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Ecohydrology of dry regions of the United States: precipitation pulses and intraseasonal drought†

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ABSTRACT

Distribution of precipitation event sizes and interval lengths between events are important characteristics of arid and semi-arid climates. Understanding their importance will contribute to our ability to understand ecosystem dynamics in these regions. Our objective for this paper was to present a comprehensive analysis of the daily precipitation regimes of arid and semi-arid locations of the United States. We collected 30 years of daily precipitation and temperature data from 289 sites in the intermountain zone and 240 sites in the Great Plains for our analysis. The daily precipitation regimes at all sites were dominated by the smallest event sizes and the shortest intervals between events. Great Plains sites on average had more small events and more short intervals than sites in the intermountain zone. In both regions, small events and short intervals were significantly negatively correlated to all other sizes suggesting they were useful for characterizing precipitation regimes. Both the smallest precipitation events and the shortest intervals between precipitation events increased as mean annual temperature decreased. Small events were negatively, but short intervals were positively related to mean annual precipitation. Additional analysis of Great Plains data suggested both quantitative and qualitative differences between precipitation regimes in wet and dry climates. These differences are attributable in large part to the differences in the relationship between precipitation and the evaporative demand of the atmosphere between the semi-arid and sub-humid portions of the Great Plains. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS arid; semi-arid; event size; small events; Great Plains; intermountain zone; precipitation regime

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INTRODUCTION

Two characteristics of the climate of arid and semi-arid environments guarantee that their ecosystems will be strongly shaped by pulse weather events. The first is the nearly constant force of huge evaporative demand that exercises a pervasive control on potential water losses by evaporation and transpiration (Sala *et al.*, 1992; Gowing *et al.*, 2006; Lauenroth and Bradford, 2006). The second is the low and variable precipitation regime that is often considered the definitive feature of arid and semi-arid regions (Noy-Meir, 1973). The interactions of these two qualities suggest that at the daily time scale, the most accurate description of soil-water availability is a continuous background of dry soil which is irregularly broken by brief periods of wet soil (Sala *et al.* 1992; Lauenroth and Bradford, 2006). The duration of these wet periods depends primarily on the size of the initiating precipitation event (Sala *et al.*, 1992) and the antecedent state of soil water. The duration of the preceding dry soil conditions depends on the length of the interval since the last precipitation event (Wythers *et al.*, 1999; Loik *et al.*, 2004).

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The size distribution of daily amounts of precipitation in the North American shortgrass steppe is considerably skewed towards the smallest sizes (Sala and Lauenroth, 1982; Sala *et al.*, 1992). These small precipitation events only wet the shallowest of soil layers and are most often rapidly lost back to the atmosphere (Sala and Lauenroth, 1982, 1985). The probability that a daily precipitation event will influence plant growth is low for the smallest sizes and increases as event size increases (Noy-Meir, 1973; Sala and Lauenroth, 1982). In the shortgrass steppe, more than 70% of precipitation events are less than or equal to 5 mm and they contribute 25% to the amount of growing season (May–October) precipitation (Sala and Lauenroth, 1982). Conversely, only 7% of events are greater than 20 cm, but they contribute 35% of growing season precipitation.

Based upon different response times between microbes and higher plants, Sala and Lauenroth (1982) suggested that the smallest pulse components of the precipitation regime would have a larger affect on processes mediated by microbes such as decomposition and nutrient cycling than on plant growth. Recently, these ideas have received considerable attention and have been extended to net ecosystem carbon exchange (Huxman *et al.*, 2004; Kurc and Small, 2007; Sponseller, 2007). Huxman *et al.* (2004) constructed a conceptual model that suggested that small events stimulated ecosystem respiration more than plant uptake and that the opposite was the case for large events. Kurc and Small (2007) working in a Chihuahuan desert

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reported that variability in evapotranspiration was most closely related to changes in soil water at 2·5 cm depth, but that carbon uptake was most closely related to soil water in deep layers. Water added to Sonoran desert field plots simulating a range of events from small to large produced rapid respiration responses to even the smallest water additions although the duration of the response was directly related to the size of the simulated event (Sponseller, 2007).

Precipitation thresholds for carbon uptake for grass and shrub communities in the Sonoran desert were 23–148 mm and 59–140 mm respectively. The large range of threshold values was a consequence of seasonal differences in evaporative demand and the length of time since the most recent precipitation event large enough to stimulate CO_2 uptake (Emmerich and Verdugo, 2008), underscoring the importance of characterizing the dynamics of wet and dry periods in pulse-driven arid and semi-arid ecosystems.

Whereas the significance of size distributions of precipitation events has been explored in the theoretical ecohydrology literature (Laio *et al*., 2001; Porporato *et al*., 2001, 2004, 2006), previous empirical analyses of size distributions of precipitation events and/or distributions of lengths of dry intervals in North America have been limited to a single site in the Great Plains and a collection of sites from the intermountain west (Sala and Lauenroth, 1982; Wythers *et al*., 1999; Loik *et al*., 2004). Our objective for this paper was to present a geographically comprehensive analysis of the daily precipitation regimes of arid and semi-arid locations in the United States. Our specific objectives were to (1) characterize the distributions of daily precipitation event sizes and their relationships to geographic and macroclimatic variables; (2) characterize the distributions of dry days between precipitation events and their relationships to geographic and macroclimatic variables; (3) contrast events sizes and dry days between wet (sub-humid) and dry (semi-arid) sites in the Great Plains.

