NOTES AND CORRESPONDENCE

Preliminary Diagnostics from a New Event-Based Precipitation Monitoring System in Support of the North American Monsoon Experiment

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ABSTRACT

The purpose of this note is to present preliminary findings from a new event-based surface rain gauge network in the region of northwest Mexico. This region is characterized as semiarid, owing the largest percentage of its annual rainfall to summer convective systems, which are diurnal in nature. Although the existing surface network and satellite-derived precipitation products have clarified some features of convective activity over the core region of the North American monsoon (NAM), a detailed examination of the spatial and temporal structure of such activity has been prohibited by the lack of a surface observation network with adequate temporal and spatial resolution. Specifically, the current network of sparsely spaced climate stations has inhibited a detailed diagnosis of the timing, intensity, and duration of convective rainfall in general, and of the topography–rainfall relationship in particular. In this note, a brief overview of the network and present preliminary analyses from the first monitoring season, summer 2002, is provided. It is shown that the diurnal cycle of precipitation varies with elevation in a way that is consistent with a hypothesis that convective events organize and, occasionally, propagate from high terrain onto lower-elevation plains, but more conclusive statements will require expansion of the network and increased record length. It is also emphasized from these studies that it is essential to evaluate wet-day statistics or rainfall intensities from precipitating periods in parallel, with comparable all-day statistics, when conducting hydrometeorological analyses in semiarid convective regimes where precipitation is infrequent and highly localized.

1. Introduction

a. General description

In this section, the implementation of the surface rain gauge network in support of coordinated field activities of the North American Monsoon Experiment (NAME) is briefly detailed. (Preliminary analyses are provided in section 2.) The NAME program is broadly aimed at improving both the understanding and predictability of warm season precipitation in southwestern North America. [Readers unfamiliar with the NAME program should refer to the NAME Science Plan (NAME Science Working Group 2002) for a detailed presentation.] The network is being installed in two phases corresponding to the 2002 and 2003 fiscal cycles. During phase 1, 50

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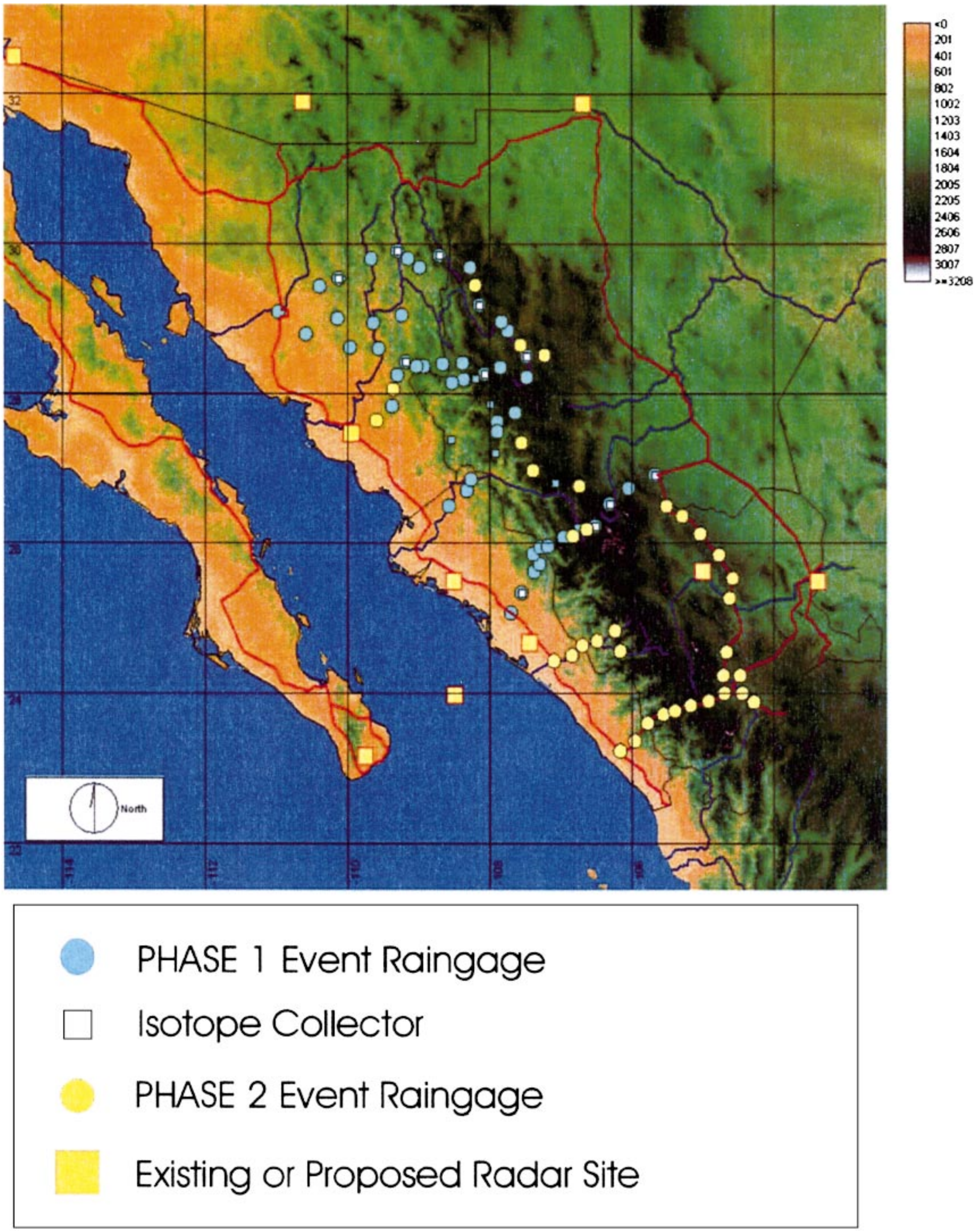

