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TRENDS IN RAINFALL EXCEEDANCES IN THE OBSERVED RECORD IN SELECTED AREAS OF THE UNITED STATES[1]

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ABSTRACT: Semantic differences have led to a gap in the understanding of the impacts of climate change on precipitation frequency estimates. There is popular perception that heavy rainfalls have become more frequent, and that this trend will increase with global warming. Most of the literature examines this question from the point of view of climatology using definitions of "heavy," "very heavy," or "extreme" rainfall, which are different from those commonly used by civil engineers. This article identifies the differences in meaning used by the climate and civil engineering communities and examines trends in the observed record in the frequency of exceedances (not trends in magnitudes). Using concepts recognized as the basis for design of the Nation's civil infrastructure, we look at trends in the number of exceedances of thresholds for a variety of precipitation frequencies and event durations used by civil engineers. We found that the estimated trends in exceedances at one-day and multiday durations were statistically significant and increasing for the Ohio River Basin and surrounding states but the reverse was true for the Semiarid Southwest (i.e., not significant and decreasing trends). In addition, we found the magnitude of the trends was small for all but the more frequent events and also small with respect to the uncertainty associated with the precipitation frequency estimates themselves.

(KEY TERMS: precipitation; climate variability/change; statistics; time series analysis; rainfall frequency; rainfall intensity; stationarity.)

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CLIMATOLOGY SEMANTICS AND STATEMENTS

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), in its Climate Change 2007: Synthesis Report (IPCC, 2007a) states: "It is likely that the frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has increased over most areas." The IPCC AR4 Working Group I report (IPCC, 2007b) states: "Groisman *et al.* (2005) found significant increases in the

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frequency of heavy and very heavy (between the 95th and 99.7th percentile of daily precipitation events)." These and similar statements in the literature define terms such as "heavy," "very heavy," or "extreme" precipitation. For example, Groisman *et al.* (2005) state: "For a given location and season, we define a daily precipitation event as heavy when it falls into the upper 10 and/or 5% of all precipitation events; as very heavy when it falls into the upper 1 and/or 0.3% of precipitation events; and extreme when it falls into the upper 0.1% of all precipitation events." They go on to say: "The return period for such events varies depending upon the frequency of days with measurable precipitation and varies, for example, from 3 to 5 yr for annual … very heavy precipitation events." We note that these terms generally apply to events of daily durations. Although this approach is the predominant one in the analysis of climate change impacts on the frequency of rainfall, some authors (e.g., Karl and Knight, 1998) acknowledge: "… there is no single method of analysis that can comprehensively cover all the important aspects of how precipitation changes over the course of time …."

CIVIL ENGINEERING AND CIVIL INFRASTRUCTURE PLANNING SEMANTICS

Civil engineers and planners rely on precipitation frequency estimates defined in terms of average annual exceedance probabilities (AEP) or average recurrence intervals (ARIs) (otherwise referred to as annual return period or return period). [See Handbook of Hydrology (Maidment, 1993), Bulletin 17B (Interagency Advisory Committee on Water Data, 1982), NOAA Atlas 14 (Bonnin *et al.*, 2006, 2011), Australian Rainfall and Runoff (Institution of Engineers, Australia, 1987, 1998), and Rainfall Frequency Atlas of the Midwest (Huff and Angel, 1992).] The terms heavy, very heavy, and extreme rainfall are generally subjective terms in civil engineering. Historically, the engineering community has been interested in ARIs ranging from 25 to 100 and 500 years but, in recent decades, with the emergence of design for environmental issues, ARIs down to one-year and lower have become more relevant. Designs for stormwater drains are typically based on ARIs around 25-35 years and floodplain management is typically based on ARIs from 100 to 500 years. Large dams are typically designed for the probable maximum precipitation, which has variously been assigned ARIs from 10,000 to 1,000,000 years. These ARIs are far greater than those addressed in the IPCC AR4 reports and in climatology literature.

It is clear then that although the climate community has defined meanings for their descriptions of the magnitude of rainfall, those definitions do not address the much higher rainfall depths and intensities that cause flooding or are of primary concern for the design of civil infrastructure. Furthermore, the meanings assigned to those terms by the climate community are inappropriate given the rainfall depths and intensities that concern the general public and the civil engineering communities. This has led to misinterpretation of statements from authorities such as the IPCC by the civil engineering community (and most likely the general public) and, conversely, a misunderstanding of the information needed for determining the potential impact of climate change on civil infrastructure by the climate community.

We suggest that as we examine the potential impacts of climate change on precipitation frequencies, we use terms, frequencies, and durations in common for the design and planning of the Nation's civil infrastructure. Specifically, we should use the terms "average recurrence interval" and "annual exceedance probability," defined in NOAA Atlas 14 (Bonnin *et al.*, 2006, 2011), Australian Rainfall and Runoff (Institution of Engineers, Australia, 1987, 1998), and recommended for use by the United States National Research Council (National Research Council, 2000).

