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How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA?

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ABSTRACT: Century-long precipitation records from stations in the contiguous USA indicate an increased frequency of rainy days over the past century and some evolution in the probability distributions of precipitation amount. Temporal trends in eight metrics of the precipitation climate are of similar magnitude and sign regardless of whether they are derived from bootstrapping of regression residuals or using the Kendall's tau statistic, though the bootstrap technique generally resolved a larger number of 'significant' trends. There is substantial variability in terms of the magnitude, significance and sign of the linear trends with specific metrics, and they are sensitive to recording bias of light precipitation events in the early part of the 20th century. The majority of stations that exhibit significant linear trends show evidence of increases in the intensity of events above the 95th percentile. The resolved trends tend to have a larger magnitude at the end of the century. Spatial variability as manifest in the spatial autocorrelation in the interannual variability and trends in extreme metrics is manifest at a range of scales, but in general the correlation between stations is significant only for separation of distances of a few tens of kilometres. The largest trends towards increased annual total precipitation, number of rainy days and intense precipitation (e.g. fraction of precipitation derived from events in excess of the 90th percentile value) are focussed on the Central Plains/northwestern Midwest. Copyright © 2008 Royal Meteorological Society

KEY WORDS extreme precipitation; probability distribution; trends

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1. Introduction

Several prior studies have sought to identify and/or quantify trends in various descriptors of the probability distribution of precipitation across the globe (e.g. Groisman *et al*., 2005). Previous research on trends over the contiguous USA has generally found tendencies towards increased total annual precipitation (e.g. Easterling *et al*., 2007) and increased heavy precipitation (e.g. Kunkel *et al*., 1999), but the characterization of temporal trends in extreme precipitation metrics has sometimes resolved contradictory results. Karl and Knight (1998) analysed gridded station data from the Historical Climate Network (HCN) and concluded that 'since 1910, precipitation has increased by about 10% across the contiguous United States' and that when averaged over the contiguous USA over half of the increase in total precipitation between 1910 and 1995 'is due to positive trends in the upper 10 percentiles of the precipitation distribution.' Conversely, Michaels *et al*. (2004) also analysed data from the HCN data set and found that 'when averaged across the USA ... precipitation trends on the 10 wettest days of the year are not significantly different from the trend in total overall precipitation.' This comparison illustrates two key issues regarding quantification of changes in extreme precipitation events:

1. Variations in the definitions of 'extreme' (Klein Tank and Konnen, 2003) or in the distributional forms (Wilson and Toumi, 2005) used to represent precipitation data impede consistent quantification of trends. Because of difficulties in accurately depicting precipitation extremes, a number of indices have been proposed. Here we analyse eight aspects of the probability distribution (Table I). The metrics include three that characterize the entire precipitation distribution (annual total, number of days with precipitation, and daily intensity) and five that characterize the high tail of the distribution [the 90th and 95th percentiles, the wettest 5-day (pentad), the total precipitation falling in the ten wettest events, and the fraction of the total precipitation falling in events exceeding the 90th percentile] (Table I). It is acknowledged that many additional metrics of extremes have been used in conjunction with precipitation data, and the metrics used herein are by no means an exhaustive synthesis of all possible metrics. However, they were selected to provide a range of descriptors in order to assess the sensitivity of the trend analyses to the specific metric used.

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Table I. Number of stations from which data exhibit statistically significant trends (at the 90% confidence level) over the course of the 20th century listed by metric, trend methodology and the temporal window of analysis (unless otherwise stated it is the entire record (1895–2002)). Also shown is the number of stations from which time series exhibit consistent sign of trends in analyses based on Kendall's tau and the bootstrapping method. The final row shows the number of stations that exhibit a significant positive or negative temporal autocorrelation with a 1-year lag.

	Total precipitation	90th percentile	Sum of precipitation on the top-10 wettest days	95th percentile	Fraction of precipitation from events in excess of p90	Wettest pentad	Daily intensity	Number of rainy days
Abbreviation used herein	Total	p90	big10	p95	fap90	wp	di	nr
Reference		Groisman *et al.* (2005)	Michaels *et al.* (2004)	Groisman *et al.* (2005)	Moberg and Jones (2005)	Hegerl *et al.* (2004)	Alexander *et al.* (2006)	
Kendall's tau								
Positive	168	90	119	77	319	79	86	407
No trend	454	380	507	461	289	550	265	196
Negative	21	173	17	105	35	14	292	40
Bootstrap								
Positive	183	88	137	84	330	76	85	418
No trend	438	353	480	433	276	542	236	181
Negative	22	202	26	126	37	25	322	44
OLSR								
Positive	302	146	270	150	405	182	121	465
No trend	288	206	318	278	176	394	143	114
Negative	53	291	55	215	62	67	379	64
Degree of correspondence (Kendall's tau vs bootstrap)								
Positive – positive	155	79	106	69	313	59	79	399
No change – no change	422	334	446	418	267	521	222	173
Negative – negative	18	165	16	98	32	13	285	40
Discrepancy	48	65	75	58	31	50	57	31
Kendall's tau: First two-thirds of the century								
Positive	25	43	34	33	272	34	61	266
No trend	539	396	546	451	331	582	300	294
Negative	79	204	63	159	40	27	282	83
Kendall's tau: Last third of the century								
Positive	41	79	61	65	101	41	129	133
No trend	592	529	563	554	480	576	438	402
Negative	10	35	19	24	62	26	76	108
Number of stations that exhibit a significant correlation at lag-1 (positive/negative)								
Stations	54/31	28/44	43/32	24/50	99/21	24/33	27/86	275/5

2. Inherent difficulties in detecting trends in rare events (Frei and Schar, 2001) and sensitivities to missing data (Zolina *et al*., 2005).

However, other important issues include:

1. Discontinuities in precipitation data records (e.g. station moves, technological/measurement changes) (Groisman and Easterling, 1994; Wijngaard *et al*., 2003).
2. Difficulties in accurately measuring both trace and heavy precipitation events and changes in our ability to do so (Groisman and Easterling, 1994; Groisman and Knight, 2007).
3. Variations in trends identified at different stations (due to meso-scale influences (Zolina *et al*., 2005)) or with different data sets.

These and other factors represent significant impediments to quantification of, and assignment of causality to, precipitation trends.

The possibility of an increase in extreme precipitation events over the contiguous USA is of great interest to a nation where flood-related annual economic losses increased from $1 billion in the 1940s to $6 billion annually in the 1990s (both figures adjusted to 1997$) (Easterling *et al*., 2000) and where prior research has indicated increases in 'great floods' under scenarios of climate change (Milly *et al*., 2002). Hence, the objectives of this study are to:

1. Identify and quantify temporal trends in precipitation at individual sites across the contiguous USA using time series encompassing the entire 20th century.

2. Assess the statistical significance of a trend and analyse the sensitivity to the metric/techniques used to describe the 'extremes'.
3. Analyse the spatial signatures of indices of extreme precipitation and temporal trends in those metrics.

While individual precipitation events may be highly spatially confined, trends should be more uniform in space assuming a large-scale driver of change. In essence, if temporal trends within coherent (homogeneous) climate zones are the result of climate evolution/change then one could postulate that the same trend should be detected at many/all stations in the zone (Pujol *et al*., 2007). Variability of individual events is a source of uncertainty in trends derived for individual stations and accordingly, Groisman *et al*. (2005) state that 'To obtain statistically significant estimates, the characteristics of heavy precipitation should be areally averaged over a spatially homogeneous region.' However, this leads to questions regarding how to measure and quantify homogeneity, which in the case of extremes may not be obvious. In addition, analysis of station trends can reveal information about important local drivers of precipitation change, including change of local land use which may be manifest at a range of spatial scales (Pielke *et al*., 2007). Herein time series from individual stations are treated separately in order to examine spatial variability on scales below those of the grid size used by Alexander *et al*. (2006) and the regions as defined by Karl and Knight (1998) and Groisman *et al*. (2005). Results from spatially clustered stations can provide a diagnostic of the coherence of temporal trends that may in turn be related to forcing mechanisms, and may also indicate appropriate scales of aggregation. The spatial coherence of temporal trends is assessed in a qualitative sense via visual inspection of maps of trend magnitudes and quantitative use of the spatial autocorrelation function as depicted on correlograms (Khalili *et al*., 2007).

As mentioned above, precipitation measurements are sensitive to changes in the location and environment of the precipitation instrument, and to methods of measurement (Groisman and Easterling, 1994). The precipitation data set used herein is comprised of daily data from 922 stations across the contiguous USA. Figure 1 shows the locations of the 643 stations from this data set that passed the selection criteria applied herein and hence are subject to trend analysis. The data set employed has been subject to substantial homogenization efforts as described in Kunkel *et al*. (1998, 2005). The record length varies by station, but many have records beginning in the 1890s, and the majority ends in 2002.