FIG. 1. Map of currently installed (phase 1, blue circles) and pending implementations (phase 2, yellow circles) of the enhanced surface rain gauge network in northwest Mexico. Shading indicates topographic relief.

tipping-bucket rain gauges were installed over the month of July and the first days of August 2002 (Fig. 1). The installation of 50 additional rain gauges, as part of the phase-2 installation, is planned for the spring of 2003. When completed, the entire network of rain gauges will consist of 100 automatic, tipping-bucket rain gauges, which have the ability to measure effective precipitation intensity values.

The tipping-bucket rain gauge used in this project is the Texas Electronics TR-525USW, which is calibrated

TABLE 1. Topographic breakdown of network and elevation band average precipitation characteristics for phase-1 rain gauge installations. Percentage of wet days (%) indicates percentage of days of record where precipitation occurred. Wet-day occurrences are defined as days with precipitation ≥0.254 mm. All intensity values: mm h^{-1}.

Elevations bands	Network	B1	B2	B3	B4	B5	B6
Elevation band interval (m)		0–500	500–1000	1000–1500	1500–2000	2000–2500	2500–3000
Total no. of gauges	50	16	10	1	10	11	2
Percent of network (%)		32	20	2	20	22	4
No. gauges reporting (2002)	47	14	10	1	9	11	2
Avg of wet days (%)	51	38	51	71	61	59	54
Std. dev of wet days (%)	15	8	11	n/a	19	10	2
Avg intensity	2.7	3.2	2.3	3.2	2.4	2.3	2.5
Avg max intensity	28.2	35.4	29.3	27.9	22.2	25.3	15.2
Std dev max intensity	13.7	15.2	10.3	n/a	10.2	15.5	5.4
Absolute max intensity	67.3	67.3	41.7	27.9	40.6	54.1	19.1

at 0.254 mm (0.01 in.) per tip. Factory calibration of the rain gauge is reported to yield an accuracy of 1% at a rain rate of 25.4 mm h^{-1}. Field calibration will be performed in coordination with the downloading and servicing of each gauge. Each tip of the bucket triggers an electronic signal, which is stored on an Onset Computer Corporation ‘‘HOBO’’ event datalogger. Rainfall events are stored on the datalogger until manually downloaded. Presently, there are no remote communication devices attached to the rain gauges. The HOBO datalogger has an 8000 event storage capacity, which results in the effective storage of 2032 mm of precipitation. This quantity is substantially higher than the mean annual precipitation in the NAME region. However, it is not guaranteed that this capacity will never be exceeded in a particular year. Thus, the entire network is scheduled to be downloaded at least twice a year to preserve as much data as possible. Technical specifications on both the rain gauge and the datalogger can be obtained from the vendor’s Web sites (available online at www.texaselectronics.com/ and www.onsetcomp.com/).