Calculating Exceedances

We attempt to bridge the semantic gap by extending the analyses of the climate community into the range of greater rainfalls, which cause flooding, and are of interest for the design of civil infrastructure. In order to root ourselves in the semantics and design standards of the civil engineering community, we have used the specific precipitation frequency estimates provided in NOAA Atlas 14 Volumes 1 and 2 as thresholds. As shown in Figure 1, Volume 1 (Bonnin *et al.*, 2011) provides estimates for the Semiarid Southwest United States (U.S.) and Volume 2 (Bonnin *et al.*, 2006) provides estimates for the Ohio River Basin and surrounding states. (For brevity, we refer to these domains hereafter as Semiarid Southwest and Ohio River Basin, respectively.) These domains are of roughly the same size and somewhat the same locations as the regions used by Groisman *et al.* (2005). We counted and analyzed exceedances of the NOAA Atlas 14 thresholds for 1-, 2-, 5-, 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-year ARIs for each station within the Semiarid Southwest and Ohio River Basin domains. In addition to daily durations, we also examined events of 6 h and 2-, 4-, 7-, 20-, and 45-day durations. We note here that we are only determining trends in the frequency of exceedances. We do not

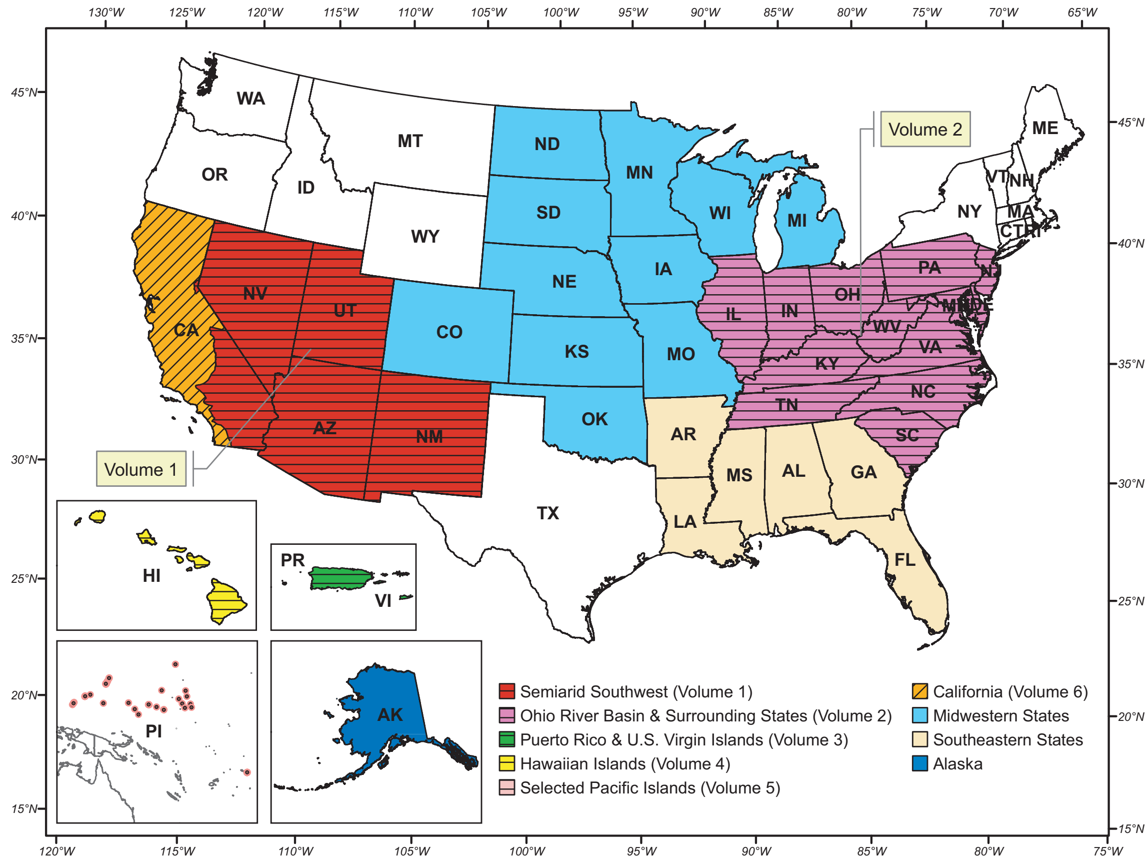

FIGURE 1. NOAA Atlas 14 Volume Domains.

address trends in magnitude. We also note that the sample sizes for exceedances at 200-, 500-, and 1,000-year ARIs were too small to conduct a reasonable analysis.

For each station in the Semiarid Southwest and Ohio River Basin domains, and for durations of 6 h and 1, 2, 4, 7, 20, and 45 days, we counted the actual number of exceedances in the available historic record, treating the historic records as partial duration series for consistency of the statistics. The observed data and stations we used for this analysis are the same as those used in the derivation of NOAA Atlas 14. The documentation for each of the volumes of NOAA Atlas 14 contains detailed information on the quality control performed on the observed data to determine its usability for producing precipitation frequency estimates. Although daily station data were available before 1900, there were an insufficient number of observations to produce meaningful results prior to 1908. As a result, our analysis for this article used data from 1908 to 2007. At the subdaily time step, there were insufficient data prior to 1948 and so we used observations from the period 1948 to 2007.

