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Water vapor and surface observations in northwestern Mexico during the 2004 NAME Enhanced Observing Period

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[1] We report on precipitable water vapor (PWV) from a Global Positioning System (GPS) receiver and surface meteorological network during the 2004 North American Monsoon Experiment (NAME) in northwestern Mexico. The monsoon onset is evident as a large PWV increase over several days beginning July 1. Data in the Sierra Madre Occidental (SMO) foothills reveal a dynamical transition in mid-August from smaller, sub-synoptic scale to larger, synoptic scale moisture structure. During the Sub-synoptic phase in the SMO foothills, a positive feedback operates where near-daily precipitation supplied moisture maintains 15% higher surface mixing ratios that lower the lifting condensation level facilitating initiation of moist convection. Along the western edge of the SMO, precipitation typically occurs hours after the local temperature maximum, triggered by westward propagating convective disturbances. Precipitation is typically preceded by a rapid rise in PWV and sharp decrease in surface temperature, implying models must include moist convective downdrafts in the NAM area.

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1. Introduction

[2] During the summer of 2004, the NAME Enhanced Observing Period (EOP, see *Higgins et al.* [2006] for details) was run in southwestern North America. The goals of the field program were to take special observations to better understand the mechanisms influencing warm season precipitation and, ultimately, to improve precipitation prediction in models. The current generation of numerical weather and climate models forecast many aspects of warm season rainfall rather poorly. This is because summer rainfall is strongly modulated by small-scale dynamical processes, topography and rapid diurnal evolution of the boundary layer, spatial and temporal scales that have proven difficult to capture in models. Since most summer precipitation in this region is convective, accurate model parameterizations of processes involved in moist convection are crucial in this region. The monsoon-affected regions of the southwest United States and, particularly, northwest Mexico, have historically been poorly observed, presenting serious challenges for model initialization and validation.

[3] We report here on GPS-derived PWV and surface meteorological observations obtained at locations in Sonora and Chihuahua, Mexico, during the NAME EOP (see Table 1 and Figure 1). Developing and installing the instrumentation, acquiring the observations and initial data processing involved researchers at the University of Arizona, University of Sonora, NOAA FSL, Suominet and JPL. This data set of PWV, surface mixing ratios, temperature and pressure complements other datasets collected during the 2004 NAME EOP, particularly rain gauge observations collected at nearby locations [e.g., *Gochis et al.*, 2004].

[4] Since convective clouds condense from atmospheric water vapor, understanding the amounts, patterns, and transport of water vapor in the pre-storm environment is critical to improving precipitation forecasts. While satellite measurements of PWV during the North American Monsoon (NAM) area can provide continuous horizontal coverage, infra-red (IR) and visible wavelengths are strongly affected by clouds and therefore cannot determine PWV when clouds are present. Satellite microwave observations of PWV are limited to large bodies of water because microwave surface emissivity varies significantly over land. In contrast, GPS derived PWV estimates in a variety of locations have demonstrated 1–2 mm accuracy across a wide range of weather conditions [e.g., *Smith et al.*, 2007]. Deriving PWV from GPS requires a GPS receiver, a surface barometer and thermometer. Data during the EOP were available in near real-time via the internet or satellite internet in more remote regions of the SMO. The near-time-continuous capability of GPS PWV coupled with its relatively low cost, ease of deployment, automated operation and high accuracy in all-weather conditions make this observing system ideal for remote locations, such as those in and around the SMO.

[5] Our network of six receivers between 27°N and 30°N sampled PWV in this convectively active area in the western side of the SMO mountains significantly better than did satellite IR, microwave and conventional sounding systems during the 2004 NAME EOP. Conventional sounding systems were concentrated around the perimeter of the

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Table 1. GPS Sensor Locations and Duration

Site IDs	Location	Lat, °N	Long, °E	Elev., m	Duration
SA21/COT1/SA46	Tucson, AZ	32.23	−110.96	786.3	2002–present
SA24	Douglas, AZ	31.37	−109.69	1263.7	2002–present
SA27	Hermosillo, Son	29.08	−110.96	216.8	2003–present
SA31	Phoenix, AZ	33.45	−111.95	384.1	2003–present
SA33	Puerto Peñasco, Son	31.30	−113.53	10.7	2003–present
NAM1/YESX	Yecora, Son	28.37	−108.93	1544.0	2004–present
NAM2	Creel, Chi	27.74	−107.63	2337.3	2004
NAM3	Tesopaco, Son	27.84	−109.37	433.9	2004
NAM4	Mazatan, Son	29.00	−110.14	549.4	2004
NAM5/USMX	Moctezuma, Son	29.82	−109.68	654.2	2004–present

