LONG-TERM PRECIPITATION TRENDS OF TWO UNIQUELY WATER-LIMITED ECOSYSTEMS: IMPLICATIONS FOR FUTURE SOIL MOISTURE DYNAMICS

LONG-TERM PRECIPITATION TRENDS OF TWO UNIQUELY WATER-LIMITED ECOSYSTEMS: IMPLICATIONS FOR FUTURE SOIL MOISTURE DYNAMICS

By

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ABSTRACT

Roughly 40% of the Earth's land surface is classified as arid or semiarid. These areas are expected to see changes in the frequency and magnitude of precipitation, which could have major implications for soil water resources, vegetation, water supply, and biome evolution. This study analyzed long-term precipitation trends in two water-limited ecosystems with bimodal precipitation regimes: a desert shrubland at the Santa Rita Experimental Range (SRER-SRC) and a mixed conifer system at the Santa Catalina Mountain Critical Zone Observatory (SCM-CZO). Specifically, we analyzed frequency and timing of precipitation in summer and non-summer seasons and compared seasonal precipitation patterns to soil moisture dynamics. Our study shows declining precipitation over the past few decades at both locations, with significant decreases in non-summer precipitation driving decreases in annual precipitation. We show that shallow soil moisture responds to storms of all sizes, and the deep layer responds to large storms or a series of small storms at both sites. Shallow soil moisture is especially vulnerable at SRER-SRC as a result of exponential water loss following a large storm. We expect that declining precipitation will have major implications for soil water resources and the healthy functioning of water-limited ecosystems.

Note:

This work is being further developed for future publication in the Water Resources Research journal in close collaboration with Shirley Papuga (University of Arizona) and Aloah Pope (University of Arizona).

1. INTRODUCTION

Water is the limiting factor for biological activity and plant growth in arid and semiarid environments [Ehleringer et al., 1991]. Vegetation in desert ecosystems is susceptible to changes in physiology and community composition when exposed to changes in soil moisture, especially when exposed to episodic events (1-10 years) such as drought or wet periods [Ehleringer et al., 1991]. While climate models are relatively reliable in predicting temperature trends, predicted changes in precipitation contain high amounts of spatial and temporal variation. Measured precipitation data is critical in order to predict how desert ecosystems will respond to changes in atmospheric composition, such as increased atmospheric CO_2 composition.

Long-term analyses of precipitation trends in semi-arid ecosystems predict drying trends such as drought and decreases in soil moisture in drylands, especially in the Southwest US [IPCC, 2013]. Literature also suggests decreases in non-summer precipitation in the Sonoran Desert of Southern Arizona [Goodrich et al., 2008]. Predictions for future precipitation events are highly dependent on the study length. For example, a study on long-term precipitation from 1956-1996 in the Walnut Gulch Experimental Watershed in Southern Arizona found an increasing trend in annual precipitation due to increase in non-summer precipitation [Nichols et al., 2002], while an updated study from 1956-2006 found these trends no longer significant [Goodrich et al., 2008].

Deserts of the southwestern United States are unique in that they receive nearly equal amounts of precipitation fall during winter and summer due to frontal and convective (monsoonal) storms, respectively [Ehleringer et al., 1991]. This trend is similar at higher elevation sites in the semi-arid Sonoran Desert, which often receives equal amounts of precipitation in summer (July-September) and non-summer months (August – May). As a result, the Sonoran desert experiences frequent small precipitation events (<5 mm) mixed with less frequent larger events (>20 mm) [Cavanaugh et al., 2011]. Shorter and more intense storms generally occur in the summer months while slower yet longer-lasting storms occur in the non-summer months. Previous research show that semi-arid ecosystems are especially sensitive to precipitation events [Austin et al., 2004; Huxman et al., 2004; Loik et al., 2004].

Large and small precipitation events vary in their ability to wet soil well below the surface. As a result of frequent small precipitation events (<5 mm) in the Sonoran Desert, it is common that only the top layer of the soil is wetted. Semiarid environments generally have a large amount of bare soil and high evaporative demand. Therefore, over 90% of all precipitation that reaches the soil in a semiarid environment returns to the atmosphere via evapotranspiration (ET) [Cavanaugh et al., 2011]. Conversely, only large precipitation events (>5 mm) or multiple small events penetrate the soil enough to reach the deep soil moisture reservoir (>30 cm), therefore reaching past the depth of evaporative demand [Kurc and Benton, 2010]. Ability of rainfall to infiltrate soil is also dependent on the physiological characteristics of vegetation, the pedology of the soil, and the type of climate (temperature, frequency, intensity, and type of precipitation) [Rodriguez-Iturbe, 2000].

Global climate models predict amplification of the hydrological cycle and increasing intra-annual variability in precipitation [IPCC, 2013; Knapp et al., 2008]. Considering that average annual precipitation worldwide is expected to fluctuate [IPCC, 2013], the associated changes in timing, frequency, and magnitude of precipitation events will have disproportionately large implications for water-limited ecosystems. Sonoran Desert encompasses biomes that receive varying amounts of precipitation and have different plant functional types. In the light of drought in the desert Southwestern United States [McClaran and Wei, 2014] and predictions for continued surface drying in the next century with climate change [IPCC, 2013], there will likely be changes in soil water content.