The thresholds in NOAA Atlas 14 were calculated using careful choices of extreme-value probability distribution functions and the regional method of L-moments to parameterize the functions (see Bonnin *et al.*, 2006, 2011; Hosking and Wallis, 1997). Civil engineering professionals and regulatory agencies require publication of estimates with ARIs up to 1,000 years. Therefore, it is critical to apply appropriate statistical tools to extend the estimates into the range of these very small probability rainfall events. Most of the tools rely on second-order or higher moment assumptions to estimate distribution parameters of extreme rainfall characteristics. But the L-moments algorithm characterizes the same features (i.e., the dispersion, skewness, and kurtosis) under first-order moment assumptions. Rather than determining and parameterizing different distributions at each observing location, the regional approach used for NOAA Atlas 14 assumes that nearby stations share a common climatology with respect to the shape of the distribution. This assumption allows for the determination and parameterization of appropriate distributions based on a much larger set of data than is used when making estimates independently at each station. It generally allows estimates of precipitation frequency to be produced up to 1,000-years ARI with confidence. Hosking and Wallis (1997) provided a systematic description of the theoretical basis and the robustness and reliability of the regional L-moment method as well as parameter estimation algorithms for commonly used extreme-value distribution functions. They also provide tools for testing the assumption of shared climatology for the shape of the distribution as well as tools for determining the degree of heterogeneity of any particular station within the set. It is self-evident, therefore, that the regional L-moment approach is different from the approach adopted by most authors in the climate community who generally use thresholds defined as a percentile of daily series (e.g., see Groisman *et al.*, 2005; Karl and Knight, 1998).

We calculated the sum of the exceedances over all stations in each domain in each year, duration, and for each ARI. We then normalized for the varying number of stations with observations in each year by dividing by the number of stations with observations in each year. By summing the values for all stations within the domain, we enhance the signal-to-noise ratio that occurs by looking at individual stations. The resulting value for each domain, year, ARI, and duration is the average number of exceedances per station per year. This number should be similar to the expected value, which can be calculated from the ARI. For example, for an ARI of 25 years, we can expect an average of four exceedances per station per century, for an ARI of 50 years we can expect an average of two exceedances per station per century, and for an ARI of 100 years we can expect an average of one exceedance per station per century.

Each of the Figures 2 to 5 comprises of a "stack" of seven individual graphs, one for each ARI. These plots include features that help interpret the results. For each one of the individual graphs in the stack, the horizontal axis is the time in years and the vertical axis is the difference between observed number of exceedances and expected number of exceedances. The scale on the vertical axis varies in the range ±50 exceedances per station per century. The data are shown as a scatter of points. A horizontal dashed line at a value of 0 helps guide the eye through the irregularities that are due at least in part to sampling variations. Under the null hypothesis, the data values (the "residuals") should be consistent with zero (i.e., a cloud of points centered on a value of zero). The solid line through the data points is the least-squares regression line. The labeling for each ARI category is placed off to the right side of the subplot. As all daily and multiday durations exhibit similar characteristics, we only present results for one-day and the six-hourly durations.

With respect to the Semiarid Southwest, most of the data points in the six-hourly duration at ARI >5 years (Figure 2) fall on either side of zero line and their corresponding linear regression lines are nearly parallel to this zero line. However, the most frequent events (ARI ≤5 years) are characterized by increasing trends. Conversely, Figure 3 shows that the cloud of data points associated with the daily duration move progressively from above 0 to below 0 and its regression line has a negative gradient. The most prominent feature of this figure is that the magnitude of the decreasing frequency is relatively larger for the most common precipitation events over the study period (1908-2007).