SMO (i.e., Gulf of California (GoC)) where the required, complex infrastructure was available and provided 1 to 4 samples per day whereas PWV estimates were derived from GPS measurements every 30 minutes (and can be processed at still finer temporal resolution).

2. Monsoon Onset of 2004

[6] The PWV data reveal a multitude of scales from 30 minutes upward to the duration of monsoon itself. Figure 2 shows several PWV time series that have been smoothed with a 24 hour running average to remove variability at shorter time scales. The smoothed GPS PWV measurements at Yecora, Moctezuma, and Hermosillo and the radiosonde at Empalme in the Mexican state of Sonora, reveal similar patterns of pre-monsoon and monsoon PWV evolution including a pre-monsoon dry period with 5 to 15 mm PWV followed by a pre-monsoon moistening event (PWV values from 20 mm to more than 35 mm) from June 18 to June 30. A brief dry period was then followed by an increase in PWV over several days from July 1 to July 8 (the period of monsoon onset as indicated by the PWV times series) followed by a long period of largely sustained high PWV values.

[7] To help determine where the water came from, Figure 2 shows the speed and direction of the water-weighted horizontal wind vector, $\vec{u}_w$, at Empalme defined as $\vec{u}_w = \frac{\int \vec{u}\rho_w dz}{PWV}$ where $\vec{u}$ is the horizontal wind vector, ρ_w is the water vapor density, and z is altitude. The weighting extracts the single vector wind from the wind column most relevant to PWV advection. For the pre-monsoon moist event, the winds begin from the west and shift to southwesterly and southerly consistent with the higher PWV values appearing first at Empalme. The peak in PWV on June 29 is clearly associated with a relatively strong southerly push of air into the region. As the event ends, the winds shift back to westerly returning dry air to the region.

[8] We define the monsoon as beginning during the 5 to 7 day onset period commencing on July 1 over which PWV values grew to sustained high values and the PWV-weighted winds at Empalme shifted from westerly to southeasterly and remained there. The PWV increase appeared first at Yecora on July 1 which, combined with the Empalme winds

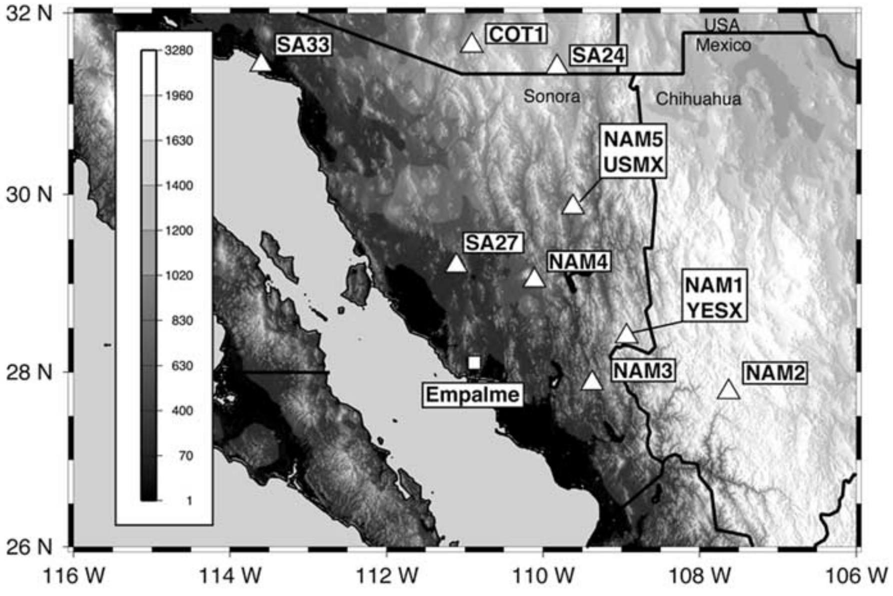

Figure 1. Locations of GPS and surface meteorological observing sites during the NAME EOP in 2004 indicated by triangles. Empalme radiosonde site indicated by a square. Contouring heights given in meters.