METHODS

Our analyses are based on 30 years of daily precipitation and air temperature data collected from the National Climatic Data Center for the intermountain zone and the Great Plains of the United States (Figure 1, Table I). We chose to evaluate the regions separately because we thought that the differences between the continental and regional controls on their precipitation regimes might result in differences in macroclimatic and geographic relationships. Furthermore, we expected that region-specific analyses would provide the most value to the ecohydrology communities working in each of the regions.

We obtained data from arid and/or semi-arid portions of both regions: 289 weather stations in the intermountain zone and 240 in the Great Plains. The intermountain zone contains both arid and semi-arid climates while the Great Plains is entirely semi-arid (Bailey, 1979, 1981; Lauenroth *et al*., 1999). We used a maximum precipitation amount of 500 mm per year to limit our analyses to the driest sites in the region (Table I).

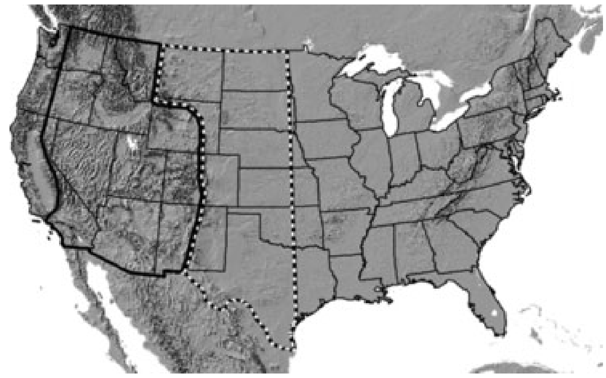

Figure 1. Map of the United States illustrating the location of the intermountain zone (enclosed in solid boundary polygon) and the Great Plains (enclosed in dashed boundary polygon).

We sorted the daily precipitation data from each site into the following seven size categories after removing the zeros (dry days): >0 to <5 mm, 5 to <10 mm, 10 to <15 mm, 15 to <20 mm, 20 to <25 mm, 25 to <30 mm, ≥30 mm. To determine the lengths of intervals between precipitation events, we counted the days without precipitation and sorted them into the following four interval sizes: 1–10 days, 11–20 days, 21–30 days, and >30 days. Our choices of size categories for precipitation events and intervals for dry periods between events were based upon their ecohydrological significance as well as conventions used by other authors (Sala and Lauenroth, 1982; Sala *et al*., 1992; Loik *et al*., 2004).

We used averages of five locations to characterize the maximum, median, and minimum percentages of small precipitation events (>0 to <5 mm) and short dry intervals (1–10 days). For example, to portray the maximum percentage of small precipitation events, we used the average of the five locations with the largest percentages. This prevented an outlier location with a non-representative large percentage of small events from dominating our results. We applied similar logic to characterize the minimum percentage. We used regression and correlation analyses to describe relationships between either event sizes or interval lengths and macroclimatic and geographic variables.

To compare wet and dry climates in the Great Plains, we constructed relationships between small events and macroclimatic variables and dry interval lengths and macroclimatic variables for wet sites (>500 mm) and compared them with extrapolations of our dry-site relationships. Our intent for these comparisons was to reveal quantitative and qualitative relationships between wet and dry sites.

RESULTS

Event sizes

Precipitation regimes at all of the sites, regardless of region, were dominated by the smallest category of

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Table I. Characteristics of 240 weather stations from the intermountain zone and 289 weather stations from Great Plains in the dry portions of the United States.

	Mean		Maximum		Minimum	
	Intermountain	Great Plains	Intermountain	Great Plains	Intermountain	Great Plains
Latitude (°N)	—	—	48.56	48.98	31.27	26.18
Longitude (°W)	—	—	−105.12	−97.05	−121.33	−110.77
Elevation (m)	1305	997	2332	1884	−59	177
Mean annual temperature (°C)	10.8	9.9	24.6	21.8	1.0	2.5
Mean annual precipitation (mm)	278	396	498	500	60	209
Days with precipitation	37	65	60	105	9	29

events. Sites in the intermountain zone tended to have lower percentages of small events than the Great Plains sites (Figure 2). The five intermountain sites with percentages of small events closest to the median averaged 54% of total events in the smallest category compared with 64% for the Great Plains sites. The averages of the five sites with the maximum and the five with the minimum percentages of small events were 72 and 33% for the intermountain zone and 80 and 36% for the Great Plains respectively. All of the event sizes were significantly correlated, but the 0 to <5 mm size category was the only one, which was negatively correlated to all of the other sizes reflecting that when the percentage of small events was large all of the other categories were small and vice versa (Table II). This suggests that information about this category of events is useful to characterize precipitation regimes in arid and semi-arid regions. The other category with large variability among sites was the one greater than 30 mm. These events tend to be few for most sites, but for the sites with the smallest contributions by 0 to <5 mm events accounted for as much as 16% of the total events. The average medians for the >30 mm category were 3% for the intermountain zone and 4% for the Great Plains (Figure 2).