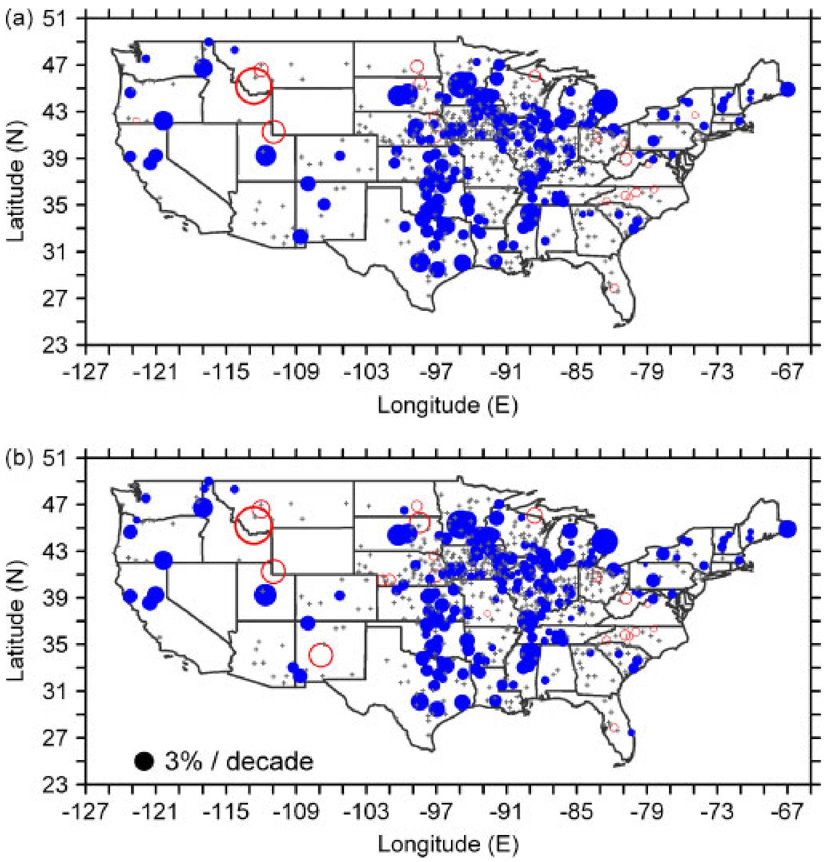

Figure 1. Linear trends in annual total precipitation amount over the 20th century at 643 stations across the USA, where the trend magnitude and significance is computed using (a) Kendall's tau statistic and (b) bootstrapping of the OLSR residuals. The changes are expressed as a change in percent per decade. In each frame the diameter of the symbol scales linearly with the magnitude of the trend. If the symbol is a filled blue dot the trend is positive, if it is a red circle the trend is negative, if the trend is not statistically significant at the 90th confidence level a grey cross is shown. This figure is available in colour online at www.interscience.wiley.com/ijoc

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2. Calculation of metrics of extreme precipitation and quantification of trends

Analyses presented herein are conducted using metrics of daily precipitation computed at the annual time scale. The data set was pre-screened to select stations that have at least 80 years of data between 1895 and 2002 during which more than 360 days of valid data per year are available, and which have the first year of valid data prior to 1905 and the last year subsequent to 1995, thus ensuring that the trends derived reflect changes over the entire course of the 20th century. The 643 stations that fulfill these criteria are not evenly distributed across the contiguous USA, and there is under-representation of the western states (Figure 1), but to ensure the comparability of time series from different stations the data set is not supplemented by data drawn from other sources.

We analyse station-specific daily precipitation time series at the annual time scale and include data from years where valid data are available for more than 360 days. Hence, if the data record from a given station fulfils the first data selection criteria (80 'complete' years and start and end dates), but does not have more than 360 days of valid observations in 1995, the trend is computed excluding 1995.

Although trend analysis is most easily accomplished by ordinary least squares regression (OLSR) and OLSR has been extensively used in prior studies, it is not very robust to outliers or to deviations from normality such as might reasonably be expected to characterize 'extreme' descriptors. Accordingly, time series of annual values of eight metrics of the precipitation probability distribution from each station are subject to two primary trend fitting methods:

1. Application of the nonparametric Kendall's tau-based slope estimator (Alexander *et al*., 2006): This technique does not assume a distribution for the residuals and is relatively robust to outliers (Sen, 1968). The linear trend is deemed statistically significant if it differs from 0 at the 90% confidence level, and the magnitude of the trend is given by the median of the series of slopes ($\frac{Y_j - Y_i}{t_j - t_i}$, where Y_x is the value of the metric at a given point t in time, and $1 \leq i < j \leq n$, where n is the total number of data points).
2. Application of bootstrap re-sampling (Lunneborg, 2000) of the residuals from OLSR analysis: These residuals are computed and then randomly selected using a bootstrapping technique and added onto the linear fit line from the trend analysis and the trend is re-estimated (Kiktev *et al*., 2003). This procedure is repeated 1000 times to generate 1000 plausible trends for each station. The trend terms from those 1000 samples are then tested to determine if a zero trend falls within the middle 900 values in an ordered sequence of the distribution of 1000 realizations. If so the original trend is deemed not significant at the 90% confidence level. The trend magnitude is given by the median value of the 1000 samples.

For comparative purposes, trends were also determined using OLSR.

Because these approaches to computing trends are highly sensitive to temporal autocorrelation in the time series, and the degree of temporal autocorrelation also reflects physical processes that may offer explanations for temporal trends, the lag-1 temporal autocorrelation of the annual values of eight metrics is also computed.

Trends in precipitation regimes need not necessarily be linear with time (e.g. Groisman *et al*., 2005). For example, Groisman *et al*. (2004) found that 'Nationwide time times of mean precipitation indicate significant interannual variability with two particularly dry decades (1930s and 1950s), followed by relatively wet decades (1970–99) giving way to a century-long precipitation increase'. To investigate the influence of temporal trends on time series duration and temporal window, subsections of the time series are also used to compute linear trends for comparison with trends from the entire record.

There is evidence that very light precipitation amounts were under-reported in the early part of the observation record (Groisman and Knight, 2007). This potential source of bias in the number of days with precipitation will also affect other metrics of the precipitation probability distribution, particularly the daily intensity. Hence, daily data records from all stations were aggregated and used to examine the frequency with which very small precipitation accumulations were reported in the first 20 and last 20 years of the record. The results indicate lower reporting of precipitation amounts below 0.05 in (1.27 mm) in the early part of the record (Figure 2). Hence, trends are computed both using the data records as reported and a precipitation threshold of 0.05 in as the definition of a rainy day. The resulting daily intensity from the later analysis will be biased high but the trends may be a more accurate portrayal of the behaviour of the physical system.

Intense, or heavy precipitation events may also be subject to large measurement uncertainties (Groisman and Legates, 1994), and changes in our ability to measure accumulated precipitation through time may influence temporal trends (Yang *et al*., 2005; Ding *et al*., 2007). However, no corrections are applied to data presented herein due to the lack of compelling evidence of temporal reporting bias for daily accumulations of over approximately 1 in (25 mm) (Figure 2).

3. Results and discussion

Based on the nonparametric Kendall's tau statistic, time series from 26% of all stations exhibit significant positive trends in total annual precipitation (Table I), with linear trends in total annual precipitation of up to 4% per decade at some sites (Figure 1). Less than 5% of all stations exhibit statistically significant negative trends and the remaining 70% of stations exhibit no trend at the 90% confidence level. While data from a large proportion of stations exhibit no trend, these results are

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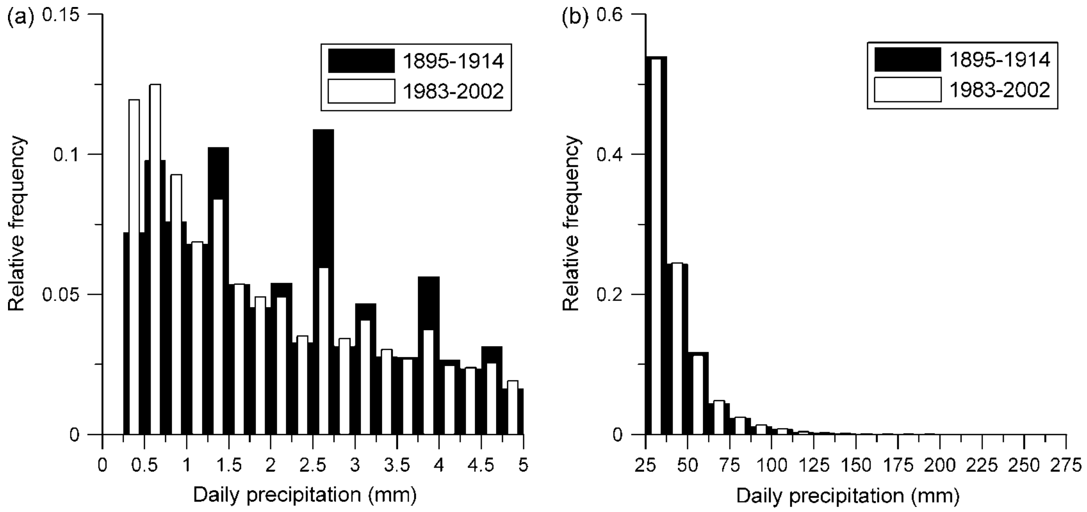