Rain gauge locations were obtained using a handheld Global Positioning System (GPS) unit. Elevation data were provided through the GPS by two different techniques. The first method uses a barometric altimeter contained within the GPS unit. The altimeter was calibrated whenever possible at known elevation locations. The second estimate of elevation uses the GPS position locator to estimate elevation. Horizontal accuracy of the GPS is reported to be 15 m or less, depending on satellite reception and signal distortion (Garmin 2002). The vertical accuracy of the barometric altimeter is reported to be 3 m when properly calibrated, while the vertical accuracy of the GPS located position is estimated to be 15 m. Extensive metadata on the gauge sites, such as site descriptions, personal contact information, soils descriptions, and a photographic archive, are compiled and available in a master network document. (Gochis et al. 2002).

b. *Research objectives*

The primary objectives for the installation of the NAME surface rain gauge network are as follows:

1) to install, maintain, and collect data from a new network of rain gauges comprising transects, accessible by road, that sample the intensity of and topographic influence on precipitation in the Sierra Madre mountain range; and
2) to make hydrologically relevant analyses of the data from the new observation network, including the derivation of intensity–duration–frequency analyses and the definition of the observed precipitation gradient relative to topography.

As can be seen from Fig. 1, the network consists primarily of multiple west–east transects that follow regional transportation corridors. These corridors provide access through the formidable Sierra Madre Occidental (SMO) mountains. While the network does not present an optimal configuration for measuring the spatial (i.e., horizontal) distribution of convective rainfall, it provides effective longitudinal and elevation sampling of precipitation at instantaneous rates, while maintaining accessibility to measurement sites for the protection, routine maintenance, and downloading of data. Twenty-one of the new rain gauges are collocated with existing daily observation climate stations operated by the Comission Nacional del Agua (CNA), which facilitates error checking and quality control in the processing of precipitation data. Installing a portion of the new rain gauges within existing CNA enclosures also provides improved security and maintenance of the overall observation network, which increases its long-term viability. Therefore, the network configuration presents a practical compromise between fulfilling the specified scientific objectives, and limiting equipment and labor expenditures.

c. *Rainfall sampling as a function of elevation*

The elevation breakdown of the phase-1 installation is provided in Table 1, and a map of the elevation bands overlain with phase-1 gauges is provided in Fig. 2. The overall range in elevation sampled by the enhanced network (71–2979 m) improves the sampling range of the existing daily climate observation network operated by the CNA (71–2347 m) by over 600 m. The mean ele-

