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Climatic changes in western North America, 1950–2005

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ABSTRACT: The rate of climatic change over western North America (WNA) is quantified for 485 climate stations for the period 1950–2005. Additionally, six stations with quality long-term records were selected and analysed for the period 1906–2005. The indicators used were developed by the World Meteorological Organization (WMO) and the World Climate Research Program's Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI). From the 27 core indices, 4 temperature-based and 4 precipitation-based indicators were selected for in-depth analysis. The 8 million km^2 study area is comprised of the 22 contiguous US states and 4 Canadian provinces west of the Mississippi River and Great Lakes. The results were divided into six general regions for interpretation and presentation. GIS interpolation of station-specific statistical output was completed to further aid in the identification of spatially coherent trends across WNA. Mean slopes were calculated over the whole study area, and by region, for each index, and then tested to determine if they were significantly different from zero.

Results of the study show statistically significant historical climate trends across the study area. As expected in a region as geographically diverse as WNA, results differed between, and within, regions. Overall, temperature-based indicators showed a general warming trend over the entire study area, with the greatest increases along the North American Cordillera. The trends in precipitation-based indicators were more varied. General trends indicate moderately increasing precipitation volume and intensity over much of WNA. The strongest precipitation trends were found in areas with climate largely controlled by air masses originating over the Gulf of Mexico. Copyright © 2011 Royal Meteorological Society

KEY WORDS climate change; climate indices; extreme temperature; extreme precipitation; North America

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1. Introduction

Water resources are coming under increasing pressure from societal demands related in large part to the growing population of Western North America (WNA). Global climate change is expected to alter the hydrologic cycle and place additional stress on water supplies and demands (Gleick *et al.*, 2010). The last two decades of research into the subject of climate change have confirmed that surface air temperatures have been significantly increasing over the period of record. It is now well established that human activities are contributing to modern climate change by altering the natural composition of the atmosphere (Karl and Trenberth, 2003; IPCC, 2007). Although global average surface air temperature is projected to continue to increase, climate change will affect different regions of the globe in different ways (Portman *et al.*, 2009). This is expected, as changes in surface temperatures are related to changes in atmospheric circulation and precipitation patterns (Dore, 2005).

Temperature and precipitation variability in WNA are driven primarily by ocean currents in the Pacific, and to a lesser extent the Atlantic. Strong links have been established between precipitation patterns over WNA and Sea Surface Temperatures (SST), primarily the Pacific Decadal Oscillation (PDO) which is generally accompanied by different phases of the El Nino Southern Oscillation (ENSO) (Lapp *et al.*, 2002; Hoerling *et al.*, 2010; St. Jacques *et al.*, 2010). The PDO is generally considered to have shifted to a warmer El Nino-dominated phase in 1976–1977, and may have shifted back to a cooler La Nino-dominated phase in 1997–1998 (Seager and Vecchi, 2010). Owing to their influence over the climate of WNA, shifts in the PDO naturally influence any trends calculated in temperature and precipitation. The length of this study was determined to be long enough to capture both phases, therefore minimising their influence on the trends. It is important to note, however, the role that natural variability plays in the changing climate of the continent, and the extent to which it may be masking anthropogenic forcing (Seager *et al.*, 2007; Hoerling *et al.*, 2010).

Different regions will vary in their long-term trends, towards more or less precipitation with warmer or cooler temperatures. A number of studies have addressed trends in extreme temperature and precipitation events across different geographic regions and timescales. Syntheses of the work that has been done on trends in the historical precipitation record showed increased annual variance during the latter half of the twentieth century in nearly all regions with sufficient records for analysis (Dore, 2005; Portman *et al.*, 2009). As anthropogenic

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atmospheric change intensifies the hydrologic cycle it is expected that there will be a change in the frequency of so-called extreme climatic events, where daily precipitation and temperature exceed their normal thresholds (Groisman *et al.*, 1999). Many studies have modelled the potential changes in climate expected over the next century as a result of human activities. The 2007 IPCC report summarizes model projections for North America, identifying an expected dramatic rise in air temperatures across WNA. Future trends in precipitation are much more difficult to model given their link to SSTs and the uncertainty towards the response of ocean oscillations to climate change (Christensen *et al.*, 2007). Results differ between regions and models but mean trends indicate an increase in precipitation over most of WNA, with decreases in the southwest portion of the continent.

Studies focusing on historical Canadian climate trends have returned mixed results. Akinremi *et al.* (1999) carried out a precipitation trend analysis for the Canadian Prairies in order to test the hypothesis that an intensification of the hydrologic cycle has accompanied global warming. The authors analysed data from 37 climate stations from 1920 to 1995 by classifying precipitation events based on intensity. The study found significant trends for total annual precipitation but no trend for heavy precipitation events. Results were similar for Mekis and Hogg (1999) who analysed a precipitation time series for all of Canada, based on homogeneous geographic regions. Zhang *et al.* (2000) analysed Canadian trends in maximum, minimum, and mean temperature, diurnal temperature range, total precipitation, and snowfall ratio for the period 1900–1998. The study found significant positive trends in annual precipitation across the country, except on the Canadian Prairies, an area which also showed the greatest amount of warming. Zhang *et al.* (2001) found few statistically significant trends in the frequency of heavy precipitation events over the twentieth century, concluding that a generalized increase in extreme precipitation over Canada has not accompanied increases in the concentration of greenhouse gases. Vincent and Mekis (2006) analysed air temperature and precipitation for Canada using indices that describe the type, frequency, and intensity of precipitation. A set of 10 indices were developed using the annual average for each station for the period 1961–1990. The study found that in the south of the country there are generally more days with precipitation, a decrease in daily intensity, and a decrease in the snowfall to precipitation ratio. Overall, studies of extreme climatic events in Canada have shown that an intensification of the hydrologic cycle in the Canadian west has not yet accompanied the increasing air temperatures associated with climate change.

Studies focusing on the Unites States have shown larger and more significant results for precipitation- and temperature-based climate indices. Kunkel (2003) examined trends in North American extreme precipitation for the period 1895–2000 using an Extreme Precipitation Index to measure the frequency of events. The results of the study showed a large increase in the frequency of extreme precipitation events over the US as a whole during the later twentieth century, while the results for Canada were more mixed. Groisman *et al.* (2004) analysed historical trends in temperature and precipitation over the conterminous US using area-weighted averages for a number of geographic regions. The study found warming trends, especially in northern regions, and a nationwide increase in intense precipitation, attributing the increase in 'very heavy' precipitation to an earlier onset of spring and summer-like conditions which creates more opportunity for the formation of convective systems. This earlier onset of spring is supported by Easterling (2002), who notes significant changes in the date of the last spring frost in all regions of the US. Meehl *et al.* (2009) found that high temperature records in the US since January 2000 outnumber extreme low temperature records by a ratio of 2 : 1. Pryor *et al.* (2009) found strong significant trends in extreme precipitation events across the US, especially in the Great Plains region.

Similar studies have been conducted focusing on the European and global picture. Frich *et al.* (2002) analysed a newly created global dataset in order to determine if there has been a change in the frequency or severity of climatic extremes during the period from 1946 to 1999. The data were scrutinized using 10 extreme climate indices, selected from a set of 27 core climate change indicators developed by the World Meteorological Organization (WMO) and the World Climate Research Program's Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) in order to coordinate global studies evaluating historical change. Global trends in extremes were analysed by calculating a simple global average of all the valid stations, with a density of one or two stations per 250 000 km^2. As expected, the results of the study for precipitation-based indicators show different patterns of change throughout the globe, although many areas show statistically significant increases in the extreme precipitation indicators. Frich *et al.* (2002) concluded that during the latter half of the twentieth century, on average, the global climate has become wetter and warmer, as expected under enhanced greenhouse conditions. Klein Tank and Können (2003) analysed trends in temperature and precipitation extremes in Europe for the period 1946–1999. Using the same core WMO indices mentioned above, the study found pronounced warming trends throughout Europe. Stations reporting significant increases in annual precipitation were often accompanied by an increasing intensity of the heaviest events. Alexander *et al.* (2006) studied changes in daily climatic extremes using a global gridded dataset. The WMO indices were applied to a newly created global dataset to assess the magnitude of change over the period 1951–2003. Using calculated global averages, the study found large significant warming trends in temperature based indices and significant increases in precipitation towards wetter conditions in the late twentieth century.

Changing precipitation patterns and intensity, coupled with rising temperatures, could potentially spell disaster for many societal sectors by increasing the risk of both drought and flooding in sensitive environments. The goal of this research was to analyse daily historical climate data to determine the extent to which the climatology of WNA has been altered over the period 1950–2005. Daily temperature and precipitation data from 490 stations across western Canada and the western United States were obtained, summarized and analysed to assess changes in climate. Previously established climate change indicators were applied to the data to evaluate historical change, and compare those changes between different regions. Trends are calculated for eight indicators focusing on station-specific temperate and precipitation thresholds that are important in defining regional climatology. Additional analysis was carried out to gauge the amount of change between 1906 and 2005 to place the larger study in context. A regional analysis based on large, generalized geographic divisions was used to compare climatic change over different areas of the continent. Station-specific statistical output was then integrated in a Geographic Information System (GIS) to aid in identification of spatially coherent trends in temperature and precipitation indices across WNA.