Figure 2. The relative frequency with which precipitation amounts (a) below 0.2 in (5 mm) and (b) above 1 in (25 mm) was observed at all stations during the first 20 years of the data record (1895–1914) and the last 20 years of the record (1983–2002).

broadly consistent with findings of prior research in that they indicate a greater prevalence of positive than negative long-term trends in annual total precipitation (Groisman *et al*., 2004). As expected, the presence (or absence) of temporal trends in the annual time series of total precipitation is insensitive to application of the precipitation threshold (*cf* Tables I and II).

Of the stations that exhibit a significant change in total annual precipitation, the majority exhibit increases, but the magnitude of changes in total annual precipitation are generally smaller than the increase in the number of days on which precipitation was observed leading to almost half of all stations exhibiting a decline in simple daily intensity (annual total precipitation/number of rainy days) over the course of the century (Table I, Figure 3). However, this result is very sensitive to possible under-reporting of very light precipitation amounts in the early part of the record. Comparisons of Figures 3 and 4 and data presented in Tables I and II, indicate that while the trend in number of rainy days (nr) remains of the same sign in most cases, the positive trends are of smaller magnitude when days with less than 0.05 in recorded are excluded from the analysis. This bias also has a substantial impact on trends in di. Over two-thirds of all stations indicate no significant trend when the accumulation threshold is applied *versus* only 40% of stations when no threshold is applied. Also, instead of mostly negative trends, using the accumulation threshold of 0.05 in fewer stations exhibit significant trends and an equal number indicate increases or decreases in daily intensity (di) (*cf* Tables I and II).

Reporting bias in light precipitation amounts also influences some of the metrics of extreme precipitation – particularly p90 and p95. When the 'raw' time series are subject to trend analyses, a larger number of stations exhibit significant negative trends in p90 and p95 (between 15 and 25% of stations) than positive trends (10–15% of stations), but when the 0.05-in threshold is applied to the data, positive trends in p90 and p95 are more prevalent than negative trends. The magnitude of trends in p90, p95 and fap90 are also sensitive to application of the threshold for detection of precipitation. For the sum of the largest 10 events (big10) and the wettest pentad (wp), metrics that will not be affected by reporting biases in light precipitation amounts, many more stations exhibit positive trends than negative trends (Tables I and II), and the trend magnitudes are, as expected, insensitive to the use of a precipitation threshold (Figures 3, 4).

In summary, for the metrics presented herein the majority of stations exhibit 'no trend', with nr being the parameter that exhibits the largest number of statistically significant trends, the overwhelming majority of which are positive. Positive trends are also more commonly observed than negative trends for total, big10, fap90 and wp. These century-long trends thus imply changes in the form of the probability distribution of precipitation that on the coarsest level might be characterized as a decrease in the magnitude and/or increase in the number of 'light' rain events (as manifest by little overall change in daily intensity relative to the number of rainy days, even when a precipitation threshold of 0.05 in is applied), but an increase in the magnitude of intense precipitation events (as manifest by increases in, for example, big10). However, there are also more subtle changes, as manifest by the occurrence of declines of p90 in the same station time series that exhibit increases in fap90 and big10.

Results presented in Tables I and II and Figures 1, 3, 4 and 5 further illustrate the following.

1. There is considerable year-to-year variability as indicated by the number of stations without a significant correlation in the lag-1 temporal autocorrelation for each metric (Figure 5, Tables I and II). The number of stations that exhibit significant temporal autocorrelation at lag-1 (i.e. year-to-year) substantially exceed the number expected by random chance (i.e. approximately 10% of 643) for nr (280 of 643 stations), and to a lesser extent for di (113 of 643 stations)

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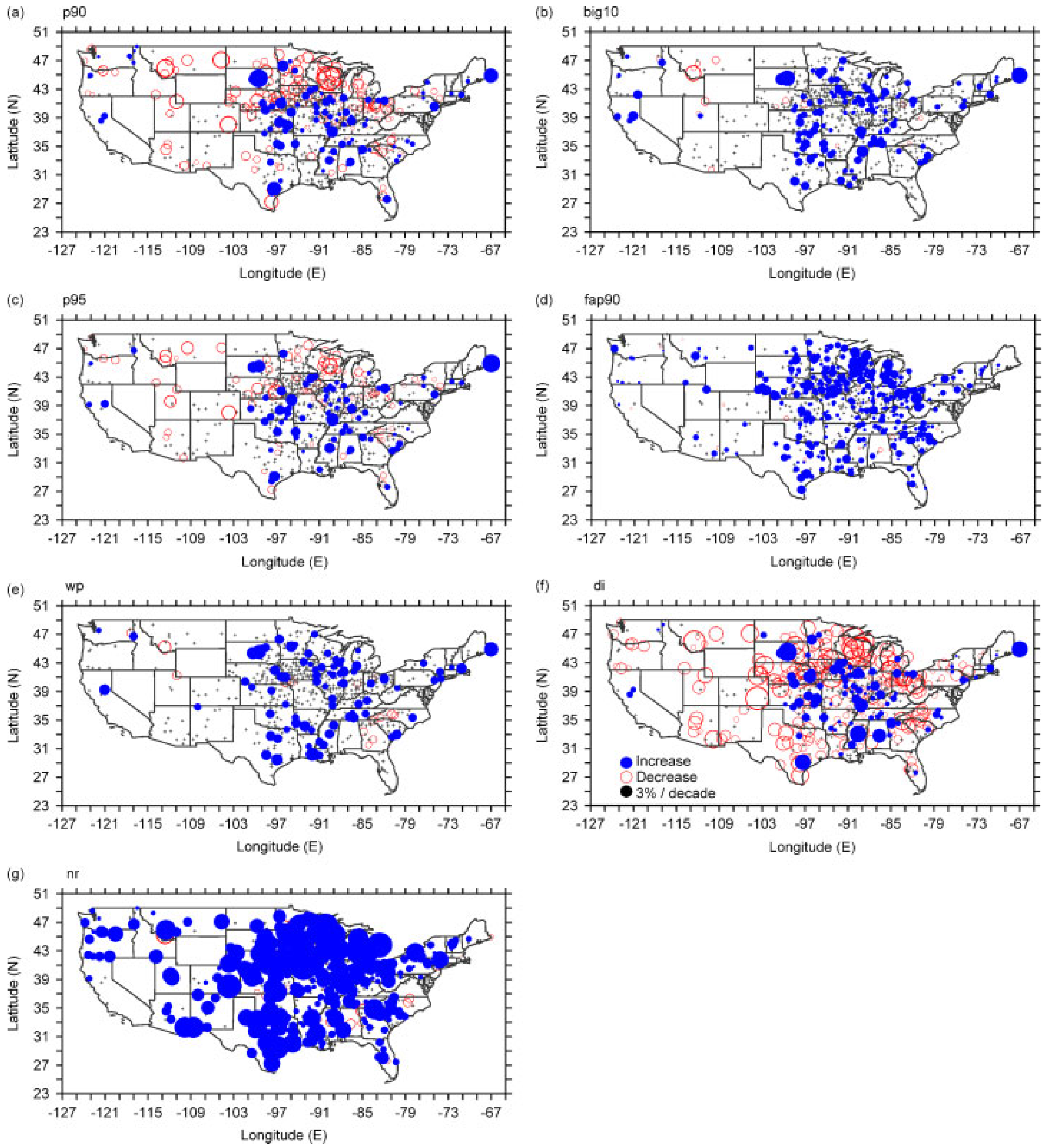

Figure 3. Linear trends in various precipitation metrics computed at the annual time scale at 643 stations across the USA, where the trend significance and magnitude was determined using Kendall's tau. Trends are shown for (a) 90th percentile daily precipitation (p90), (b) the sum of precipitation accumulated during the 10 wettest days in a year (big10), (c) 95th percentile daily precipitation (p95), (d) fraction of the annual total precipitation derived from events in excess of the 90th percentile computed for that year (fap90), (e) annual wettest pentad (wp) (5-day period), (f) simple daily intensity (annual total/number of precipitation days) (di) and (g) number of precipitation days (nr). As in Figure 1, the trend is expressed as a change in percent per decade, and the diameter of the symbol scales linearly with the magnitude of the trend. If the symbol is a filled blue dot, the trend is positive; if it is a red circle, the trend is negative; if the trend is not statistically significant at the 90th confidence level, a grey cross is shown. This figure is available in colour online at www.interscience.wiley.com/ijoc

and fap90 (120 of 643 stations), while for the other metrics, the number of stations that exhibit significant temporal autocorrelation is relatively small. This indicates the 'memory' of the system is stronger for the number of rainy days than for any of the extreme metrics. A further implication is that the trend results should not be substantially biased by temporal autocorrelation, though they will be 'liberal' indicating an excess number of rejections of the null hypothesis of no trend (von Storch, 1999). It should be further noted that application of the 0.05-in precipitation threshold further decreases the number of stations that exhibit a significant temporal autocorrelation at lag-1 for any of the metrics considered (*cf* Tables I and II).

