. Suggestions for future research

One of the major operational goals of the NWS is to provide the most accurate forecasts of flooding that are possible. This is an enormous task that cannot be
addressed adequately without accurate “forcing” information, such as quantitative precipitation estimation (QPE), quantitative precipitation forecasting (QPF), and the surface energy balance (evapotranspiration).

The HMT program plans to investigate the surface energy balance–evapotranspiration problem by upgrading the existing observational capability at selected HMT observing locations. At these sites, instruments are being added that will allow the estimation of each component of the surface energy balance. Solar irradiance observations are made using the high-accuracy component summation method (Zamora et al. 2005), eddy correlation latent and sensible heat fluxes, and ground heat flux using heat flux plates. Currently, these special observing platforms are deployed in the Russian River basin near Cazadero, California, and Granby, Colorado.

River basins in the NWS Hydrology Laboratory Research Distributed Hydrological Model [HL-RDHM; formerly the Hydrology Laboratory Research Modeling

![Graph](image1)

**FIG. 13.** Evolution of the cumulative precipitation and soil wetness fractions measured at 10-, 20-, and 50-cm depths for the period 18–26 Jul 2008 at WSE.

![Graph](image2)

**FIG. 14.** As in Fig. 13, but for ELG.

![Graph](image3)

**FIG. 15.** As in Fig. 13, but for FMS.

![Graph](image4)

**FIG. 16.** Observed discharge as a function of time at (a) USGS 09471400 (NWS BABA3) located 5.4 km downstream of Whetstone and (b) USGS 08471380 (NWS UPBA3) for the 2008 North American monsoon.
FIG. 17. NAM grid points (yellow) and HMT soil moisture locations (black).

FIG. 18. Difference (observations minus NAM) at 5-cm depth for the period 18–28 Jul 2008: FMS, grid point 3 (blue); ELG, grid point 7 (green); and WSE, grid point 9 (red).

FIG. 19. As in Fig. 18, but at 20-cm depth.
System (HL-RMS))] (Koren et al. 2004) are broken down into individual cells that contain the channeling or connectivity of the streams in the cell along with the cell’s ability to transmit water from the surface into the water table or into the streams. This grid system is known as the Hydrologic Rainfall Analysis Project (HRAP) grid coordinate system (Reed and Maidment 1999). Each HRAP cell covers approximately 16.0 km² of a river basin. The head water stations located at Canelo, Freeman Spring, and Black Oak Cemetery were sited within a single HRAP cell with the expectation that these stations would allow the identification and quantification of hydrological processes operating at scales smaller than the HRAP scale. This research is ongoing.

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