2. Study area regions

The area of concern for this research was WNA, a region that produces a substantial proportion of the world food supply through irrigation-based agriculture, and is home to an increasingly large population. The study area covers a large geographical range that includes many diverse ecological zones. The 485 climate stations used here are spread over an area of more than 8 million km^2 that includes 22 states west of the Mississippi River and 4 Canadian provinces west of the Great Lakes. The climatology varies widely, from the hot deserts of southern Arizona to the temperate rainforests of the Pacific Northwest. Previous studies have found some of the largest positive trends for extreme precipitation are in North America's central Great Plains, while negative trends are most common in the interior western states (Groisman *et al*., 2004; Pryor *et al*., 2009). Focusing on WNA, as opposed to the entire continent or the globe, allows for more detailed investigation regarding the potential causes and regional implications of the results, while still maintaining a broad focus.

For the purposes of this study, WNA was divided into six general geographic regions (Figure 1). Political boundaries were used to delineate the regions to simplify the process and aid in identification of regional trends. Owing to the diverse climate and terrain in WNA, these regions should not be regarded as cohesive ecological units, as all units encompass a number of different climatic regimes. Regions were defined based on similarities according to the Koppen-Geiger Classification System (Peel *et al*., 2007), on the regions used by Karl and Koss (1984) and Groisman *et al*. (2004), as well as by the air masses that control their climate (Ahrens, 2008). The six regions used here are as follows (Figure 1).

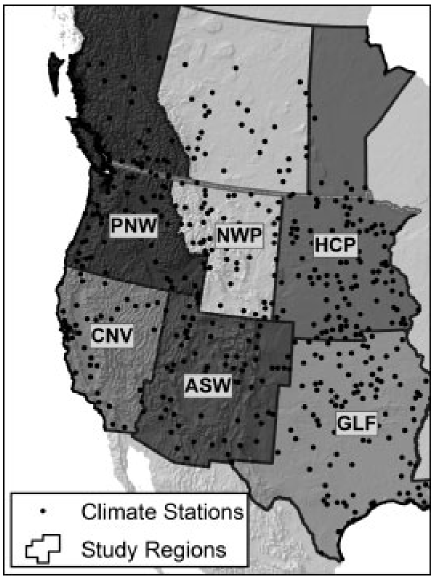

Figure 1. Study area map showing regional classification system and locations of climate stations used. Regions (clockwise from top left): Pacific northwest (PNW), northwest plains (NWP), humid-continental plains (HCP), Gulf (GLF), American southwest (ASW), California–Nevada (CNV).

2.1. The Pacific northwest region (PNW)

This is centred on Washington State and also includes Oregon, Idaho, and British Columbia. The geography of the region is dominated by mountainous terrain, encompassing the Coast Range, the Cascades, and the northwestern portion of the Rocky Mountains. The climate is largely controlled by the maritime air mass of the northern Pacific. The highly varied topography results in a region made up of a wide spectrum of climatic zones, due primarily to the effects of orographic precipitation. The climate is so varied that it includes eight different climatic types according to the Köppen-Geiger classification that vary from the warm and dry northern Mediterranean zone in Oregon to the snow-dominated sub-polar regions of the northern Cordillera.

2.2. The northwest plains region (NWP)

This is comprised of the northern states of Montana and Wyoming, and the Canadian provinces of Alberta and Saskatchewan to the north. The area includes the eastern slopes of the northern Rocky Mountains, as well as the arid foothills and plains located in their rain shadow. The climate is primarily driven by the continental polar air mass and its interactions with the maritime pacific air mass from the west. The region is dominated by dry semi-arid steppe and highland plateaus. Much of the landscape in the region has been given over to agricultural development, with cereal grains, oilseeds, pasture, and hay, as the primary crops being cultivated.

2.3. The humid continental plains region (HCP)

This includes the states of North Dakota, South Dakota, Nebraska, Minnesota, and Iowa, as well as the Canadian province of Manitoba. The climate is driven primarily by interactions between the dry continental polar air mass originating in the Canadian Arctic and the warm moist maritime tropical air masses that originate in the Gulf of Mexico and the Pacific. The region's climatology is dominated by the humid-continental zone, with northern regions experiencing more severe winters than those in the southern half of the region.

2.4. The Gulf region

This is made up of states whose climate is mostly driven by the maritime tropical air mass that originates over the Gulf of Mexico and includes Texas, Oklahoma, Kansas, Missouri, Arkansas, and Louisiana. This area falls mostly within the humid-subtropical zone, and as such, it is a moist climate with usually mild winters. The Gulf region is the most likely to be affected by tropical storms, and includes the southern portions of 'tornado alley' located on the southern Great Plains.

2.5. The American southwest region (ASW)

This includes the 'Four Corner' states of Utah, Colorado, Arizona, and New Mexico. The geography of this area is dominated by the Colorado Plateau and the southern Rocky Mountains, and although it is almost semi-arid throughout, areas of higher elevation act as the crucial water tower of the Colorado River which provides water and hydroelectric power to millions of people in the American southwest (Barnett and Pierce, 2008). The climatology of the region in the summer is driven primarily by the hot and dry continental tropic air mass that originates over central Mexico. In the winter, interactions between various air masses contribute to heavy snowfall in some areas. It is classified mostly as arid desert and semi-arid steppe, although the relief of the southern Rocky Mountains and the Colorado Plateau provide great variability in some areas.

2.6. The California-Nevada region (CNV)

This simply encompasses the states of California and Nevada. The region's climatology is driven by the Pacific maritime polar air mass in the north, and the tropical maritime air mass in the south. Most of the area is classified as a warm-dry Mediterranean-type climate, with central California producing much of North America's commercial vegetable production through intensive irrigation. The region also includes the hot deserts of southeastern California and southern Nevada, as well as the snow-dominated alpine regions that make up the Sierra Nevada Mountains.

3. Data

Daily historical air temperature and precipitation data for the US were obtained from the Historical Climatology Network (HCN), a database compiled by the National Climate Data Center, and comprised of a subset of stations from the US Cooperative Observers Network (COOP). This database offers historical climate records from over 1200 stations across the continental United States. Stations included in the HCN database were selected to minimize inhomogeneities associated with observation times, station relocation, and the potential for heat island bias (Williams *et al*., 2006). Daily historical data for Canada were downloaded from Environment Canada's National Climate Data and Information Archive, with preference given to those stations with the most complete records of observation.

A common problem when analysing historical climate records is missing weather data. Programs were developed to quantify the amount of missing data present in each record and flag those stations with a substantial amount of missing daily values. Following the general procedure of Frich *et al*. (2002), annual records were considered to be missing if more than 10% of daily values were missing, or if more than 3 months contained more than 20% missing days. Stations were excluded that did not have at least 75% of years reporting. No effort was made to replace missing days with estimated daily values taken from nearby stations as this would compromise the analysis of the daily record. The final database for the analysis included 490 North American climate stations in WNA (Figure 1).

Programs were developed to extract the required elements from the different formats used by the two countries, convert US temperature and precipitation data into degrees Celsius and millimeters, and place all the data into a single format for use in analysis. Although some station records in North America date back over a century, in order to run this analysis with as many stations as possible it was determined to begin at 1950 and end at 2005. This time frame is similar to that used in other recent studies (Alexander *et al*., 2006; Portman *et al*., 2009) and allowed for inclusion of more stations, as a far greater number have good historical records post 1950. Extending the time frame into decades prior to 1950 presents many difficulties with regard to data availability. Many records are very sparse or non-existent in the 1930s and 1940s due to the stresses associated with the Great Depression and World War 2. While it is true that some stations have quality records dating back to the turn of the century, the majority, unfortunately, do not. Data downloaded from the US HCN V2 database at the time of analysis extended through 2008 for some stations. However, data availability was not uniform across all states and stations. Data downloaded from Environment Canada was also sparse for recent years, especially in British Columbia, where online database reports for most stations only extended through the end of 2004. Further complicating the issue is the fact that many stations in the historical database have undergone a transition to an automated system over the last decade, often moving locations at the same time. This prohibits the use of some recent data in our study, since due to homogeneity concerns, no station joining or data infilling was attempted for this project. To

Table I. Summary definitions of selected ETCCDMI climate indices used in this study.

Temperature	Indices	Definition
Frost Days	FD0	number of days where Tmin < 0 °C
Growing Season	GSL	period when Tmean > 5 °C for > 5 days and when Tmean > 5 °C for > 5 days
Warm Nights	TN90P	percentage of days where Tmin > 90th percentile
Warm Days	TX90P	percentage of days where Tmax > 90th percentile
Precipitation	**Indices**	**Definition**
Daily Intensity	SDII	total annual precip/number of events greater than 1 mm
Wet Days	R5MM	number of days where precip > 5 mm
Very Wet Days	R95P	annual total precipitation from events > 95th percentile
Total Annual	PRCPT	total annual precipitation from events greater than 1 mm

provide some comparison with longer-term trends, analysis was also completed for the period 1906–2005 for 6 high-quality stations, one from each region, testing all indices for trends for a 100-year period. It is important to note that while a single station cannot necessarily capture trends over a whole region, a longer analysis provides a valuable tool for comparing trends calculated over different time scales. In some cases, the time period sampled can have an impact on the calculated trends (Figure 9).