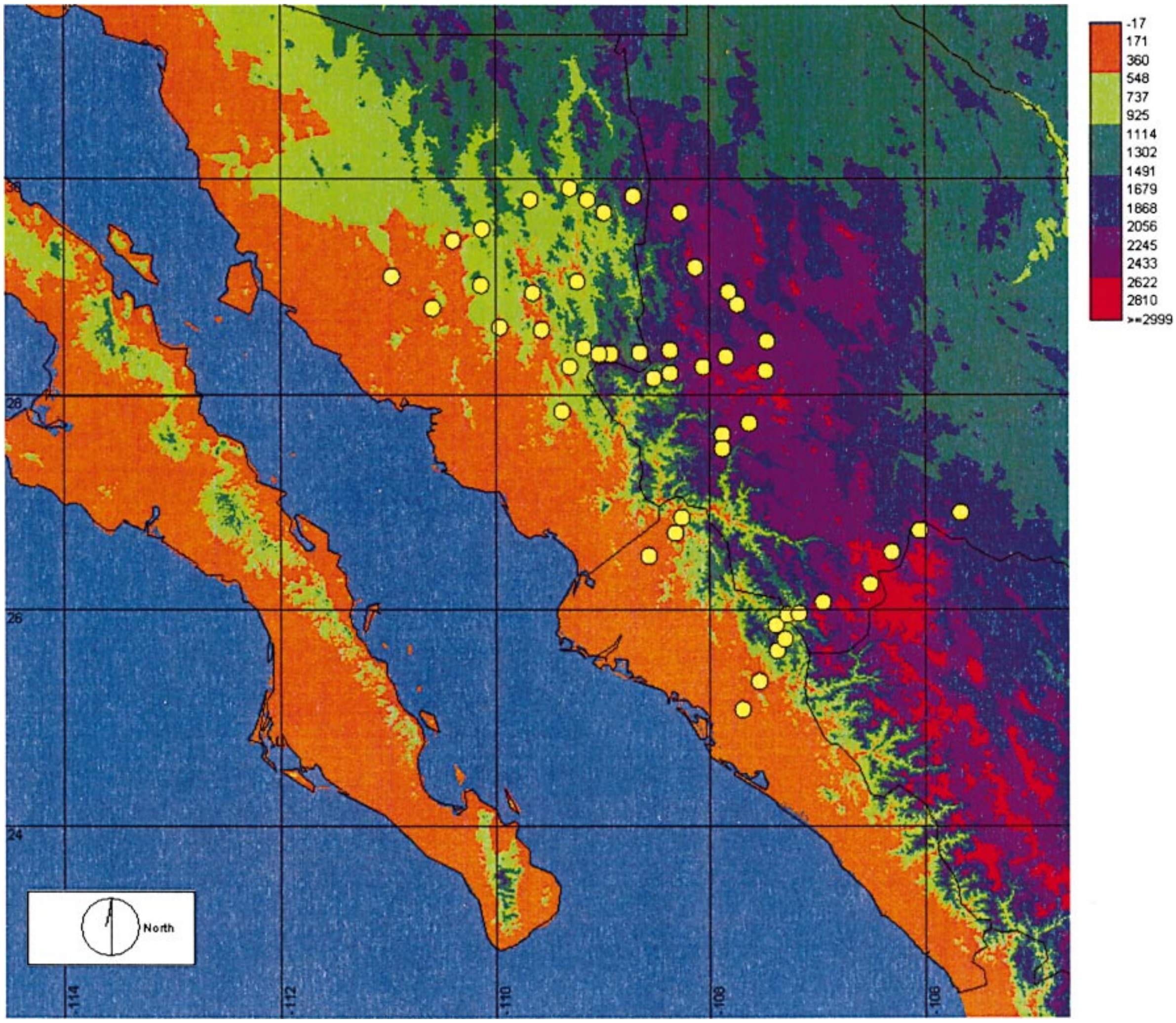

FIG. 2. Map of phase-1 rain gauges overlain topography separated by elevation bands. Shading color indicates elevation band: band 1 (orange), band 2 (light green), band 3 (aqua), band 4 (blue), band 5 (purple), band 6 (red). Note the distinct lack of terrain in elevation band 3 along the western Sierra Madre Occidental.

vation of the enhanced network is 1226 m compared with 886 m of the CNA climate-observing network, which helps to remove a low-elevation bias in the original observational network compared with the regional topography. Additionally, there are now 13 gauges located at over 2000-m elevation, where before there were two. As shown later in the analyses, these new high-elevation stations are critical for analyzing temporal features of terrain-induced convective precipitation. A notable feature from Table 1 is the dearth of gauges located in the 1000–1500-m interval (elevation band 3). It is apparent from Fig. 2 that there is comparatively little terrain in this elevation band along the western slope of the SMO. In fact, the terrain in this region is quite steep, rising from average valley elevations between 400 and 1000 m (shown in orange and green in Fig. 2) to the plateau and ridgeline elevations over 1500 m. Consequently, sampling in the 1000–1500-m band is currently deficient, though phase-2 enhancements will increase sampling in this interval.

d. *Coordinated isotopic sampling*

In addition to the automatic, tipping-bucket rain gauge network, 12 bulk rainfall collectors were deployed at selected sites for the collection and analysis of isotopes. Isotopes can potentially serve as atmospheric and terrestrial tracers of moisture sources, paths, and processes. These sites, shown as white squares on Fig. 1, are intended to sample the longitudinal and elevational gradient of isotope content in monsoon rainwater, most prominently tritium and δO^{18}. The bulk collectors consist of a metal garbage can, approximately 1 m in height, which has an 8-in. hole cut into the lid. Rainwater is collected in polyvinyl chloride (PVC) bags, which are fitted inside the can and collared by a large washer. The collar prevents evaporation from the rainwater reservoir, which would result in isotopic enrichment. Details on the construction and performance of the bulk precipitation collectors can be found in USGS (1994).

