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Regional trends and local variability in monsoon precipitation in the northern Chihuahuan Desert, USA

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ABSTRACT

In the southwestern United States, monsoon precipitation can affect changes to the land surface, vegetation communities and ecosystem services. To better understand monsoon precipitation, we quantified change in precipitation properties from 1910 to 2010 at 22 sites across the northern Chihuahuan Desert using United States Historical Climatology Network daily data. We also assessed precipitation variability at the Sevilleta National Wildlife Refuge (SNWR) – located at the desert's ecological boundary – using daily data from a recent 10-year period. Evaluating precipitation at these locations allows for comparison of precipitation variability between ecologically-stable ecoregions and the less-stable boundaries where ecological change may be more likely to occur. Regional data from 1910 to 2010 show an increase in the number of precipitation events, a decrease in their magnitude, and also an increase in the length of extreme periods with and without precipitation. At the SNWR, total precipitation is influenced by a small number of large events, while the majority of events (65%) have an insignificant effect. These analyses suggest that local variability in precipitation may be greater than is often attributed to the summer monsoon, and the difference between wet and dry monsoons depends on the occurrence of a small number of large events.

1. Introduction

Monsoon precipitation exerts a strong control on the ecology and hydrology of arid ecosystems in North America and is especially important in shaping vegetation communities in the southwestern United States (Notaro et al., 2010; Pennington and Collins, 2007). In many years, the summer monsoon is the main component of southwestern US growing seasons (Notaro et al., 2010), and produces the majority of annual vegetation productivity and ecosystem carbon uptake (Muldavin et al., 2008; Pennington and Collins, 2007). Monsoon precipitation is known to be highly variable across space and time (Higgins and Shi, 2000; Higgins et al., 1999). This variation influenced shifts in vegetation communities throughout the 20th century and continues to affect the biotic and abiotic components of southwestern US ecology locally and regionally (Snyder and Tartowski, 2006). In many water-driven ecosystems, vegetation productivity is influenced by variation in total precipitation at seasonal to interannual timescales, but productivity is also influenced by precipitation at shorter timescales as well (Alessandri and Navarra, 2008; Vargas et al., 2012).

Arid and semiarid ecosystems account for approximately 40% of global land area and may be among the first affected regions in cases of strong climatic change (Diffenbaugh et al., 2008). Climate change predictions for the southwestern US call for greater regional aridity (Gutzler and Robbins, 2011; Seager and Vecchi, 2010), but it is unclear how this aridity will be manifest and at what spatial and temporal scales ecosystems will respond. It is also unclear what the driving variables of future climate will be; model simulations from Seager and Vecchi (2010) and Gutzler and Robbins (2011) agree that increased temperature will induce greater regional aridity, but the role of precipitation has not been determined. Seager and Vecchi (2010) and Gutzler and Robbins (2011) both suggest decreased total precipitation and increased annual variability could occur, but precipitation projections are quite uncertain. Furthermore, predictions for increased aridity are in themselves problematic because climate is an aggregation of environmental conditions, and the extrema of these conditions may play a large or even larger role in shaping ecological responses than average values do (Fay et al., 2008; Pennington and Collins, 2007).

The North American Monsoon System (NAMS) is a primary component of the growing season in western North America. While not clearly understood, the monsoon is influenced at annual to inter-decadal timescales by the Pacific Decadal Oscillation (PDO)

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and the El Niño Southern Oscillation (ENSO) (Mock, 1995). The El Niño and La Niña components of ENSO also influence NAMS rainfall, and their combination and timing can induce both wet and dry conditions (Adams and Comrie, 1997; Gochis et al., 2006; Mock, 1995). In the northern Chihuahuan Desert, one of three major deserts in North America, the summer monsoon occurs roughly from July through September (DOY 182–273) and accounts for 40–50% of annual precipitation on average (Douglas et al., 1993). In this and many other arid and semiarid systems, precipitation feeds back on soil moisture (Brunsell et al., 2011; Findell and Eltahir, 2003; Mendez-Barroso and Vivoni, 2010; Xu and Zipser, 2012), and these dynamics may vary across climatic and topographic gradients (Gebremichael et al., 2007; Taylor et al., 2012; Vivoni et al., 2010). Monsoon precipitation often accounts for a large but variable percentage of ecosystem activity locally (Mendez-Barroso et al., 2009; Muldavin et al., 2008), and variation in precipitation–vegetation dynamics may upscale to influence carbon balance (Kurc and Small, 2007; Throop et al., 2013), ecosystem state-transitions (Schlesinger et al., 1990; Van Auken, 2009), and regional precipitation and temperature anomalies (D'Odorico et al., 2012; Ivanov et al., 2008) in the Chihuahuan Desert region.