4. Climate change indices

In an effort to harmonize climate investigations and facilitate easier comparisons between studies, a single set of indicators was proposed by a WMO Commission. A set of 27 core climate change indices were developed by the WMO and the ETCCDMI in order to coordinate global studies evaluating historical change (Frich *et al*., 2002); Peterson, 2005; Alexander *et al*., 2006. The climate change indicators focus primarily on daily precipitation and temperature events that have a return period ranging from weeks to months, rather than years. While this means that the events may not be 'extreme' in the classic sense, the lower thresholds allow for better trend detection and calculation over longer time periods. The 27 WMO core climate indices were calculated for all stations that met the data requirements of the study. A full list of the 27 core indices and their descriptions can be found in Zhang and Yang (2004). Eight indicators were selected for further analysis and interpretation, which are summarized in Table I. Four indices were chosen to quantify change in temperature, and four indices quantify changes in precipitation over WNA.

The temperature indices chosen were among the most representative of changes that would likely have a direct impact on the environment and population of the study regions, as opposed to being the most 'extreme' indices.

4.1. Frost days (FD0)

This is the annual count of days when the minimum temperature is below 0 °C, representing the amount of time during the year that frost is possible. This index was chosen over the similar Ice Days index (when T_{max} < 0 °C) because it is capable of detecting trends in southern regions where the maximum daily temperature rarely falls below freezing.

4.2. Growing season length (GSL)

This is defined as the annual count of days between the first occurrence of 6 consecutive days with a daily mean temperature ≥5 °C, and the first occurrence after 1 July of 6 consecutive days with a daily mean temperature ≤5 °C. This annual count roughly represents the amount of time that a region can be agriculturally productive. Any changes in the GSL (as well as the FD0) could have profound implications in regions where late or early frosts have the potential to devastate entire crops.

4.3. Warm days (TX90p)

This is the annual percentage of days when the maximum temperature is greater than the station-specific 90th percentile, defined based on a 1961–1990 base period. This index was chosen to be most suited to determine whether maximum temperatures increased during the study period.

4.4. Warm nights (TN90p)

This is the annual percentage of days when the minimum temperature is greater than the station-specific 90th percentile, defined based on a 1961–1990 base period. This index further quantifies the amount that the climate is warming through an increase in minimum temperatures.

The precipitation-based indices used in this study were also chosen from the 27 core indices on the basis of importance to the environment and population ofWNA.

4.5. The simple daily intensity index (SDII)

SDII is calculated by dividing total annual precipitation (PRCPT) by the total number of precipitation events (>1.0 mm). This simple measure provides an indication of whether an intensification of the hydrologic cycle has accompanied any temperature changes inWNA.

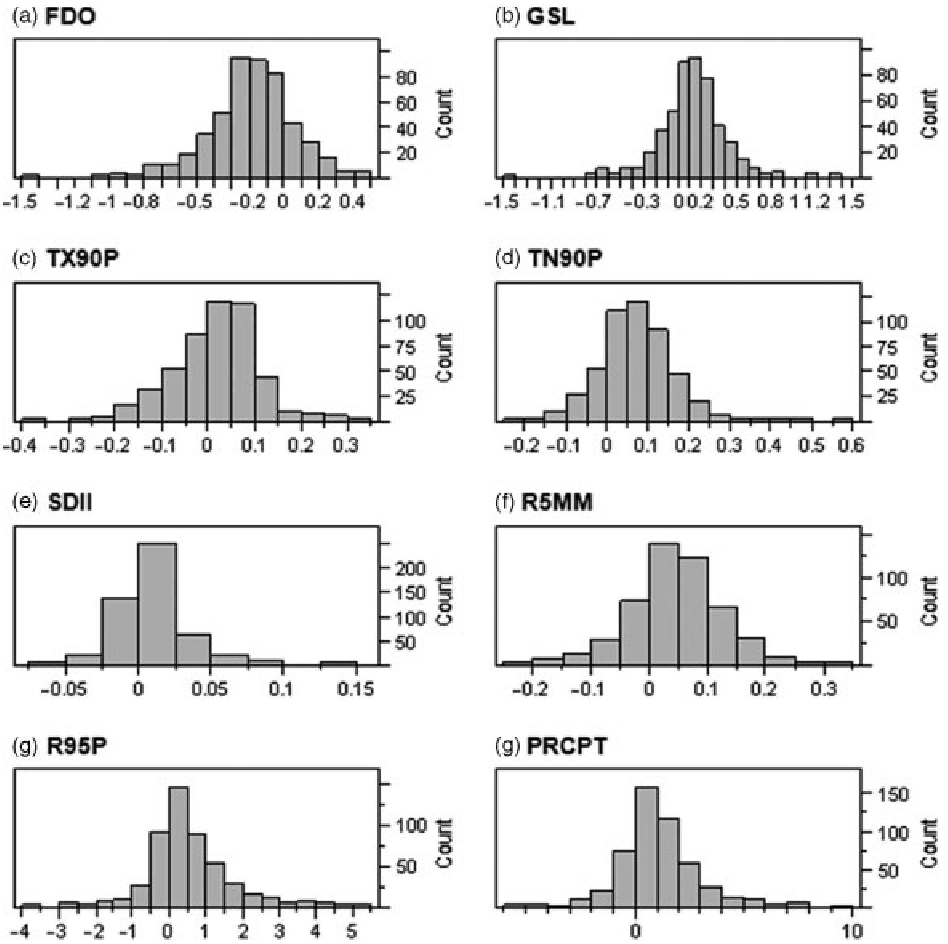

Figure 2. Frequency histograms of weather station trend slopes for the period 1950–2005, for each climate indicator over western North America.

4.6. Significant wet days (R5mm)

This index is defined as the annual count of precipitation events greater than 5 mm. R5mm events represent days where the amount of precipitation received is enough to potentially have an effect on arid and semi-arid ecosystems where heavy precipitation events are rare.

4.7. Very wet days (R95p)

These are defined as the annual total precipitation that is received from events that are greater than the station-specific 95th percentile, defined based on a 1961–1990 base period. The R95p index provides a measure of the extent to which an increase in PRCPT is driven by extreme events.

4.8. Total annual precipitation (PRCPT)

This is the annual sum of all recorded precipitation events greater than 1 mm. The 1 mm threshold removes the effects that trace measurement recording efficiency can have on trend calculations.

5. Methods

Indices were calculated on an annual basis for each station for the period 1950–2005, and for one station from each region for the period 1906–2005, utilising the RClimDex software developed at the Climate Research Branch of Meteorological Service of Canada, in conjunction with the ETCCDMI (Zhang and Yang, 2004). Trends were calculated using linear regression, and significance levels were determined using a nonparametric Mann-Kendall test to determine whether the slopes differed significantly from zero. A number of programs were developed and used to aid in processing the vast amount of output data generated by the individual analyses conducted on all climate stations. Trends calculated for each climate indicator were combined in a single database file for further analysis. Regional and 100-yr station time-series have been presented for a unique index for each region (Figures 8 and 9).

Linear trends for each station were used to calculate mean trends over the whole study area and by region for each index. The distributions of slopes were examined and found to be normally distributed in the vast majority of cases (Figures 2 and 3). The regional mean slope of the trend of each index distribution was then tested to determine if they were significantly different from zero. Slope of the regression line was used as an indication of a detectable increasing or decreasing trend in each index, over the time period specified. The objective was not to examine the exact shape of the relationship, or to compare

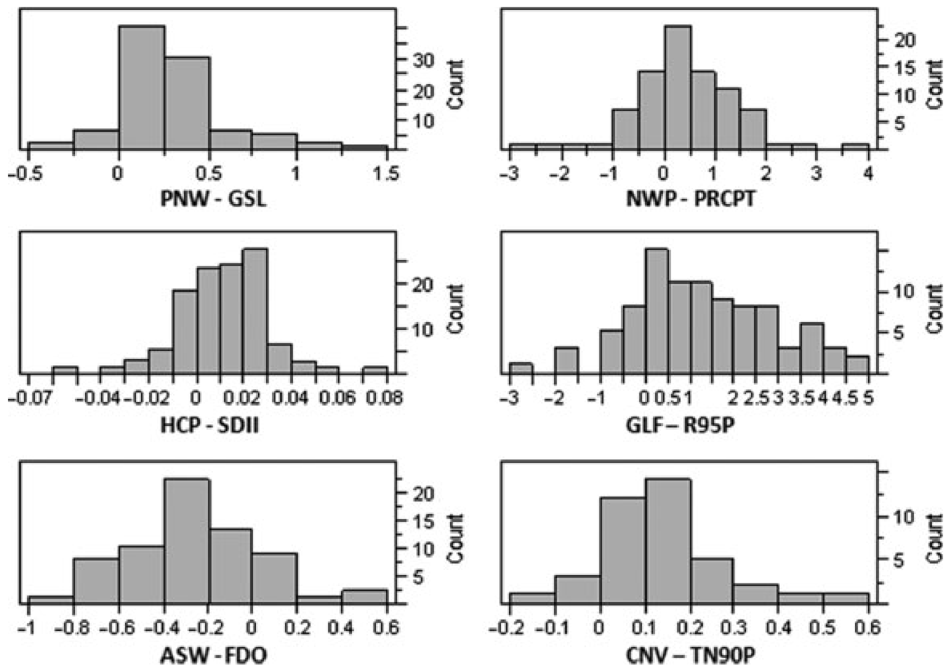

Figure 3. Frequency histograms of weather station trend slopes for the period 1950–2005, for selected climate indicator over each region in western North America.

variation on shorter time scales, but to compare overall trends. If there were no regional trends, the distribution of slopes for an index would be expected to have a mean value not statistically discernible from zero, given the variability among sites. To test against the hypothesis that the expected value of any given mean slope was equal to zero, distributions were examined and then a t-test and a nonparametric Wilcoxon test was applied to each index. A two-tailed test was used because the overall expected value of the slope for an index could be either negative or positive, and no prejudice was imposed over which way it was likely to be. In all cases, the conclusions of the parametric and nonparametric tests agreed. Regional time series were also produced by calculating the annual average index value for all stations in each region. These values were then plotted to provide visualisation of regional trends.