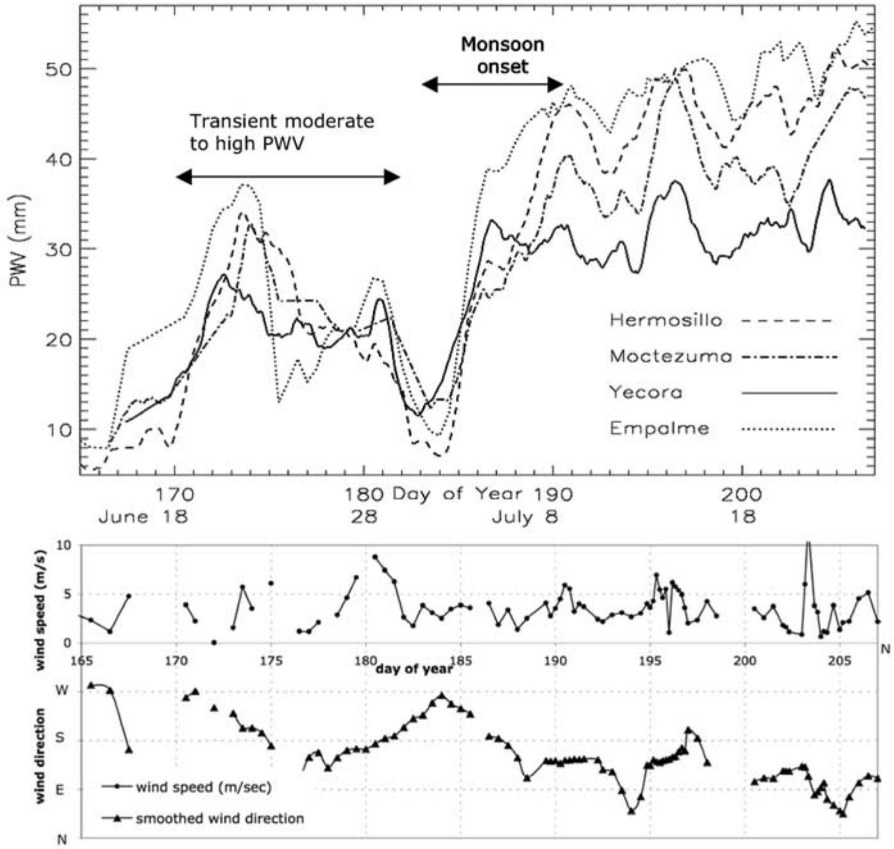

Figure 2. (top) The 2004 NAM onset as captured by PWV measurements from the Empalme radiosonde and GPS PWV sites at Hermosillo, Yecora (YESX), and Moctezuma (USMX). (bottom) Water vapor-weighted wind speed and direction derived from Empalme radiosonde profiles. PWV and wind direction data have been smoothed with a 24 hour running average to make larger scale trends more evident.

and PWV and GOES mid-tropospheric water vapor images, suggest a moisture plume from the southwest with a sharply defined moisture boundary on its northern edge. The increase in surface specific humidity at Yecora begins 2 days later on July 3 indicating the moistening occurs initially at mid-tropospheric levels. Examination of the Chihuahua radiosonde winds, reanalysis winds and satellite water vapor indicate the moisture does not come from the east. The PWV at Yecora reaches a maximum of 33 mm by July 5 whereas the increase at Hermosillo extends from July 2 to July 8 with a rapid increase to 25 mm over a day followed by a further increase to 45 mm over the next 5 days. PWV at Empalme, Hermosillo and Moctezuma continue to increase gradually by 5 to 10 mm after July 8 as the overall wind pattern at Empalme shifts from somewhat southeasterly to more easterly. After July 8, the PWV measurements at the 4 sites in the figure are related inversely to the site altitude with Empalme at 12 MSL typically highest and Yecora at 1544 MSL typically lowest.

