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Research article

Examination of Extreme Rainfall Events in Two Regions of the United States since the 19th Century

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Abstract: A common hypothesis regarding human-induced climate change is that precipitation processes will accelerate leading to an increasing magnitude of rainfall amounts on a daily time scale as the atmosphere warms. This assertion is supported by two physically demonstrable facts, (1) warmer air accommodates more water vapor, and (2) precipitation processes become more efficient as the cloud environment warms. However, by definition, extreme events are rare, and thus statistics of their occurrence and possible long-term changes present difficult challenges, some herein addressed. In any case, the observational datasets on which hypothesis tests may be carried out should cover the longest periods possible because precipitation can naturally vary considerably on even century time scales. In this study we focus on this temporal issue by building long-term daily precipitation datasets for twenty stations, ten along or near the US Pacific Coast (PC) and ten along or near the coast in the US Southeast (SE). Observations for these stations begin between 1840 and 1890 and end in 2018, using the water year (Oct to Sep) to define the annual period. For some metrics, e.g. the annual total precipitation or the number of days per year measuring greater than 25 mm, there is no discernable change over the most recent 145 years (1874–2018). For other metrics, e.g. the magnitude of the wettest day per year or the temporal distribution of the 29 wettest 2-day events in the past 145 years (i.e. nominal 1-in-5-year occurrence), there appears to be an increase in SE and a decrease in PC. Whether these trends are significant for the relatively short climate record of 145 years will be discussed with the conclusion being the limited time frame of analysis does not lead to decisive claims that these changes are outside of the range of natural variability.

Keywords: extreme precipitation events; climate change; US rainfall

1. Introduction

As the concentration of greenhouse gases increases leading to an expected rise in atmospheric temperature, the Intergovernmental Panel on Climate Change (IPCC) indicates there is "medium confidence" that will be an "increase in the frequency, intensity, and/or amount of heavy precipitation" over most land areas [1]. Again, the IPCC states "there is high confidence that, as climate warms, extreme precipitation rates on, for example, daily time scales will increase faster than the time average" [2]. Recent research provides some evidence that "extreme daily precipitation averaged over both dry and wet regimes shows robust increases" since 1951 [3] and that hourly extreme rates in Australia since 1966 have also increased [4]. A limitation of these and other such studies is that the time periods examined are relatively short for a highly variable quantity such as extreme precipitation. This is one of the limitations of earlier research addressed in this paper.

Table 1. Information on the 20 stations selected for this study. The median annual total and the trend values are calculated from 1874 (or first year thereafter) to 2018. The * indicates significant at the 95% confidence interval. The large variability in annual totals expands the significance range accordingly, hence trends of even 12 % cen^{-1} are not significant. Statistics of the regional averages are performed on the annual totals after normalization by the median.

	Symbol	Median Annual Total (mm)	Total Years 1850–2018	Trend in Annual Total %/century
Astoria	AST	1791	149	−6.4
Portland	PTL	991	157	−14.4*
Salem	SLE	978	149	+2.1
Eureka	EKA	979	134	−4.0
Red Bluff	RBL	543	141	−10.8
Sacramento	SCT	427	149	+3.4
San Francisco City	SFOC	518	169	+0.0
Fresno	FNO	234	146	+12.3
Los Angeles City	LOX	320	141	−13.9
San Diego	SAN	231	161	−7.3
Shreveport	SHV	1137	146	+8.6
Vicksburg	VKS	1334	149	+3.6
New Orleans	NEW	1520	153	+9.0
Mobile	MOB	1588	158	+7.7
Pensacola	PEN	1547	139	+15.3*
Montgomery	MGM	1283	146	+0.1
Quitman	QMN	1285	139	−7.5
Augusta	AUG	1082	149	−6.9
Jacksonville	JAX	1292	150	+1.7
Charleston City	CHSC	1158	156	−8.0
Pacific Coast	PC			−3.3
Southeast US	SE			+1.6
All				−0.8

The physical basis of the claim of increasing amounts of rain is straightforward on two counts, (1) a warmer atmospheric column will accommodate more water vapor and thus increase the water available for precipitation [5], and (2) precipitation processes are more efficient as the cloud-condensation environment warms [6]. Thus, with a warming atmosphere, the precipitation process should be immediately affected (a fast response) and therefore potentially measurable. However, these two factors do not explain all precipitation variability as impacts can arise due, for example, to (a) the natural chaos of the system, (b) regional modifications such as land-use/cover or redistribution of water in human-engineered systems (e.g. [7]), (c) unknown microphysical processes that may lead to negative feedbacks and (d) to macro-scale changes in the overall atmospheric or oceanic circulation over long periods (i.e. natural slow modes, [8,9]). As such, it is very difficult to determine attribution of the changes that might be observed so that we shall essentially limit our discussion to "what" has happened rather than "why" it has happened.

Precipitation is also a metric with significant challenges for statistical interpretation of changes in its frequency and intensity. Both spatially and temporally, daily precipitation exhibits a chaotic type behavior that reduces the confidence of concluding that a change may be significant or simply a part of the natural fluctuations inherent in a highly non-linear dynamical system due to that constraint of a finite (and small) sample size.

The focus of efforts in this study is to reduce the uncertainty related to temporal variability by selecting daily observations from stations with very long records, 134 to 169 years, all ending in 2018. Such a time-requirement reduces the availability of stations considerably. Spatially, the focus will be on two climatically different regions within the United States (US), (1) along and near the Pacific Coast with a distinct cool, rainy season and (2) near-coastal stations in the Southeast US which reside in a humid, subtropical climate in which significant rain may fall in any month.

In the following sections, the construction of the observational dataset will be described followed by the depiction and description of times series of various metrics based on one and two-day total rainfall events. The study concludes with a discussion of the potential detection of change in rainfall extremes for these two regions.

2. Observational dataset

Many studies of daily rainfall extremes begin usually around 1900 or even much later when the number of available stations increased as climate information became more important, primarily for agricultural concerns. The U.S. government's *Climate Science Special Report* [10] for example provided analysis for Periods of Record (PORs) that began in 1901 to beginning as late as 1986, leaving out the 19th century entirely. Because climate variables such as rainfall have fluctuations on all time scales, including century-scale, it is entirely possible that any changes in the past three to five decades (or three to five centuries) are simply part of the natural chaotic behavior (non-stationarity) of the climate system.

Ideally, we would prefer to have many centuries of daily data to properly assess any recent change. That ideal is, of course, impossible to create. However, adding a few more decades to the analysis to enlarge the temporal sample space gives opportunity to place current variations in a somewhat longer historical context.

Because the emphasis of this study is to identify changes over longer periods of time for rare events, we sought to expand the PORs. In the two climate regions in the US that were chosen, each has ten stations with continuous daily records beginning by 1889 and with most stations several years prior. All are current through 2018. Stations in the first region reside along the Pacific Coast (PC) and are (north to south) in the state of Oregon: Astoria (AST), Portland (PTL), Salem (SLE), and in California: Eureka (EKA), Red Bluff (RBL), Sacramento (SCT), San Francisco City (SFOC), Fresno (FNO), Los Angeles downtown (LOX) and San Diego (SAN). The climate of this region is generally Mediterranean in which most of the rain falls in the cool season, beginning in Oct and becoming mostly dry by May. Because of this regime, we shall use the water-year (1 Oct to 30 Sep) as the annual time period for the analysis. Thus, a year indicated as "2018" for example refers to the water-year 1 Oct 2017 through 30 Sep 2018. Figure 1 displays the location of the stations and Table 1 provides further information.