Changes in seasonal precipitation will have different implications for plant types. Grasses rely on summer precipitation [McClaran and Wei, 2014], while winter precipitation encourages growth of deeper-rooted shrubs and trees. Plants with deep root systems tend to use deep soil water resources, which persist for longer periods of time, making water stress rare but long-lasting [Rodriguez-Iturbe et al., 2000]. In contrast, plants like C4 grasses that have shallow rooting depths tend to have shorter yet more frequent periods of water stress [Rodriguez-Iturbe et al., 2000].

Here, we explore the effects of historic precipitation events on two water-limited ecosystems in Southern Arizona: A desert shrubland and a mixed-conifer system. We expect that changes over recent time periods in the frequency and timing of precipitation events will have effects on shallow and deep soil moisture at both sites.

2. METHODS

2.1 Study Areas

We chose two study areas to represent unique water-limited ecosystems present in semi-arid regions: a desert shrubland and a subalpine mixed conifer forest. Our study areas, the Santa Rita Experimental Range and the Santa Catalina Critical Zone Observatory, are located in the Sonoran Desert region, which covers much of the southwestern United States and northwestern Mexico. The two sites differ in vegetation, slope, mean temperature, and type of precipitation in the winter season. The region experiences bimodal precipitation with summer precipitation dominated by large, intense monsoon rain events and winter precipitation that can fall either as rain or snow depending on elevation.

2.1.1 Desert Shrubland: Santa Rita Experimental Range (SRER-SRC)

The Santa Rita Experimental Range (SRER-SRC) is located in a creosote bush-dominated desert shrubland, approximately 25 km south of Tucson, Arizona ((31.9083 N, 110.8395 W), Figure 1). The study area is relatively flat (0-5% grade) at an elevation of approximately 950 m. Soil is a sandy loam with no caliche layer present within the depths of this study (< 1 meter) [Kurc and Benton, 2010]. Mean annual precipitation in the SRER-SRC is 294 mm (from a four-year record), with 60% of annual precipitation accumulating as rain in the months of July, August, and September [Sanchez-Mejia and Papuga, 2014]. In contrast to the summer monsoon season, winter rains (December, January, February) account for only ~20% of annual precipitation. Mean annual temperature is 20° C [Sanchez-Mejia and Papuga, 2014].

2.1.2 Mixed Conifer System: Santa Catalina Mountain Critical Zone Observatory (SCM-CZO)

The Santa Catalina & Jemez River Basin Critical Zone Observatory is a subalpine mixed conifer system, located within Coronado National Forest in the Santa Catalina mountain range in southeastern Arizona ((32.4292 N, -110.7667 W), Figure 1). The Marshall Gulch site contains two V-shaped zero order basins that range in elevation (2,200-2,700 m) along an average 33% grade [Heidbüchel, Troch, and Lyon, 2013]. Soil is a sandy loam weathered mostly from granite bedrock with schist bedrock on the lower half of the catchment [Heidbüchel, Troch, Lyon, and Weiler 2013]. Mean annual precipitation at Marshall Gulch is 800 mm, which commonly accumulates as snowfall in winter months [Heidbüchel, Troch, and Lyon, 2013]. About 45% of rainfall falls during the summer (July-September) and about 34% of precipitation occurs between December and March in the Mount Lemmon region [Griffiths et al., 2009]. Mean annual temperature is 8.5° C [Heidbüchel, Troch, and Lyon, 2013].

2.2 Data

2.2.1 Precipitation Measurements

Long-Term Precipitation

Since no single data source provides a continuous precipitation record for the entire study period for each study area, multiple data sources were combined to create the longest possible temporal range of continuous precipitation data. Long-term precipitation data for the SRER-SRC was collected from 1922-2014 at SRER-SRC (Northeast Station; http://ag.arizona.edu/SRER/data.html) and 1960-2014 at Santa Rita Creosote (SRER-SRC) Ameriflux eddy covariance site (Santa Rita Creosote Site; http://ameriflux.ornl.gov). At the SCM-CZO, data from National Oceanic and Atmospheric Administration (NOAA) "Palisade Ranger" and "Mount Lemmon" Stations, CZO Marshall Gulch site, and Daymet pinpointed near the CZO Marshall Gulch site were used to create a continuous precipitation data set from 1960 to 2014. Spatial variation in rainfall data was considered insignificant in this study.

Short-Term Precipitation

Six years of continuous precipitation data was collected half-hourly from 2008 to 2014 for both sites to assess short-term trends in precipitation. At SRER, precipitation was measured using one tipping bucket rain gauge (TE525, Texas Electronics Inc., Dallas, TX, USA). At SCM-CZO, precipitation was measured at six locations using a cluster of three RAINEW 111 Tipping Bucket Wired Rain Gauges [Troch, Heidbüchel and Abramson, 2014].

2.2.3 Soil Moisture Measurements

At the SRER-SRC study area, soil moisture volumetric content is measured with a water content reflectometer (CS 616, Campbell Scientific Inc., Logan, UT, USA) at 30 minute intervals at seven depths: 2.5, 12.5, 22.5, 37.5, 52.5, 67.5, and 82.5 cm. At the SCM-CZO study area, data are measured by a soil moisture sensor (EC-20 Soil Moisture Smart Sensor S-SMA-M005) and recorded every 30 minutes in various depths at 8 different sites located within the Marshall Gulch catchment basin [Troch, Heidbüchel, Abramson and Guardiola-Claramonte, 2014].