e. Plans for 2003 and 2004

Approximately 50 additional gauges will be installed during the spring of 2003, which will increase the number of tipping-bucket gauges in the network to 100. Proposed locations for new rain gauge sites are shown as yellow dots in Fig. 1. One additional ‘‘supertransect’’ will be installed, which will proceed from the southern coast of Sinaloa, Mexico, near Mazatlan, northeastward to the capitol city of Victoria de Durango. This addition will form the fourth supertransect, which completely traverses the Gulf of California’s coastal plain and the cordillera of the SMO. Continued installation of small transects inland from the coast is planned as well. Combined with the larger supertransects, these smaller transects provide the dual benefit of characterizing the precipitation gradient along the western slope of the SMO as well as enhancing latitudinal coverage of propagating disturbances, such as ‘‘gulf surges’’ (e.g., Hales 1972; Fuller and Stensrud 2000) that move parallel to the axis of the Gulf of California. Remaining gauges will fill critical gaps in the existing network. For reference, several remote sensing platforms, which are expected to be operational during the NAME intensive observation period (IOP) in the summer of 2004, are shown in Fig. 3. Deployed radars, in particular, will provide valuable information on the three-dimensional distribution of rainwater, which, when properly calibrated by surface rain gauges, yield detailed information on landfalling precipitation characteristics across the core North American Monsoon (NAM) region.

2. Analyses

a. General precipitation characteristics

A wet-day analysis was performed to determine the elevational dependence of the frequency of measurable precipitation days [$\geq$0.254 mm (0.01 in)]. From Table 1 there appears to be a general relationship between the percentages of wet days (i.e., % wet days = 1/frequency of days with precipitation) with elevation up to the 1000–2000-m elevation range. (Note that elevation bands 3 and 6 contain only one and two gauges, respectively, and, thus, do not represent a broad sampling in their respective elevation bands.) At higher elevation bands (5 and 6) the percentage of wet days decreases slightly. This feature indicates a maximum frequency of precipitation occurrence along the upper western slope of the SMO cordillera. Hence, time mean precipitation rates, especially at low elevations, are likely to have a low bias in average precipitation rates due to the inclusion of a significant number of zero precipitation members. Similar wet-day analyses were performed as functions of both latitude and distance from the coast of the Gulf of California, although neither produced any coherent relationship.

There is considerable uncertainty in wet-day/elevation relationship, though, as evidenced by the large amount of scatter at most elevation bands shown in Fig. 4. Standard deviations of wet-day average percentages (Table 1) across 0–500-, 500–1000-, 1500–2000-, and 2000–2500-m bands are all around 20%–30% of mean values. At the time of this writing it is not known whether this scatter is strictly due to the short record or to climatically stable local variations in precipitation (i.e., stationary spatial variation of precipitation). Such variations could, likely, be caused by climatically preferable locations for precipitation occurrence or nonoccurrence, which are related to the topography. Work is proceeding along this line to determine the degree of intraelevation band variability.

Table 1 also presents rainfall intensity values separated by elevation bands. Rainfall intensity values are calculated as the hourly rate of rainfall using only hours that have measurable precipitation. Elevation band average precipitation intensity values range between 2.3 and 3.2 mm h^{-1} and do not show much of an elevation dependence. In a region of strong localized convection, however, these average values likely mask a strong range in precipitation intensities. In fact, the elevation band average maximum intensity values are substantially higher than the band average values and do tend to reveal a relationship with elevation. From this preliminary dataset it appears that the band average maximum values tend to decrease with increasing elevation. Elevation band 1 (0–500 m) contains the largest absolute maximum intensity as well as the large band average intensity and elevation band 6 (2500–3000 m) contains the smallest band average maximum and absolute maximum values. This relationship holds for all bands except for elevation band 5 (2000–2500 m), which is larger than band 4. From the elevation band absolute maximum and standard deviation values, it is likely that the elevation band 5 average maximum value is biased by an single intense event (54.1 mm), which is only exceeded by more intense events in elevation band 1. Standard deviation values for maximum precipitation intensities range from 5.4 mm h^{-1} for elevation band 6 to 15.5 for elevation band 5, signifying substantial variations in maximum precipitation intensities between SMO convective events.