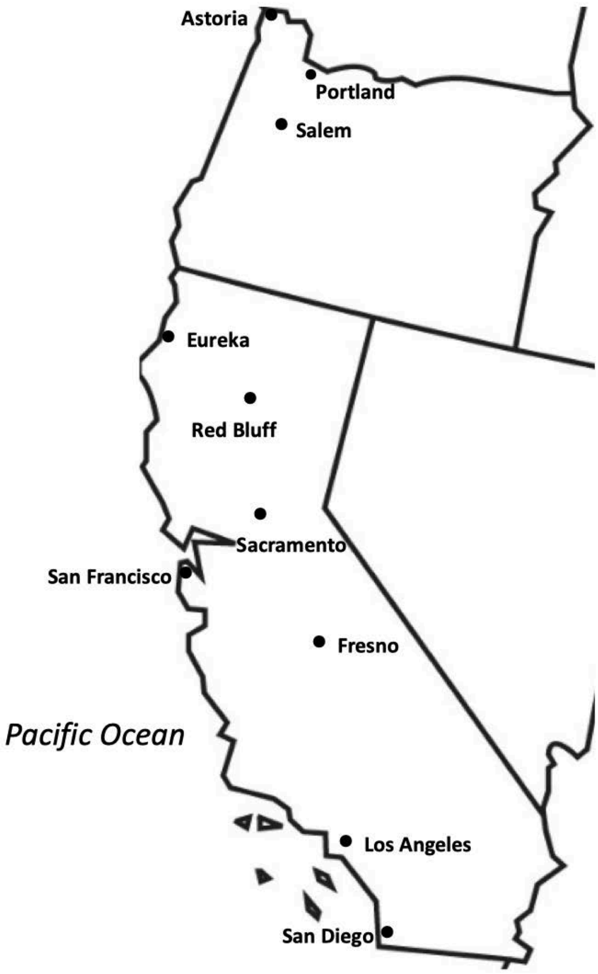


Figure 1. Map of Pacific Coast stations utilized in this study.

The stations in the second region are in the Southeast US (SE) and relatively near the coast. These sites were selected to avoid snow events as much as possible because of the varying ways in which snowfall and liquid equivalent precipitation were measured through the years. These stations reside in a humid, subtropical environment with substantial precipitation possible in any month, but with a minimum in late summer and fall. As such, we shall utilize the water year Oct–Sep as well. The stations (west to east) are Shreveport LA (SHV), Vicksburg MS (VKS), New Orleans LA (NEW), Mobile AL (MOB), Pensacola FL (PEN), Montgomery AL (MGM), Quitman GA (QMN), Augusta GA (AUG), Jacksonville, FL (JAX), and Charleston downtown SC (CHSC). The locations of the stations are given in Figure. 2 and further information in Table 1. In all, there are 1496 complete water-years in PC and 1485 in SE.

Figure 2. Map of Southeast stations.

The data were accessed through various archives in the US; (a) the Climate Data Online website operated by the National Centers for Environmental Information (NCEI), (b) NCEI's image archive of original paper documents of weather observation forms and monthly reports, (c) the Forts archive operated by the MidWest Regional Climate Center and, (d) xmACIS2 operated by the Northeast Regional Climate Center. In several cases where the digital archives indicated missing values after 1890, the values were found on the climatological forms and, though manually intensive, were able to be filled by retrieving and examining these forms. Only water-years in which complete data were available were used in the analysis and are shown in Figure. 3 for 1850 to 1890 (all stations were complete from 1889 to the present).

Some of the analyses below utilize station-years binned into five-year periods or "pentads." Data collection in the 1860s was particularly sparse as the American Civil War (1861–1865) and years following affected normal operations. To utilize as much early data as possible, two "pseudo-pentads" were generated for each region, in which the actual bins were larger than five years to accumulate a minimum number of station-years (25). Pentad #1 (identified as ending in 1860* in PC and 1858* in SE) is 1850–1860 and 1850–1858 for PC and SE respectively. Pentad #2 (identified as ending in 1873*) is 1861–1873 and 1859 –1873 for PC and SE. All other pentads are composed of five-year bins. In general, the first two pseudo-pentads will be shown only for display purposes while the statistical analysis will begin with the third pentad (1874–1878). The values shown will be normalized by the number of station-years available in each pentad and thus comparable from pentad to pentad.