[9] We also note that relatively little PWV is required at Yecora before moist convection begins, with PWVs of 20 to 27 mm being sufficient to trigger rainfall there on most days during the pre-monsoon moist event. PWV at Yecora also increases relatively little beyond its July 5 value of 33 mm over the following 20 days when it rains most days while PWV at the lower elevation sites continues to gradually increase. This behavior may be associated with the significant moist convective cooling at Yecora that limits the amount of water the column can contain.

3. Distinction Between Two Phases of the NAM Summertime Wet Period

[10] The PWV and surface specific humidity at Hermosillo and Mazatan in Figure 3 span the start of data acquisition at Mazatan through the passage of the remnants of Hurricane Javier (after which the region became much drier). Mazatan (NAM4, el. 549 msl) is located at the western edge of the SMO approximately 90 km east of Hermosillo (SA27, el. 217 msl). The data in Figure 3 reveal a distinct change over this portion of Sonora in mid-August in terms of the bias and cross correlation between the surface specific humidity and PWV measured at Mazatan and Hermosillo. We define the two intervals, July 20 to August 14 and August 22 to September 21 as "Sub-synoptic scale" and "Synoptic scale" respectively.

[11] The annotations in Figure 3 summarize key statistical differences between the moisture behavior in the two intervals separated by the very dry interval in mid-August. Mazatan, with its higher elevation and smaller air mass column, generally had less PWV than Hermosillo over the entire mid-July to mid-September period. However, the

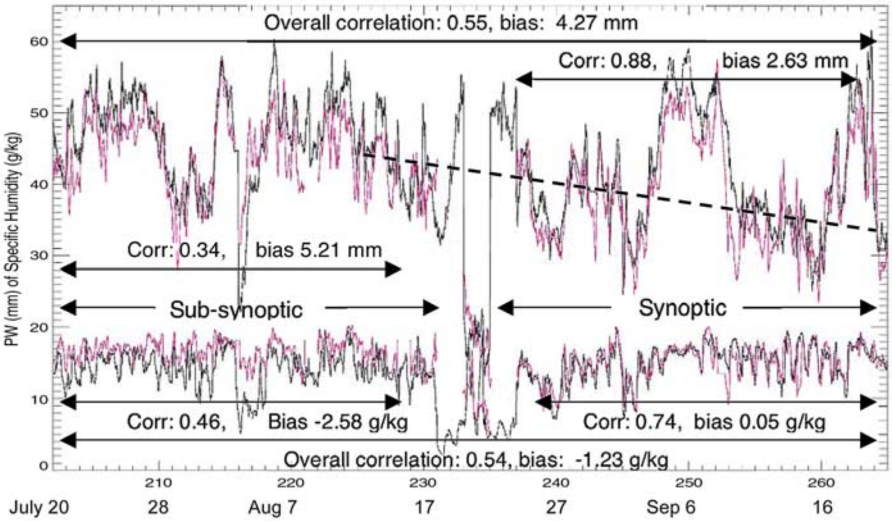

Figure 3. Two months of PWV (top) and surface q (bottom) measured at Hermosillo (black) and Mazatan (red) from July 20 to September 20, 2004. Bias is defined as Hermosillo minus Mazatan. Diagonal dashed line indicates overall drying trend in the PWV beginning around August 12 (DOY 225).

Hermosillo minus Mazatan bias changed from 5.21 mm during the Sub-synoptic interval to half that (2.61 mm) during the Synoptic interval. In terms of surface mixing ratios, during the Sub-synoptic interval, Mazatan surface mixing ratios ***exceeded*** those at Hermosillo by an average of 2.6 g/kg, varying between 15 and 19 g/kg, whereas, during the Synoptic-scale interval, the Mazatan q's decreased, becoming essentially identical to those at Hermosillo.

[12] A second key difference between the two intervals is cross-correlations between the Hermosillo and Mazatan moisture variables are significantly smaller during the Sub-synoptic interval indicating increased moisture variability at scales significantly smaller than the 90 km separating Mazatan and Hermosillo. This variability is presumably due to some combination of local moist convection and a mountain circulation in the SMO. Subsequently, in the post-August 18 interval, the significantly higher Hermosillo-Mazatan moisture cross-correlations indicate variability is dominated by larger synoptic scale ($\geq$90 km) moisture structures advecting through the region and the effects of the small scale local convection and the enhanced Mazatan surface moisture source have largely disappeared.