2. There is very good correspondence between stations identified as having statistically significant trends in the various metrics using both the Kendall's tau and bootstrapping trend methodology (Table I). Over 80% of stations that are categorized as having significant trends (of a given sign) in a specific metric by

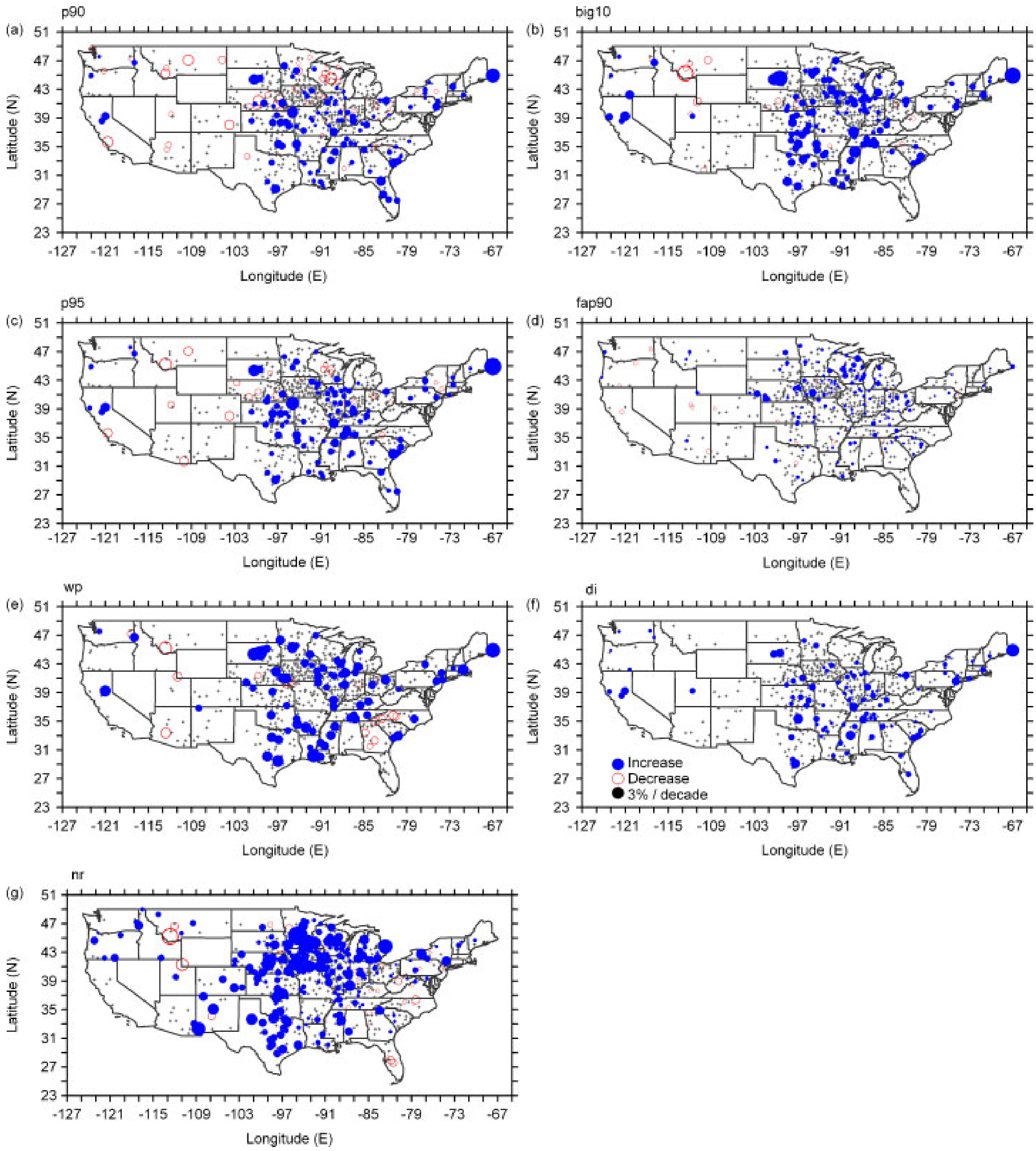

Figure 4. As Figure 3, except that a threshold of 0.05 in is used for a day to be treated as a rainy day. This figure is available in colour online at www.interscience.wiley.com/ijoc

the Kendall's tau statistic are similarly designated in the bootstrapping analysis of residuals. The trend magnitudes are also very strongly related, though trend magnitudes are typically larger in the analyses based on the bootstrapping method. Nevertheless, the close correspondence implies that the trends are relatively robust to the technique used to determine the linear trends, with the caveat that use of OLSR leads to an (erroneous) increase in the probability of detecting a 'statistically significant' trend (Power, 1993). For some metrics, use of OLSR doubles the number of stations that exhibit 'significant' trends (Table I). Kendall's tau is more conservative than the other two approaches in rejecting the hypothesis of 'no trend' and hence herein we focus on results from this approach.

While parts of the contiguous USA are under-represented in the station sample available for this analysis, consistent with prior research (Groisman *et al*., 2004) generally the spatial patterns of the trend analysis results indicate that some of the largest positive linear trends in metrics of extreme precipitation are observed in the central Great Plains of North America. Negative trends in all metrics of extreme precipitation are most prevalent in the interior western states. At the regional or national scale, trends and variability of extreme precipitation have been linked to teleconnection patterns (such as indices of the ENSO phenomenon and the Pacific North

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Table II. As Table I except that the results are only shown for trend analyses conducted using Kendall's tau and a threshold of >0.05 in of accumulated precipitation for a day to be included as a rainy day.

	Total precipitation	90th percentile	Sum of precipitation on the top-10 wettest days	95th percentile	Fraction of precipitation from events in excess of p90	Wettest pentad	Daily intensity	Number of rainy days
Entire time series								
Positive	162	99	119	99	134	77	94	249
No trend	458	491	507	515	485	550	446	351
Negative	23	53	17	29	24	16	103	43
Kendall's tau: First two-thirds of the century								
Positive	23	33	34	33	133	34	40	101
No trend	535	496	546	538	492	582	443	466
Negative	85	114	63	72	18	27	160	76
Kendall's tau: Last third of the century								
Positive	41	60	61	61	42	40	86	43
No trend	591	565	563	565	573	578	538	552
Negative	11	18	19	17	28	25	19	48
Number of stations that exhibit a significant correlation at lag-1 (positive/negative)								
Stations	56/29	21/59	43/32	27/40	43/32	27/32	21/73	99/17

American index) (Montroy *et al*., 1998; Meehl *et al*., 2007); additionally at the regional scale these trends may reflect changes in synoptic scale regimes (e.g. the frequency of cyclone passages and intensity of synoptic systems) (Grover and Sousounis, 2002; Polderman and Pryor, 2004). However, it may also be noteworthy that the central Great Plains is a region previously characterized as exhibiting a high degree of land surface – atmosphere coupling in terms of the dependence of Summer precipitation on soil moisture (Koster *et al*., 2006), and that this region has experienced some of the greatest evolution of land use, including the introduction of irrigation (Pielke *et al*., 2007). Figures 3 and 4 also indicate that relatively few stations in the states of Missouri and Arkansas exhibit temporal trends in annual precipitation total and the extreme metrics. These states form part of a region previously identified as a 'warming hole' (Liang *et al*., 2006), the existence of which has been attributed to an increased frequency of low-level jets in response to depleted soil moisture (Pan *et al*., 2004).