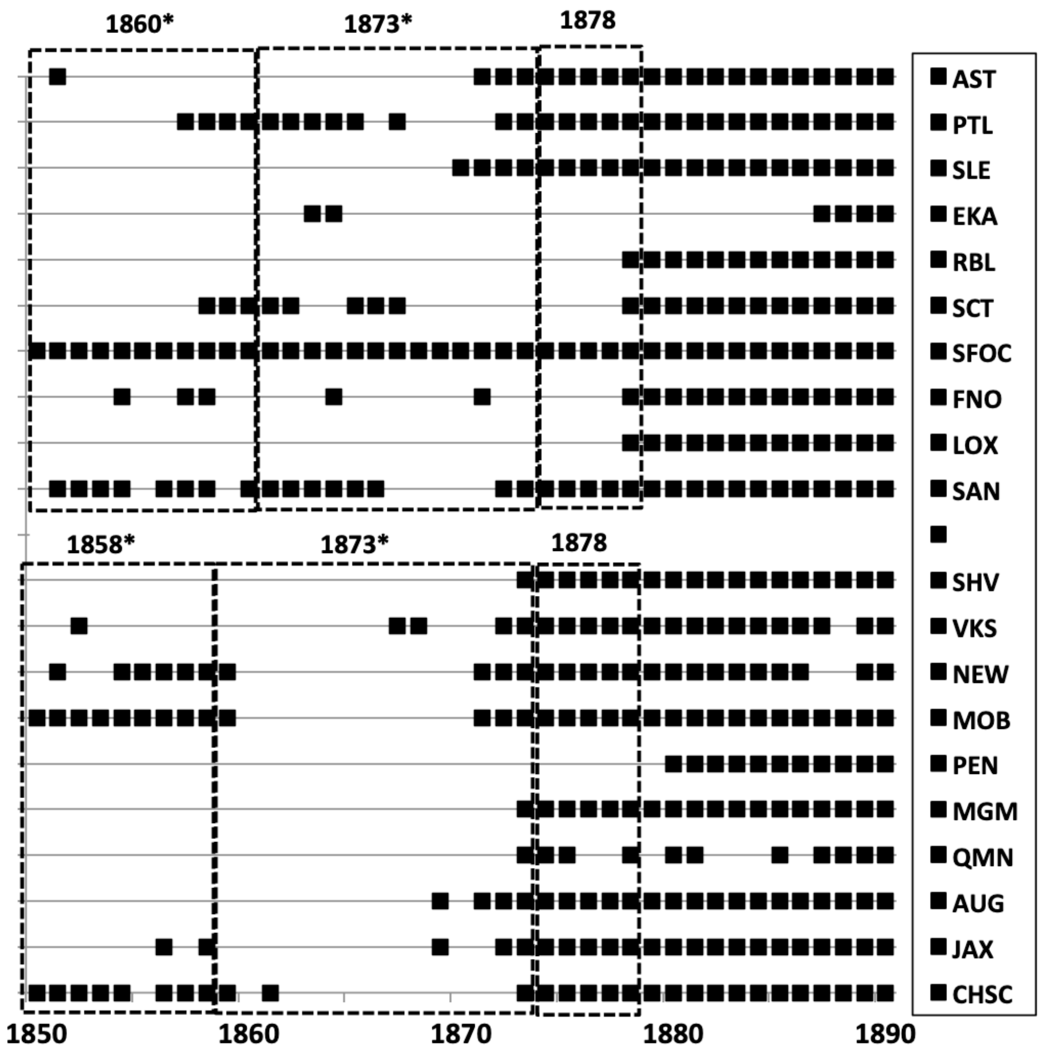
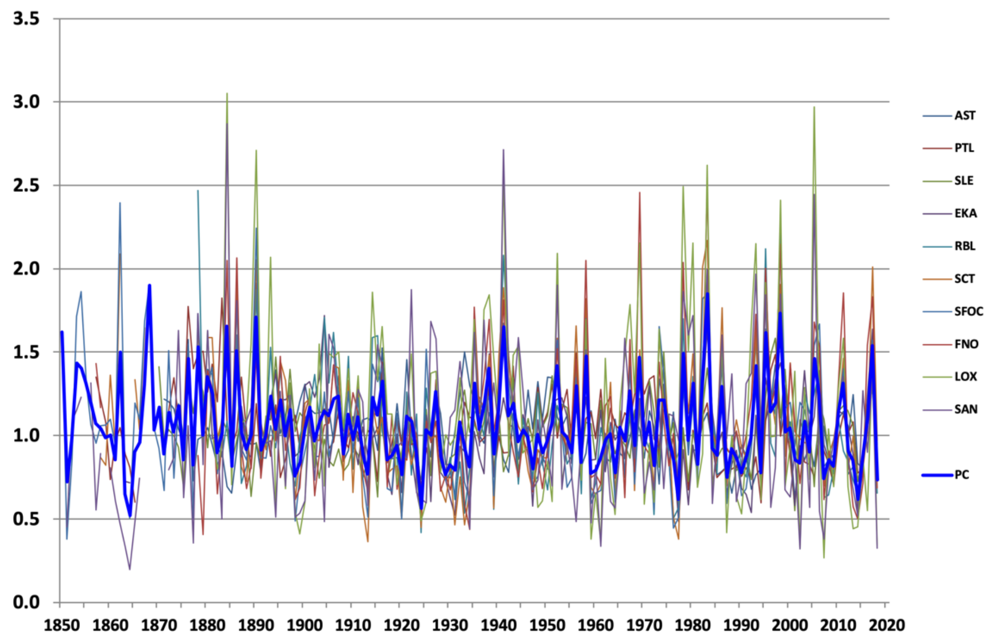


Figure 3. Years with complete available daily data as shown by stations. Formal analysis will utilize data beginning with the pentad labeled "1878" (i.e. 1874–1878) with two pseudo-pentads preceding this one for illustrative purposes.

3. Results

The time series of annual total precipitation for individual stations and their regional averages as a fraction of their medians are shown in Figure 4. Trends were calculated from 1874 when at least five stations in each region were available, giving a POR of 145 years (this will be the nominal period for statistics referenced below). Immediately obvious is the higher interannual variability in the PC stations for which absolute annual totals of several stations are on average only one third or less of the SE stations. It is apparent the SE distribution is narrower than that of PC, in which 35% and 47% of annual totals are within ±15% of the median for PC and SE respectively. In terms of trends (performed on the average), the values are −3.3 % cen^{-1} and +1.6 % cen^{-1} for PC and SE respectively (Table 1). Neither trend value is significantly different from zero.



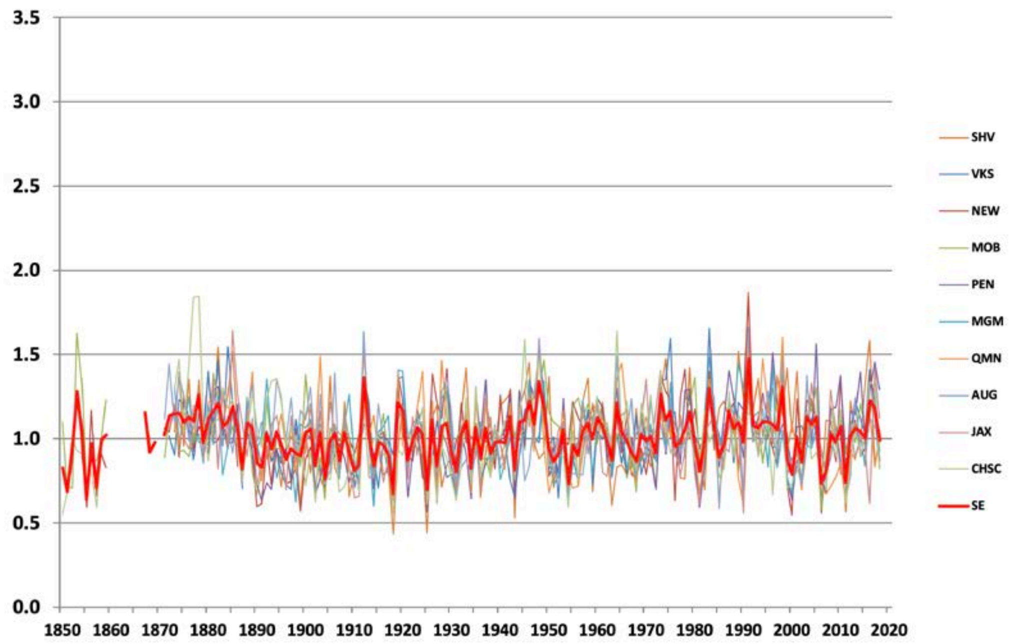


Figure 4. Time series of annual total precipitation as a ratio relative to the median of the values calculated from the period 1874–2018 for Pacific Coast (top) and Southeast (bottom). Thick lines are regional averages.

The question of changes in the frequency and intensity of extreme rainfall over the POR on the time scale of a day or two is the key metric of interest here. There are many ways to analyze extreme events with numerous decision points to consider such as threshold-magnitude and time-window allowed. This study will attempt to limit the analysis to a few key metrics that are likely of most use to the study of climate extremes as well as to hydrologic planners.

In the US a popular metric, sometime described as a heavy event or "downpour", is a day with greater than 25.4 mm (1 inch) of precipitation. In Figure 5 we display the number of days of this event for the stations described and is an example of a threshold metric. The values are first normalized by the median number of 25.4 mm events per year, so that the median of the entire series is one and no station thus contributes more to the metric than any other. Neither region, PC (−9.4 % cen^{-1}) or SE (+3.3 % cen^{-1}), generates a trend significant from zero due to the high variability of the metric. Thus, the number of these events has remained relatively constant. However, only in the drier stations in PC might 25.4 mm be thought of as an extreme event. In other words, this threshold is not close to the "extreme" tail of the daily total precipitation in the distribution of most stations.