2.3 Data Analysis

2.3.1 Precipitation Trend Analysis

The monsoon season is defined by the "the shortest continuous period of the year during which 50% of the annual precipitation accumulates" [Sanchez-Mejia and Papuga, 2014]. We define the summer monsoon season as July, August, and September [Sanchez-Mejia and Papuga, 2014]. Non-summer (January-June, October-December) is defined as all other months of the calendar year excluding summer (July-September). Mean summer, non-summer, and annual precipitation of equal study lengths (1960-2014) at each site were calculated. Standard deviation of each year's precipitation from the long-term mean was calculated to determine if temporal variation in precipitation reveals any significant long-term trends. Mean percent contribution of seasonal precipitation to annual precipitation is calculated by dividing mean summer or non-summer precipitation by mean annual precipitation for the study period.

2.3.2 Storm Size Analysis

In this study, a single storm is defined as the total precipitation accumulated at a single location within 24 hours (12:00am – 11:59pm). Daily precipitation values are then categorized by storm size; large storms are designated as daily precipitation values equal to or larger than 8 mm while small storms are all storms less than 8 mm.

2.3.3 Soil Moisture Analysis

Based on previous ecohydrological studies, a two-layer framework can be used to show soil water residing in a shallow layer (0-20 cm) and a deep layer (20-60 cm) behaves similarly [Sanchez-Mejia and Papuga, 2014]. The shallow soil layer is dependent on direct precipitation accumulation as well as atmospheric evaporative demand, E, while deep soil moisture is mainly used by plants for transpiration, T [Kurc and Small, 2007; Cavanaugh et al., 2011]. Mean soil moisture in the shallow and deep layers is calculated by the relative contribution of soil moisture at varying depths. At the SRER-SRC area, average shallow and deep soil water content are calculated using the following equations [Sanchez-Mejia and Papuga, 2014]:

$$\theta_{shallow} = 0.33\theta_{2.5} + 0.5\theta_{12.5} + 0.17\theta_{22.5} \quad (1)$$

$$\theta_{deep} = 0.25\theta_{22.5} + 0.375\theta_{37.5} + 0.375\theta_{52.5} \quad (2)$$

where $\theta_{2.5}$ is the soil water content at 2.5 cm, $\theta_{12.5}$ is the soil water content at 12.5 cm, etc. The radius of each soil moisture sensor is 7.5 cm.

At SCM-CZO, soil moisture in the shallow and deep layers is calculated for six sites in the Schist basin at Marshall Gulch. Average soil moisture in the shallow (0-20 cm) and deep layer (20-60) were calculated using the following equations:

$\theta_{shallow-1} = \theta_{15}$ (3)

$\theta_{deep-1} = 0.17\theta_{15} + 0.25\theta_{36} + 0.25\theta_{60} + 0.08\theta_{70}$ (4)

$\theta_{shallow-2} = 0.8\theta_{10} + 0.2\theta_{30}$ (5)

$\theta_{deep-2} = 0.07\theta_{10} + 0.37\theta_{30} + 0.37\theta_{50} + 0.18\theta_{63}$ (6)

$\theta_{shallow-3} = \theta_{10}$ (7)

$\theta_{deep-3} = 0.1\theta_{10} + 0.6\theta_{40} + 0.3\theta_{60}$ (8)

$\theta_{shallow-4} = 0.625\theta_{10} + 0.375\theta_{23}$ (9)

$\theta_{deep-4} = 0.074\theta_{10} + 0.265\theta_{23} + \theta_{45} + \theta_{60}$ (10)

$\theta_{shallow-5} = 0.57\theta_{10} + 0.43\theta_{20}$ (11)

$\theta_{deep-5} = 0.07\theta_{10} + 0.22\theta_{20} + 0.44\theta_{40} + 0.22\theta_{60} + 0.04\theta_{72}$ (12)

$\theta_{shallow-6} = 0.8\theta_{15} + 0.2\theta_{30}$ (13)

$\theta_{deep-6} = 0.15\theta_{15} + 0.38\theta_{30} + 0.38\theta_{50} + 0.08\theta_{70}$ (14)

where θ_{15} is the soil water content at 15 cm, θ_{36} is the soil water content at 36 cm, etc. The radius of each soil moisture sensor is 15 cm.

Drydown Curves

Soil moisture dry down curves are constructed for a period of 14 days following the occurrence of a large storm. Fourteen days is considered enough time for soil moisture to return to its pre-storm condition, and is used as a conduit of evapotranspiration in this study. A time constant can be achieved by fitting an exponential curve to time versus shallow soil moisture, then using the following equation to find a time threshold, tau (τ):

$$y = a * exp^{-b*x} + c \; (15)$$

, where *y* is soil moisture, *x* is number of days following a large storm, and *a*, *b*, and *c* are calculated constants. The inverse of *b* (1/*b*) is a time threshold tau (τ) [Kurc and Small, 2004]. Tau indicates the moment at which ⅓ of initial soil moisture is lost.

3. RESULTS

3a. Long-term Precipitation

SRER

Annual precipitation at SRER-SRC has generally been above the long-term average from 1978 to 1988 and below the long-term average (1960-2014) from 1990 to 2015, especially since 2000 (Table 1; Figure 2). Since 2000, 14 out of 16 years were below one standard deviation of annual precipitation.

Non-summer precipitation, which contributes on average to 49% of annual precipitation, has generally been above the long-term average (1960-2015) from 1977 to 1987 and below the long-term average from 2000 to 2014 (Table 1; Figure 2). Since 2000, 13 out of 15 years were below one standard deviation of non-summer precipitation.

Summer precipitation, which contributes on average to 52% of annual precipitation, shows no consistent temporal trend of deviation from the long-term average (1960-2014) (Table 1; Figure 2). Since 2000, 2 out of 15 years were above the standard deviation and 1 out of 15 years were below one standard deviation of summer precipitation.