The biotic and abiotic components of local ecology, such as soil moisture and vegetation productivity, respond to climate forcings at different spatial and temporal scales (Raupach, 1995; Ridolfi et al., 2000; Teuling et al., 2006), which often makes the prediction of ecological responses to climate difficult (Brunsell and Gillies, 2003a, 2003b; Koster and Suarez, 1999; Porporato et al., 2004). In many cases, it is possible that large-scale average values closely associated with climate, such as those of precipitation, mask the smaller scale dynamics that are most important locally. Vegetation in the Chihuahuan Desert responds strongly to monsoon precipitation totals, especially in drier locations (Mendez-Barroso et al., 2009; Pennington and Collins, 2007), but it is less clear how precipitation properties affect vegetation at ecological boundaries, which may be more sensitive to climate variation than the larger ecoregion is (D'Odorico et al., 2013; Gosz, 1993). In response, the analysis of fine-scale precipitation data and its variability across spatial and temporal scales is becoming an important component of predicting the characteristics of global climate change and its potential effects on ecosystem state transitions (Scheffer et al., 2009; Wan et al., 2013). Model simulations and field experiments in arid and semiarid systems both show that varying the properties of precipitation at a single site may produce disparate moisture availabilities and widely varying effects on vegetation fluxes of water and carbon (Petrie et al., 2012; Vargas et al., 2012). There is value in comparing precipitation variability from different spatial scales to better ascertain its influence on ecological communities regionally, and also in within-region locations that may be highly susceptible to climate change.

To better understand precipitation in the southwestern United States in the context of global change projections, we analyzed spatial and temporal variability in monsoon precipitation for the northern Chihuahuan Desert region and locally at the Sevilleta National Wildlife Refuge (SNWR), central New Mexico, USA. Our primary goal was to determine if the properties of precipitation events have changed over the past 100 years. We address the following questions: 1) Has total monsoon precipitation changed from 1910 to 2010 in the northern Chihuahuan Desert region? 2) Have the properties of regional scale precipitation events changed? 3) Has precipitation become more variable over time and does this variability change from dry to wet monsoons? 4) What type of precipitation event magnitudes and event frequencies account for the majority of monsoon precipitation at the SNWR? and 5) Does the nature of monsoon precipitation at SNWR sensors provide further evidence that small-scale precipitation forcings need to be better captured by larger-scale global climate models? By exploring monsoon season precipitation between these locations, this research provides insight on how regional monsoon characteristics may contrast with local characteristics at ecological boundaries, where variability in precipitation may be most influential in a changing climate.

2. Sites

In this study we explored change and variability in monsoon precipitation for the United States portion of the northern Chihuahuan Desert of North America, located in the states of New Mexico, Arizona and Texas (Fig. 1). Elevation in the desert ranges from approximately 800–1800 m. A large portion of annual precipitation may occur during the summer monsoon season (40–50% on average, 5.7 cm regionally from 1910 to 2010) (Douglas et al., 1993; Muldavin et al., 2008). Vegetation is dominated by woody species and grasses in the south (*Larrea tridentata*, *Prosopis glandulosa*, *Bouteloua eriopoda*) and desert grasslands (*Bouteloua gracilis*, *Bouteloua eriopoda*) in the north. The region exhibits an out-of-phase interaction between the spring and summer growing seasons, where precipitation events induce ecosystem pulses of vegetation productivity, nutrient cycling and fluxes of water and carbon differently between the spring and summer (Collins et al., 2008; Muldavin et al., 2008; Schwinning and Sala, 2004; Vargas et al., 2012). Two United States Long Term Ecological Research Network (LTER) sites are located in the region: at the Jornada Basin in southern New Mexico and the Sevilleta National Wildlife Refuge in central New Mexico [http://www.lternet.edu/]. In the first part of the study, we analyzed daily precipitation data for the US portion of the Chihuahuan Desert using United States Historical Climatology Network (USHCN) data from 1910 to 2010 (Williams et al., 2006) [http://cdiac.ornl.gov/epubs/ndp/ushcn/usa.html] (Table 1). An elevation ceiling of 1650 m was employed to ensure sites were located in the Chihuahuan Desert. In total, 22 sites were included: 3 in Arizona, 13 in New Mexico and 6 in Texas (Table 1, Fig. 1). Data records at these sites ranged from 50 to 108 years in length (mean = 80 years) and 16.3% of years included all 22 sites.

The second part of this study focused on the variability of monsoon precipitation at the SNWR, located at the northern boundary of the Chihuahuan Desert in central New Mexico (34.3° N

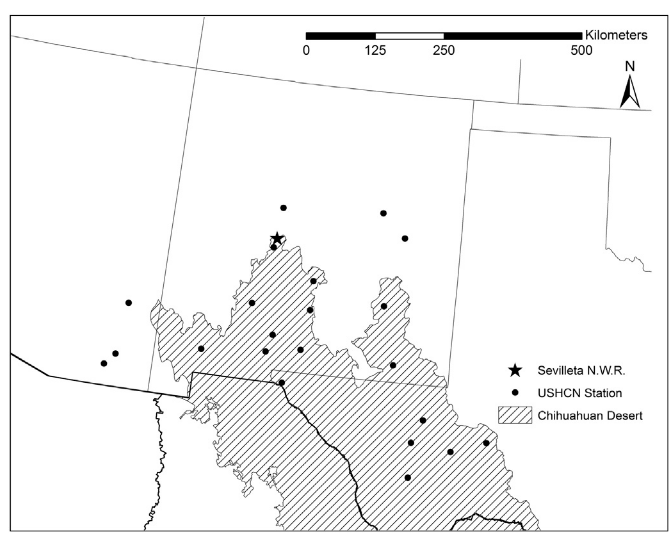

Fig. 1. The United States Environmental Protection Agency's Chihuahuan Desert ecoregion, United States Historical Climatology Network site locations and the Sevilleta National Wildlife Refuge.