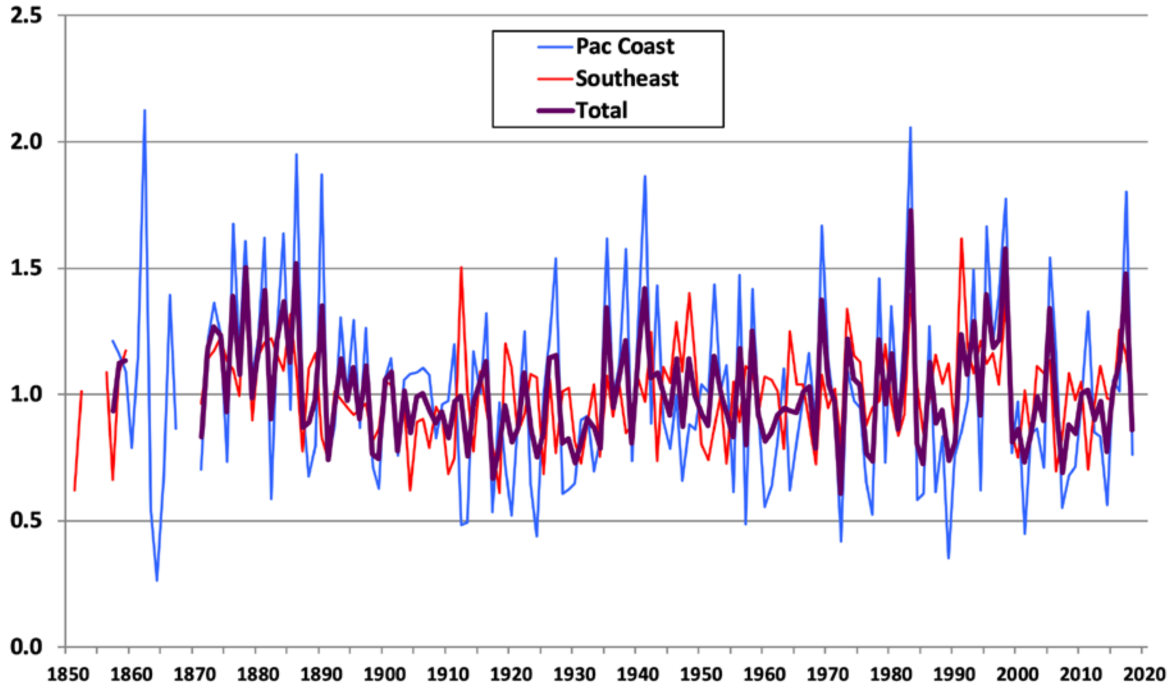


Figure 5. Time series of number of days with > 25.4 mm of precipitation as a proportion of the median total for such days per year. The median of the annual number of 25.4 mm events is first calculated for each station (over 1874–2018) then divided into the number of events that occurred each year for each station. The values shown are the averages of those ten stations per region (blue PC, red SE) as well as the average of both regions together (purple).

Next is shown the time series of a different metric, the magnitude of the wettest day per year as a ratio of the median of all wettest days per year (Figure 6, median determined from 1874–2018 observations). The time series for PC indicates a downward trend since 1874 of −11.2 % cen^{-1} (significant in average total with four individual stations individually significant). Relative to an average of about 47mm, this would suggest a decline in the magnitude of these extreme events of about 8 mm over the 145 years. The result for the SE indicates an upward trend (+9.0 % cen^{-1}, significant with two individual stations significant) which would quantitatively suggest the amount of the wettest day (average of 100 mm) has increased about 13 mm over the past 145 years. The mean of the two regions indicates a trend of −1.1 % cen^{-1} and is not significant.

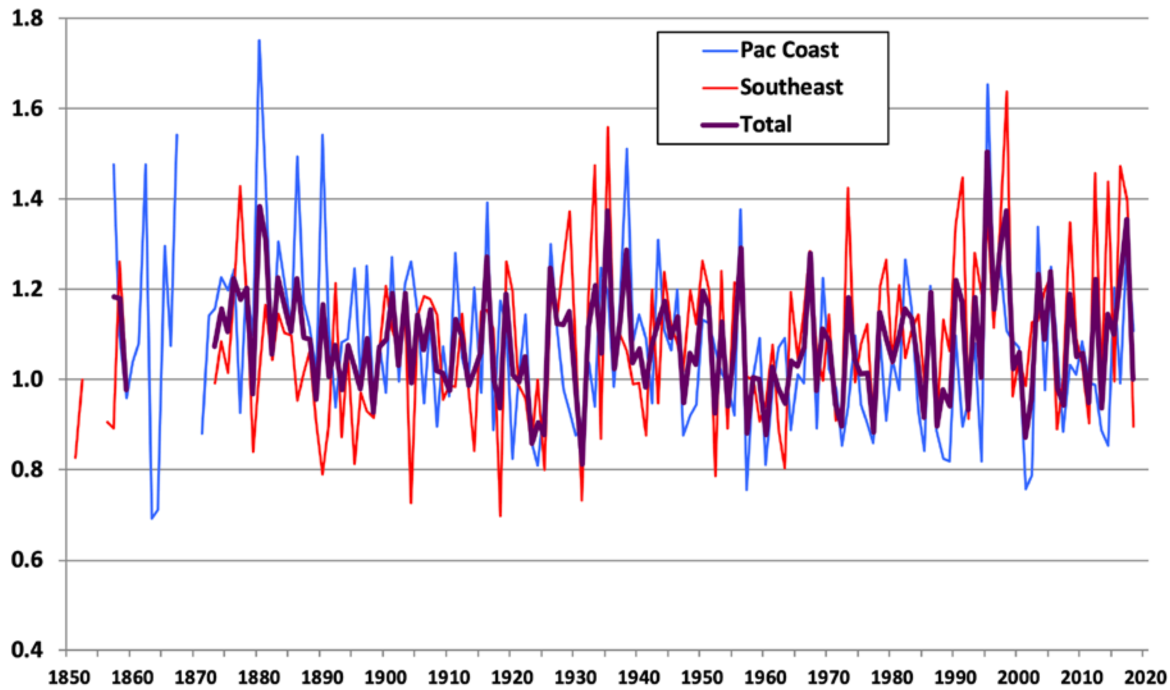


Figure 6. Time series of the ten-station average of the ratios of the annual maximum 1-day precipitation versus the median of the maximum 1-day per year.

A second extreme metric is the magnitude of the wettest consecutive two days. This metric reduces the effect of cutting off a several-hour heavy event at the end of an observation period (midnight in most of these cases) and provides a slightly more statistically robust metric [10]. As in Figure 6 we show the time series of maximum 2-day totals in Figure 7 except we include the individual values per year per station. Trends of the averages since 1874 are −13.4 and +7.6 % cen^{-1} (both significant at the 95% level) for PC and SE respectively.

In the case of PC where the average 2-day wettest event is about 65mm, this result indicates a decline in the magnitude of approximately 15 mm since 1874 and if projected to 2100 a further decline of roughly 8 mm per event. For SE, the median wettest 2-day event per year is about 120 mm, so this would indicate a change from 1874 to 2018 of an additional 14 mm per event. If the trend continued until 2100, the increase would be an additional 8 mm per extreme event. Thus, in terms of absolute magnitude (mm), the decline in PC is almost identical to the rise in SE. When the two regions are averaged, there is no significant change in the long-term trend (−2.9 % cen^{-1}.)