Trends in precipitation regimes need not necessarily be linear with time and it has been suggested that the magnitude of temporal trends in precipitation increased in magnitude towards the end of the 20th century (e.g. Groisman *et al*., 2005) assert that 'all of the increase has occurred during the last third of the century'). Hence linear trends derived using Kendall's tau for the last 33 years of the 20th century are computed and compared with the trends derived using the first 66 years of the century and those computed for the entire data record. Fewer stations exhibit significant trends in either of the short time windows than over the entire record in part because of the high interannual variability. Of the stations that exhibit significant trends in annual total precipitation, over 85% are positive over the entire record; an almost equivalent fraction of them are negative over the first two-thirds of the record, while a comparable fraction of them exhibit positive trends in the last third of the century (Figure 6, Tables I and II). When similar analyses are conducted for the other metrics in general the results indicate typically declining values of p90, p95, big10 and di in the first two-thirds of the century, with a greater fraction of stations indicating positive trends in the latter one-third for all metrics. Thus, the results of this analysis are supportive of assertions by Groisman *et al*. (2005), but it should be noted that the overwhelming majority of stations exhibit no trend in any of the metrics over the last one-third of the century in part due to the very high interannual variability, and the dominance of natural variability on these timescales.

The year 1976 is widely cited as denoting a 'climate shift' (Trenberth, 1990) and 'to mark a time when global mean temperatures began a discernible upward trend that has been at least partly attributed to increases in greenhouse gas concentrations in the atmosphere' (Trenberth *et al*., 2007). Prior research has indicated a 'regime shift' in atmospheric and oceanic conditions over the North Pacific during the winter of 1976–1977 (Hare and Mantua, 2000; Bond *et al*., 2003) and a possible subsequent shift in the winter of 1988–1989 (Overland *et al*., 1999). To further investigate the influence of the time series duration, start and end dates on the temporal trends presented herein, the annual time series of each precipitation metrics from each station were truncated in 1-year increments for the first 30-years and last 30-years of the records. Only five stations that exhibit significant trends for any of the metrics over the entire record exhibit converse trends for any of the truncated records, indicating that the significant trends presented herein are robust to the time series duration. The results further indicate that truncation of the first 30 years of the data set tends to increase the number of stations that exhibit significant positive trends for p90, p95, big10 and the wp (by up to 100 stations in the case of p90 and big10;

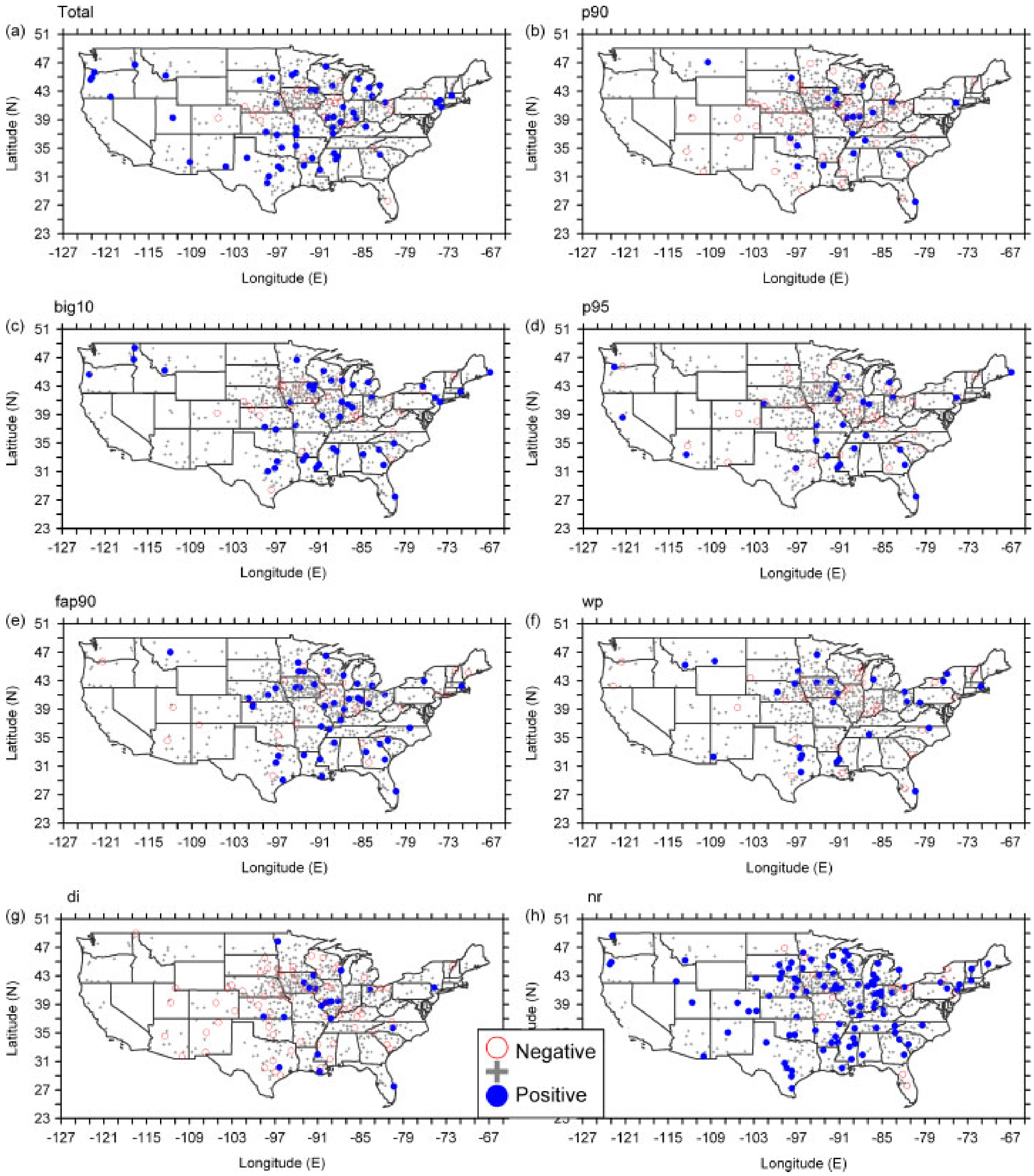

Figure 5. Temporal autocorrelation at lag-1 (i.e. 1-year lag) over the 20th century in (a) annual total precipitation (Total), (b) annual 90th percentile daily precipitation (p90), (c) the sum of precipitation accumulated during the 10 wettest days in a year (big10), (d) annual 95th percentile daily precipitation (p95), (e) fraction of the annual total precipitation derived from events in excess of the 90th percentile computed for that year (fap90), (f) annual wettest pentad (wp) (5-day period), (g) simple daily intensity (di) (annual total/number of precipitation days), and (h) number of rainy days (nr). In each case, if the TAC is positive and significant the symbol is a blue dot; if it is significant and negative the symbol is a red circle; otherwise the station is shown by a grey cross. This analysis was conducted using a threshold of 0.05 in for a day to be treated as a rainy day. This figure is available in colour online at www.interscience.wiley.com/ijoc

see Figure 7). Truncation of the last 30 years tends to increase the number of stations that exhibit negative trends in p90, p95 and big10, but generally by a smaller number of stations than gain significance by removal of the first portion of the data record. This implies that the last 30 years of the 20th century were characterized by atypically high values of the extreme metrics as were the years at the beginning of the century, but that the end of the 20th century has evolved beyond the envelope of conditions experienced at the beginning of the century either in terms of the duration of higher indices or the magnitude of the extreme metrics. The only metric that exhibits an increase in the number of positive trends with removal of both the beginning and end of the record is fap90. This implies some degree of decoupling between trends in p90 and fap90. Trends in wp and big10 appear to be less sensitive to truncation of the last 30 years of the data set, with relatively few stations exhibiting a