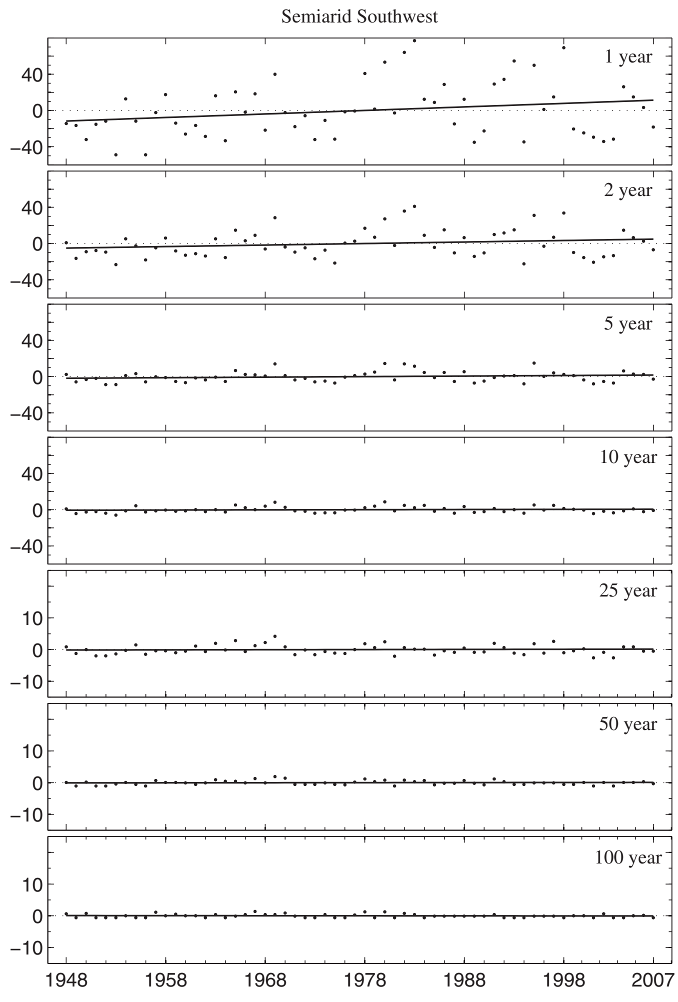

FIGURE 2. Semiarid Southwest Six-Hour Exceedances. Each of the seven graphs represents analytical results for a given ARI. The horizontal axis is time (1948-2007). The vertical axis is the numeric difference between observed number of exceedances and expected number of exceedances expressed as the number of exceedances per station per century. The data are shown as a scatter of points and there are two lines shown; a horizontal dashed line at a value of 0 and a solid one showing the regression line. Under the null hypothesis, the data values (the "residuals") should be consistent with zero. The labeling for each ARI category is on the right-hand side of the subplot. Attained two-sided significance levels for the Mann-Kendall test statistic are provided in Table 1.

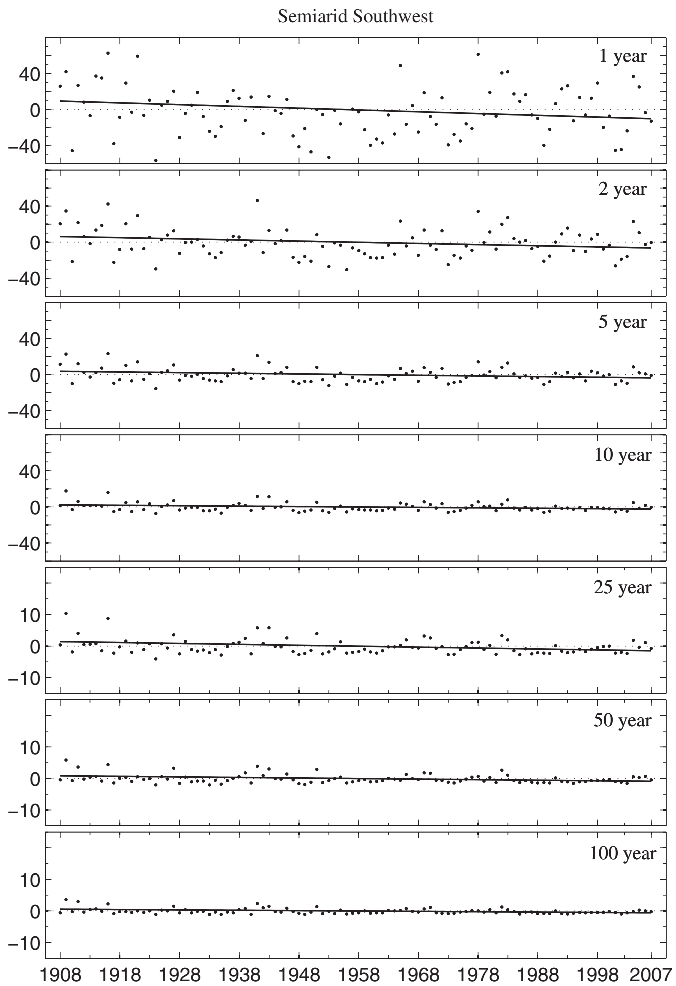

FIGURE 3. Semiarid Southwest One-Day Exceedances. Similar to Figure 2, except the period covered is 1908-2007. Similar results were obtained at other multiday durations.

All frequencies in the Ohio River Basin are characterized by increasing trends for all multiday durations whereas the six-hourly duration does not show any measurable trend (Figures 4 and 5). Here the multiday results demonstrate that these positive trends decrease with increasing ARI. For example, noticeable increasing trends are registered at ARI <25 years but only small non-zero trend is identified at the 100-year ARI. Additionally, observed sampling variability is relatively larger at the more common events than at rare events.