[13] The dashed line in Figure 3 suggests a general drying trend beginning around August 12 that coincides with a shift to westerly winds in the upper troposphere evident in the Empalme radiosonde profiles and satellite images of upper level clouds. This drying trend continues through September upon which the moisture associated with two storms, a tropical incursion (Sept. 4–9) and tropical storm Javier (Sept. 18–20), are superimposed. There is some indication that wet surface conditions at Mazatan disappear several days before the August 17 drying event. High specific humidities at Mazatan during the Sub-synoptic period may be due to evapotranspiration and the reduction after mid-August may reflect a vegetative change.

[14] Defining the monsoon simply in terms of PWV indicates the 2004 NAM ended on September 20, following the passage of TS Javier through the region. The mid-August changes in the moisture biases and correlation-length scales suggest the monsoon or at least the local Sub-synoptic phase of the monsoon ended in mid-August. It is clear that observations of the sort made here need to be made over multiple years to determine how representative the moisture behavior observed in 2004 is. For example, is the Sub-synoptic phase of the monsoon and its transition to a larger, Synoptic scale wet period a robust annual feature and an indicator of the end of the monsoon and, if so, what causes the transition.

4. Diurnal Dependence of Moist Convection

[15] Figure 4 shows 8 consecutive diurnal cycles of surface and column water vapor, surface temperature and precipitation measured at Hermosillo and Mazatan beginning July 20, 2004. While surface temperatures exhibit the largest and most consistent diurnal signatures, the moisture fields, in particular, exhibit a great deal of day-to-day variability. Figure 4 demonstrates that the relation between PWV and precipitation is not simple. For instance, maximum PWV over Hermosillo is higher on July 22 than July 21 but rain was measured on July 21, not the 22nd. The diurnal timing of the PWV maximum is clearly relevant. It is not clear how much of this is local convergence versus moisture advected into the area. PWV peaks on July 21, 23, 24 and 25 are similar in their timing and relation to precipitation. The peak on July 22 occurs significantly later and there is no local rainfall or cold downdraft. On July 26 there is a less well-defined PWV peak at a similar time that is associated with rainfall.

[16] On 5 of the 8 evenings, sharp drops in temperature immediately precede precipitation, indicating moist convective or mesoscale downdrafts and outflows. This sequence coincides with a relative maximum in PWV associated with convergence of water vapor into the air column overhead during deep convective events. Minimum and maximum temperatures both decrease noticeably as PWV and precip-