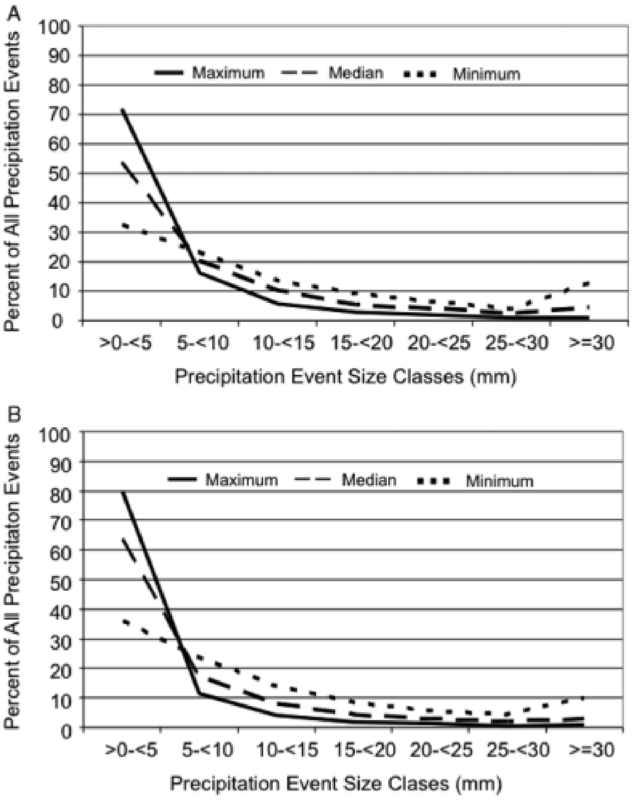

Figure 2. Distribution of precipitation events among seven size categories for 289 sites in the intermountain zone (A) and 240 sites in the Great Plains (B) of the United States. Each point represents an average of five sites. Max = average of the five highest values, Med = average of the five values closest to the median, and Min = average of the five lowest values.

Relationships of events to climate and geography

The percentage of 0 to <5 mm precipitation events was significantly and negatively related to both mean annual precipitation and mean annual temperature for both the intermountain zone and the Great Plains (Figure 3). The percentage of 0 to <5 mm events was greatest at the driest sites and lowest at the wettest sites. It is worth noting that these small events accounted for an average of 45 and 59% of all events at the wettest sites for the intermountain zone and Great Plains respectively. The relationship with mean annual precipitation for the intermountain zone ($y = 0{\cdot}67 - 0{\cdot}0004x$; $P < 0{\cdot}001$; $r^2 = 0{\cdot}26$) represented a much larger range of precipitation than did the relationship for the Great Plains ($y = 0{\cdot}77 - 0{\cdot}0004x$; $P < 0{\cdot}001$; $r^2 = 0{\cdot}06$) (Figure 3a). On average, the driest sites in the Great Plains received more than 200 mm of annual precipitation while the driest sites in the intermountain zone received less than 100 mm.

The ranges of mean annual temperatures were similar between the two regions and the contributions of 0 to <5 mm events were greatest at the coldest sites and smallest at the warmest sites. The relationship for the Great Plains ($y = 0{\cdot}75 - 0{\cdot}013x$; $P < 0{\cdot}001$; $r^2 = 0{\cdot}34$) decreased more rapidly as mean annual temperature increased than did the relationship for the intermountain zone ($y = 0{\cdot}60 - 0{\cdot}005x$; $P < 0{\cdot}001$; $r^2 = 0{\cdot}08$). Because the range of latitudes was similar for the two regions, it is not surprising that the range of mean annual temperatures was also similar.

Significant relationships between the percentage of 0 to <5 mm events and latitude and longitude confirm the relationships with climate variables. The response plane for the intermountain zone ($y = 0{\cdot}20 + 0{\cdot}007x_1 - 0{\cdot}0007x_2$; x_1 = latitude, x_2 = longitude; $P < 0{\cdot}001$; $R^2 = 0{\cdot}14$) was almost parallel to the longitude axis indicating no change in the percentage of small events in

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Table II. Product moment correlation coefficients among percentage contributions of event sizes and with mean annual precipitation for 289 weather stations from the intermountain zone and 240 weather stations from the Great Plains of the United States. Critical values of the correlation coefficient ($P = 0.01$) are 0·17 for 238 degrees of freedom and 0·15 for 287 degrees of freedom.