The information contained in the stacked plots is not sufficient to discern whether the observed trends are significant. As discussed below, we tested whether the trends in the exceedances were statistically significant (see Helsel and Hirsch, 2002; Hirsch *et al.*, 1982; Haan, 2002). The Mann-Kendall test was used, because the data are temporally evenly spaced, and this method is known to be insensitive to outliers (see Hirsch *et al.*, 1982). The Mann-Kendall is a rank-based nonparametric algorithm that examines the direction of change in the number of exceedances *vis-à-vis* time (direction of slope) for all pairs of ordinal time points. The summary statistic describing the direction of trend is derived as a function of the sum of all signs of the slopes (Helsel and Hirsch, 1992). The exceedances dataset for this analysis covers the period 1908-2007 for all durations except the six-hour duration where the historic record spans the period 1948-2007. We tested each dataset using the Mann-Kendall test for trend. The null hypothesis is that the data are independent and identically distributed over time. We rejected the null hypothesis using an alpha level of 0.05 and Table 1 indicates these instances in bold. In addition, we compute the two-sided attained significance level for each instance and report those values on Table 1 as well.

Table 1 presents an estimate of the Mann-Kendall statistic and its associated *p*-value (the attained two-sided significance level). Bold numbers indicate statistical significance at the 0.05 level. From these results, we make the following inferences:

1. In the Semiarid Southwest domain, it is observed that at durations of one or more days almost all are downward trends. At the one-day duration, all of these trends are significant, except for the one-year ARI. At the six-hour duration, all trends are upward but they are not significant.
2. In the Ohio River Basin domain, estimated trends at all durations and all ARIs are positive with only two exceptions (six-hour duration at one- and two-year ARIs and are non-significant). At durations of 1-day through 20-days, almost all trends are statistically significant, whereas for the six-hour and 45-day durations most trends are not significant.

As a supplementary effort, the parametric *t*-test (Haan, 2002) tool was applied and similar conclusions emerge.

In addition, an assessment of trends in the frequency of exceedances over time for a restricted period of record, 1970-2007, yielded no statistically significant trends in either study domain. However, the pattern of these trends was in close agreement to those computed for the full periods used in the study.

Rates of Change

Another interpretation of the trend emerges from a regression-type analysis (Draper and Smith, 1998). This analysis is performed on exceedances in each spatial domain over the time period 1908-2007 for all durations (with the exception of the six-hour

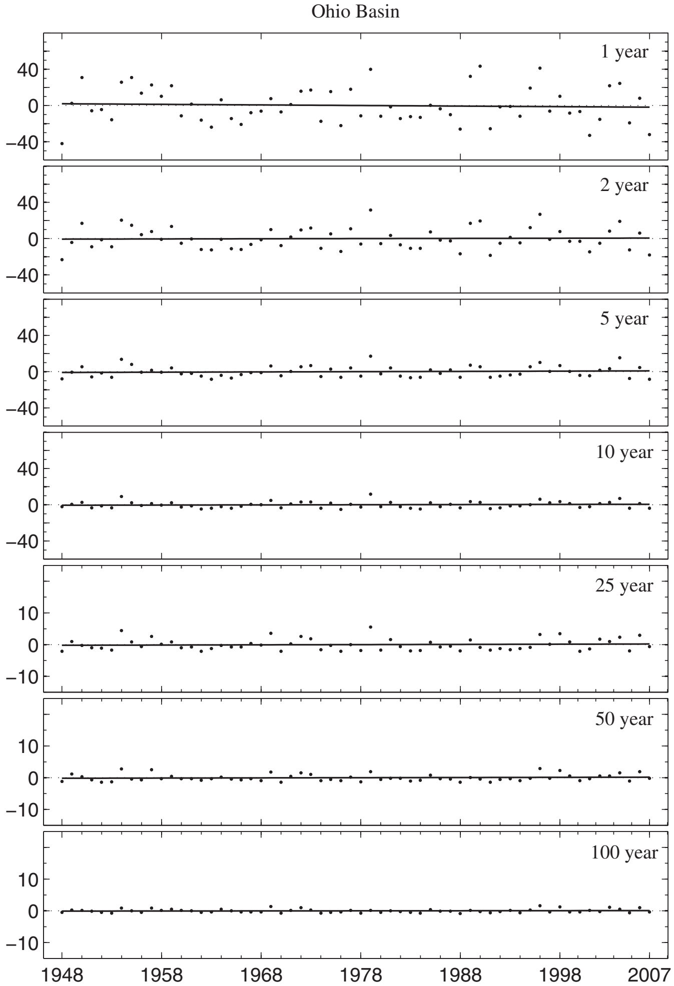

FIGURE 4. Ohio River Basin Six-Hour Exceedances. See Figure 2 for explanation.