Output data was integrated into a GIS to identify spatial trends in the selected climate indices across WNA. The sign of the slope for indices calculated at each station was plotted over the study area. Station results by region are presented in Table II. Additional trend surface analysis was used to interpolate spatial patterns based on station-specific output. The calculated slopes for each station were interpolated over the study area to smooth the results from the individual stations and give a sense of the rate of change over WNA. Results for temperature indices are presented in Figures 4 and 5, precipitation in Figures 6 and 7. A combination of Global and Local polynomial interpolation was chosen as the method that was best suited to analyse trends over an area as large asWNA. Basic Global polynomial interpolation uses a single polynomial to create a surface that varies gradually through the points over the entire study area. However, this method fails to capture the regional variability of trends over such a diverse area. Local Polynomial interpolation uses many polynomials to better represent trends over user-specified local neighborhoods (Johnston *et al*., 2001). Error in the fitted surface was minimized by varying influence of surrounding points on the surface values produced by the interpolations. Varying the width of the neighborhood used to define the weight of calculated slopes allowed for the production of smooth surfaces over WNA while preserving smaller regional trends. Although exact interpolations are not possible over such a large area, they are a valuable visualisation tool to identify possible spatial trends; particularly given that trends should be more uniform in space if they are in fact driven by large-scale climatic change (Pryor *et al*., 2009). No interpolation is able to eliminate all error through the entire predictive surface. The method used here is no different. Error is exaggerated towards the edges of the fitted surface, particularly in areas with limited data availability like Northern Canada. Error in the final maps was reduced by presenting the interpolated surfaces in classes. Exaggerated values were curtailed by displaying the amount of historical change as being either greater than, or less than, a plausible value. Regional averages presented in the maps were calculated based on the station data, and therefore, are not influenced by any errors present in interpolated surfaces.

6. Results

6.1. Pacific northwest

Many of the calculated trends for the Pacific Northwest (PNW) vary as much as the micro-climatology of the

Table II. Summary of station-specific trends by region for all indices. The positive/negative signs (+/−) denotes any trend where the slope is >0 or <0, respectively. Station trends were considered to be significant (Sig. +/−) when $p < 0.1$.

(a)

PNW - STATION TRENDS				
INDEX	Sig. (+)	(+)	Sig. (−)	(−)
FD0	3	10	55	86
TN90P	65	89	1	7
TX90P	46	77	4	15
GSL	39	86	1	8
PRCPT	11	57	6	39
SDII	19	48	9	42
R5MM	10	50	4	43
R95P	7	56	9	40

(b)

NWP-STATION TRENDS				
INDEX	Sig. (+)	(+)	Sig. (−)	(−)
FD0	9	18	42	64
TN90P	56	71	4	12
TX90P	46	73	3	9
GSL	31	76	1	7
PRCPT	18	58	2	25
SDII	14	52	3	27
R5MM	15	54	5	28
R95P	13	55	0	28

(c)

HCP - STATION TRENDS				
INDEX	Sig. (+)	(+)	Sig. (−)	(−)
FD0	9	26	47	86
TN90P	68	93	6	18
TX90P	26	69	2	43
GSL	29	86	0	26
PRCPT	28	88	1	24
SDII	31	78	4	28
R5MM	19	77	1	34
R95P	29	89	1	22

(d)

GLF - STATION TRENDS				
INDEX	Sig. (+)	(+)	Sig. (−)	(−)
FD0	8	23	45	70
TN90P	35	57	15	35
TX90P	3	14	35	79
GSL	4	38	12	55
PRCPT	42	86	0	7
SDII	35	71	2	22
R5MM	38	84	0	8
R95P	27	76	1	17

Table II. (*Continued*).

(e)

ASW - STATION TRENDS				
INDEX	Sig. (+)	(+)	Sig. (−)	(−)
FD0	3	12	44	54
TN90P	43	53	7	13
TX90P	29	41	3	25
GSL	13	40	5	26
PRCPT	32	57	1	9
SDII	14	43	8	22
R5MM	28	59	2	7
R95P	16	49	1	17

(f)

CNV - STATION TRENDS				
INDEX	Sig. (+)	(+)	Sig. (−)	(−)
FD0	4	4	27	36
TN90P	28	36	4	4
TX90P	11	21	7	18
GSL	11	31	1	9
PRCPT	8	36	0	4
SDII	4	22	1	17
R5MM	7	36	0	4
R95P	3	30	1	10

cordillera. An overwhelming majority of stations in the region have experienced warming over the period of study (Table II(a)). All regional mean temperature indices are reporting significant trends for the region (Table III). One indicator that shows very strong trends throughout the entire region is FDO (Figure 4(a)). As stated above, FD0 measures the annual count of days when the daily minimum temperature falls below 0 °C, roughly indicating the length of winter. Negative trends are clearly evident over the entire Pacific Northwest, with an average reduction in the number of annual frost days of 2.4 per decade, significant at $p < 0.001$ (Figure 5(a)). It is possible that a reduction in the number of frost days may potentially lengthen the growing season. Highly significant trends in the GSL index support this notion. This region has experienced the most amount of change in WNA for this index, with an average increase in the annual GSL of 0.31 days per year (Figure 5(b)). The general increase in GSL can be seen in the annually averaged time series in Figure 8(a). The 1906–2005 trend calculated for Agassiz BC also agreed with the regional results (Figure 9(a)). Significant positive trends were also found in the TN90P, TX90P, and WSDI indices (Table III). On the basis of these results, there is little doubt that the Pacific Northwest experienced significant warming from 1950 to 2005.

The precipitation-based indices are much more varied over the Pacific Northwest, with some areas experiencing wetter conditions while others appear to be drying out. This type of diversity is expected in a region with such

Table III. Summary table for regional analysis. Mean slopes for each index by region were tested to determine if trends over each region were significantly different from zero. Shaded areas denote a regional trend that is significant at the 99% confidence interval.

Region	FD0	GSL	TN90P	TX90P	SDII	R5MM	R95P	PRCPT
ASW	**−0.27177**	0.020788	**0.078591**	**0.048167**	0.006333	**0.071045**	**0.388803**	**1.209318**
GLF	**−0.13954**	−0.0877	0.026269	**0.01486**	**0.024581**	**0.096376**	**1.325323**	**2.807398**
HCP	**−0.1132**	**0.144821**	**0.067866**	**0.020438**	**0.010241**	**0.036482**	**0.696214**	**1.059875**
NWP	**−0.16488**	**0.24112**	**0.072928**	**0.058793**	**0.005265**	0.023735	**0.251675**	**0.407916**
PNW	**−0.24417**	**0.3115**	**0.09399**	**0.046728**	0.000646	−0.00155	0.046802	−0.02231
CNV	**−0.24788**	0.068125	**0.125875**	0.01759	0.0025	**0.06105**	0.184925	**1.011575**
ALL WNA	**−0.18496**	**0.12669**	**0.072127**	**0.01486**	**0.009082**	**0.01801**	**0.0449**	**0.529941** **P < 0.001**