Intermountain zone

	>0 to <5	5 to <10	10 to <15	15 to <20	20 to <25	25 to <30	≥30	MAP
>0 to <5	1							
5 to <10	−0·51	1						
10 to <15	−0·82	0·47	1					
15 to <20	−0·85	0·35	0·69	1				
20 to <25	−0·82	0·14	0·60	0·71	1			
25 to <30	−0·75	0·05	0·55	0·69	0·74	1		
≥30	−0·78	−0·01	0·46	0·59	0·72	0·69	1	
MAP	−0·51	0·27	0·38	0·35	0·43	0·39	0·43	1

Great Plains

	>0 to <5	5 to <10	10 to <15	15 to <20	20 to <25	25 to <30	≥30	MAP
>0 to <5	1							
5 to <10	−0·83	1						
10 to <15	−0·95	0·79	1					
15 to <20	−0·93	0·69	0·86	1				
20 to <25	−0·90	0·62	0·83	0·86	1			
25 to <30	−0·84	0·50	0·76	0·80	0·80	1		
≥30	−0·84	0·45	0·74	0·83	0·84	0·87	1	
MAP	−0·25	0·03	0·22	0·35	0·32	0·30	0·35	1

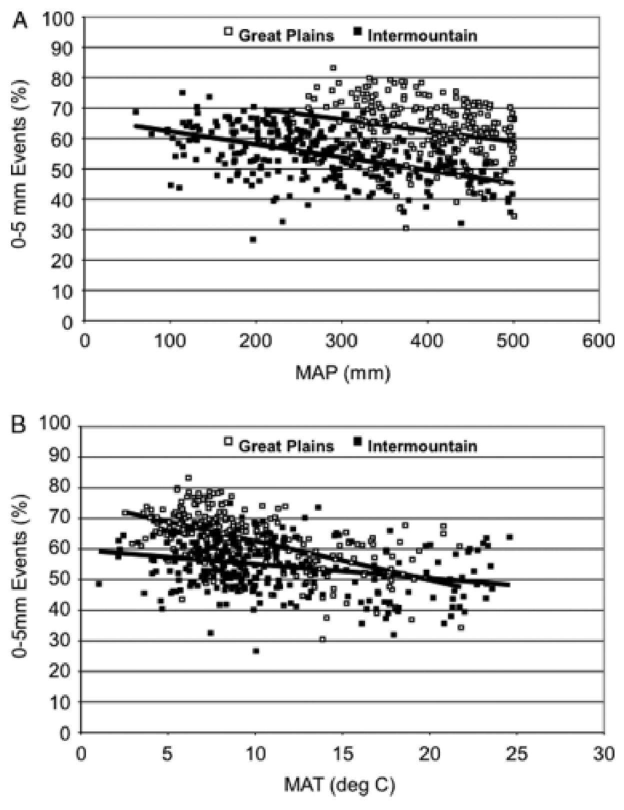

Figure 3. Regression relationships between the percentage of 0 to <5 mm events and mean annual precipitation (MAP) and mean annual temperature (MAT) for 289 sites in the intermountain zone (A) and 240 sites in the Great Plains (B) of the United States. See text for regression equations and statistics.

an east to west direction across the region (Figure 4a). The increase in small events as latitude increases is consistent with the decrease as mean annual temperature increases. By contrast, the response plane for the Great Plains ($y = -0.60 + 0.009x_1 - 0.0087x_2$; x_1 = latitude, x_2 = longitude; $P < 0.001$; $R^2 = 0.44$) sloped relative to both the latitude and the longitude axis (Figure 4b). In the Great Plains, the percentage of small events increased from south to north and decreased from west to east. The west to east decrease in small events reflects the increase in mean annual precipitation along the same gradient.

Dry days

The intermountain zone has a greater range of values for the percentage of all dry days, which fell into both the shortest and longest intervals (Figure 5). The average percentages of all dry periods between 1 and 10 days in the five highest and lowest sites ranged from 0·87 to 0·39 for the intermountain zone and 0·91 to 0·58 for the Great Plains. Despite the larger range in the intermountain zone, the Great Plains sites had larger percentages of dry days in the shortest interval (Figure 5b). The minimum percentage of dry days in the shortest interval category was greater than 50% indicating that the mean dry period for all sites in the Great Plains was 10 days or shorter. By contrast, frequency analysis of the intermountain zone data revealed that 22 sites had minimum percentages of the shortest intervals less than 50% indicating that the average length of dry intervals for those sites was greater than 10 days.

Similar to the smallest precipitation event category, the percentage of dry days in the shortest interval was the only category that was negatively correlated to all of the interval size categories. As the percentage of