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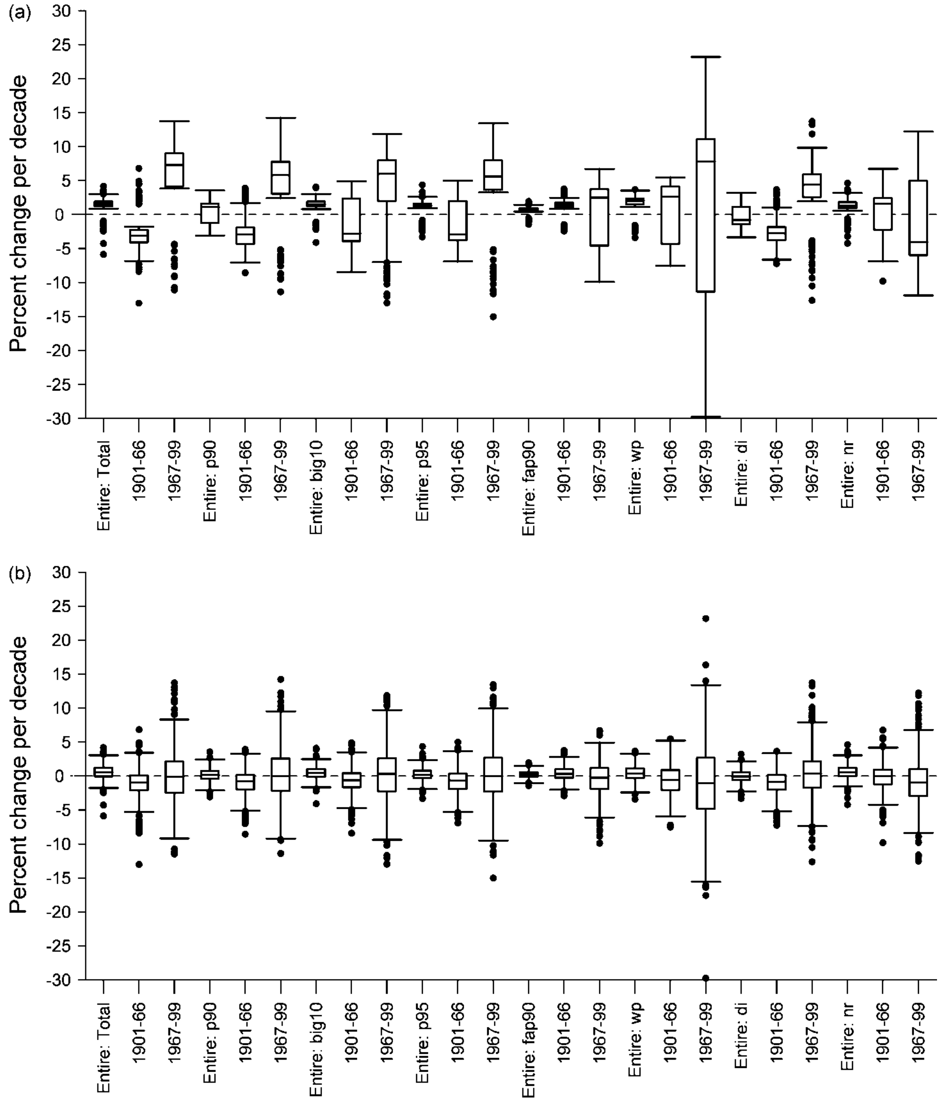

Figure 6. Box and whisker plot of the (a) statistically significant station trends and (b) all station trends depicted for analyses of the entire data record, the first two-thirds of the 20th century and the last third of the 20th century. This analysis was conducted using a threshold of 0.05 in for a day to be treated as a rainy day.

transition from 'no trend' to either a positive or negative trend when the last 30 years of the record are removed.

To examine changes in the probability distribution of precipitation amount further, the daily data from each station for each of the thirds of the 20th century are:

1. Used to compute empirical quantile–quantile (EQQ) plots (Karl, 1978) for precipitation amounts for the 0.1 to 99.9th percentiles (in 0.1% increments) and
2. Fitted to a mixed-exponential distribution (Wilks, 1999):

$$f(x) = \frac{\alpha}{\beta_1} \exp\left[\frac{-x}{\beta_1}\right] \times + \frac{1-\alpha}{\beta_2} \exp\left[\frac{-x}{\beta_2}\right], x, \alpha, \beta_1, \beta_2 > 0 \quad (1)$$

where x is the daily precipitation amount, α is the shape parameter, and β_1 and β_2 are scale parameters.

EQQ plots make no assumptions about the form of the distribution of the variables and may be used to make direct comparisons between percentiles computed from different data sets or portions of the same data set. Fitting of the data to a mixed-exponential distribution has been shown to be an adequate representation of non-zero daily precipitation amounts over the contiguous USA (Wilks, 1999) and allows examination of the evolution of the upper tail of probability distributions in more detail. As examples, results from two representative stations from the Midwest (Chicago University in Northeast Illinois and Independence in Southeast Kansas) are given in Figure 8. As shown, at these stations, as at many of the stations considered, the major changes in the probability distribution of precipitation are focussed on the high tail of the distribution – above the 95th percentile. According to the EQQ plots, the differences between daily precipitation amounts in the first, second and third portions of the 20th century lie in the portion of the distribution that

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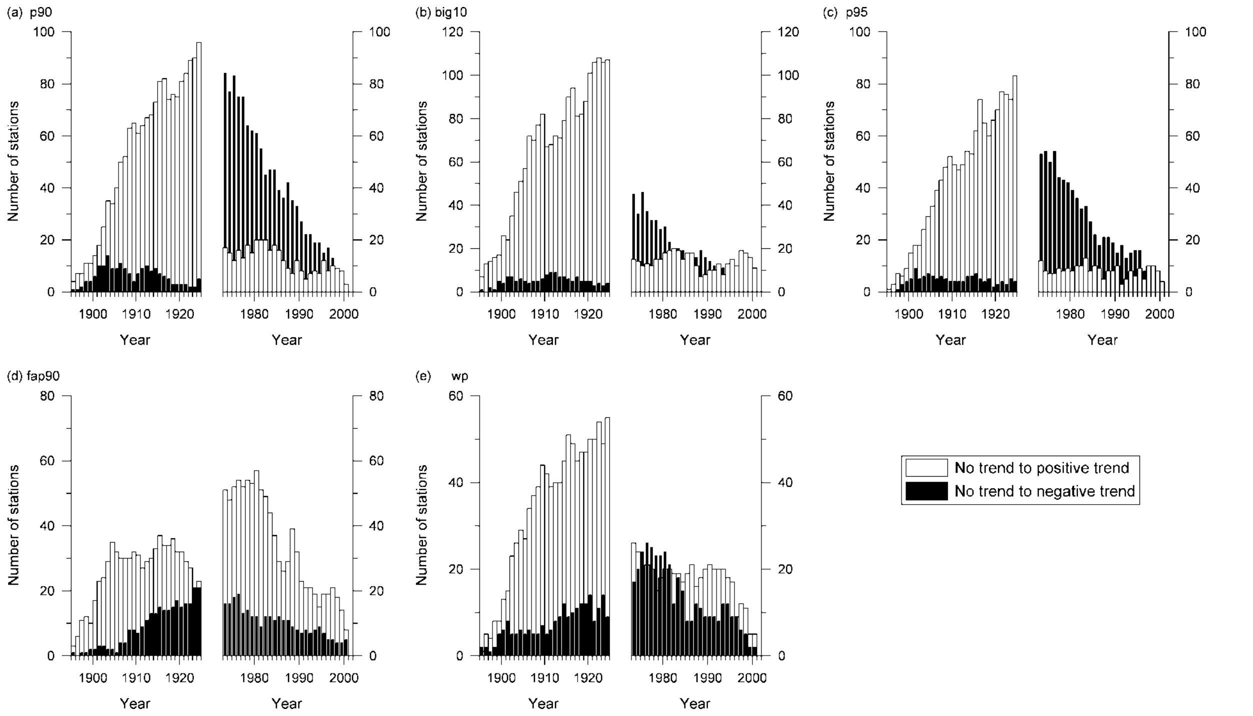

Figure 7. The number of stations that exhibit 'no trend' when the analysis is conducted using the entire data record but exhibit a statistically significant positive or negative trend when the data series are truncated. The results are shown by the start year (left frame) or end year (right frame) of the truncated data sets for each of extreme metrics; (a) p90, (b) big10, (c) p95, (d) fap90 and (e) wp.

lies above the 98th percentile, and consistently indicates higher values of the 98th to 99.9th percentiles (i.e. the 20 highest data points plotted in the EQQ plots; Figure 8(b) and (d)) in the 1934–1966 and 1967–1999 time windows than in 1901–1933 with the magnitude of the differences being greater in the 1967–1999 period. Probability distributions computed by fitting data from these three windows to the mixed-exponential distribution also indicate greatest divergence for large events that have probabilities $\leq 3 \times 10^{-3}$ (and at these sites magnitudes in excess of approximately 40 mm; see Figure 8(a) and (c)) with consistently higher accumulation amounts for these extreme events in the later time segments. While these intense events may be subject to large measurement uncertainties (Groisman and Legates, 1994), they are of critical importance in dictating flood frequency and changes therein (Bell *et al.*, 2007) and hence are of particular interest. The implied extension of the upper tail of the probability distribution of precipitation accumulations is consistent with results of other analyses presented herein and prior research that shows extreme precipitation events of 1–7 day duration increased by approximately 3% per decade between 1931 and 1996 over much of the upper Midwest (Kunkel *et al.*, 1999).