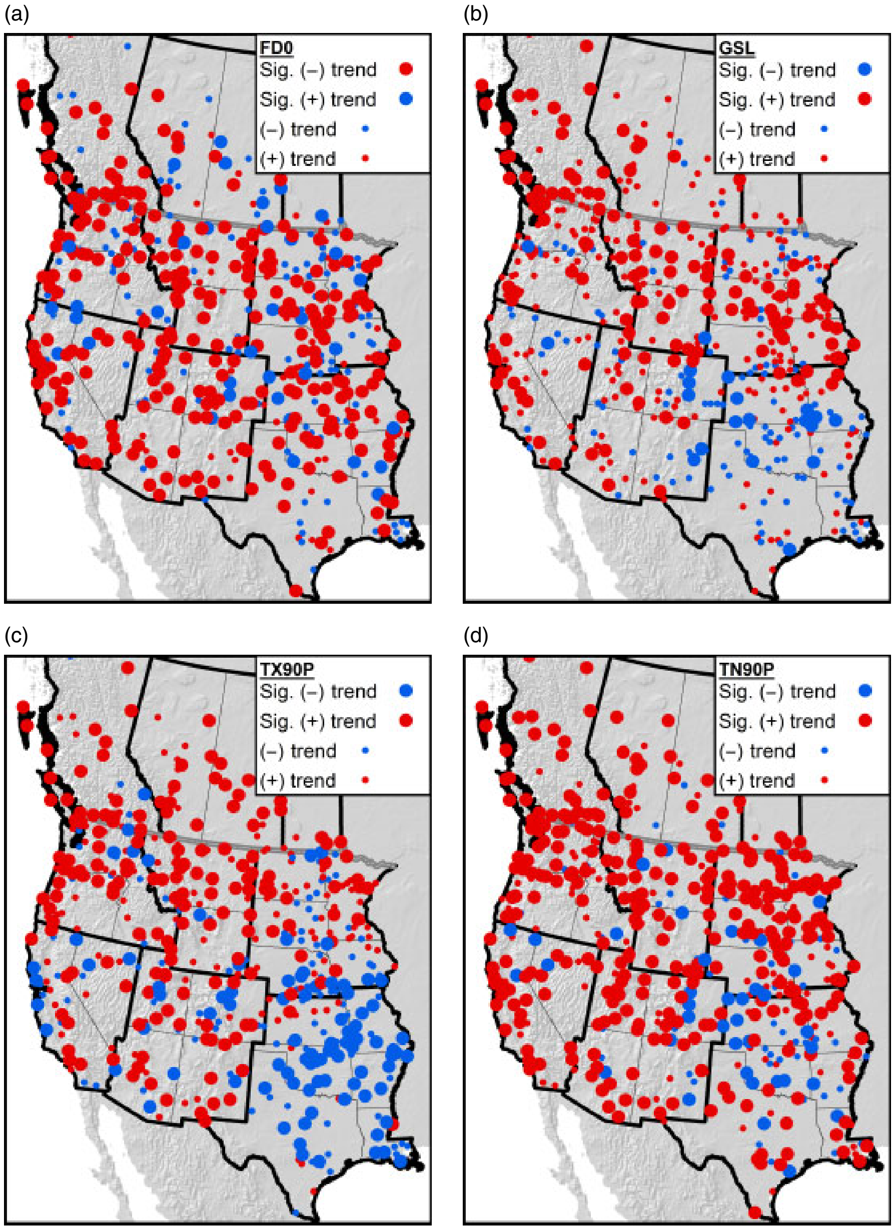

Figure 4. Calculated trends in temperature indices across WNA by station. Red points indicate warming trends and blue dots indicate cooling. Larger points are significant at the $p < 0.1$ level. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

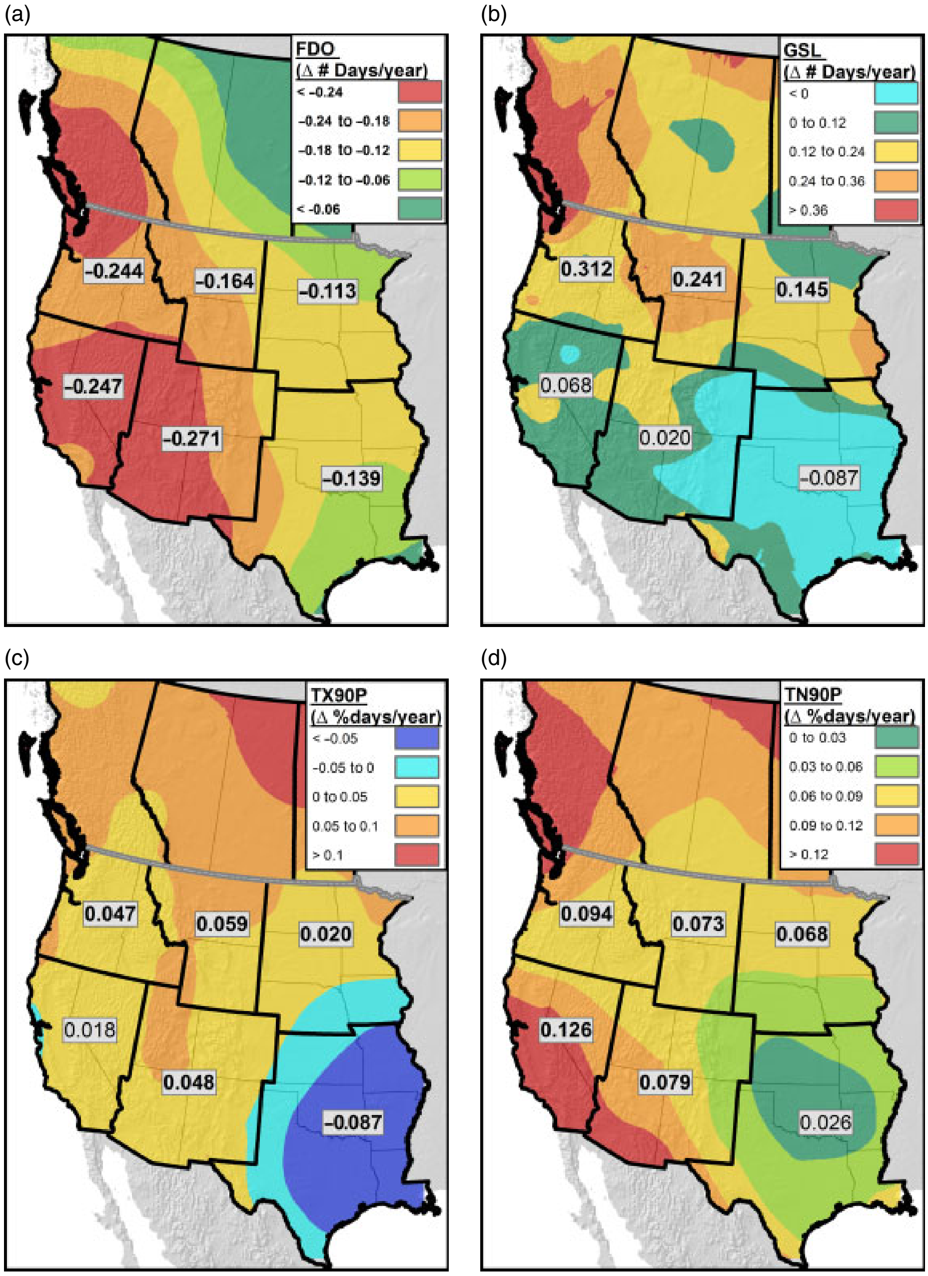

Figure 5. Spatial interpolation of calculated trends in temperature indices across WNA. Regional mean trends calculated using station-specific trends and are overlaid their respective regions. Bold numbers (i.e. **−0.244**) were found to be significant at the $p < 0.001$ level. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

mountainous topography. The spatial variability of trends in the precipitation indices over the PNW resulted in no significant trend in the region-wide means (Table III). Although a number of stations in the interior of British Columbia are reporting significant increases in PRCPT (Figure 6(d)), a drying cell located over Oregon stands out in the interpolation (Figure 7(d)). Strong significant negative trends in PRCPT are found in station records in the south and central areas of the region. This decline in total annual precipitation seems to be driven by negative trends in the number of high-intensity events, as the SDII and R95P indices are also reporting significant negative trends over the area (Figure 6(a) and (c)). Even when considering the cell centered on Oregon, precipitation intensity seems to be increasing in some areas, as indicated by moderate positive trends found in SDII over much of British Columbia, Washington, and Idaho (Figure 7(a)).

Results from the Pacific Northwest region have a number of potentially serious ramifications. Strong negative trends detected in the FDO are important because a reduction in the number of frost days in alpine regions indicates a shortening of the winter season, and a potential change in the timing of the spring snowmelt runoff, which has been noted in a number of other studies (Easterling, 2002; Kunkel *et al*., 2004; Barnett *et al*., 2005; MacDonald *et al*. 2011). Shorter and warmer winters in high alpine areas are partially responsible for the outbreak