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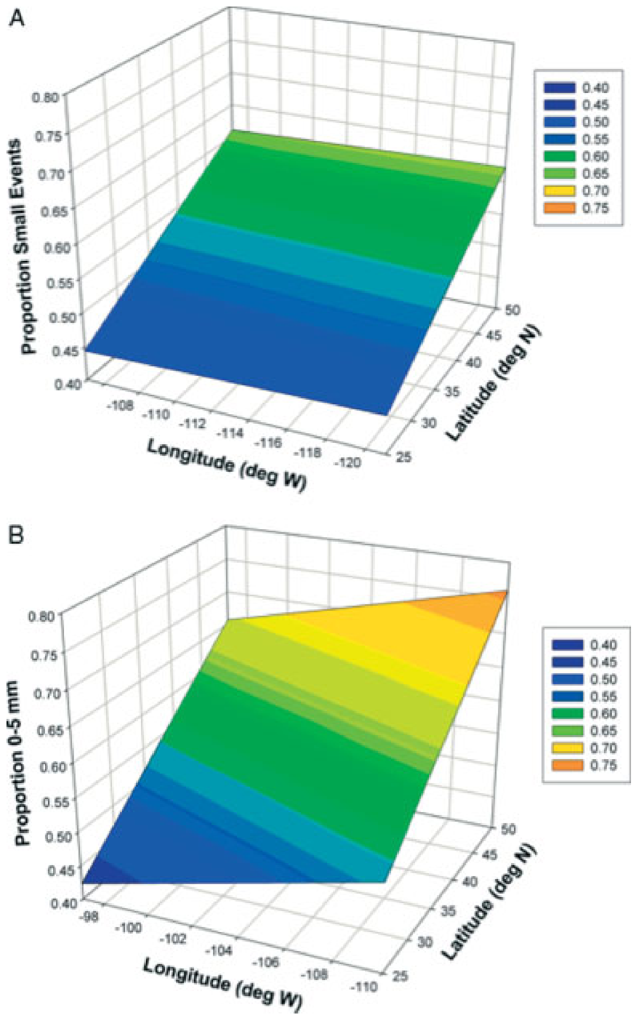

Figure 4. Regression relationships between the percentage of 0 to <5 mm events and latitude and longitude for 289 sites in the intermountain zone (A) and 240 sites in the Great Plains (B) of the United States. See text for regression equations and statistics.

short intervals decreases across sites, all of the other interval categories increase (Figure 5). The sites with the smallest percentages of short intervals have the largest percentages of dry periods greater than 30 days. This is most pronounced for sites in the intermountain zone (Figure 5a). The 22 intermountain zone sites with less than 50% of their dry days in the shortest interval have an average of 26% in the greater than 30-day interval with a range of 17–35%.

Relationships of dry days to climate and geography

The percentage of dry days in the 1–10-day category was significantly related to both mean annual precipitation and mean annual temperature (Figure 6). The relationship with mean annual precipitation was positive for both regions. The relationship for the intermountain zone ($y = 0{\cdot}43 + 0{\cdot}09x$; $P < 0{\cdot}001$; $r^2 = 0{\cdot}65$) had a steeper slope than the relationship for the Great Plains ($y = 0{\cdot}68 + 0.03x$; $P < 0{\cdot}001$; $r^2 = 0{\cdot}05$). The relationships with mean annual temperature were negative. As mean annual temperature increases, the percentage of dry intervals in the 1–10-day category decreased. The regression

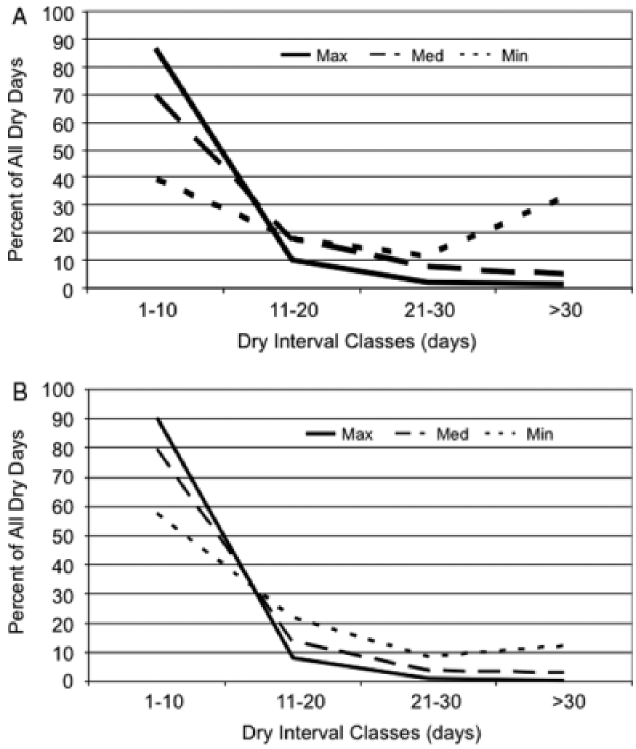

Figure 5. Distribution of dry days among four size categories for 289 sites in the intermountain zone (A) and 240 sites in the Great Plains (B) of the United States. Each point represents an average of five sites. Max = average of the five highest values, Med = average of the five values closest to the median, and Min = average of the five lowest values.

equation for the intermountain zone is $y = 0{\cdot}78 - 0{\cdot}009x$ ($P < 0{\cdot}001$; $r^2 = 0{\cdot}18$) and the equation for the Great Plains is $y = 0{\cdot}92 - 0{\cdot}014x$ ($P < 0{\cdot}001$; $r^2 = 0{\cdot}61$).

The relationships between the percentages of dry days falling into the 1–10-day interval were positive for latitude and longitude for both regions (Figure 7). The largest coefficients were associated with latitude. In the intermountain zone, the proportion of short dry intervals (1–10 days) ($y = 0{\cdot}79 + 0{\cdot}016x_1 + 0{\cdot}0067x_2$; x_1 = latitude, x_2 = longitude; $P < 0{\cdot}001$; $R^2 = 0{\cdot}40$) increased from south to north as well as from west to east (Figure 7a). By contrast, in the Great Plains, the proportion of short dry intervals ($y = 0{\cdot}58 + 0{\cdot}01x_1 - 0{\cdot}002x_2$; x_1 = latitude, x_2 = longitude; $P < 0{\cdot}001$; $R^2 = 0{\cdot}58$) changed dramatically from south to north and very slightly from west to east (Figure 7b). Both the geographic relationships are consistent with the relationships of short-interval dry days to regional changes in mean annual precipitation and mean annual temperature.