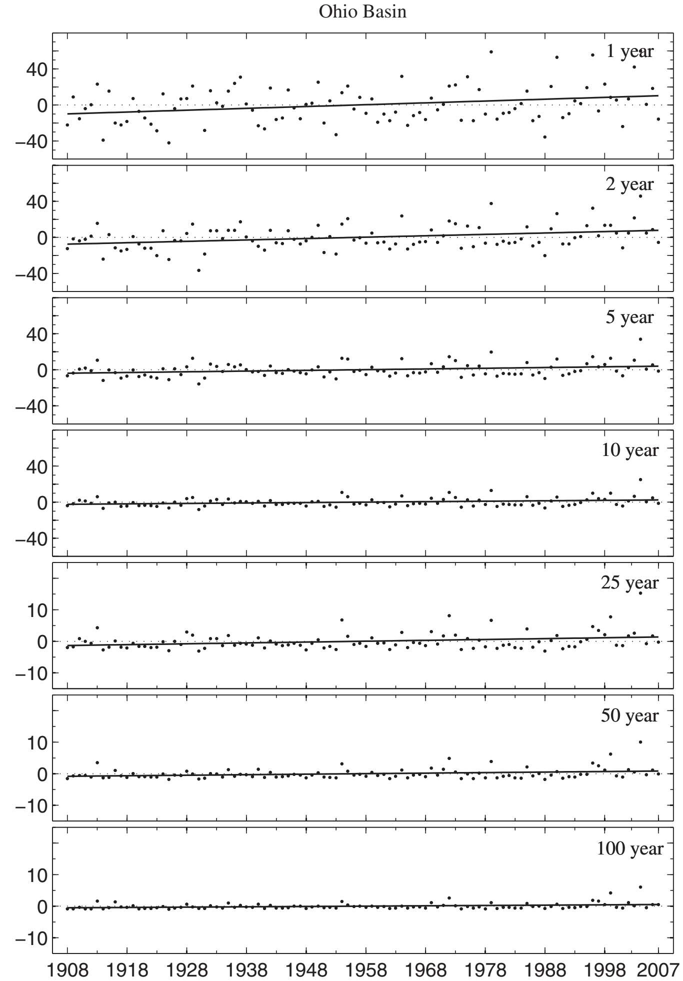

FIGURE 5. Ohio River Basin One-Day Exceedances. Similar to Figure 2, except the period covered is 1908-2007. Similar results were obtained at other multiday durations.

duration where the reference period is 1948-2007). The first step in this scheme is to group the duration-based data into ARI bins. Next, calculate the average number of observed exceedances per station per century and the corresponding expected number of exceedances per station per century (from a standard such as NOAA Atlas 14) for each ARI bin. Finally, the test statistic (Δ) is computed as the average change expressed as a percentage of the expected value:

$$\Delta = \left(\frac{O - E}{E}\right) \times 100\%,$$

where O and E are the observed and the expected number of exceedances per station per century, respectively. For example, suppose that the one-day 50-year ARI data have an observed frequency of 2.06 events per station per century, when this event is expected twice per century on average, then the average change is an increase of 3% ($\Delta = [(2.06 - 2.00)/2.00] \times 100\% \approx +3\%$).

Figures 6 and 7 show the average percentage change in the number of exceedances per station per century for stations in the Semiarid Southwest and the Ohio River Basin, respectively. Each figure contains a set of two plots. The main plot consists of a set of line graphs where each line represents a duration-based regional average percentage change in exceedances at key ARIs for civil engineering design. The inserted box shows the full range of the ARI.

Figure 6 shows that for the Semiarid Southwest, the numeric change in the number of exceedances for each duration and frequency are different; changes ranging from +37 to −20% at one-year ARI, to much less than ±4% at an ARI of 25 years and beyond. We observe that all multiday durations are comprised of negative values whereas the six-hour duration

TABLE 1. Results of Kendall's Tau Trend Analysis for the Average Number of Exceedances per Station per Year.