Analysing time series from individual stations allows examination of local trends. Plotting the resulting trends spatially allows examination of whether the detected local changes are regionally coherent. However, to investigate the spatial scales of the extreme metrics and trends therein, the most densely sampled region, the Midwest, was selected for a more detailed analysis. This region exhibits a substantial risk of increased 'great' flood frequency under climate change scenarios (Milly *et al.*, 2002), and an increase in the intensity and/or frequency of extreme precipitation in the climate change simulations of Zwiers and Kharin (1998). Wisconsin, Minnesota and Michigan were classified as region 3; and Iowa, Missouri, Illinois, Indiana, Ohio and Kentucky as region 8 in the analysis of Groisman *et al.* (2005), and were two of three regions identified by that study as exhibiting a 20% increase in the frequency of very heavy precipitation (the upper 0.3% of daily precipitation events) over the period 1893–2002.

While the majority of stations (25%) within the Midwest that exhibit statistically significant trends indicate a trajectory towards increased annual total precipitation over the course of the 20th century (Figure 1), there are some pronounced sub-regional scale spatial variations particularly in terms of the temporal trends in extreme precipitation metrics (Figure 9). In agreement with analyses of the frequency of precipitation events of 7-days duration that exceed a 1-year recurrence interval (Kunkel *et al.*, 1999), the northern Midwest exhibits positive trends in fap90 (Figure 9(d)) and there is some evidence for declining values of p90 (Figure 9(a)). This part of the region (coincident with the NCDC climate region 'East North Central') also exhibits the largest increases in nr and declines in di even when the 0.05-in threshold is applied (Figure 9(g)). In the southern Midwest (in NCDC climate region 'Central') there is a greater prevalence of positive trends in p90 and p95 (Figure 9(a) and (c)).

As also shown in Figure 9, heterogeneity in the trends is manifest at multiple spatial scales. Not only are some of their important spatial variations across latitude

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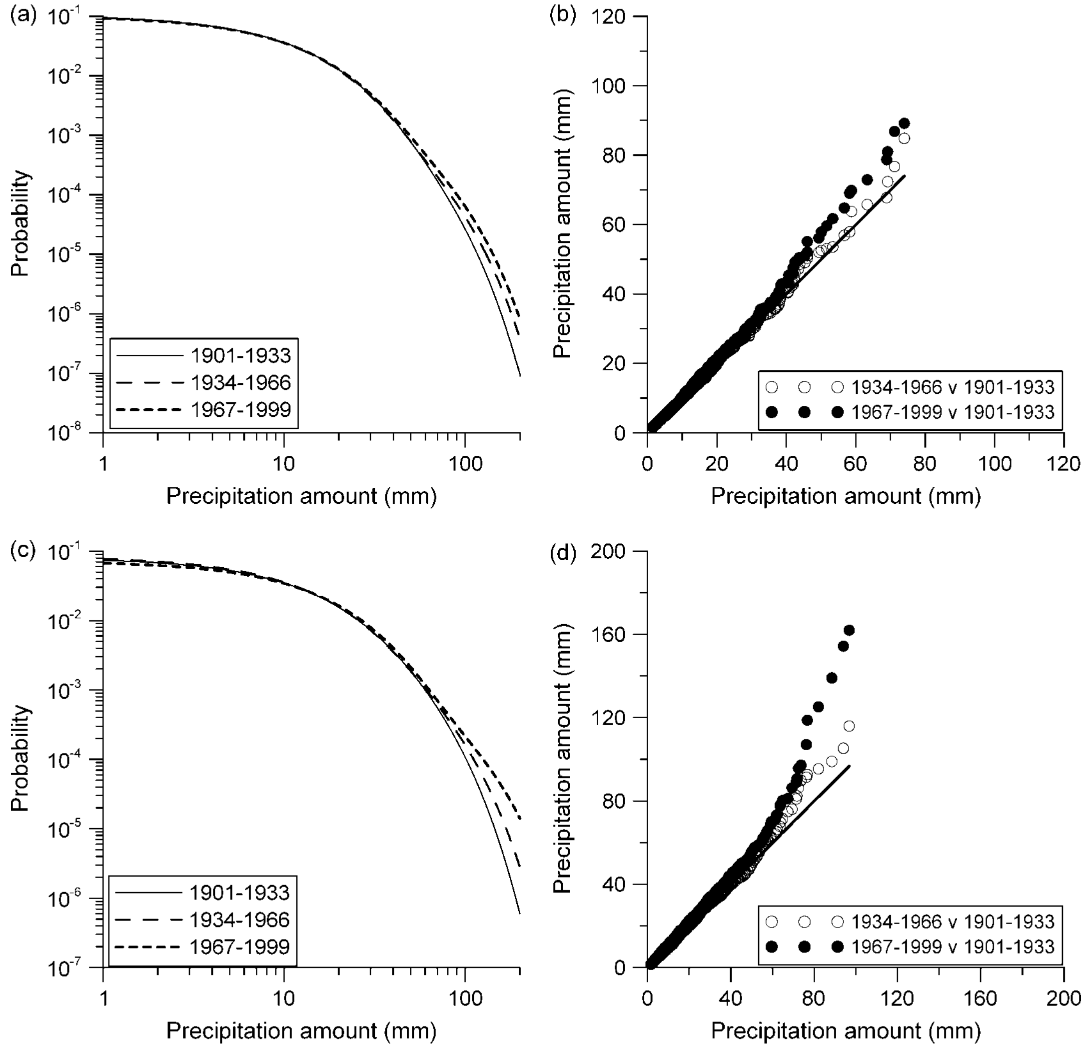

Figure 8. (a) and (c) The probability distribution function for wet-day precipitation amounts and (b) and (d) empirical quantile-quantile plots from the three time-windows (1901–1933, 1934–1966 and 1967–1999) at two sample stations (a) and (c) Chicago University, IL and (b) and (d) Independence, KS. In frames (b) and (d) data from 1901–1933 are plotted on the x-axis.

bands, there are many examples where data series from geographically proximal stations exhibit substantial differences in trend magnitude or opposing signs of temporal trends. Variability in trends at this scale most likely represent stochastic 'noise', but may potentially reflect physical phenomena such as the influence of historical land cover change on records of precipitation (Diem and Mote, 2005; Pielke *et al.*, 2007). The degree of spatial continuity of annual time series of precipitation metrics may provide guidance regarding appropriate scales of data aggregation. Accordingly, correlograms of the various precipitation metrics were computed for the Midwest. Power law best-fit lines fitted to cross correlations from all station pairs are shown in Figure 10 and indicate that with the exception of annual total precipitation, the correlations are generally not significant for separation distances of beyond a few tens of kilometres. To investigate the role of linear temporal trends in dictating the spatial association, the cross correlations were also computed for detrended time series where the annual trend derived using the Kendall's tau approach was removed from the time series of each metric from each station. The detrended annual time series exhibit even lower spatial coherence even at short separation distances (Figure 10) which implies that the spatial coherence that is observed between annual time series of precipitation metrics is predominantly attributable to common temporal evolution, and that the spatial coherence of extreme metrics is low relative to descriptors such as annual total precipitation.

4. Summary

Trends in precipitation from stations across the contiguous USA during the 20th century are generally robust to the precise techniques used to derive them. Over 80% of stations that are categorized as having a significant positive trend, a significant negative trend or 'no trend' in a specific metric by the Kendall's tau statistic are similarly designated in the bootstrapping analysis of OSLR residuals. The trend magnitudes are also strongly related, though trend magnitudes are typically larger in the analyses based on the bootstrapping method.