Wet and dry sites

Our previous analysis of relationships with mean annual precipitation and temperature provided the basis for this analysis. We compared an extrapolation of our dry-site relationship between small events and mean annual precipitation to the same relationship for both wet and dry sites ($y = 71e^{-0.00042x}$; $r^2 = 0{\cdot}42$; $P \leq 0{\cdot}05$; y = percentage contribution of small events; x = mean annual precipitation). At the wettest sites (1700 mm/year), our extrapolated dry Great Plains relationship predicted fewer

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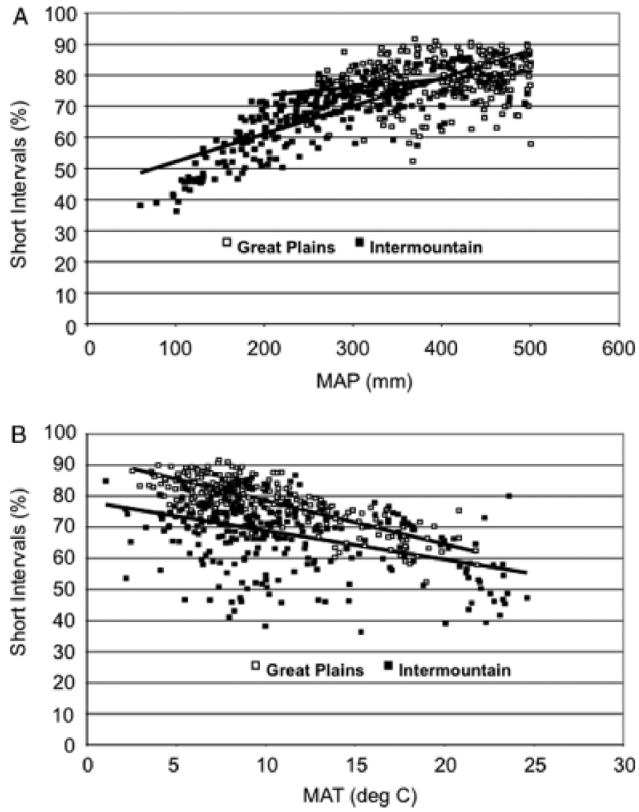

Figure 6. Regression relationships between the percentage of dry days falling into the 1–10-day interval and mean annual precipitation and mean annual temperature for 289 sites in the intermountain zone (A) and 240 sites in the Great Plains (B) of the United States. See text for regression equations and statistics.

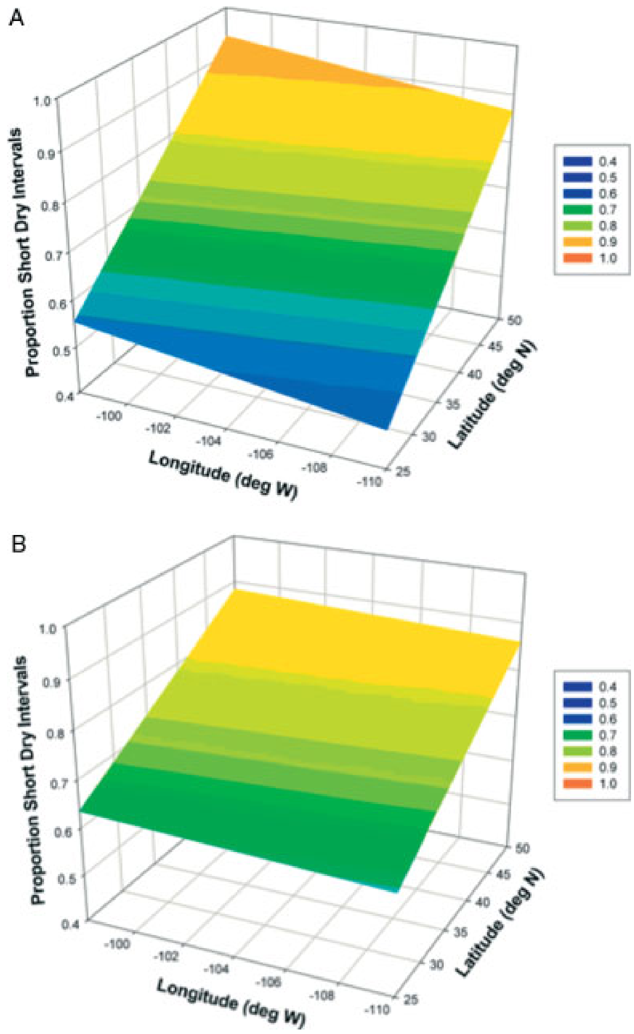

Figure 7. Regression relationships between the percentage of dry days falling into the 1–10-day interval and latitude and longitude for 289 sites in the intermountain zone (A) and 240 sites in the Great Plains (B) of the United States. See text for regression equations and statistics.