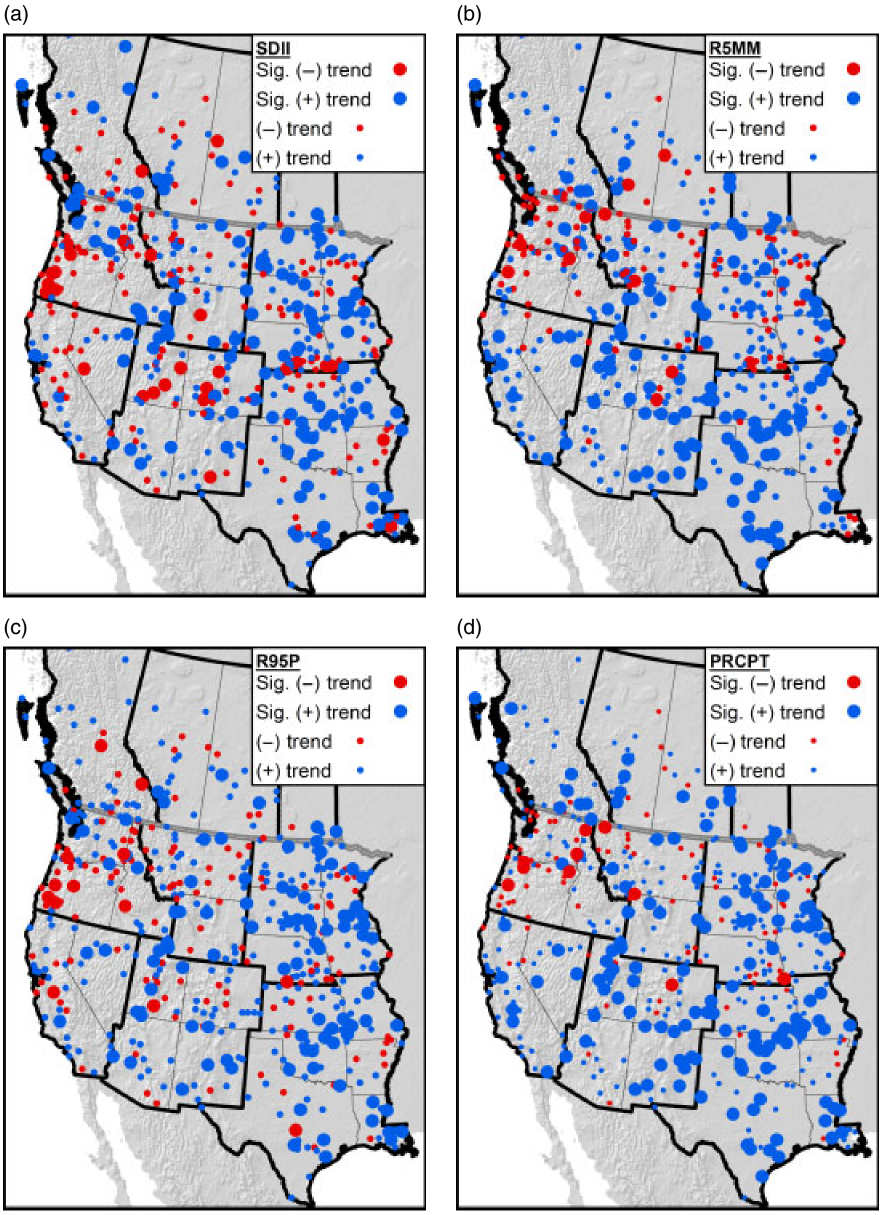

Figure 6. Calculated trends in precipitation indices across WNA by station. Blue points indicate increasing precipitation trends and red dots indicate decreasing precipitation. Larger points are significant at the $p < 0.1$ level. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

of the mountain pine beetle that has been devastating forests in many areas throughout the PNW and other regions over the last decade. According to the mean of the future models investigated by the IPCC, inland and higher-elevation areas in the PNW are expected to see dramatic increases in temperature over the next century (Christensen *et al*., 2007). As the temperature rises, some pest species are able to move into new areas in higher elevations and latitudes where they were previously not able to survive (Kurz *et al*., 2008). Some areas in the region have also clearly received less precipitation than in the past. When combined with a potential earlier onset of spring and an increase in summer temperatures, a reduction in rainfall substantially increases the risk of forest fire. An earlier onset of spring means that forests will lose their snow cover earlier and have more time to dry out, thus lengthening the fire season throughout the northern regions (Running, 2006; Westerling *et al*., 2006). An intensification of precipitation events in some areas of the PNW may increase the risk of flooding and landslides, especially in mountainous areas that have previously succumbed to pest infestation and/or fire. The significant negative trends detected in the precipitation indices over Oregon potentially signifies a northward expansion of the warmer and drier Köppen-Geiger Mediterranean climate zone historically found in central and northern California (Peel *et al*., 2007). Northern portions of the Pacific Northwest region are expected to receive 5–10% more precipitation by 2099 (Christensen *et al*., 2007). However, the drying cell over Oregon may continue into the future as many model projections show negative trends in

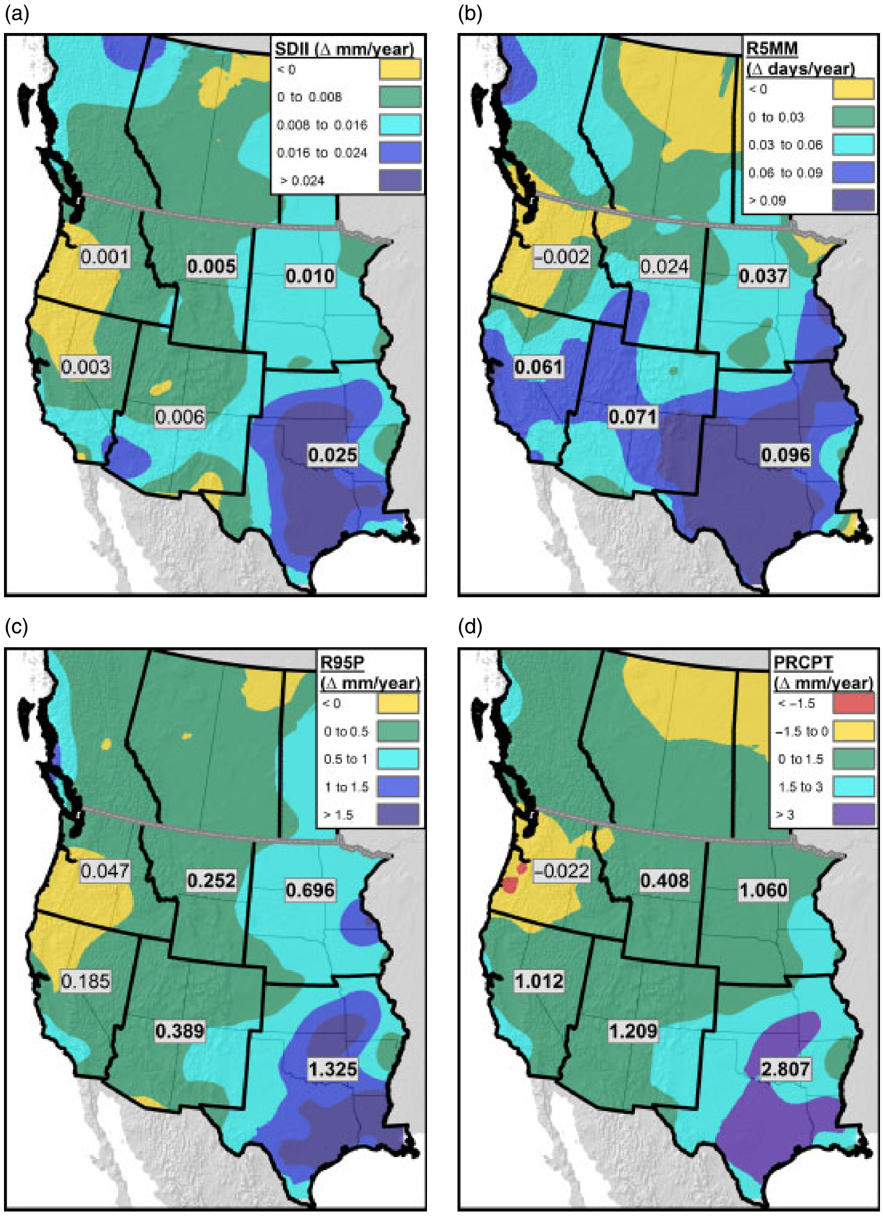

Figure 7. Spatial interpolation of calculated trends in precipitation indices across WNA. Regional mean trends calculated using station-specific trends and are overlaid their respective regions. Bold numbers (i.e. **0.025**) were found to be significant at the $p < 0.001$ level. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

precipitation over the southwest portion of the continent extending into northern California and Oregon.

6.2. Northwest plains region

The northwest plains (NWP) region is characterized by the Rocky Mountains and the semi-arid steppe that sits in their rain shadow. Climatic trends are not as strong as in the Pacific Northwest but they appear to be more spatially coherent, likely due to the more uniform landscape. Temperature-based indices overwhelmingly show moderate to strong warming over the region as a whole (Table II(b) and Figure 4). The calculated regional trends for the FD0, GSL, TN90P, and TX90P indices were all significant at the $p < 0.001$ level (Table III). Although a few stations are reporting significant positive trends in the number of frost days per year, the vast majority display significant declines in their annual FD0 count, with an average reduction in the number of annual frost days of 0.16 per year, significant at $p < 0.001$ (Figure 5(a)). Negative trends in FD0 are consistent with the positive trends in the GSL index (Figure 5(b)). GSL trends for the northwest plains region are among the strongest in WNA, with some stations reporting a lengthening of the annual growing season of about 4 days per decade with a calculated region-wide average of 0.24 days per year. Significant increasing trends are also found throughout the region in the TN90P and TX90P station-specific temperature indices (Figure 5(c) and (d)).