Table 1
Summary of United States Historical Climatology Network precipitation sites from 1910 to 2010.

Site	State	Lat [°N]	Lon [°W]	Elevation [m]	Length [yr]	$\bar{P}$ [mm]
292848	NM	33.1	107.2	1395	108	57.8
293368	NM	32.2	108.1	1365	94	61.6
298535	NM	32.3	106.8	1183	87	50.2
294426	NM	32.6	106.7	1300	92	68.1
296435	NM	32.4	106.1	1275	98	52.7
299165	NM	33.1	106.0	1350	89	53.0
291515	NM	33.6	106.0	1647	51	42.6
297610	NM	33.3	104.5	1112	93	50.9
291469	NM	32.3	104.2	951	55	54.6
298387	NM	34.1	106.9	1395	93	65.9
293294	NM	34.5	104.2	1227	105	47.1
295150	NM	34.8	106.8	1475	50	49.9
298107	NM	34.9	104.7	1405	90	48.9
415707	TX	31.1	102.2	758	76	78.6
413280	TX	30.9	102.9	926	80	59.5
416892	TX	31.4	103.5	796	62	46.3
410498	TX	31.0	103.7	982	62	52.1
410174	TX	30.4	103.7	1356	74	49.1
412797	TX	31.8	106.4	1194	70	43.9
027390	AZ	32.8	109.7	900	56	72.6
026393	AZ	31.9	109.8	1326	61	43.0
028619	AZ	31.7	110.0	1405	107	82.1

latitude, 106.8° W longitude; Fig. 1). The SNWR is located at the confluence of Colorado Plateau and Great Basin desert shrubland and grassland, Chihuahuan Desert grassland and semiarid shortgrass steppe (Gosz, 1993; Muldavin et al., 2008). Many arid ecosystems exhibit bistable dynamics between more and less-degraded ecosystem states with low reversibility (D'Odorico et al., 2010; Okin et al., 2009), and current expansion of C_3 desert shrubland dominated by creosote bush (*L. tridentata*) into C_4 grasslands of blue and black grama (*B. gracilis* and *B. eriopoda*, respectively) is a concern at the SNWR. We analyzed daily precipitation data for sensors at the SNWR using Sevilleta Long Term Ecological Research Network (LTER) meteorological data (SEV001) from 2001 to 2010, which include a range of precipitation that is illustrative of wet to dry monsoon seasons [http://sev.lternet.edu/projects.php?meid=15] (Table 2). These sensors roughly cover an area of 50 km^2 and sensors are located approximately within a 5 km^2 radius from any other sensor. For clarity, we refer to USHCN measurement locations as sites and SNWR measurement locations as sensors.

3. Methods

To determine if monsoon precipitation has changed in the Chihuahuan Desert region and to assess the variability of this precipitation at scale of individual locations, we conducted a regional analysis of precipitation variability across the northern Chihuahuan Desert (Section 4.1) and a local analysis at the SNWR (Section 4.2).

Table 2
Summary of precipitation sensors at the Sevilleta National Wildlife Refuge from 2001 to 2012.

Sensor	Lat [°N]	Lon [°W]	Elevation [m]	Length [yr]	$\bar{P}$ [mm]
01	34.35	106.88	1466	10	92.2
40	34.36	106.68	1600	10	108.7
41	34.30	106.79	1538	10	107.4
43	34.28	107.03	1766	10	114.3
44	34.38	106.93	1503	10	102.3
45	34.38	107.00	1547	8	83.6
49	34.33	106.73	1615	10	132.4
50	34.33	106.63	1670	9	129.8

The monsoon season was defined as July–September (DOY 181–273), adjusted for leap years (Adams and Comrie, 1997). USHCN sites without a full yearly monsoon record (92 days) were not included in the analysis except in calculating precipitation event timing [λ: events day^{-1}] and magnitude [α: cm event^{-1}]. In the second part of the study, we analyzed daily precipitation data from sensors at the SNWR from 2001 to 2010. A secondary part of this analysis included hourly data from 2006 to 2010, resulting in slightly better determination of event frequency compared to daily data because an event that occurs before and after midnight is not separated into 2 events. Implementing a 0.5 cm day^{-1} high-pass filter on the precipitation records (not shown) maintained the precipitation trends presented in this manuscript, suggesting that instrumentation changes through time have not influenced data quality.