SCM-CZO

Annual precipitation at SCM-CZO has generally been above the long-term average (1960-2014) from 1978 to 2000 and below the long-term average from 2001 to 2014 (Table 1; Figure 3). Since 2000, 13 out of 15 years were below one standard deviation of both annual precipitation.

Non-summer precipitation, which contributes on average to 56% of annual precipitation, has generally been above the long-term average (1960-2014) from 1978 to 2000 and below the long-term average from 2001 to 2014 (Table 1; Figure 3). Since 2000, 13 out of 15 years were below one standard deviation of non-summer precipitation.

Summer precipitation, which contributes on average to 43% of annual precipitation, shows no consistent temporal trend of deviation from the long-term average (1960-2014) (Table 1; Figure 3). Since 2000, 1 out of 15 years were above the standard deviation and 2 out of 15 years were below one standard deviation of summer precipitation.

3b. Short-term Precipitation and Soil Moisture

SRER

Precipitation

Precipitation is bimodal, with summer storms generally occurring between July and September. In summer 2008, there were few but intense storms (Figure 4). In contrast, the summer 2012 season brought more frequent, less intense storms. The driest summer season (July-September) was in 2012 (129.7 mm), while the wettest summer season was in 2008 (227. 1 mm).

Non-summer storms occur throughout the year, with only the winter 2008-2009 (December-February) showing storms clumped within that three-month period (Figure 4). Winter 2007-2008 precipitation data is incomplete due to time of installation of the precipitation gage at SRER.

From 2008 to 2012, the highest precipitation at SRER-SRC occurred in 2010 with an annual sum of 333.3 mm. The year with the lowest recorded precipitation was 2009 with an annual sum of 205.5 mm. Average contribution of summer storms to annual precipitation over the 5-year record is 62%. Average contribution of non-summer storms to annual precipitation over the 5-year record is 38%.

Soil Moisture

Surface soil moisture responds to storms of all sizes. Shallow soil moisture also dries without storms of any size. A dry period between November 2010 and June 2011 shows consistently low shallow soil moisture and low but sustained deep soil moisture (Figure 4). During the 5-year record, the highest shallow soil moisture occurred in 2010 with a value of 0.20 m^3m^{-3}, and the minimum value of 0.06 m^3m^{-3} occurred in 2009.

Deep soil moisture is less responsive to precipitation events than shallow soil moisture, which is especially noticeable at SRER (Figure 4). For example, deep soil moisture at SRER-SRC remained between 0.1 and 0.14 m^3m^{-3} throughout heavy monsoonal storms.

In general, large storms (>8 mm) result in sustained soil moisture in both layers. A very large storm in January 2010 of 48.3 mm shows a spike in both shallow and deep soil moisture (Figure 4). Shallow soil moisture increased by nearly 0.09 m^3m^{-3} since the day before the storm and deep soil moisture increased by 0.02 m^3m^{-3} since the day before the storm. Deep soil moisture increased by 0.03 m^3m^{-3} between the day of the storm and day following the storm.

The year with the highest average deep soil moisture at SRER-SRC was 2012 with an average value of 0.11 m^3m^{-3} and the year with the lowest average soil moisture value was 2008 with an average deep soil moisture value of 0.10 m^3m^{-3}. During the 5-year record, the highest deep soil moisture occurred in 2011 with a value of 0.16 m^3m^{-3}, and the minimum value of 0.08 m^3m^{-3} occurred in 2009.

SCM-CZO

Precipitation

Precipitation is bimodal, with summer storms generally occurring between July and September. In summer 2008, there were many intense storms (Figure 5). In contrast, the summer

2012 season brought much less intense storms. The driest summer season was in 2009 (54.5 mm), while the wettest summer season was in 2008 (425.5 mm).

Non-summer storms occur throughout the year. A very long dry period with few non-summer storms occurred from September 2009 to July 2010 (Figure 5).

From 2008 to 2012, the highest precipitation at SCM-CZO occurred in 2008 with an annual sum of 571.4 mm. The year with the lowest recorded precipitation was 2009 with an annual sum of 215.8 mm. Average contribution of summer storms to annual precipitation over the 5-year record is 67%. Average contribution of non-summer storms to annual precipitation over the 5-year record is 33%.

Soil Moisture

Surface soil moisture responds to storms of all sizes (Figure 5). The year with the highest average shallow soil moisture at SCM-CZO was 2008 with an average value of 0.24 m^3m^{-3} and the year with the lowest average soil moisture value was 2012 with an average shallow soil moisture value of 0.13 m^3m^{-3}. During the 5-year record, the highest shallow soil moisture occurred in 2008 with a value of 0.48 m^3m^{-3}, and the minimum value of 0.04 m^3m^{-3} occurred in 2011.

The year with the highest average deep soil moisture at SCM-CZO was 2008 with an average value of 0.21 m^3m^{-3}. During the 5-year record, the highest deep soil moisture occurred in 2008 with a value of 0.31 m^3m^{-3}, and the minimum value of 0.01 m^3m^{-3} occurred in 2010.

2008, the year with maximum shallow and deep soil moisture of all 5 years *and* the highest average shallow and deep soil moisture, also was the year with the highest annual precipitation. Similarly, 2009 was the lowest annual precipitation of all years at SCM-CZO and also was the year with the lowest average deep soil moisture.