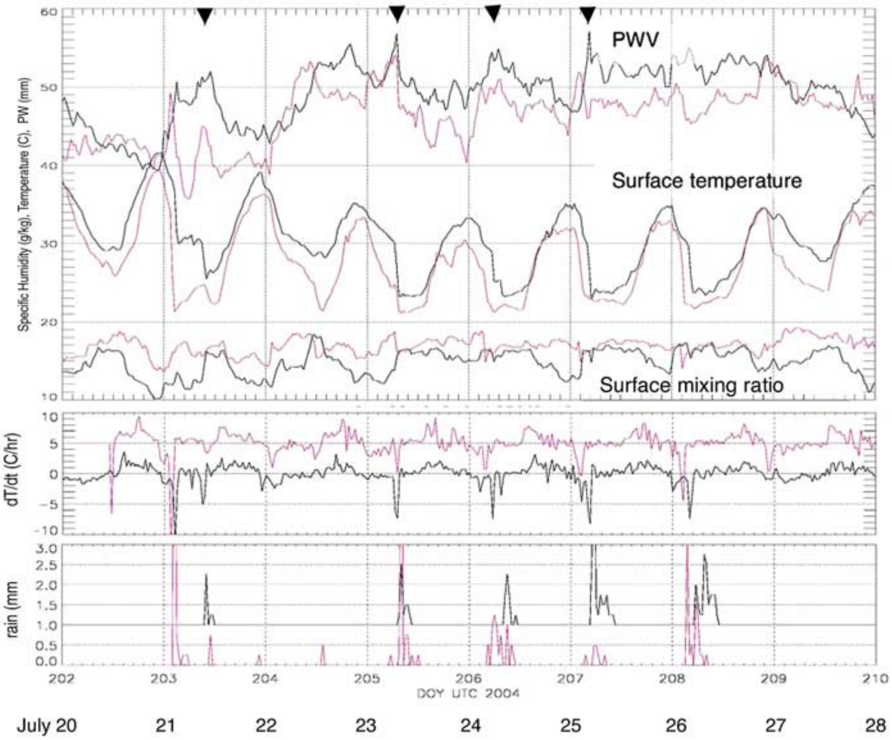

Figure 4. 8 days of diurnal variation observed at Mazatan (red) and Hermosillo (black). From top to bottom: PWV (mm), surface temperature (°C), surface specific humidity (g/kg), the time rate of change of surface temperature (°C/hour) and half hourly precipitation (mm). To separate the behavior, the Mazatan temperature gradient has been offset by 5°C/hr and the Hermosillo rain has been offset by 1 mm. Time is in UTC, 7 hours ahead of local Mountain Standard time (MST).

itation increase reflecting the radiative impact of clouds and water vapor as well as sharp 5 to 10°C drops in temperature reaching minima that are only possible with evaporative cooling associated with moist convective downdrafts. Clearly models must include the effects of moist convective downdrafts to represent the diurnal cycle in the NAM area.

[17] Since peak temperatures are typically reached near 00 UTC (5 PM MST in Sonora), a few hours before precipitation begins, convection is not triggered locally at either of these sites but is instead triggered by convective outflows propagating in from higher terrain further east. Convection typically occurs earlier and more often at Mazatan than at Hermosillo reflecting the larger scale precipitation climatology observed in satellite images and rain gauges where convection and precipitation initiate earlier in the day at higher elevations in the SMO and typically propagate westward toward lower elevations and the coastal plain with decreasing rainfall frequency further west [*Gochis et al.*, 2004]. Westward propagating convective systems are evident in comparing the Mazatan and Hermosillo downdraft signatures particularly on days July 24–26. Satellite images show that on each of these days a convective system forms to the east/northeast of Mazatan and propagates west/southwest through the region.

5. Lifting Condensation Level

[18] Based on representative late afternoon values of surface mixing ratio and temperature of 18 g/kg and 32°C at Mazatan versus 12 g/kg and 35°C at Hermosillo, the lifting condensation level (LCL) above Mazatan of 1.2 km is approximately 1 km lower than the LCL of 2.3 km over Hermosillo (above the local surface in both cases) making it significantly easier for condensation and presumably moist convection to form over Mazatan. The difference is due in part to the tendency of q over Hermosillo to decrease in the afternoon presumably associated with less latent heat flux at the surface and deeper boundary layer entrainment of drier air over Hermosillo. Such behavior is particularly evident in the drier periods of the Synoptic-scale interval where q at Hermosillo and Mazatan routinely exhibits an overnight maximum and late afternoon minimum. In the Sub-synoptic interval, afternoon values of q at Mazatan (prior to convection) are often higher than the morning values suggesting some combination of (1) a local surface evapotranspiration flux as the day warms, (2) a moister layer aloft that is entrained into the surface boundary layer as it grows during the morning and early afternoon, and (3) horizontal advection of air in from a more moist surface area presumably from the SMO foothills, but not from the drier plains to the west. In fact, increases in q that often occur after the peak afternoon temperature when surface temperatures are decreasing may be the signature of a cold surface outflow from moist convection at higher elevations to the east, which lifts the boundary layer at Mazatan thereby initiating deep convection. In general, higher q's at Mazatan are consistent with more daily precipitation at Mazatan which creates a wetter surface and higher soil moisture than Hermosillo, which together with evapotranspiration, sup-

plies moisture to the near-surface atmosphere, indicating a positive feedback is operating in the SMO during the Subsynoptic phase of the NAM.

6. Future

[19] A permanent GPS and rain gauge network should be established in the United States Southwest and Northwestern Mexico to provide critical data on diurnal processes related to water and precipitation in the SMO and initializing weather forecasts, and determine interannual variability and trends. Over the long term, such a network could determine whether predictions of regional wintertime drying [e.g., *Seager et al.*, 2007] and monsoon intensification analogous to Asian monsoon predictions [e.g., *Kripalani et al.*, 2007] will prove to be true.

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