3.1. Chihuahuan Desert extreme values of precipitation

To determine how extreme wet and dry periods have changed regionally from 1910 to 2010, we employed a peak over threshold analysis of extreme values of groups of days with and without precipitation. Groups were defined as periods of consecutive days at a single USHCN site with or without precipitation, where the shortest possible group is one day and the longest is 92 days, corresponding to the length of the entire monsoon. For example, a USHCN station receiving 3 consecutive days without precipitation in 1910 would result in a value of 3 in the corresponding without precipitation tally for 1910. Peak over threshold analysis identifies changes to the one-tailed confidence threshold, where values above the threshold are extreme with regards to the rest of the record. The magnitude of the confidence threshold is incrementally adjusted to account for the frequency and magnitude of large values in the record using a floating baseline value. We used the technique from Coelho et al. (2008) for peak over threshold determination and present an analysis for wet and dry periods across all sites from 1912 to 2008 at 95% confidence ($p = 0.05$). We implemented the 5-year mean as the floating baseline value, and adjusting the length of this value between 3 and 10 years did not affect the results of our analysis.

3.2. Sevilleta National Wildlife Refuge spatial kriging of precipitation

To visualize spatial variability in monsoon precipitation across the SNWR, we employed a kriging technique to estimate total mean precipitation and the mean standard deviation of precipitation at SNWR sensors from 2001 to 2010 ($n = 77$, Table 2) using the R-project gstat package (R Development Core Team, 2011), utilizing a linear variogram model in 8 directions for the kriging estimation. This technique does not account for topography in estimating total monsoon precipitation, and kriged values presented here are therefore not an accurate approximation over the non-Chihuahuan Desert eastern and western boundaries of the SNWR, which are higher in elevation and not located in the Chihuahuan Desert.

4. Results

4.1. Analysis of regional precipitation from 1910 to 2010

Linear correlation of data from 1910 to 2010 show no trend in total USHCN site precipitation and weak trends in average event timing [λ] and average event magnitude [α], with high variability in precipitation between sites and years (Fig. 2). Based on the slope of the regression line, average precipitation event timing has increased from 1910 to 2010, from a frequency of approximately

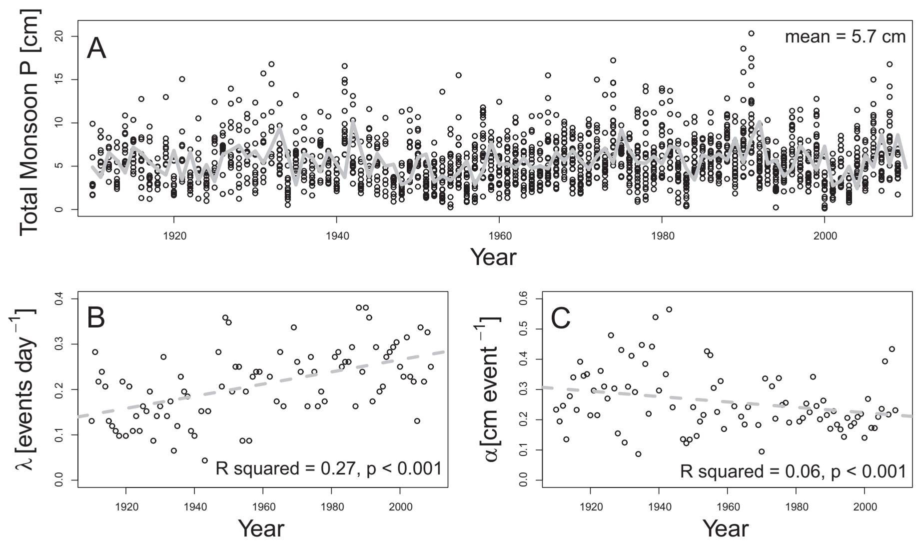

Fig. 2. Total USHCN site precipitation (Panel A), average monsoon event timing [λ: events day^{-1}] (Panel B) and average monsoon event magnitude [α: depth event^{-1}] (Panel C) for up to 22 sites in the northern Chihuahuan Desert from 1910 to 2010. Mean annual monsoon precipitation from 1910 to 2010 is indicated by the line in Panel A.

one event every 7.0 days ($\lambda = 0.14$ events d^{-1}) in 1910 to approximately one event every 3.6 days ($\lambda = 0.28$ events d^{-1}) in 2010 (Panel B). The average magnitude of precipitation events has decreased to a small degree from approximately 3.0 mm per event in 1910 to 2.1 mm per event in 2010 (Panel C). These trends (more events of slightly lower magnitude) qualitatively support our determination of no trend in total monsoon precipitation.