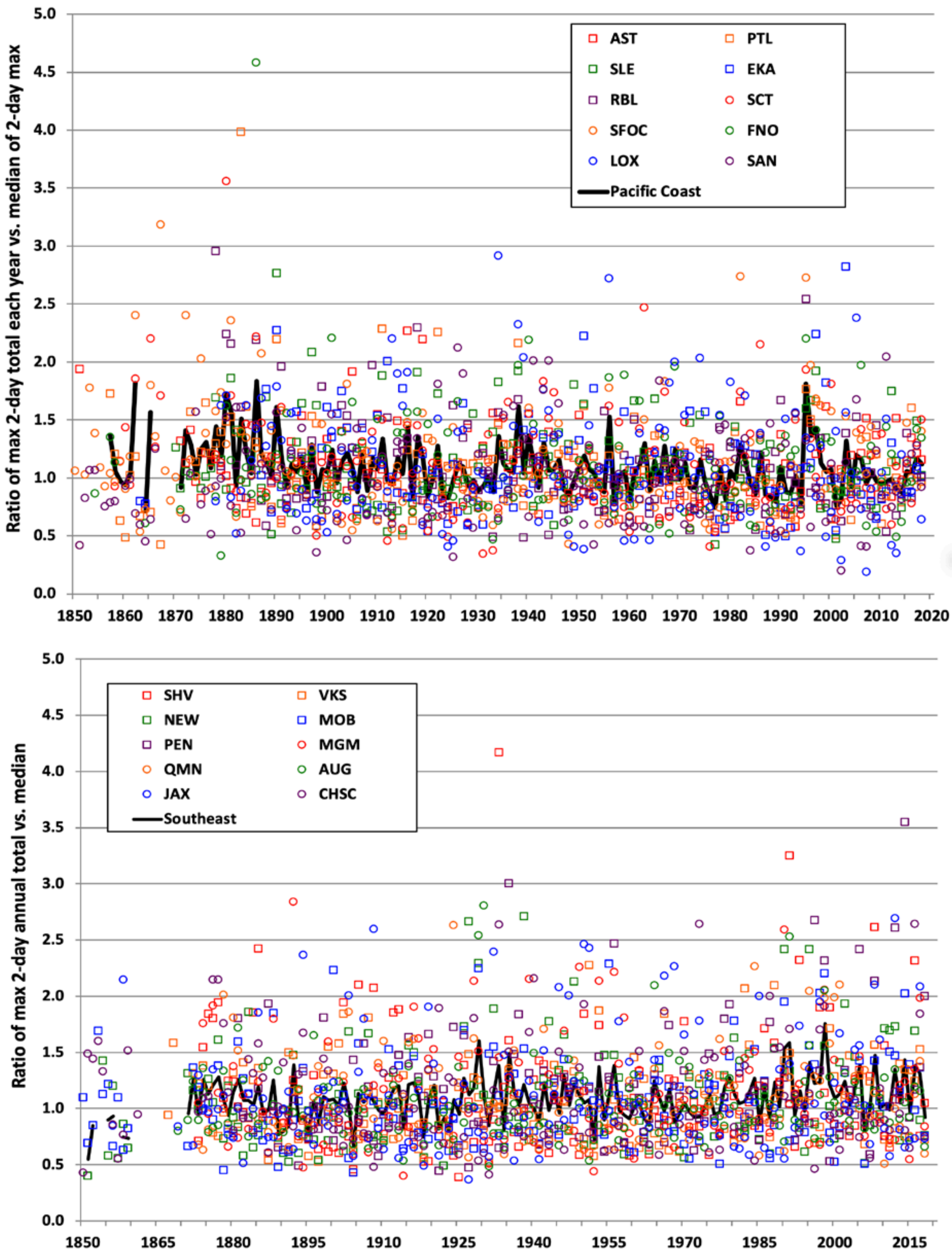


Figure 7. Time series of the maximum 2-day total precipitation per year as a ratio versus the median of all of the maximum 2-day totals (median calculated over 1874–2018). Top is PC and bottom is SE. Black line is the average of the ten stations.

The metric above may be taken a step further by examining the time series of the wettest 20 2-day events per year per station, rank by rank. Figure 8 displays the average trend (cm cen^{-1}) for the ten PC and ten SE stations for each rank of wettest days. The key feature is that changes that are evident in the wettest day of the year decline rapidly to trends within a very few mm per century and insignificantly different from zero. In other words, the wettest 20 2-day totals are not systematically becoming wetter or drier in proportion to the change in the wettest event. For example, in SE (PC), the second wettest event value is on average 71% (74%) of the wettest day, yet its trend is only 43% (40%) that of the wettest day. Similarly, for the third wettest day, the SE (PC) total averages 58% (62%) while the trend magnitude is 30% (23%) of the wettest day. This implies that though the far tail of the distribution shows a tendency to extend (retract) further, the main structure of the wetter part of the distribution shows little change.

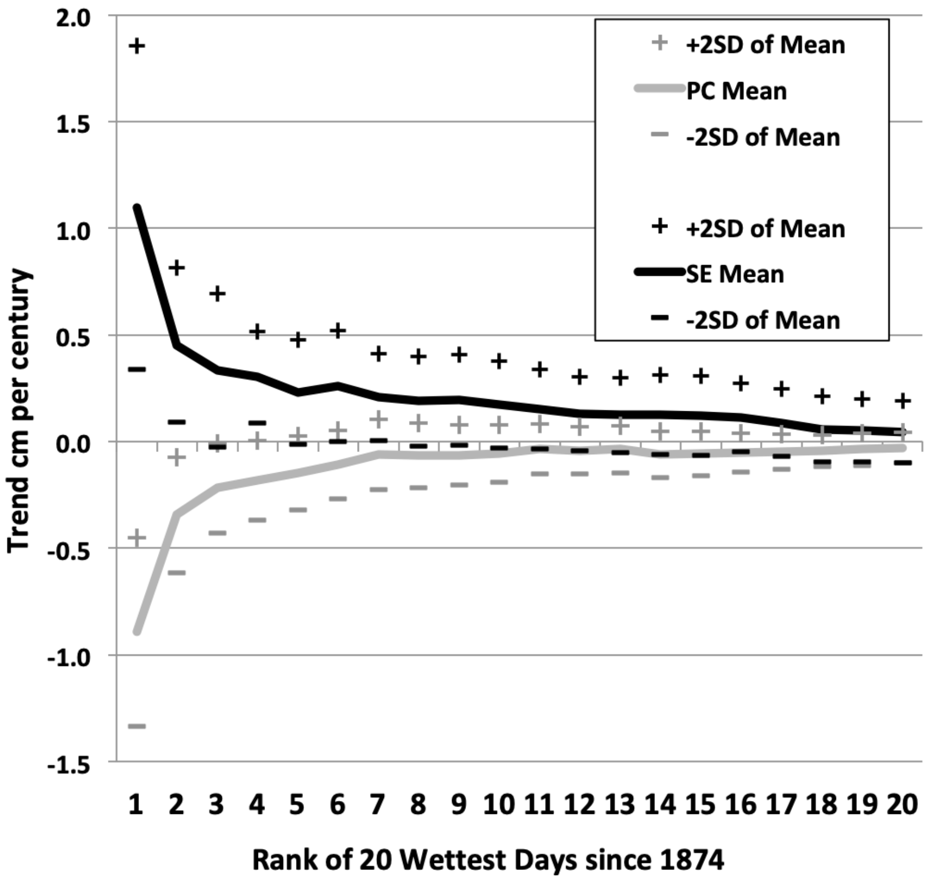


Figure 8. Trend since 1874 of the wettest 2-day totals, rank by rank from the wettest to the 20th wettest. Each value in the black (SE) and gray (PC) lines represents the average of ten stations in each region for each rank. The spread of the individual station trends is represented by the symbols quantifying the +/−2 standard deviation values of the ten stations' individual trends.