Deep soil moisture as an average of all sites at SCM-CZO is not dependably lower than shallow soil moisture as an average of all sites at SCM-CZO. For example, deep soil moisture exceeded that of shallow soil moisture during summer 2010 after a series of intense monsoonal storms.

3c. Storm Size Seasonality

SRER

Annual

There is a strong correlation between large storms and high annual precipitation at SRER-SRC (Figure 6). This shows that large storms tend to occur in years with high annual precipitation. At SRER-SRC, years with high annual precipitation have less small storms (Figure 6; R^2= 0.36).

Summer

There is little correlation between high summer precipitation and number of small storms at SRER-SRC (R^2= 0.006), showing that summer precipitation is reliant on large storms in the desert shrubland. Large storms tend to occur in years with high summer precipitation at both sites shown by the strong correlation between large storms and summer precipitation at both SRER-SRC (Figure 6; R^2= 0.75) and SCM-CZO (Figure 7; R^2= 0.94).

Non-summer

There is a strong correlation between large storms and non-summer precipitation at SRER-SRC (Figure 6; R^2 0.87). There also is a strong relationship between the number of small events and non-summer precipitation at SCM-CZO (Figure 6; R^2= 0.90), excluding the year 2010. At SRER-SRC, years with high non-summer precipitation have less small storms (Figure 6; R^2= 0.90).

SCM-CZO

Annual

There is a strong correlation between large storms and high annual precipitation at SCM-CZO (Figure 7; R^2= 0.97). This shows that large storms tend to occur in years with high annual precipitation. At SCM-CZO, years with high annual precipitation have more small storms (Figure 7; R^2= 0.45). There is a strong correlation between large storms and high annual precipitation at SCM-CZO (Figure 7; R^2= 0.97).

Summer

In contrast, there is a relationship between number of small storms and high summer precipitation at SCM-CZO (Figure 7; R^2= 0.31) showing summer precipitation is reliant on small and large storms in the mixed conifer system.

Non-summer

There is a strong correlation between large storms and non-summer precipitation at SCM-CZO (Figure 7; R^2= 0.76). At SCM-CZO, years with high non-summer precipitation have more small storms (Figure 7; R^2= 0.73).

3d. Soil Moisture Depletion

SRER-SRC

The soil moisture depletion curve shows an exponential relationship at SRER-SRC for shallow soil moisture (Figure 8a). An exponential curve shows an excellent fit over the 14 day period (Figure 8a; R^2=0.97). For the shallow soils at SRER-SRC, soil moisture can be characterized using the equation:

$$y = 0.07798 * exp^{-0.1287*x} + 0.06599 \quad (16)$$

where x is the days vector, y is soil moisture and b is a constant. Shallow soil moisture ranges from 0.08 to 0.13 m^3m^{-3}. For the shallow soil moisture curve at SRER-SRC, b of 0.1287 and tau of 7.77 indicates that after 7.77 days, ⅓ of initial soil moisture remains.

Deep soil moisture at SRER-SRC can be characterized using the equation:

$$y = -0.0009199 * x + 0.1109 \quad (17)$$

where x is the days vector and y is average soil moisture per day. Deep soil moisture ranges from 0.09 to 0.11 m^3m^{-3}. Deep soil moisture decreases linearly over time (Figure 8b; R^2= 0.44).

SCM-CZO

There is no relationship between surface soil moisture and time in the shallow layer in the exponential curve at SCM-CZO (Figure 8c). For the shallow soils at SCM-CZO, soil moisture can be characterized using the equation:

$$y = 0.03612 * exp^{-0.4089*x} + 0.2095 \quad (18)$$

where x is the days vector, y is soil moisture and b is a constant. Shallow soil moisture ranges from 0.20 to 0.23 m^3m^{-3}. For the shallow soil moisture curve at SCM-CZO, b of 0.4089 and tau of 2.45 indicates that after 2.45 days, ⅓ of initial soil moisture remains.

Deep soil moisture at SCM-CZO can be characterized using the equation:

$$y = -0.00006707x + 0.1857 \quad (19)$$

where x is the days vector and y is average soil moisture per day. Deep soil moisture ranges from 0.18 to 0.19 m^3m^{-3}. Deep soil moisture shows no linear relationship of soil moisture depletion (Figure 8b; R^2= 0.004).

4. DISCUSSION

Our data shows that long-term precipitation analysis, especially seasonal analysis of storm size, is crucial in understanding soil moisture dynamics in shallow and deep soil layers. Long-term precipitation records showed decadal variance above and below the mean throughout the study period. However, the time period from 1990 to 2015 generally showed precipitation below the long-term mean at both sites. This is consistent with long-term drought studied at the desert shrubland site (Santa Rita Experimental Range) [McClaran and Wei, 2014]. Our results are also consistent with literature showing megadrought in Southern Arizona and the greater Southwest [Seager et al., 2007].

Short-term precipitation and soil moisture analysis showed the relationship between precipitation and soil moisture in the shallow and deep layers. We show, generally, that one-day storms in the mixed conifer system are more intense than in the desert shrubland. At both sites, shallow soil moisture responds quickly to storms of all sizes. Deep soil moisture responds to large storms or to a series of small storms. Shallow and deep soil moisture in the mixed conifer system are more similar to one another throughout the study period than are both shallow and deep soil moisture at the desert shrubland.

Analysis of storm size seasonality is a powerful tool to analyze the importance of timing and intensity of storms. Our study showed that years with high annual precipitation in the desert shrubland also had a high number of large storms. There was little correlation between high precipitation and small storms. This trend was also true in the desert shrubland for summer and non-summer seasons. In the mixed conifer system, years with high annual precipitation had a high number of both small and large storms. This trend was also true in the mixed conifer system for summer and non-summer seasons. This shows that the desert shrubland is dependent on large storms for high precipitation, while the mixed conifer system relies on both small and large storms for high precipitation.