b. Characterization of the diurnal cycle

As mentioned in section 1.2, one of the primary research objectives in installing this network was to define the diurnal cycle of precipitation occurring over the core region of the NAM. To do so the raw event precipitation data was first converted from mountain standard time

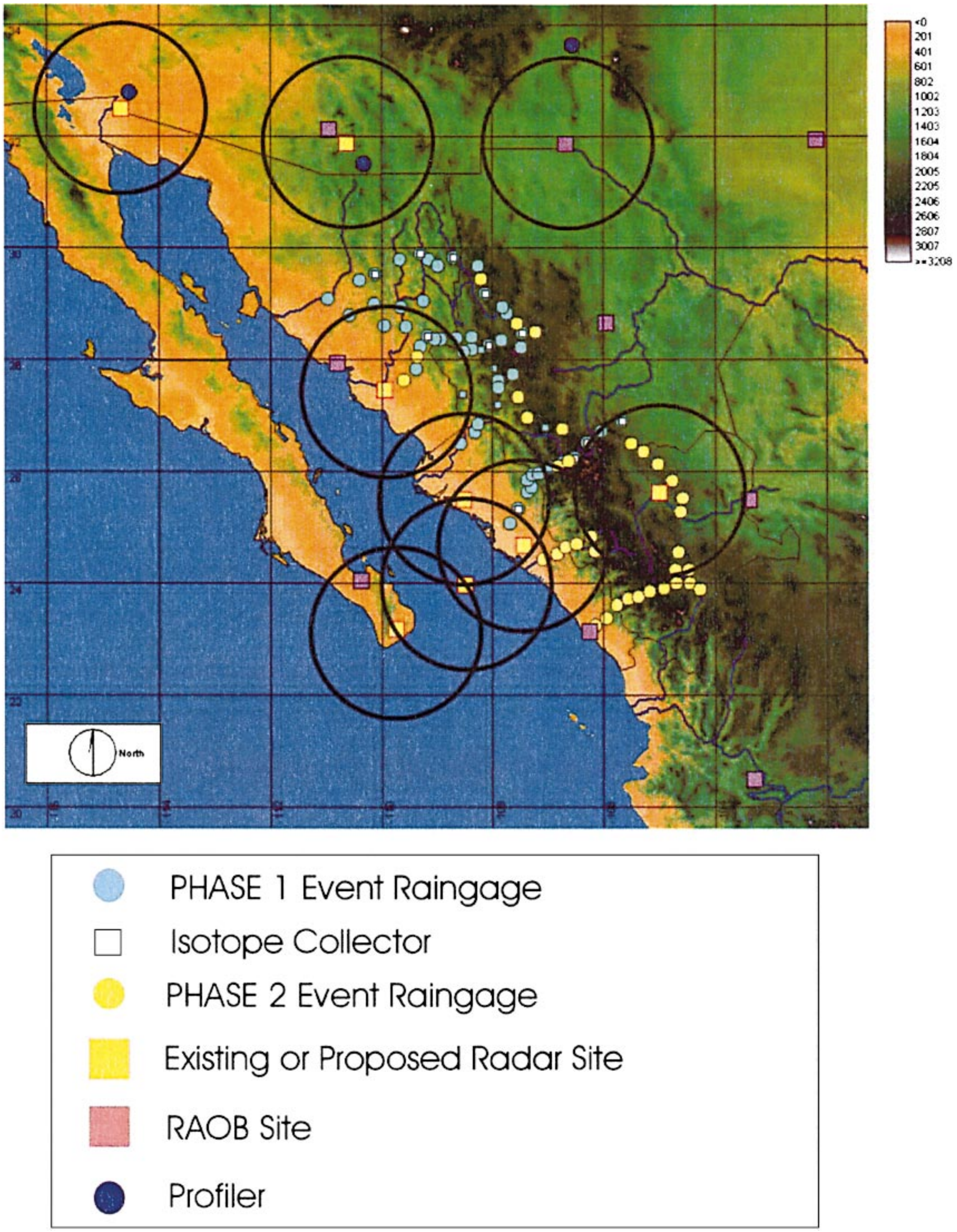

FIG. 3. Map of phase-1 rain gauges and other instrument platforms expected to be deployed during the NAME IOP in summer 2004. Heavy circles represent typical range of radar coverage without adjustment for terrain blockage.