Peak Over Threshold (POT) analysis shows a slight increase in the 95% confidence threshold from 1910 to 2010 for groups of days with precipitation ($R^2 = 0.07$, $p = 0.05$, Fig. 3A), indicating that extreme periods of continuous precipitation have increased in magnitude from approximately 11 days in 1910 to 13 days in 2010, based on the slope of the regression line. This is consistent with the observed small increase in event timing in Fig. 2B. Conversely, POT analysis of extreme periods without precipitation also shows an increase from approximately 38 days in 1910 to 46 days in 2010 ($R^2 = 0.03$, $p = 0.05$), and also shows spikes of high values that are consistent with known dry periods for the region during the 1950s

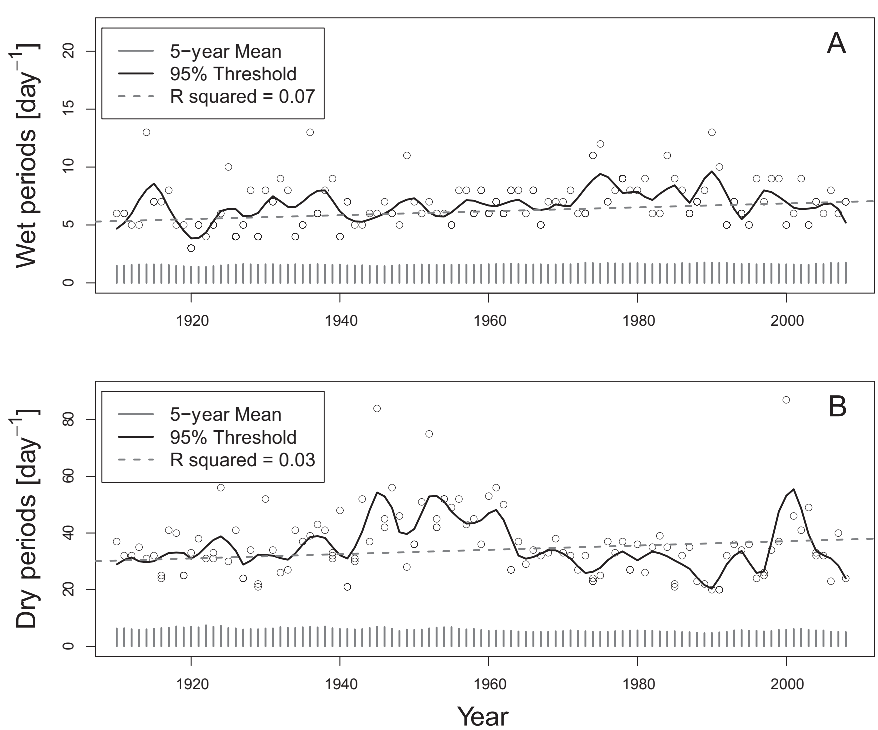

Fig. 3. Peak over threshold analysis of consecutive days with precipitation (Panel A) and without precipitation (bottom) during the monsoon season from 1912 to 2008. Points denote periods above the 95% confidence threshold ($p = 0.05$); the threshold is lowess smoothed by 10% for illustration purposes and is denoted by a dashed line, while the 5-year mean of precipitation is illustrated as vertical lines. Extreme dry periods have increased from an average of 38 days in 1910 to 46 days in 2010, while extreme wet periods have increased from an average of 11 days–13 days over the same period.

and early 2000s. Although average total precipitation has not changed over the past 100 years, monsoon precipitation events in the northern Chihuahuan Desert region have become more numerous and slightly smaller in magnitude, with greater average length of the very wettest and driest periods.

4.2. Monsoon precipitation at the Sevilleta National Wildlife Refuge

From 2001 to 2010, average monsoon precipitation at the SNWR was higher than in the Chihuahuan Desert region, although the SNWR experienced two years with lower average precipitation than in the larger region (2007, 2009; Table 3). Normalized variability in total precipitation was lower at the SNWR during this period (Table 3), and total precipitation was slightly higher at sensors located at the east side of the refuge (Fig. 4A). Precipitation at SNWR sensors shows no consistent spatial pattern, however, and the normalized standard deviation of monsoon precipitation at a sensor is 50% of the 10.8 cm average (Fig. 4B). Therefore, individual sensors at the SNWR experienced precipitation totals both higher and lower than the 10.8 cm average in most years, and this high variability is characteristic of both the SNWR and the Chihuahuan Desert.

The primary reason for high variability in monsoon precipitation at the SNWR is the occurrence of large rainfall events. In Fig. 5, monsoons at the SNWR were organized into wet (2002, 2006, 2008; $n = 23$ sensors), average (2001, 2004, 2005, 2010; $n = 30$) and dry (2003, 2007, 2009; $n = 24$) groups based on average total precipitation. The distribution of precipitation events (mm day^{-1}) between these groupings shows that the primary difference between wet, average and dry monsoons is the occurrence of large events (10+ mm). Large events may account for as few as 20% of total events (Fig. 5A), but contribute the majority of monsoon precipitation (Fig. 5B). At the SNWR, large events accounted for 66% of total precipitation in wet years compared to 28% in dry years. Furthermore, a more sensitive analysis of hourly data at individual sensors from 2006 to 2010 ($n = 52$) shows that events of less than 3.68 mm accounted for 65% of total events at a sensor on average, but had an insignificant effect on total monsoon precipitation (One-tailed, paired t-test, $p < 0.05$).