The time variation of the occurrences of extreme events may be seen in a different way. Consider the wettest 2-day event that occurs in a five-year period. With 145 years of data, or 29 pentads (five-year periods) we can identify the 29 wettest 2-day events for the entire POR no matter in which pentad they occurred. In this way we can document changes through time of the occurrence of this metric. With ten stations in each region, there would nominally be 50 station-years available per pentad to determine this metric. In PC, the first three standard pentads (1874–1878, 1879–1883, 1884–1888) fell short of the 50 station-years yielding 29, 45, and 47 station-years for averaging respectively. The first three pentads in SE contained 43, 46, and 45 station-years respectively. All other subsequent pentads were complete with 50 station-years in PC and SE. (Note the two pseudo-pentads prior to these defined above contained 30 and 45 station-years for PC and 26 and 25 for SE and are included for illustrative purposes.)

The question here is how the wettest 29 events in 145 years are distributed in time. If there were a sufficiently large population of stations and the typical assumption of stationarity held, we would expect an average of one occurrence every five years in the grand average per station, i.e. the expected value would be 1.0 for each pentad in the figure.

Figure 9 displays the time distribution of the occurrences of the distribution of the 1-in-5-year events based on the reference POR beginning in 1874. The PC results fluctuate considerably with a tendency for more events to have occurred prior to 1947 than after. On two occasions (ending in 1873* and 1883) the average for the PC stations was at least 1.7 "1-in-5-year" events for all stations. (Note that the pseudo-pentad for PC 1873* includes the record California precipitation of the 1862 water-year.) An average of 2.2 1-in-5-year events occurred in SE for the pentad ending in 1998. A noticeable respite from the extreme events in both regions occurred between the 1939–1943 and 1984–1988 pentads inclusive which is an indication of the non-stationarity of this metric.

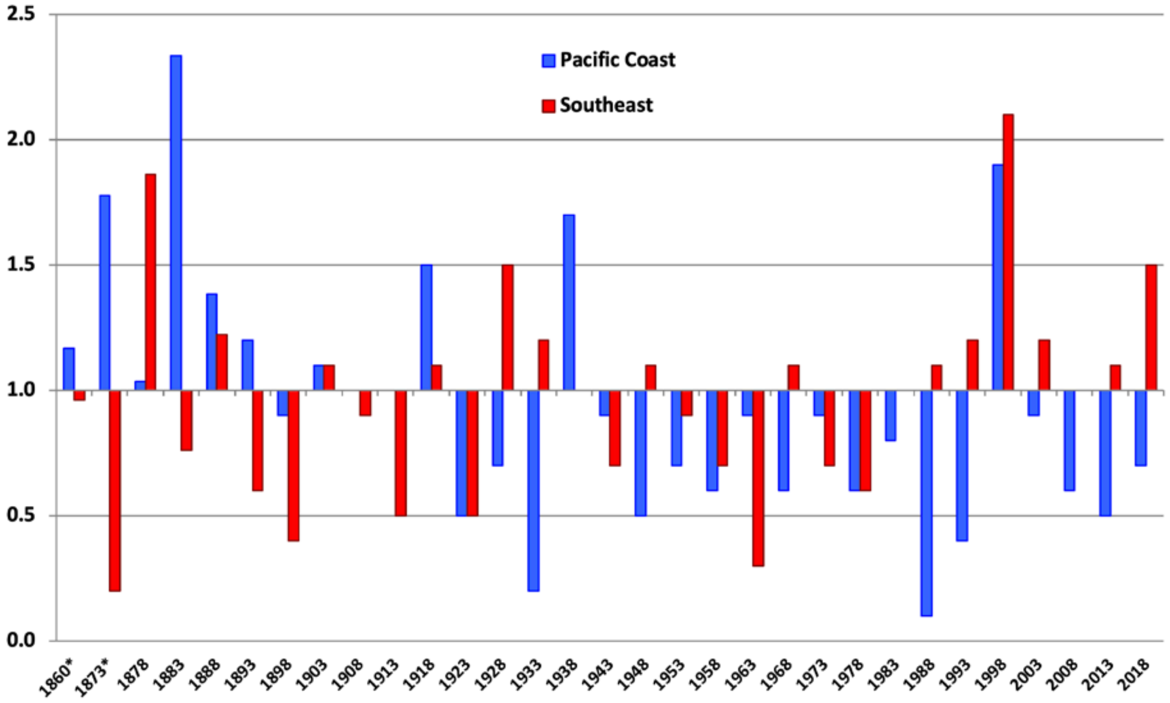


Figure 9. The distribution in time of the 29 maximum rainfall events to occur in 29 pentads (1874–1878 to 2014–2018, with two pseudo-pentads plotted in the initial two pentads noted by *.) This is the distribution in time of the occurrence of the 1-in-5-year maximum events.

The SE distribution indicates a slightly narrower range (σ = 0.39 vs. σ = 0.47 for PC) as well as an increase in the frequency of occurrence toward the end of the POR. Indeed, the last five pentads average 1.38 implying the occurrence of this particular metric of extreme precipitation has recently increased 38% over what was expected. This is roughly consistent with the result in [10] for the region and will be addressed in the discussion section. Conversely, in PC, the average for the five early pentads of 1883 to 1903 also yields an average of 1.38.

In Figure 10 we show the average of both regions. The trends in the annual values of the occurrence of these events are −11.0, +4.6 and –3.2 % cen^{-1} for PC, SE and their average respectively. The PC value is significant at the 95% confidence level, but not the others due to the high variability of the metric. The approximate meaning of the changes, if any, in the average of the last 25 years (last five pentads) is that the nominal 1-in-5 year wettest 2-day total still occurs about once in five years in PC (1.00 to 0.92) and once in almost four years in SE (1.00 to 1.38).