to local solar time (LST). The data was then reprocessed into hourly aggregates, which creates a uniform dataset for each gauge containing hourly precipitation totals. All-day and wet-day hourly rain-rate averages for the entire network and for individual elevation bands given in Table 1 were then computed. Wet-day hourly rain rates were used as opposed to hourly precipitation intensities because of the limited amount of data available

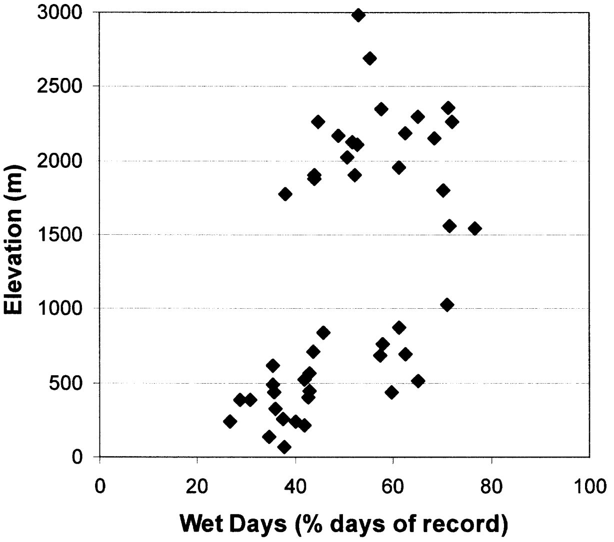

FIG. 4. Scatterplot of the percentage of wet days of record (%) vs rain gauge elevation (m MSL).

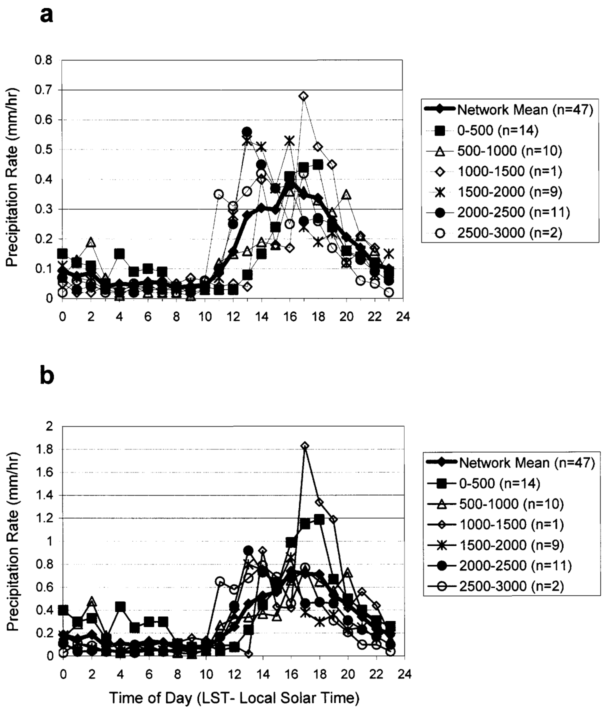

FIG. 5. Diurnal cycle of mean hourly precipitation rates and precipitation intensity (mm h^{-1}) for the entire network and for specified elevation bands. (a) Hourly rain-rate averages computed using all days of record. (b) Hourly rain-rate averages using wet days of record. Small numbers in parentheses indicate the number of gauges used in each average. [Note: band 3 (1000–1500 m) has only one gauge and band 6 (2500–3000 m) has two gauges currently available and are subject to marked uncertainty.]

for individual precipitating hours. Analysis of the diurnal cycle of precipitation intensity will be pursued as more data becomes available.