Soil moisture depletion curves show that the study sites vary highly in the shallow soil layer's ability to retain moisture following a large storm. At both sites, surface soil moisture is lost after large storms. The time period with which this soil moisture is lost varies between the two sites. Shallow soil moisture is depleted at both sites in less than the 14-day study period. Deep soil moisture persists in the soil after large storms at both sites. Soil moisture depletion curves show especially more intense effects at the desert shrubland than mixed conifer, possibly due to higher albedo, less canopy cover, higher temperature and higher evapotranspiration rates experienced in the desert shrubland.

The majority of climate models in the Southwest looking at data from 1950 to 2000 predict a drier climate and a decreasing difference between precipitation and evaporation (P-E) in the future [Seager et al., 2007]. This decreasing deficit predicts less water reaching the land surface than is exiting via evaporation. Rising temperatures are known to exacerbate low precipitation, leading to high evaporation and evapotranspiration rates and ultimately drought. Overall, drying is predicted for the Southwest for all emissions scenarios for all study periods from 2021 to 2099 [Garfin et al., 2013]. Severe droughts lasting multiple years in the Southwest U.S. are found to result from reduced frequency or intensity of winter storms [Garfin et al., 2013].

Less winter and less non-summer precipitation is predicted for the desert Southwest. Since small storms are slowly infiltrating and cooler temperatures cause reduced evapotranspiration rates, winter precipitation events result in greater soil recharge [Huxman et al., 2004]. If trends in reduced non-summer precipitation continue, there will be less recharge in non-summer months.

Soil moisture in the shallow layer supplies water for shallow-rooted vascular plants. In theory, summer precipitation recharges the upper soil layer but may not recharge the deep soil layer due to high runoff and evaporation rates [Huxman et al., 2004]. Large storms, which often occur in the summer at these study sites, are expected to have the most significant effect on microbial dynamics and vascular plant life [Huxman et al., 2004]. Soil moisture in the deep layer is important for deep-rooted plants as well as water storage later in the year. Deep soil moisture responds only to large storms or a series of storms, and is indicative of infiltration, soil type, soil structure, hydraulic redistribution, and a number of other factors that vary between both study sites. Hydrogen isotope analysis of soil water can be used to trace movement of water within the soil profile, showing that winter-spring storms infiltrate into the deep layer [Huxman et al., 2004].

Water-limited ecosystems receive discrete rainfall pulses that affect plant productivity [Huxman et al., 2004]. According to this study, summer storms are generally more intense, which are pulses of high precipitation causing green-up in plants. Non-summer storms were found to be generally less intense and more frequent, and contribute to maintenance of soil moisture.

Long-term changes precipitation and soil water storage will have implications for many desert plant species [Salguero-Gómez, Siewert, Casper and Tielbörger, 2012]. However, desert flora have evolved mechanism to survive intermittent drought [Salguero-Gómez, Siewert, Casper and Tielbörger, 2012]. Changes in precipitation patterns will alter distribution of soil water both spatially and temporally within the profile [Loik et al., 2004]. If trends in decreasing non-summer precipitation continue, plants may be affected by decreasing soil water availability throughout the year, especially in the deep soil layer. Variation in both canopy cover and the timing and size of rain events in all deserts could modify the physiology of leaves, roots, and microbes [Huxman et al., 2004]. More long-term studies that expose desert plants to different possible precipitation situations will help in determining plant reactions to changing precipitation regimes.

5. FIGURES

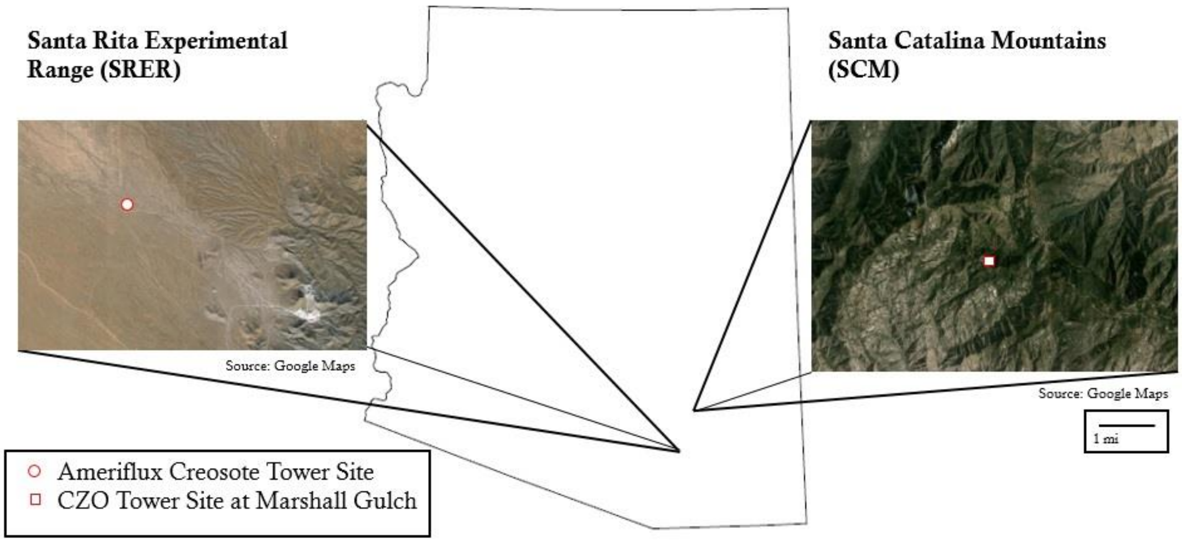

Figure 1. Map of study sites.