The SNWR received higher average monsoon precipitation than the Chihuahuan Desert region from 2001 to 2010 (59% higher), and also experienced lower average normalized standard deviation in precipitation (34% lower, Table 3). While the 2001–2010 period was wetter than average across the region, the majority of the northern Chihuahuan Desert – which is located south of the SNWR – was comparatively drier and experienced higher spatial variation in rainfall. There is also a negative relationship between total precipitation and normalized variability in precipitation for all USHCN and SNWR data ($R^2 = 0.23$, $p < 0.001$, Fig. 6). This relationship suggests that regional variability in monsoon precipitation may partly be due to differing total precipitation in spatially distinct locations (such as high precipitation at the SNWR) in many years. Also, this relationship shows that a single location within the region is likely to experience similar changes in rainfall variability in wetter or drier monsoon years that occur at the larger regional scale (Fig. 6).

Table 3
Summary of precipitation at Sevilleta National Wildlife Refuge stations from 2001 to 2012 ($n = 77$) and at Chihuahuan Desert USHCN sites from 2001 to 2010 ($n = 183$). Normalized standard deviation of precipitation [σ_P: %] is shown as the average between sensors within a year (intraannual), and for as the average of mean precipitation between years (interannual).

Year	SNWR $\overline{P}$ [mm]	SNWR $\overline{\sigma_P}$ [%]	USHCN $\overline{P}$ [mm]	USHCN $\overline{\sigma_P}$ [%]
2001	96.5	22.4	27.5	63.3
2002	156.5	30.8	33.0	47.8
2003	55.4	33.2	49.7	38.5
2004	96.4	21.7	24.2	61.6
2005	104.9	40.1	63.0	37.5
2006	170.9	22.2	49.1	36.5
2007	75.4	28.7	86.6	32.3
2008	139.6	19.5	51.6	35.2
2009	82.9	21.1	86.1	40.6
2010	98.0	37.5	48.4	27.9
$\bar{x}$	107.7	27.7	67.8	42.1

5. Discussion

5.1. Regional precipitation from 1910 to 2010

Regional precipitation exhibits trends in average event timing and magnitude (Fig. 2), but these compensating changes have not induced change in total average monsoon precipitation at USHCN sites over the last 100 years. Although the scales of analysis differ, our results are similar to those of Anderson et al. (2010), who saw no trend in summer precipitation for much of the southwestern US, but are different than the results of Turnbull et al. (2013), who saw a slight increase in annual precipitation at a single site at the Jornada LTER from 1914 to 2011. The Jornada site was part of our analysis (USHCN site 294426, Table 1), but Turnbull et al. (2013)'s observations are muted by variability at other sites in the regional record. Furthermore, the sites presented in this study are similar in elevation (800–1800 m) and do not experience high topographical variation in precipitation that is seen in other monsoon precipitation studies (Gebremichael et al., 2007; Gochis et al., 2003, 2006; Mendez-Barroso and Vivoni, 2010). These results further emphasize issues of scale in climate data and suggest that trends occurring at single sites may be masked in larger-scale mean values; changing monsoon patterns are more likely to be localized than widespread. In our study, however, the statistical extrema of periods with and without precipitation show that precipitation is becoming more variable across the entire northern Chihuahuan Desert region during the summer monsoon (Fig. 3) and extreme periods of wet and dry days are increasing in length (Fig. 3A,B). The regional historical record also captures discrete, punctuated periods in the 1950s and early 2000s that correspond to known regional droughts (Fig. 2A). Episodic dry events may occur independently from regional trends but, in the case of changing monsoon patterns (Grantz et al., 2007) and a warmer climate (Gutzler and Robbins, 2011; Seager and Vecchi, 2010), it is very unclear how change in the frequency and severity of these episodic events could affect local ecology and hydrology.

While change in the properties of precipitation is a concern for predicting the future ecology of southwestern ecosystems (Knapp et al., 2008), our analyses suggest that trends in the properties of summer precipitation did not necessarily produce greater regional aridity in the second half of the 20th century. While the Chihuahuan Desert is experiencing longer wet and dry periods, illustrated by the changing length of extreme events, this variability appears to be occurring at local scales instead of occurring regionally. It is likely that individual locations may become wetter or drier with no notable change in the larger region. Unless the properties of precipitation change to a greater degree than has been observed over the past 100 years, we believe that predicted increases in surface temperature are likely to be the primary cause of increasing regional aridity in the southwestern US in coming decades. The possibility of this is not explored here, but we suspect that precipitation-driven aridity would require a large, directional shift in forcing to disrupt the inherent variability of the monsoon season. Although monsoon precipitation has changed regionally from 1910 to 2010, high variability in total precipitation during this period