than 10% small events whereas the all-site (wet and dry) relationship predicted 35%. The average small-event contribution for the five wettest sites is 41%. Even though our dry-site relationship under-predicted the actual contribution by small events, the trend of decreased importance as mean annual precipitation increases was confirmed. Wet sites have 14% fewer small events and 14% more of the larger sized events. The largest size events ($\geq$30 mm) contribute 6% more at the wettest sites. The relationships between mean annual temperature and the contribution by small events for the dry sites and the wet and dry sites combined, had identical slopes indicating that the trend of decreased importance of small events at the warmest sites was similar regardless of the amount of mean annual precipitation. The intercept was greater for the dry sites indicating that at each temperature.

Do the wet and dry portions of the Great Plains differ with respect to the contribution of short dry intervals between precipitation events? Again we used our analysis of the relationships with mean annual precipitation and temperature to provide a basis for answering this question. Comparing an extrapolation of our dry-site relationship with mean annual precipitation with an all-site relationship ($y = 74 + 0{\cdot}13x$; $r^2 = 0{\cdot}34$; $P \leq 0{\cdot}05$; y = percentage contribution of short intervals; x = mean annual precipitation) suggests large differences at the wet sites. The all-site regression predicts 96% short intervals at the wettest site and the dry-site regression predicts 113%. The average for the five wettest sites is 92%. Despite the over-prediction, the trend from the dry sites is confirmed when the wet sites are included; as mean annual precipitation increases the importance of short intervals increases.

The importance of short intervals between precipitation events decreases as mean annual temperature increases. Analysis of combined wet and dry Great Plains sites revealed that the relationship using only the semi-arid sites has too steep a slope. The dry-site regression predicts 59% short intervals at the warmest site and the all-site regression predicts 79%. The average of the five warmest sites is 73%. Although they decrease with mean annual temperature, short intervals are very important at Great Plains sites regardless of temperature.

DISCUSSION

The driest locations in the United States share a number of features of their precipitation environments, which

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ensure that daily soil-water dynamics will be characterized by pulse behavior. The most common daily precipitation amounts are small. This guarantees that there will be a high probability that the soil will dry out between events. At all sites in the Great Plains and the intermountain regions, at least 30–40% of precipitation events occur in the smallest size category (0 to <5 mm). The prevalence of the smallest event size category decreases as both mean annual precipitation and mean annual temperature increase. The intra-seasonal dry periods that are typical of arid and semi-arid regions are most commonly short (≤10 days) and account for at least 40% of all the dry intervals. Their importance increases as mean annual precipitation increases and declines as mean annual temperatures decrease. Both the distribution of event sizes and the distribution of dry periods are significantly related to latitude and longitude providing insight into the geographic patterns of these important influences on ecohydrology of the arid and semi-arid portions of the United States.

Event sizes

Small precipitation events are a dominating feature of the precipitation regime in arid and semi-arid regions of the United States. All of the other size categories and mean annual precipitation are strongly and significantly negatively correlated with the percentage of small events (Figure 3a, Table II). Sala *et al.* (1992) reported for the shortgrass steppe of the Great Plains that as annual precipitation increased, the contribution by the 0- to <5-mm size category changed only a small amount. By contrast, the amount contributed by events larger than 10 mm increased rapidly, which lead the authors to conclude that the difference between a wet and a dry year was dependent on a very small difference in the number of events in the largest categories. Huxman *et al.* (2004) found similar results for North American subtropical deserts. We found that the mean annual percentage of 0- to <5-mm events was negatively correlated with mean annual precipitation ($r = -0{\cdot}25$, $P \leq 0{\cdot}05$, Great Plains; $r = -0{\cdot}51$, $P \leq 0{\cdot}05$, intermountain zone) and the mean annual percentage of greater than 10 mm events was positively correlated with mean annual precipitation ($r = 0{\cdot}33$, $P \leq 0{\cdot}05$, Great Plains; $r = 0{\cdot}48$, $P \leq 0{\cdot}05$, intermountain zone).

Dry days

Intervals between precipitation events can range between a few to several days, although our analyses suggest that the majority of them are short (Figure 5). Analysis of 54 years of precipitation records for the shortgrass steppe revealed that the average number of days between both growing season and non-growing season precipitation events was 7 days, and 90% of all dry periods were fewer than 15 days (Wythers *et al.*, 1999). Our analysis found that on average 90% of all of the dry periods for both regions were 10 days or shorter for 5% of our sites, 20 days or shorter for 67% of our sites, and 30 days or shorter for 88%.

Short dry intervals are most prevalent at the wettest sites and least prevalent at the driest sites. This is consistent with the positive relationship between the number of days with measurable precipitation and the amount of annual precipitation (Lauenroth and Burke, 1995) and the decrease in the importance of small events (Figure 3). As annual precipitation increases, the number of days with measurable precipitation must increase, which means the average interval between them has to decrease or the size of an average precipitation event has to increase. Our results suggest that both occur (Figures 3 and 6).