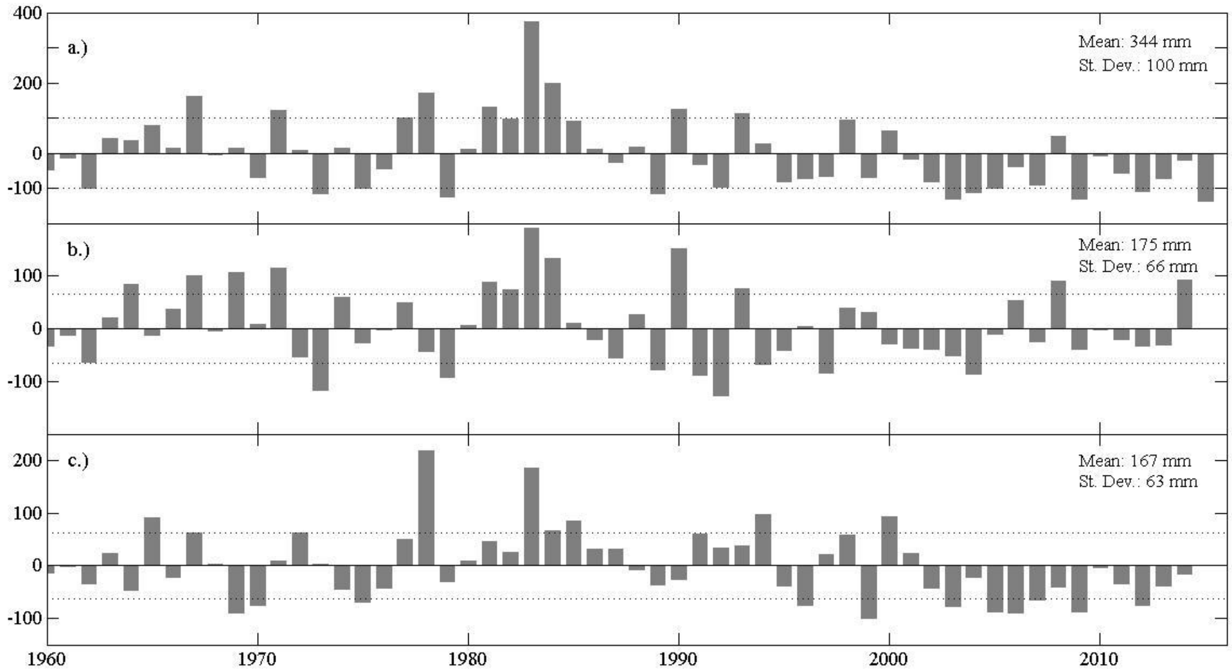

Figure 2. Long-term precipitation record from 1960 to 2015 at SRER-SRC for total annual (a.), summer (b.) and non-summer precipitation (c.) shown as anomaly or deviation from mean precipitation from 1960-2014. Dotted lines show standard deviation from mean precipitation over the entire record.

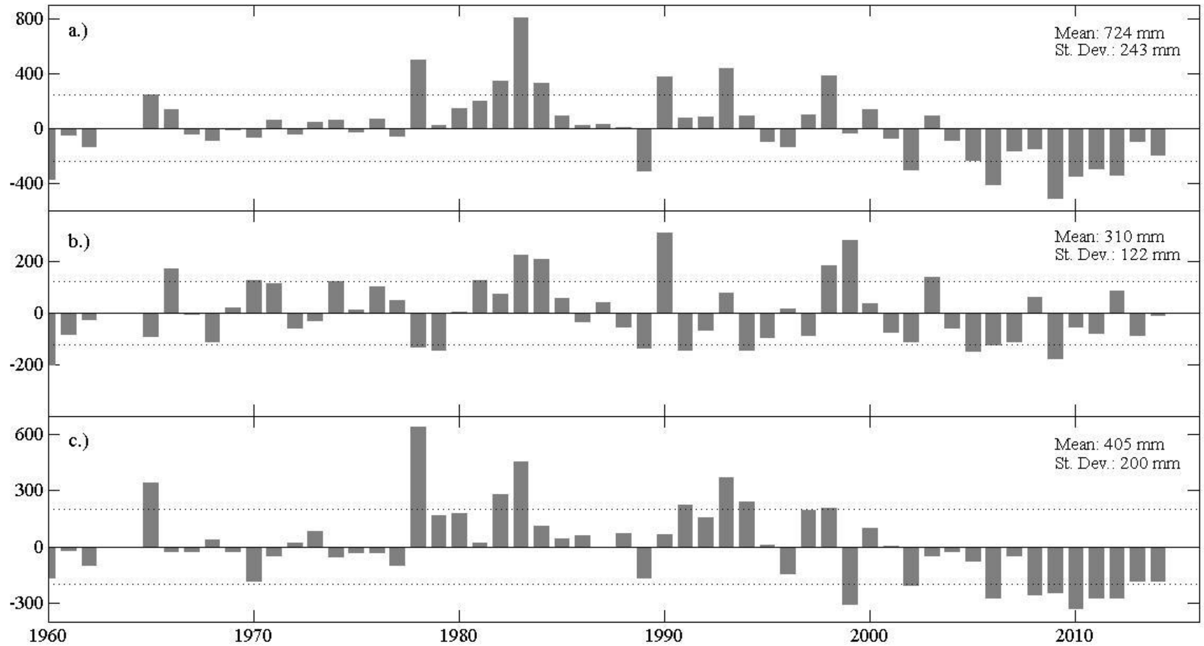

Figure 3. Long-term precipitation record from 1959 to 2014 at SCM-CZO for total annual (a.), summer (b.) and non-summer precipitation (c.) shown as anomaly or deviation from mean precipitation from 1959 to 2014. Dotted lines show standard deviation from mean precipitation over the entire record.