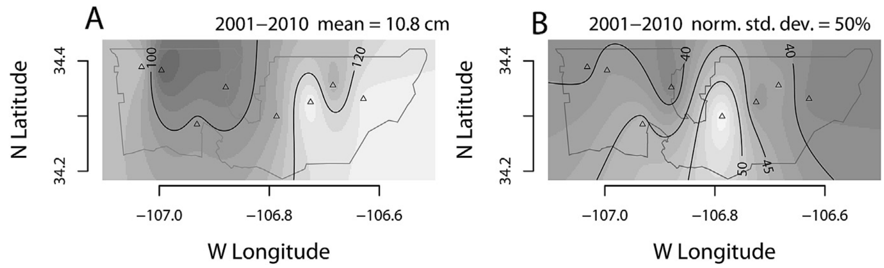

Fig. 4. Average total monsoon precipitation (Panel A) and normalized standard deviation of monsoon precipitation (Panel B) for sensors across the Sevilleta National Wildlife Refuge from 2001 to 2012, kriged using a linear variogram model. Normalized standard deviation of precipitation [σ_P: %] was calculated from total annual precipitation at all sensors ($n = 77$). Sensors are shown as triangle symbols on the map.

suggests that locations in the Chihuahuan Desert are more likely to experience changes in episodic events, such as drought, than they are to experience long-term, important changes in precipitation patterns. These episodic dry periods, which we observed in both the long-term record and in the analysis of extreme events during the 1950s and early 2000s (Figs. 2A and 3B) are likely to be increased in frequency and magnitude by increased surface temperature as well (Gutzler and Robbins, 2011).

5.2. Monsoon precipitation drivers and annual dynamics

Long-term, regional climate data may often mask the change in climate at smaller scales. In our study, total precipitation at SNWR sensors and USHCN sites may correspond to regional averages, but the high annual variability observed in these data shows that both higher and lower than average precipitation is a frequent occurrence. At the SNWR, total precipitation and variability in precipitation between sensors fluctuates between wet and dry monsoons, and within year variability is very high (Table 2, Fig. 4). As a result, sensors may rarely receive precipitation near mean values. This variability has important implications for climate change in aridland ecosystems; vegetation communities at scales of <5 km^2 may experience total precipitation that varies widely from mean values at subgrid scales (roughly 50 km^2 in this case).

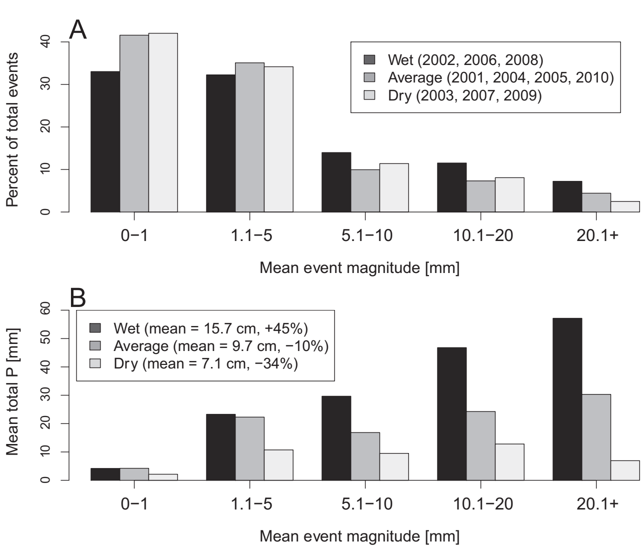

Fig. 5. Percentage distribution of precipitation events by magnitude (Panel A) and the mean total precipitation from these events (Panel B) at the Sevilleta National Wildlife Refuge from 2001 to 2012 for wet ($n = 23$ sensors), average ($n = 30$) and dry ($n = 24$) monsoon seasons. Average monsoon precipitation during this period was 10.8 cm, and the difference between this and the wet, average and dry values is shown as a percentage (Panel B).

Fig. 5 shows that the very largest events occur at a low frequency but produce the majority of monsoon precipitation at the SNWR. Our results corroborate with Xu and Zipser (2012) and Wall et al. (2012), who saw similar precipitation patterns across the southwestern United States using TRMM satellite data. In addition, the dominance of infrequent, large events on total site precipitation perhaps explains why changes in regional precipitation event timing and magnitude (Fig. 2) do not affect average regional precipitation: the number of events does not necessarily correlate to total precipitation and regional decreases in average event magnitude are not very large. Thomey et al. (2011) found that a small number of large precipitation events induces a greater soil moisture response than a larger number of smaller events in Chihuahuan Desert soils, and our results, which show a reduction in the average magnitude of events, suggest that these changing patterns of precipitation warrant further attention. Furthermore, the SNWR experienced reduced normalized variability in total rainfall from 2001 to 2010 compared to the Chihuahuan Desert region (Fig. 6), suggesting that regional-scale monsoon precipitation may contrast with local conditions, especially at ecosystem boundaries such as those experienced at the SNWR. Should monsoon rainfall be reduced at the SNWR, our data suggest that variability in precipitation between SNWR sensors will increase as well, likely becoming more similar to sites located farther south in the desert (Fig. 6). These properties of precipitation are difficult to extend to local ecology, however, because small precipitation events (<5 mm) may play a disproportionately large role in regulating nutrient availability and water balance, in addition to larger events (Lauenroth and Bradford, 2012; Sala and Lauenroth, 1982). Although our analyses point to the importance of large events, the way that statistical probabilities of all precipitation event distributions change in future climate scenarios may help assess the relationships between total precipitation, precipitation variability, and the importance these for local ecological functioning.