The warmest and driest sites have the fewest short dry intervals (Figure 6) and therefore more long intervals (Figure 5). Is the increased prevalence of long dry periods compensated by a shift in the precipitation regimes towards larger precipitation events? The average percentage of >30-mm events for the 10 sites with the fewest short dry intervals in the intermountain zone was equal to the median for the region. In the Great Plains, the 10 sites with the fewest short dry intervals had an average percentage of large events below the median. This suggests that, in both regions, the sites with the largest percentages of long dry intervals do not appear to have a compensating precipitation regime.

Geographic patterns

The clearest large-scale geographic pattern for both the smallest precipitation events and the shortest intervals between events is a south to north increase in each (Figures 4 and 7). Both trends are also correlated with the south to north decrease in mean annual temperatures (Figures 3b and 6b). Whether the climate system processes that explain the decrease in mean annual temperature with increasing latitude are also the explanation for the increases in small precipitation events and short dry intervals must await further development of process-level understanding of atmospheric process controlling daily precipitation (Lee *et al.*, 2007; Schwartz *et al.*, 2008).

The Great Plains also has an increasing trend in small events from east to west correlated with the decreasing trend in mean annual precipitation (Figure 4). This pattern means that locations in the southeast have the smallest contribution by small events and locations in the northwest, the largest. A similar, but very slight trend occurs for the intermountain zone with no associated east-to-west trend in mean annual precipitation. By contrast, the intermountain zone has a clear east-to-west trend of decreasing importance of short dry intervals (Figure 7). No similar trend occurs in the Great Plains.

The east-to-west decrease in short dry intervals results in locations in the southwest portion of the Intermountain Zone having the smallest contributions by short intervals. A possible explanation is that the precipitation climates in the southwestern portion of the zone are more heavily influenced by the North American monsoon compared with locations in the northeast. The same relationship is

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weakly hinted at by the Great Plains data. The difference between the two regions may be the degree of influence of the monsoon (Higgins *et al*., 1999; Liebmann *et al*., 2008). The intermountain zone has substantial and the Great Plains much less monsoonal influence.

Distinctiveness of arid and semi-arid precipitation climates

We collected data from wet sites in the Great Plains as well as from semi-arid locations. Because the Great Plains has little topographic variability, these data offer us the opportunity to investigate differences between semi-arid and sub-humid and humid sites without the discontinuities introduced by abrupt changes in elevation (Lauenroth *et al*., 1999). A key boundary between the semi-arid and sub-humid portions of the Great Plains is created by the ratio of mean annual precipitation to mean annual potential evapotranspiration (Lauenroth and Burke, 1995). The semi-arid portion has a ratio greater than 1 and the opposite is true for the sub-humid and humid portions. This means that on an annual basis, the potential of the atmosphere to evaporate water is always greater than the amount supplied by precipitation (Porporato *et al*., 2004). Sala *et al*. (1992) explained why periods of wet soil are possible by pointing out the temporal-scale dependence of this relationship. They analysed data from 33 growing seasons and found for a shortgrass steppe site that the probability of a ratio of precipitation to potential evapotranspiration greater than 1 was 0·01 for 30 consecutive days, 0·07 for 7 days, and 0·12 for a single day. Complementing this is the idea that at the daily scale, the coefficient of variation of precipitation can be an order of magnitude greater than the coefficient of variation of potential evapotranspiration (Lauenroth and Bradford, 2006).

Semi-arid Great Plains precipitation climates are qualitatively and quantitatively different from those in sub-humid and humid portions of the region (Porporato *et al*., 2004). The qualitative difference is the result of the relationship between precipitation and the evaporative demand of the atmosphere. Crossing the threshold from locations in which annual precipitation is most often greater than annual evaporative demand to those with the opposite relationship corresponds to a threshold across which the dominant signal characteristic of soil-water changes from low to high frequency (Laio *et al*., 2001; Porporato *et al*., 2004). This threshold occurs at the boundary between semi-arid and sub-humid climate types (Lauenroth *et al*., 1999). On the sub-humid side of the threshold, the percentage of small precipitation events is low, the percentage of short intervals between events is high, and there is a low probability that soil water will be depleted by bare soil evaporation or transpiration between events. The semi-arid side of the threshold has high percentages of small events, lower percentages of short intervals between events and a high probability that soil water will be depleted between events. All of these qualities of semi-arid climates are exacerbated in arid climates. These features of semi-arid and arid climates guarantee that temporal soil-water behavior will be characterized by pulse dynamics.

Climate change implications

Human influences on the atmosphere suggest future changes in both temperature and precipitation (Intergovernmental Panel on Climate Change. 2007). The most robust findings are related to changes in temperature and some of the least robust are related to changes in precipitation. Focusing on temperature and making the assumption that our relationships between event sizes and dry days and mean annual temperatures can be used as a guide, we should expect that as climates warm event sizes will increase and the lengths of intra-seasonal dry periods will increase. Our regressions suggest that decreases in the importance of small events will be greatest in the Great Plains, but will occur in both regions. The lengthening of dry periods will occur at approximately the same rates for both regions. Understanding the consequences of such changes awaits further data collection and analyses.

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