Average Recurrence Interval	No. Records (years)	Semiarid Southwest		Ohio River Basin	
		Kendall's Tau	Probability Value	Kendall's Tau	Probability Value
6-Hour					
1	60	0.041	0.630	−0.127	0.134
2	60	0.044	0.607	−0.047	0.580
5	60	0.143	0.090	0.020	0.816
10	60	0.163	0.054	0.091	0.285
25	60	0.164	0.054	**0.171**	**0.044**
50	60	0.153	0.075	**0.221**	**0.009**
100	60	0.061	0.496	**0.181**	**0.033**
1-Day					
1	100	−0.118	0.074	**0.160**	**0.015**
2	100	**−0.134**	**0.043**	**0.197**	**0.003**
5	100	**−0.123**	**0.041**	**0.160**	**0.015**
10	100	**−0.136**	**0.040**	**0.136**	**0.039**
25	100	**−0.148**	**0.025**	**0.151**	**0.022**
50	100	**−0.168**	**0.011**	**0.130**	**0.048**
100	100	**−0.155**	**0.019**	**0.210**	**0.001**
2-Day					
1	100	−0.078	0.236	**0.189**	**0.004**
2	100	−0.061	0.353	**0.183**	**0.005**
5	100	−0.086	0.194	**0.182**	**0.006**
10	100	−0.090	0.171	**0.172**	**0.009**
25	100	−0.123	0.063	**0.177**	**0.007**
50	100	−0.129	0.050	**0.192**	**0.004**
100	100	−0.110	0.096	**0.206**	**0.002**
4-Day					
1	100	−0.061	0.359	**0.183**	**0.005**
2	100	−0.053	0.422	**0.200**	**0.002**
5	100	−0.078	0.238	**0.207**	**0.002**
10	100	−0.087	0.188	**0.209**	**0.002**
25	100	−0.084	0.203	**0.211**	**0.001**
50	100	−0.101	0.125	**0.211**	**0.001**
100	100	−0.049	0.464	**0.247**	**0.000**
7-Day					
1	100	−0.033	0.615	**0.167**	**0.011**
2	100	−0.057	0.388	**0.176**	**0.007**
5	100	−0.047	0.474	**0.202**	**0.002**
10	100	−0.050	0.451	**0.206**	**0.002**
25	100	−0.085	0.198	**0.185**	**0.005**
50	100	−0.063	0.341	**0.208**	**0.002**
100	100	−0.029	0.666	**0.203**	**0.002**
20-Day					
1	100	−0.027	0.678	0.062	0.345
2	100	−0.035	0.600	**0.131**	**0.047**
5	100	−0.018	0.785	**0.176**	**0.008**
10	100	0.001	0.996	**0.194**	**0.003**
25	100	−0.029	0.664	**0.213**	**0.001**
50	100	−0.022	0.737	**0.212**	**0.001**
100	100	0.048	0.471	**0.243**	**0.000**
45-Day					
1	100	−0.022	0.738	0.056	0.400
2	100	−0.038	0.567	0.088	0.185
5	100	0.005	0.940	0.105	0.110
10	100	0.014	0.835	0.114	0.083
25	100	0.033	0.620	0.125	0.058
50	100	0.046	0.494	**0.134**	**0.043**
100	100	0.019	0.776	0.107	0.105

Note: Bolded numbers indicate significant at 95% confidence level ($p \leq 0.05$).

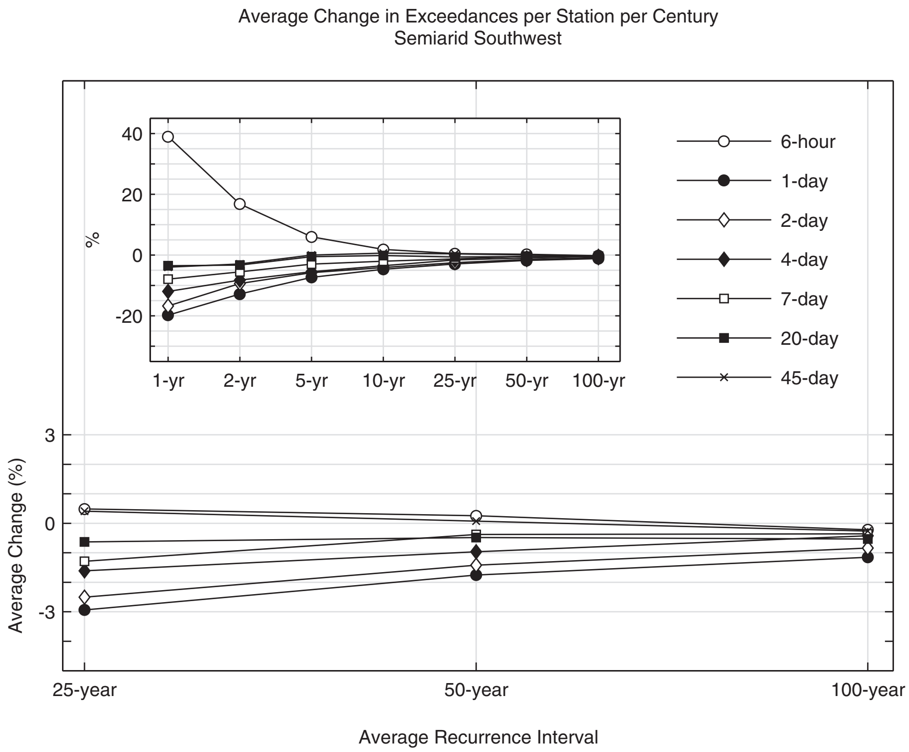

FIGURE 6. Average Change in Number of Exceedances per Station per Century for the Semiarid Southwest (see main text for details).

behaves in a similar manner but in the opposite direction.

In the Ohio River Basin, the change in the number of exceedances for all multiday durations are positive, ranging from +25% at one-year ARI to much less than +3% at ARI of 25 years and beyond (Figure 7). The six-hour duration is characterized by negative values at ARI of <5 years.

Overall, the responses at the six-hour duration are in stark contrast to other durations in each study area. An assessment of the day to multiday events over the same data record length as the six hour, 1948-2007, yielded a qualitatively similar pattern of trends (not shown) as those shown in this study. This scenario is consistent with the findings of a similar study by Jakob *et al.* (2010). Possible reasons for this difference may include the differences between the atmospheric dynamics of the six-hour precipitation events and events of longer durations.