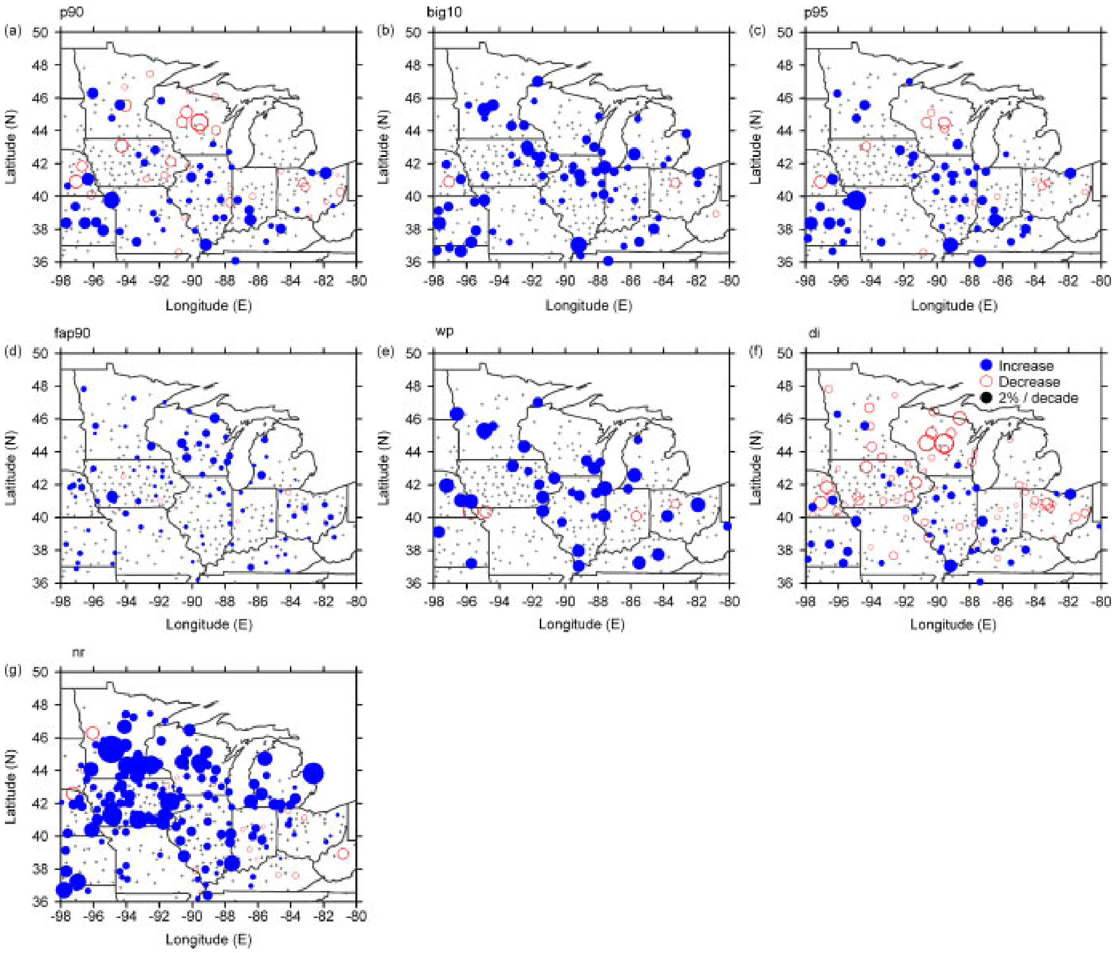

Figure 9. As Figure 4, except data are only shown for the Midwest. Note the scale for the trends differ from that in Figure 4. This figure is available in colour online at www.interscience.wiley.com/ijoc

Over the course of the 20th century, the largest increases in annual total precipitation (of up to 4% per decade at individual stations) were observed in the central USA. Generally increases of the largest magnitude in extreme precipitation are observed at stations in the central Great Plains/northern Midwest (north of the region characterized by the largest magnitude changes in annual total precipitation). There are also trends in daily intensity and number of rainy days which, though partly attributable to reporting bias in the early portion of the century also indicate increased frequency of precipitation particularly in the Great Plains and northern Midwest. Metrics of extreme precipitation exhibit some important differences in the magnitude and sign of linear trends at individual stations, and even the upper percentiles of the precipitation amounts (p90 and p95) are sensitive to possible reporting biases in light rain events at the beginning of the data records. The majority of stations exhibit no trend in any of the extreme metrics, but the statistically significant changes that are observed indicate a tendency towards increased values, particularly in the portions of the probability distribution above p95. The largest changes in the probability distribution of precipitation thus appear to be an increase in the number of rainy days and increases in intensity focussed on components of the distribution that lie above the 95th percentile. These events may be subject to the largest measurement uncertainties, but they are of critical importance in dictating flood frequency.

The magnitude of the temporal trends is not constant over the entire century, and as indicated in prior research the trends towards increasing values are of large magnitude and more prevalent at the end of the century.

Changes implied by analyses presented herein are to some degree consistent with the following.

1. Analyses of trends in precipitable water from around the USA that indicate increases of over 10% between 1973 and 1995 (Ross and Elliott, 1996), and thus increased low-level moisture availability and horizontal moisture convergence (Trenberth *et al*., 2003).
2. Projected changes in precipitation regimes as documented in the regional climate change assessment programme that indicated an extension of the upper tail of the precipitation probability distribution (Easterling and Karl, 2000), and analyses of the change in daily precipitation *versus* intensity under a global warming scenario in two regional climate simulations of the USA which showed that nearly all high intensity daily precipitation contributes a larger fraction of the total

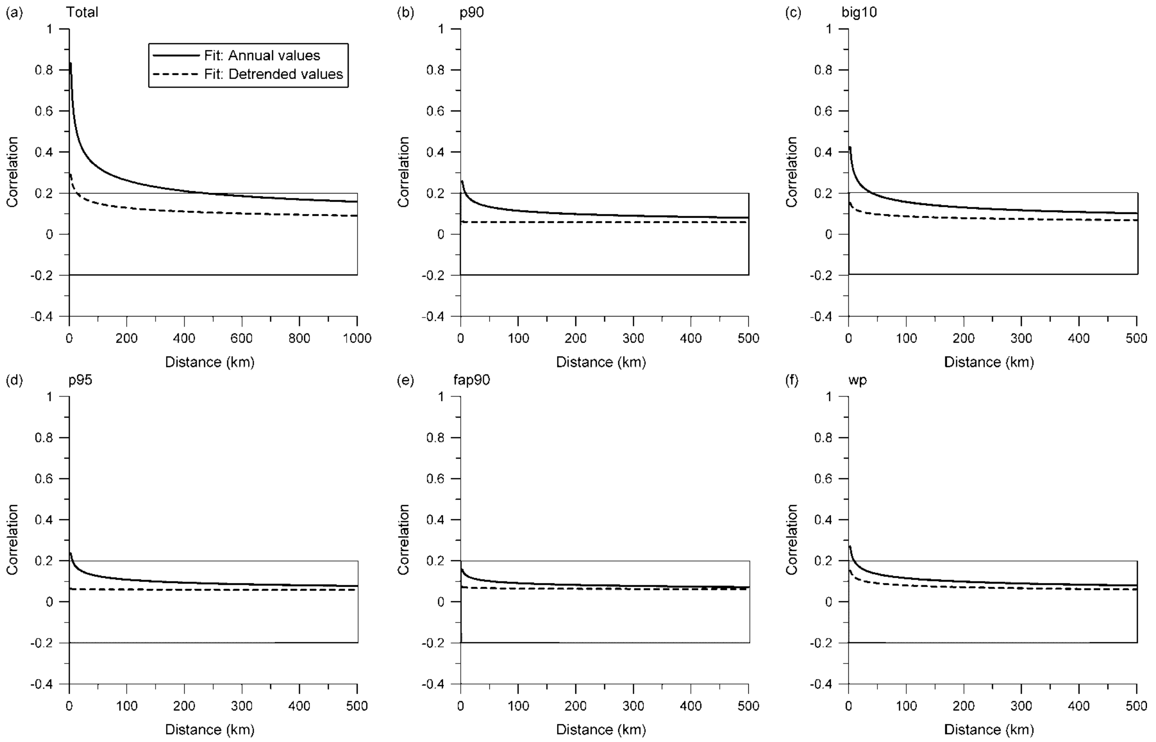

Figure 10. Correlograms computed for all station pairs within the Midwest that are separated by distances of less than 500 km. Data for all station pairs have been synthesized to produce a best-fit line of power-law form. The frames show results for each metric of precipitation: (a) annual total precipitation (total), (b) annual 90th percentile daily precipitation (p90), (c) the sum of precipitation accumulated during the 10 wettest days in a year (big10), (d) annual 95th percentile daily precipitation (p95), (e) fraction of the annual total precipitation derived from events in excess of the 90th percentile computed for that year (fap90), (f) annual wettest pentad (wp) (5-day period). Two sets of fits are shown for each parameter – one derived using the annual values for each metric, and the other derived from time series that had been detrended. The shaded area between correlations of -0.2 and 0.2 denotes the region of statistically insignificant correlations. This analysis was conducted using a threshold of 0.05 in for a day to be treated as a rainy day.

precipitation in the climate projections, and nearly all low intensity precipitation contributes a reduced fraction (Gutowski *et al*., 2007).

Using the example of the midwestern USA, it is shown that there is substantial spatial variability in trend magnitude and sign at the sub-regional spatial scale. Metrics of extreme precipitation from individual stations exhibit some spatial coherence that appears to be predominantly associated with long-term temporal trends, but on average spatial correlations of those metrics are significant only over a scale of a few tens of kilometres.

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