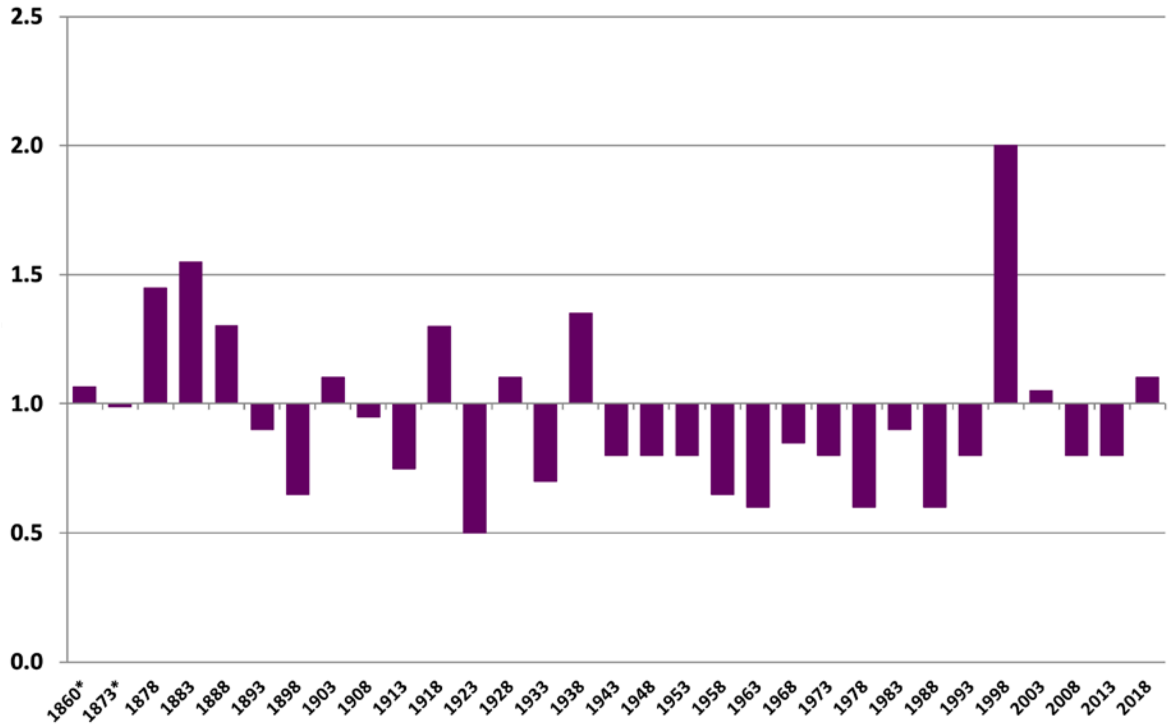


Figure 10. As in Figure. 9 but for the average of the two regions.

A final note on the results here is to be made. In general, precipitation was measured in a consistent manner up until the late 20th century. What had been a simple instrument, a Standard Rain Gauge (SRG) - a container with a top-mounted funnel of diameter 203 mm into which rain fell and was measured with a dipstick - has been replaced in most cases. Since the 1990s, the systems used here have been modernized to measure by tipping bucket or weighing bucket (the signal is sent electronically to the office), which is often surrounded by a rain shield to reduce the influence of the wind which might blow rain droplets across the funnel and thus improve (increase) the catch. The level of the funnel in some cases has also been lowered which would reduce the loss to wind (yet perhaps also inadvertently increasing the “catch” due to capturing spray from the surface.) This issue is being investigated and may play a role in the rise of rainfall amounts in the last 25 years (D. Legates, personal communication.). Also, much of the differences between the early and later systems occurs with snowfall, a precipitation type we have largely avoided with our selection of near-coastal, low elevation stations. Detailed studies have been done and adjustments made to the new equipment to allow it to be as backward-compatible as possible with the SRG [11].

4. Discussion

Our interest in pursuing an examination of the possible changes in 1- and 2-day precipitation extremes was initiated by [10], Figures. 7.3 and 7.4. In these figures there were shown large changes in the US Southeast for 1901–2016 and 1958–2016 and a relationship to increasing greenhouse gases has been proposed as a cause for such changes. A closer look, however, indicates less concern as an increase of 50% of the occurrence of a 1-in-5-year event simply means that in their analysis there are now three events in ten years rather than two. Of interest too for PC is that the increase in greenhouse gases has been offered to explain the recent droughts there. Here we will briefly discuss issues regarding this possibility.

It has been hypothesized that human-induced climate change will cause storm tracks to retreat poleward. One test of this claim is to examine the long-term records from PC where the precipitation is derived almost exclusively from baroclinic systems crossing the Pacific Ocean as the storm track moves south in the cool season. Thus, the further south the storm track moves, more precipitation is seen in the southern stations of PC. As seen in Figure 4, we find no meaningful reduction in precipitation – a result which is inconsistent with the hypothesis. Indeed, the trend of annual precipitation in the five southern PC stations (SCT, SFOC, FNO, LOX and SAN) is −1.1 % cen^{-1}, while that of the northern stations (AST, PTL, SLE, EKA and RBL) is −6.7 % cen^{-1}, the opposite of what would be expected if the storm track were moving poleward. Neither trend is significantly different from zero. Also note that another study [12] examined snowfall time series from 1878 for the western slope of the Sierra Nevada Mountains in CA and determined there was no significant trend in this metric as well.

Similar non-significant results for shorter periods have been noted previously. Regarding very recent changes in U.S. heavy precipitation events [8] suggests the recent changes since 1979 are “intimately linked to internal decadal ocean variability and less so to human-induced climate change.” This supports the hypothesis stated here that natural variability exerts a strong imprint of long-term precipitation variations (see below as well.) A related metric to these types of heavy rain events is independently documented through stream gauge measurements of flooding events. A recent study [13] shows there is “little evidence of regional changes in flood risk across the USA.” Supporting this result is the earlier work [14] which found that when the U.S. is divided into regions that in “none of the four regions defined in this study is there strong statistical evidence for flood magnitudes increasing with increasing (CO2 concentrations).”

Data from the additional decades of the 19th century suggests that the climate of the 20th century alone is likely not a sufficiently representative sample of the range of natural variability against which one might detect and attribute recent weather changes to changes in concentrations of atmospheric greenhouse gases.

Of particular interest here is the observational results in PC that were not included in the analyzed POR for PC averages. SFOC and SCT reported rainfall events in the 1850s and 1860s that surpassed the incidents of extremes utilized in the formal POR here. Using the value calculated to identify the 29 extreme 2-day precipitation events in the 145 years of 1874–2018, we find for SFOC that two of these extreme events occurred in three single years: 1853, 1865 and 1867 while three occurred in the historic flood year of 1862. Only twice in our analyzed POR (1874–2018) did two events occur in a single year for SFOC, that being very early in 1875 and again in the major El Niño year of 1998. In the 20 years of 1853–1872, SFOC experienced a total of 10 of these 1-in-5-year events, or an average of 2.5 per pentad (expected value is 1.0).

On the other end of the time series, MOB experienced 11 events in the final five pentads, or an average of 2.2 1-in-5-year events per pentad. Indeed, half of MOB's extreme events occurred in the last 40 years of its 156-year POR. The next largest count for a 25-year period in MOB was only 6 (1909–1933.) In particular, the pentad ending in 1998 produced an average across all SE stations of 2.2 events with 1998 alone recording 11 (half) of the events for the pentad as a whole. (The PC average value for the 1998 pentad was similarly high at 1.9 events.) This points to the remarkable influence a single, major warm El Niño – Southern Oscillation (ENSO) event may have.

The annual total of SE rainfall is modestly correlated with ENSO events. The Jan–May Multivariate ENSO Index [15] achieves a correlation with SE annual rainfall of +0.53 for the period 1950–2018. Extreme events tend to have a preference for years with above-average annual totals, an examination of a longer history is useful with an average correlation between the 2-day extreme and annual rainfall at +0.55 for the 20 stations.