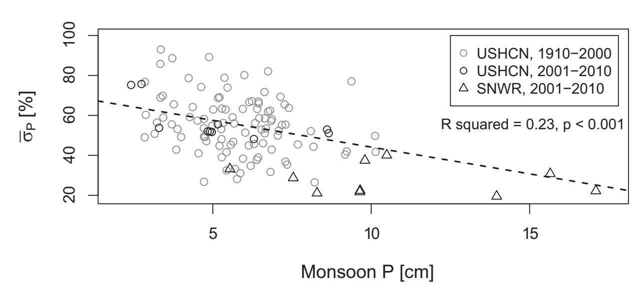

Fig. 6. Relationship between average annual monsoon precipitation [cm] and normalized annual variability in total precipitation for USHCN sites in 1910–2010 and SNWR sensors in 2001–2010 ($R^2 = 0.23$, $p < 0.001$).

5.3. Implications for global climate modeling

Subgrid scale precipitation data in the Chihuahuan Desert may contain information that is not resolved by global climate models (GCM). GCM outputs, often at large spatial scales (>10,000 km^2) (Flato et al., 2000; Johns et al., 1997), do not capture the spatial heterogeneity that defines subgrid scale precipitation variability, especially at short timescales (Wan et al., 2013). In this study we provide additional evidence that regional scale precipitation statistics do not capture precipitation patterns locally, and that a high degree of variability exists in total sensor precipitation within and between years. While we are encouraged that satellite and sensor data agree on the influence of large events on total precipitation (Wall et al., 2012), the even smaller spatial resolution of GCM outputs likely does not capture this dynamic. In the case of monsoon precipitation at SNWR sensors, in which we found high within year variability, GCMs likely underestimate subgrid-scale variability total precipitation. Our data suggest that precipitation variability may increase at sites in the Chihuahuan Desert if total rainfall is reduced (Fig. 6). Adequate soil moisture is critical for producing soil moisture–precipitation feedbacks and for large-scale vegetation activity in the Chihuahuan Desert during the summer monsoon (Mendez-Barroso and Vivoni, 2010; Mendez-Barroso et al., 2009), but it is unclear how the increased small-scale variability in precipitation that we observed also affects these processes.

The importance of capturing variability in model outputs of precipitation may also depend on the frequency that precipitation-related climatic perturbations occur. Two sub-continental drought events occurred in parts of the Chihuahuan Desert during the 1950s and early 2000s, resulting in vegetation die-offs in upland woodland ecosystems at the SNWR and in the larger southwestern US (Breshears et al., 2005). In our analysis, these droughts are distinguishable as extreme periods without precipitation (Fig. 3B), but are not distinguishable in the regional precipitation record (Fig. 2A). Climatic events such as these may need to encompass a very large spatial extent, affect a number of ecosystem types and occur over a number of years before they can be resolved in current GCM outputs, especially due to the difficulty of recreating climate extremes in GCMs (Wan et al., 2013). The small scale variability inherent to monsoon precipitation and the episodic nature of climatic events are both likely not accounted for in GCM outputs, and may limit analyses to the largest global change type events and trends.

6. Conclusions

Monsoon precipitation events in the northern Chihuahuan Desert have increased in frequency and decreased in magnitude over the past 100 years, and the length of the very wettest and driest periods have increased (Figs. 1 and 2). These changing patterns have not changed average total monsoon precipitation regionally. The reason for no change in average total precipitation is perhaps explained at the SNWR, where a small number of very large events can account for the majority of total precipitation and the smallest 65% of events are often insignificant in terms of total precipitation. There is great spatial and temporal variability in total monsoon precipitation at SNWR sensors within and between years. We have determined that monsoon precipitation near the regional, long-term mean rarely occurs at SNWR sensors, and variability in total precipitation at these sensors is much higher than is often accounted for in ecological analyses.

Future climate predictions for the southwestern United States call for increased surface temperature and altered or reduced precipitation to induce greater regional aridity (Gutzler and Robbins, 2011; Seager and Vecchi, 2010). The fact that regional monsoon precipitation totals from 1910 to 2010 has not changed does not contradict these predictions and instead sharpens questions on how future aridity could be realized. Increased surface temperature may induce more predictable responses in ecological functioning than altered precipitation (Petrie et al., 2012). This reality may be inconsequential, however, if the driver of ecological change in the Chihuahuan Desert is extreme dry periods, which are likely to increase in frequency and magnitude in a more arid climate (Gutzler and Robbins, 2011). If precipitation dynamics do change in the southwestern US, a shift towards larger events would likely increase soil moisture availability (Heisler-White et al., 2008) and facilitate soil moisture–precipitation feedbacks (Mendez-Barroso and Vivoni, 2010), although changing event intensity [magnitude per unit time] may alter the availability of this precipitation, especially in cases of high surface runoff due to soil texture or topography (Vivoni et al., 2010). At both local and regional scales, our analyses suggest that high annual variability will continue to characterize monsoon precipitation.

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