Much fewer significant trends were found in the precipitation-based indices over the northwestern plains region (Table II(b)). The lack of overwhelming station-specific significant trends for the extreme-based R95p

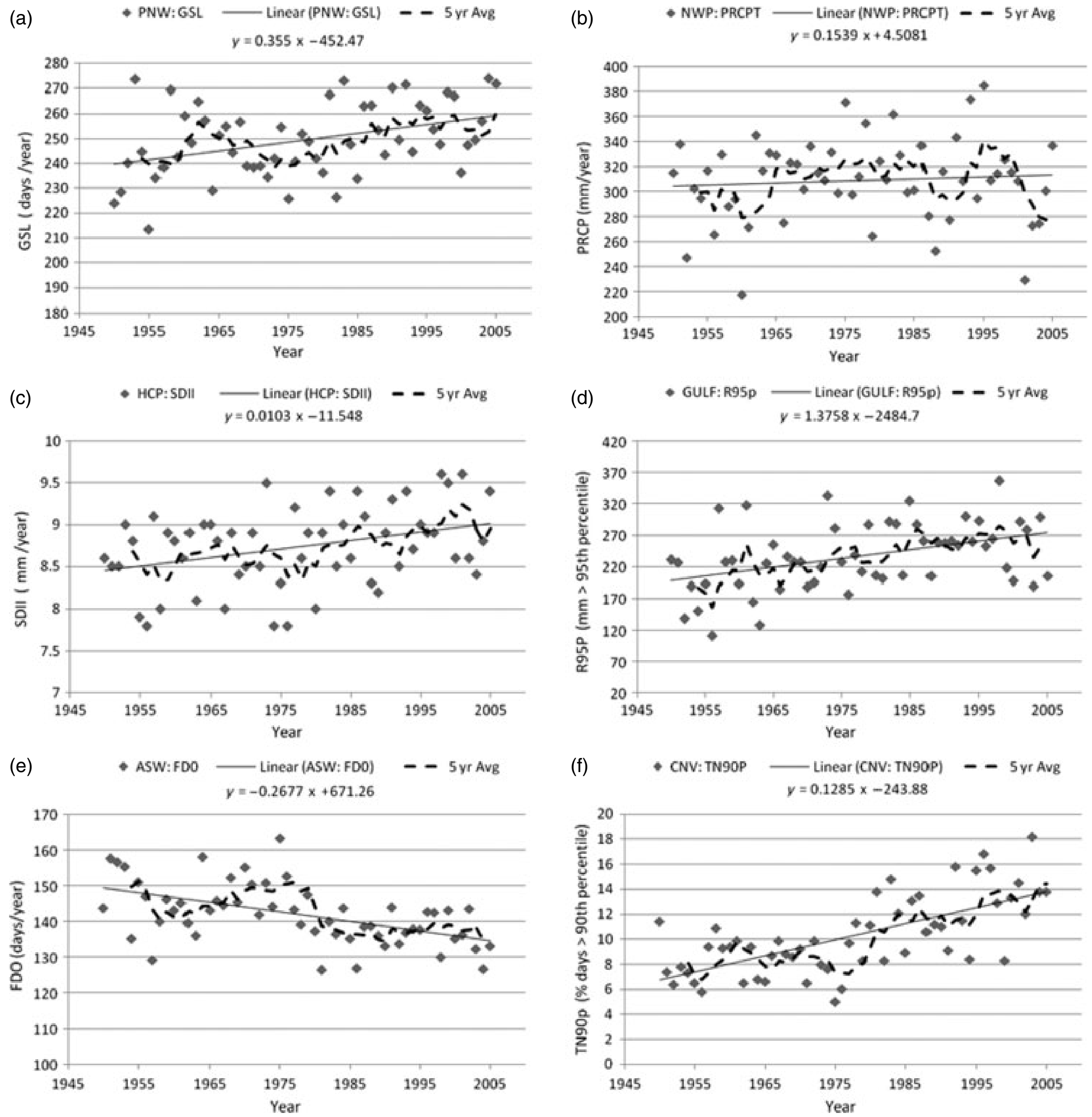

Figure 8. Regional mean time series for selected indices. Annual mean index counts were calculated for each index in each region and plotted over time. Linear trends are shown with solid line. The 5-year moving averages were calculated and are shown with dashed line.

indicator makes it difficult to conclude for certain that an intensification of the hydrologic cycle is accompanying the clear warming trend over the northwestern plains. Stations that are reporting significant trends indicate moderately increasing precipitation over the region. Regional analysis results for the NWP suggest that precipitation has increased over the area, with the SDII, R5MM, and PRCPT indices all reporting trends that are significantly different from zero (Table III). The regional time series plot (Figure 8(b)) suggests that this positive trend is quite weak owing to large inter-annual variability. The 1906–2005 time series at Kalispell MT also shows moderately increasing PRCPT.

Owing to the semi-arid climate in the northwest plains region, any change in the hydrologic regime could pose serious problems for areas dependent on irrigation-based agriculture. Overall results suggest that most of the region is receiving as much or more precipitation as in the past (Figures 12–21), and IPCC mean modelled future projections suggest that the area will likely receive more precipitation than in the past. However, the significant warming, especially in the mountainous areas in the west, may negate the effects of any overall increase in precipitation. Higher temperatures indicate higher potential evapotranspiration which can have a negative impact on soil-moisture content and the productivity of grassland and crop-based ecosystems (Hughes and Diaz, 2008; Liu *et al*., 2009). The shortening of winter, as depicted by the FDO and GSL indices, has resulted in an earlier onset of spring throughout the highlands of the eastern slopes (Barnett *et al*., 2005; Lapp *et al*., 2005; MacDonald *et al*. 2011. If warming

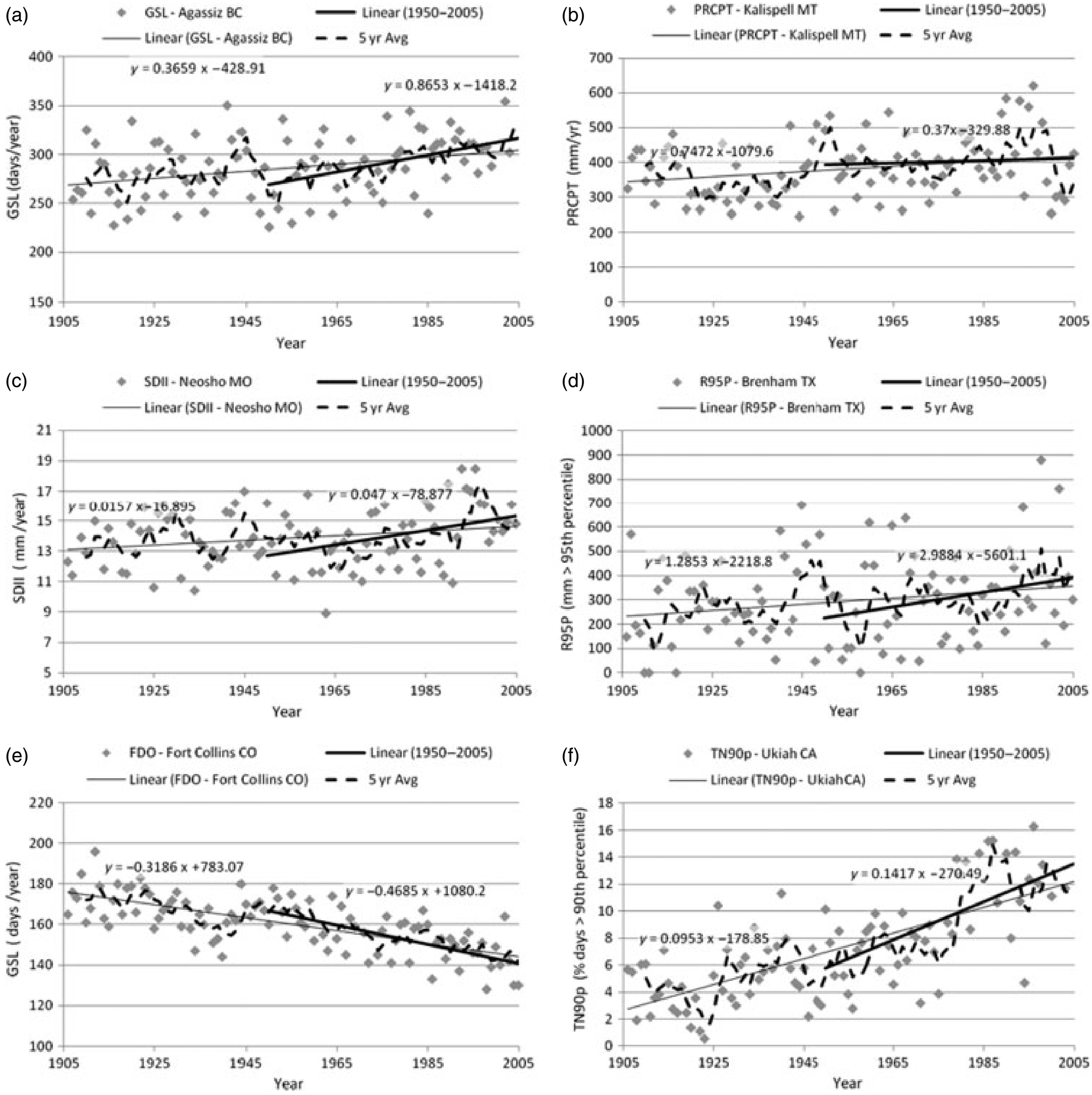

Figure 9. The 100-year station-specific time series. Trend analysis was performed for all indices for selected climate stations with high quality long-term records; 1906–2005 linear trends are shown with thin solid line; 1950–2005 linear trends are shown with bold solid line; 5-year moving averages are shown with dashed line.

trends continue into the future as forecasted by the IPCC, it is likely that watershed managers throughout the region will have to adapt to an earlier spring runoff and prepare for potentially longer periods of low flow. The problem is compounded by shrinking alpine glaciers that traditionally supply a substantial proportion of summer flows in dry years, and may have already passed the peak of meltwater generation (Moore *et al.*, 2009).