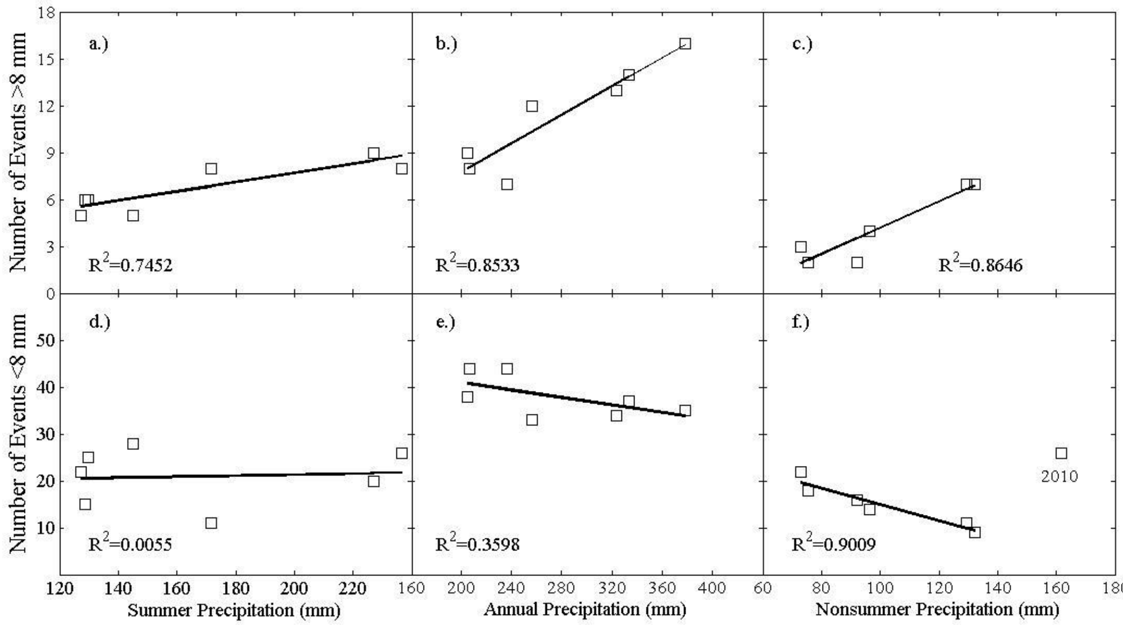

Figure 4. The relationship between total summer, annual, and non-summer precipitation for large events >8 mm (a.-c.) and small events <8 mm (d.-f.) at SRER-SRC. Year 2010 is considered an outlier and is excluded from linear analysis in non-summer precipitation for small events (f.).

The image part with relationship ID rId11 was not found in the file.

Figure 5. The relationship between total summer, annual, and non-summer precipitation for large events >8 mm (a.-c.) and small events <8 mm (d.-f.) at SCM-CZO. Summer, annual, and non-summer precipitation at this site show a positive relationship between precipitation and number of both small and large events.

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Figure 6. Time series of precipitation (a.) and soil moisture (b.) over a 5-year record from 2008 to 2012 at SRER-SRC. Soil moisture represents volumetric water content (VWC) in the shallow layer averaged from 0 to 20 cm below the surface (thin line) and in the deep layer from 20 to 60 cm below the surface (thick line).

The image part with relationship ID rId11 was not found in the file.

Figure 7. Time series of precipitation (a.) and soil moisture (b.) over a 5-year record from 2008 to 2012 at SCM-CZO. Soil moisture represents volumetric water content (VWC) in the shallow layer averaged from 0 to 20 cm below the surface (thin line) and in the deep layer from 20 to 60 cm below the surface (thick line).

Figure 8. Soil water depletion curves up to two weeks following large storms (>8 mm accumulated in one day). Shallow soil moisture at SRER-SRC (a.) and SCM-CZO (c.) show an exponential relationship between soil moisture and days after the precipitation event. Deep soil moisture and days following the event at SRER-SRC (b.) and SCM-CZO (d.) show little linear relationship.

6. TABLE

		Precipitation (mm), SRER-SRC, Northeast Station	Precipitation (mm), SCM-CZO, Marshall Gulch
Annual			
	1923-2014	329.83	711.78
	1923-1979	322.91	729.37
	1980-2014	339.93	693.85
Summer			
	1923-2014	174.59	316.15
	1923-1979	172.89	308.28
	1980-2014	177.77	319.48
Non-summer			
	1923-2014	156.04	394.25
	1923-1979	150.01	417.91
	1980-2014	164.83	379.47

Table 1. Precipitation from one site at SRER-SRC (Northeast Station) and one site at SCM-CZO (Marshall Gulch), averaged over three time periods: the entire record (1923-2014), an early time period (1923-1979) and a recent time period (1980-2014).

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6. ACKNOWLEDGEMENTS

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