Figure 5a shows the diurnal cycle for hourly rain rates for all days of record while Fig. 5b shows the same diurnal cycle for wet days. From both figures, there is a distinct precipitation maximum in the early afternoon, beginning around 1300 LST, and continuing until early evening, around 1800 LST. The exact timing of the maximum is dependent upon elevation. The first elevation bands to peak in the all-day diurnal cycle (Fig. 5a) are elevation bands 4, 5, and 6. Conversely, lower-elevation stations in elevation bands 1, 2, and 3 tend to peak later in the afternoon. (Again, elevation band 3 (1000–1500 m) only contains one station at this time and, thus, is subject to considerable uncertainty.) Elevation band 6, the highest elevation band (2500–3000 m), shows a diurnal cycle similar to elevation bands 4 and 5 in intensity but shifted early in the day by about 1 h. However, there are currently two gauges in elevation band 6 as indicated by the small number next to the elevation band in the legend, which results in increased uncertainty of the hourly mean estimates.

One shortcoming of the all-day analysis is that the values given in Fig. 5a include many time occurrences when zero precipitation is recorded. As noted above and in Gochis et al. (2003), precipitation signals in this region can be masked by taking spatial or temporal averages where large precipitation-free regions and periods exist. This is likely true for many semiarid regions, in particular, and in regions of warm season convection, in general. To refine the conceptual picture of the diurnal cycle, we repeated the hourly precipitation analysis using only wet days as defined above. The wet-day diurnal cycle averages shown in Fig. 4b illustrate several differences from the all-day averages in Fig. 4a. Most remarkable is the large increase in peak mean hourly rain rate in the lowest elevation band (elevation band 1, 0–500 m) from 0.4 to over 1.1 mm h^{-1}. Increases in mean rain rate occur within all elevation bands that contain a significant number of rain gauges, but the effect is clearly most pronounced in elevation band 1. This indicates that while precipitation may be less frequent at lower elevations, there is a tendency for such events to be of greater intensity. It may also be suggestive of the fact that low-elevation locations are controlled by a different precipitation regime (e.g., transient disturbances, such as gulf surges) rather than terrain-induced convection. These conclusions, however, will need to be verified using a longer record of precipitation intensity values computed from only precipitating periods. As pointed out in Gochis and Shuttleworth (2002, unpublished manuscript) and Gochis et al. (2003), these specific precipitation characteristics can have a significant impact on hydrological responses, such as the generation of surface runoff. Also, the network mean hourly average rain rates nearly double when wet-day values are used. This feature reiterates the importance of using wet-day or precipitation intensity precipitation information when performing detailed hydrometeorological analyses and/or verification in semiarid regions of localized convection.

The daily precipitation cycle clearly appears to originate first at the highest elevations and slightly later at correspondingly lower elevations. This transition is notably similar to that occurring over the eastern Rocky Mountains and western Great Plains (e.g., Dai et al. 1999; Carbone et al. 2002), where frequent high-elevation thunderstorms originating over large topographic features often organize and propagate off high terrain and onto lower-elevation plains. However, it is not definitive from this analysis that the transition in peak intensity times is evidence of continuous or discrete propagation of convective events from high to low elevation locations. Clearly it is possible for a variety of convective processes to be at work in this environment, and gaps in the current network, in particular, the lack of observations in the 1000–1500-m interval, contribute to this uncertainty. It is suspected that both continuous and discrete propagation of events contribute to the diurnal evolution of wet-day precipitation, as depicted in Fig. 5b, and investigation of this question is the subject of ongoing research. However, definitive information on the covariance structure of gauge precipitation and propagating storms as observed by calibrated radars, await the installation of additional gauges under phase 2 and the upgrade and deployment of local radars planned for the NAME IOP in 2004.

3. Conclusions

The first phase of a new network of event rain gauges has been deployed in the core region of the North American monsoon in northwest Mexico. The primary objectives in installing such a network are to increase understanding of the diurnal cycle of convection and its topographic dependence and to provide a ground-truth dataset for remote sensing estimates of precipitation during the NAME IOP in 2004. The preliminary examination from the first season of data has disclosed a distinct diurnal cycle of precipitation, previously only inferred through personal observations, remotely sensed estimates, large-scale analyses, and limited numerical modeling experiments. On average, convective rainfall appears to initiate first and most frequently over the higher terrain of the SMO. Less frequent, but higher-rate events occur over the lower-elevation foothills and coastal plains of the region. It was suggested that wet-day statistics and/or precipitation intensities are invaluable when calculating time-integrated values of precipitation in semiarid regions of localized convection. As work progresses, the development and maintenance of this network is bound to make significant contributions to understanding hyrdometeorological processes in western Mexico.

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