A recent study [16] produced a 1,100-year history of ENSO amplitude in which the most recent 150-year period is characterized by a relatively low amplitude compared with the 500 years prior. The amplitude (range in values) for 1850 to 1999 is 0.85 to 1.85, while between 1350 and 1850 the range was 0.4 to 2.2, or almost twice as large as 1850–1999. Though somewhat speculative, it is entirely possible that with ENSO amplitudes both much larger and smaller than those which occurred in the current POR, one cannot assert that internal natural variability is not the cause of the recent upturn in SE extreme events. Indeed, if the single ENSO year 1998 is removed from the POR, the SE trend in maximum annual 2-day total becomes non-significant (trend falls from +7.6 to +6.4 % cen^{-1}). Note too that eleven 1-in-5-year 2-day maximum precipitation events occurred in the SE stations in 1998 alone versus the expected value of 2, though the trend in the distribution of 1-in-5-year events was positive, but non-significant.

The evidence above suggests that precipitation regimes have significant inter-century variability that may underlie and influence the small changes in extreme events observed over periods less than 150 years as studied here. For example, the well-known mega-droughts of the PC region before the 14th century were very likely accompanied by significant changes in the distribution and magnitude of the daily event extremes.

A compilation of the Palmer Modified Drought Index (PMDI) from year 0 to the present has been assembled for examination of changes over the past two millennia over most of North America [17,18]. The metric calculated is the summer PMDI which, because it represents a time-integrated value of hydrologic drought, is strongly related to precipitation during the previous several months (r ~ 0.7 vs. the precipitation totals here.) From the half-degree gridded data, the time series for PC and SE regions has been generated and shown in Figure 11.

The PC time series indicates there was a sudden decline in the 31-year running average in the most recent few decades. The results are somewhat consistent with the evidence here in that PC precipitation has declined at a rate of 35% cen^{-1} since 1980. However, as Figure 4 demonstrates, these types of large short-term trends are common for PC's climate record, for example, the trend from 1876 to 1913 (same length) was −65% cen^{-1}. Figure 11 also indicates that the period from the 15th to the 20th centuries were largely free of the "mega-droughts" that lasted decades each before the 14th century when alpine lakes in the Sierra Nevada Mountains were dried so completely that trees, now drowned, grew to maturity [19]. The last 700 years have been especially moist (mean PMDI +0.16 above the 2000-year mean) while in the first 1000 years, the average was −0.13 below the mean.

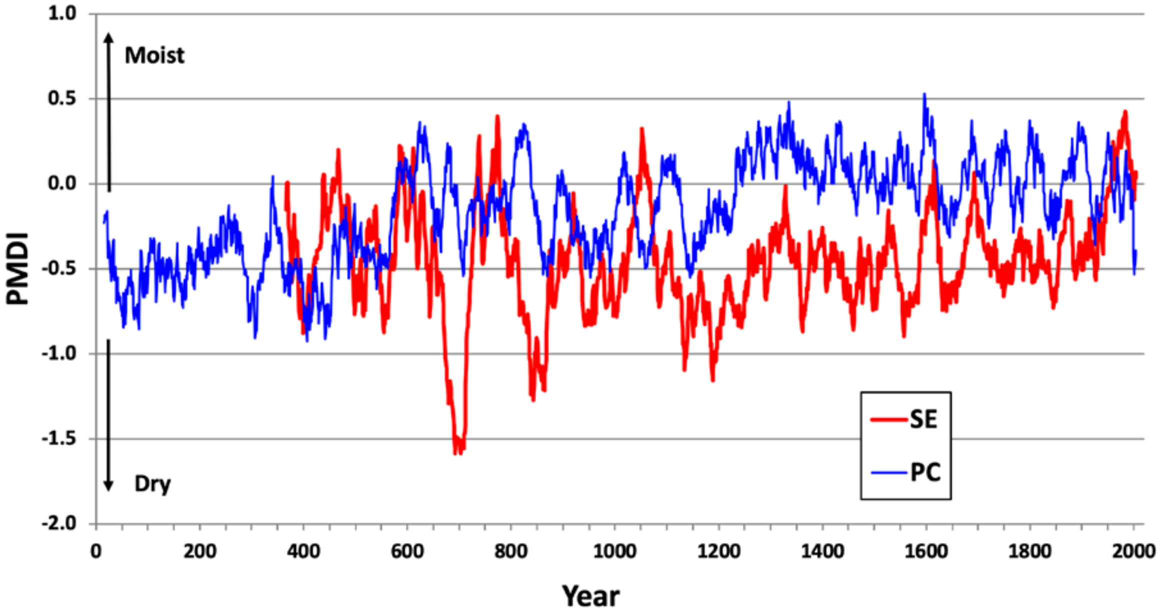


Figure 11. Time series of the 31-year running average (centered) of the Palmer Modified Drought Index [18] for the two regions, SE (red) and PC (blue) generated from gridded data.

The SE PDMI time series is quite different indicating that since 1900 the climate has been very moist, with a PDMI of +0.43 above the overall average. The evidence is compelling that significant drought conditions that were common prior to 1900 have not been experienced by the present population. The presence of significant variability in the past 2000 years with excursions from the long-term mean greater than is seen in the past few decades is evidence that suggests variations in the precipitation metrics shown here (i.e. annual total, magnitude of annual 2-day extreme, occurrence of 1-in-5-year events) may be influenced by factors other than increasing greenhouse gases. In other words, because variations much larger than today's in precipitation indices have occurred in the past without the presence of increased greenhouse gases, it is possible, even likely, that the fluctuations we measure today are largely influenced by the internal natural complexities of the dynamical system we call climate.

5. Conclusion

Before changes in extreme precipitation metrics may be identified as unusual or non-natural, a proper characterization of the system is required. Climate is a system that is especially difficult to characterize in this way because our sample size of observations is relatively short and small compared with the types of changes we desire to detect. To address the shortness of most analyses of extremes, we use 145 years of daily precipitation in two regions of the US with ten stations each, the Pacific Coast (PC) and the coastal Southeast (SE). The results indicate (1) no significant trend in annual rainfall in either region, (2) no significant trends in number "downpours" of > 25.4 mm day^{-1} per year in either region, (3) significant downward (upward) trend in the magnitude of the wettest day per year in PC (SE) of, on average, −8 mm (+13 mm) over 145 years, (4) significant downward (upward) trend in wettest 2-day amounts for PC (SE) of, on average, −15 mm (+14 mm) over 145 years, and (5) a significant decrease in the occurrence of 1-in-5-year wettest 2-day events in PC.

The results above define "what" has happened with these extreme metrics of precipitation, which was the main thrust of this research. The Period of Record (POR) examined here was 145 years, 1874–2018, though some information from earlier years was offered. A concern today is to determine whether a cause may be determined for the modest changes that have been documented, i.e. the "why."

Though daily precipitation is not a metric that can be reconstructed from paleo-records, it has been shown that extreme precipitation metrics are strongly related to indices of annual rainfall and ENSO. Time series of these two quantities, based on proxies that go back over 1000 years, demonstrate that the climate system has undergone variations that exceed the magnitude seen in the last 145 years. Since these indices are somewhat related to the magnitude of the extreme events documented here, it is possible, even likely, that the modest changes in these events may be largely the result of the internal natural variability of the system. This hypothesis suggests that attribution of observed changes will be extremely difficult because we do not have a full understanding of the internal natural variability of the climate system as indicated by the paleo-records**.**

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Conflict of interest

The author indicates no conflict of interest.

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