We draw the following conclusions:

1. These results suggest that precipitation regimes for ARIs <25 years have experienced the largest changes, in the range [±37 to ±8%]. Therefore, special attention may be necessary for engineering practices where critical design criteria depend on storms having an ARI of <25 years (e.g., design for pollution controls for runoff from roads, instream fish habitat, etc.).
2. The greatest percentage change in 25-year and above ARI cases is less than ±4% for both study areas. On the other hand, the 90% confidence intervals provided in NOAA Atlas 14 range from the order of ±30% of the mean in sparsely instrumented areas with shorter periods of record to ±10% in areas with more dense instrumentation and longer periods of record. Thus, such a rate of change is still small when compared with the error associated with the estimates themselves. Because the changes in the frequency of precipitation of primary relevance for flooding and for civil engineers are small with respect to our ability to accurately define those estimates, civil engineers and planners should be considering the uncertainty in the precipitation frequency estimates in addition to considering any potential future changes in the estimates.

For more frequent events, these results are consistent with past studies in somewhat identical domains (e.g., Karl and Knight, 1998; Groisman *et al.*, 2004, 2005). For example, Groisman *et al.* (2005) assessed

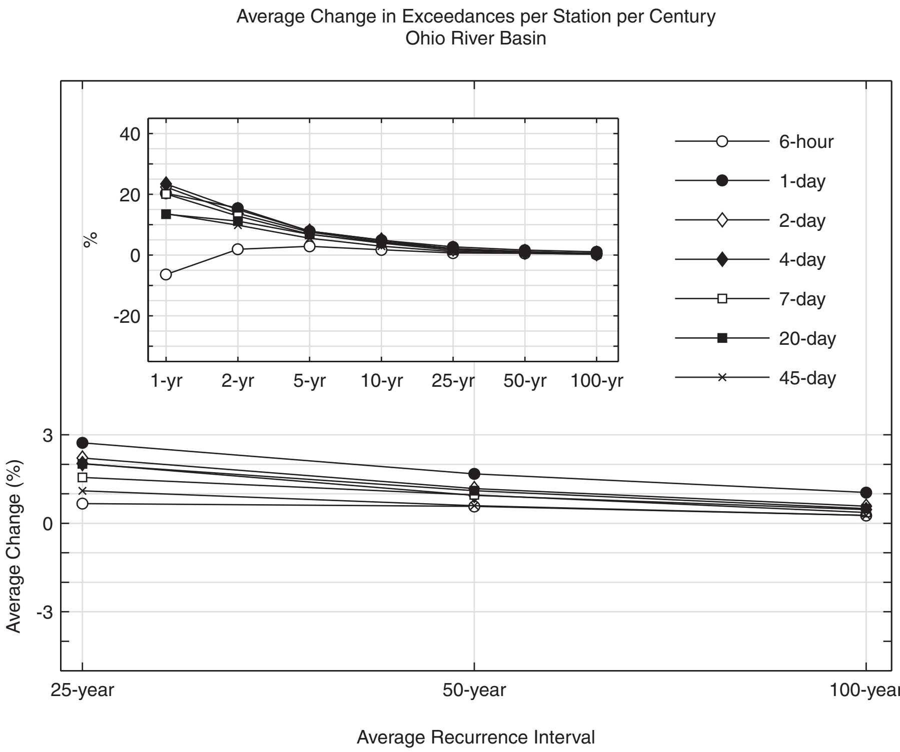

FIGURE 7. Average Change in Number of Exceedances per Station per Century for the Ohio River Basin (see main text for details).

trends in daily precipitation events of ARI between two and five years for the period 1893-2002 across the conterminous U.S. Their study indicates that there has been about a 20% increase in the frequency of precipitation events in the central U.S. (corresponding to our Ohio River Basin study area) but no discernible trend in the frequency of exceedances for the Southwest (corresponding to our Semiarid Southwest study area).

CONCLUSION

The literature in the climate community examining potential impacts of climate change on rainfall frequencies uses terms, which on their face, appear to address the frequencies required by those who plan and account for those impacts on the Nation's civil infrastructure. However, because of differences in semantics, this literature does not properly address precipitation frequencies important to the Nation's civil infrastructure. It further appears that at least in the historical record, the uncertainty associated with the precipitation frequency estimates themselves is of greater importance than changes in the frequency of exceedances over time in the historical precipitation record. We suggest that as we examine the potential impacts of climate change, we use terms, frequencies, and durations, in common for the design and planning of the Nation's civil infrastructure. Specifically, we should use the terms "average recurrence interval" and "annual exceedance probability." This study has demonstrated that while the estimated trends for the Semiarid Southwest are negative for all multiday durations, only the one-day duration trends are statistically significant. For the Ohio River Basin, there was a statistically significant increase in the number of exceedances for all multiday durations (but with some exceptions as shown in Table 1). These changes are much smaller than the uncertainty associated with the precipitation frequency estimates themselves.

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