6.3. Humid continental plains region

The humid continental plains region is similar in relief to the eastern portion of the northwest plains, but is lower in elevation and largely falls within a wetter climate zone. Calculated temperature trends vary from north to south in the region, roughly following the climatic zones according to Köppen-Geiger classification (Peel *et al.*, 2007). While most stations are reporting significant negative trends for FDO, a number of stations are actually reporting significant increases in the number of frost days per year which substantially reduces the average regional trend (Table II(c) and Figure 4(a)). The resulting mean trend in FD0 for the region amounts to a reduction in the number of annual frost days of 0.11 per year, significant at the $p < 0.001$ level, but it is the weakest trend in FD0 among all regions in WNA (Table III). Trends calculated for TN90P are overwhelmingly positive, outnumbering negative trends by a ratio of more than 5 : 1, indicating a highly significant increase in the number of days per year when the minimum temperature is above the baseline 90th percentile. A general warming of the region is also indicated by trends in GSL, with a moderate region-wide lengthening of the annual growing season of 1.4 days per decade. Strong significant positive trends are concentrated in the southern half of the region, with more northern stations reporting less significant historical trends (Figure 4(b)). The region is reporting significant increases in TX90p, indicating that from 1950 to 2005 there was a moderate increase in maximum temperatures, especially in the northern HCP (Figures 4(c) and 5(c)).

Positive trends heavily outweigh negative trends for the precipitation-based indicators (Table II(c)), which are all reporting significant regional trends during the period (Table III). Significant increases in PRCPT are found throughout the region, with an average increase of 0.11 mm per year (Figure 7(d)). Increases in PRCPT over the region appear to be driven by an intensification of the hydrologic cycle. The SDII and R95P intensity-based indicators are depicting significant increases over the humid plains, with greater increases found in the eastern portion of the region (Figure 7(a) and (c)). The regional SDII mean time series (Figure 8(c)) supports the hypothesis that precipitation intensified in the region, as does the 1906–2005 analysis performed on station data from Logan, IA. This means that more precipitation was likely delivered from heavy and extreme events, supported in part by the more moderate trends found in the R5MM index (Figure 7(b)). These findings support the work done by Pryor *et al*. (2009) who found that some of the largest positive trends for extreme precipitation events could be found in North America's central Great Plains.

Overall results indicate that the humid plains region has generally gotten wetter and warmer over the period 1950–2005, although maximum temperatures have not increased at the same rate as minimums, based on the TN90P and TX90P results. The increases in GSL may benefit this region whose economy is heavily dependent on the agricultural sector. However, the significant increases found in precipitation-based indices pose serious problems for the populations living in the Northern humid plains. A rise in the number and severity of heavy and extreme precipitation events places the region at an increased risk of flooding. According to Kunkel (2003), flooding over the region has increased during the latter part of the study period. Many urban areas and much prime agricultural land are located on the floodplains of major rivers in the region, meaning that they are directly at risk when prolonged heavy precipitation coupled with a faster spring snowmelt causes the rivers to rise rapidly. Modelled future changes in precipitation over the humid plains seem to vary depending on the model you look at, with a mean increase of around 5% by 2099, meaning that there is great uncertainty as to what effect global change will have on the climatology of the region (Christensen *et al*., 2007).

6.4. Gulf region

Between 1950 and 2005, the Gulf region in the southeast corner of the study area experienced significant changes in both temperature and precipitation indices (Table II(d)). Overall, the minimum-temperature-based FDO index is reporting significant negative trends, despite the fact that some stations in the region have experienced significant increases in the number of frost days (Table III, Figures 4(a) and 5(a)). The TN90P index is showing more stations with significant negative trends than the FDO, although overall the average trend still suggests some moderate warming over the region (Figures 4(d) and 5(d)). In contrast, the maximum-temperature-based indices have seen strong significant negative trends throughout the Gulf region. TX90P results showed a clear majority of stations in the Gulf region have experienced significant historical reductions in the number days exceeding the 1961–1990 90th percentile (Figures 4(d) and 5(d)). The GSL signal is by far the weakest of the temperature indices. The regional mean does depict a slight reduction in growing season length over much of the area (Figure 4(d)).

Precipitation-based trends calculated for the Gulf region are the greatest throughout all of WNA (Table III). Calculated trends were overwhelmingly positive across the region (Table II(d)). PRCPT has increased at an average rate of 2.8 mm per year, placing the region in a class by itself. It appears this increase in annual precipitation may be due to increases in the amount of precipitation delivered by heavy events. The region is reporting the strongest significant increases in the SDII in WNA, indicating an intensification of the hydrologic cycle (Figure 7(a)). Trends calculated for the R5MM and R95P indices also follow the same pattern of intensification (Figure 7(b) and (c)). The regional time series shows a strong trend for the R95P index (Figure 8(d)), echoed by the 1906–2005 trend found at Brenham, TX (Figure 9(d)).

Overall trends in temperature are difficult to quantify for the Gulf region. While minimum temperatures are rising, this increase is offset by apparent declines in daily maximum temperature. Although not reporting significant trends over the region as a whole, the GSL appears to be significantly decreasing in the northern states of the region. This decrease may be connected to an increase in the number of frost days found at a number of stations in the same areas. These trends may pose a challenge for agricultural operations that could be devastated by an early or late frost. The cooling trend found in the maximum temperature index TX90P may be tied to the strong increases found in the precipitation indices. Portman *et al*. (2009) showed that the largest warming trends were found in dry areas, whereas wetter areas have experienced some negative trends in temperature. This decrease in maximum temperatures may be partially explained by increased cloudiness associated with more precipitation and a partitioning of heat units to evapotranspiration rather than to daytime sensible heating. The expected future mean temperature response to anthropogenic forcing in this region is about 3.5 °C by 2099 (Christensen *et al*., 2007). The increases in precipitation over the Gulf region could be caused by a number of factors, but perhaps the strongest argument could be made in favour of an increase in extreme weather events like tropical depressions and super-cell convective systems (Groisman *et al.*, 2004). Elsner *et al.* (2008) has found an increasing intensity of tropical systems originating over the Atlantic Ocean and the Gulf of Mexico which often make landfall in the region and deliver massive quantities of precipitation. This region also includes the southern portion of 'tornado-alley', and an increase in the frequency of intense convective storms associated with a general warming of the lower atmosphere may also be partly to blame for increases in precipitation over the southern interior of the US. Many future climate scenarios forecast a significant reduction in precipitation over the region, while others project a continuing increase over the next century, more similar to areas in eastern half of North America (Christensen *et al.*, 2007).

6.5. Southwest region

The arid southwest region is characterized by a mix of hot desert, arid steppe, and highland terrain. Trends in the temperature indices vary spatially over the region, but overall results seem to indicate a general warming (Table II(e)). Similar to the other mountainous regions, very strong negative trends in the FDO were found across the southwest (Figure 4(a)). The FD0 regional average was the highest among all regions, experiencing a reduction in the number of annual frost days of 2.7 per decade, significant at the $p < 0.001$ level (Table III and Figure 5(a)). The ASW annually averaged FD0 time series also supports the argument for a significant reduction over the period (Figure 8(e)). Analysis run for 1906–2005 for Fort Collins, CO, shows a consistent warming trend in the FDO over the period, with an acceleration post-1950 (Figure 9(e)). The TN90P and TX90P indices also displayed significant regional trends. The TN90P is strongest in the southern and western areas of the region (Figure 5(d)). Stations located in and around the Colorado plateau display a significant positive trend in the TX90P (5e). Trends in GSL were positive in the western portion of the region but not strong enough, overall, to result in a significant regional trend, perhaps owing to the normally higher average temperatures of the region (Figures 4(b) and 5(b)).

Significant regional trends were found in three out of four precipitation indices for the American southwest (Table III). Trends in precipitation are strongest in Utah and New Mexico, with a majority of stations in those states receiving significant increases in PRCPT (Figures 6(d) and 7(d)). In some stations, this increase in precipitation seems to be coming from an increase in the number of small events, as trends in R5MM seem to mimic PRCPT while the SDII does not (Figure 6). Groups of stations in the region have experienced significant increases in the SDII although results were too mixed for a significant regional trend to be detected. Overall, precipitation trends were relatively weak over desert areas, likely owing to the small amount of precipitation they receive per year, and the infrequent nature of big events.

Although overall precipitation trends for the southwest indicate that the climate may have gotten wetter between 1950 and 2005, rising temperatures will likely negate any positive influence for this arid region. Shorter winters, as indicated by a decline in FDO, potentially mean a shorter snow accumulation season in the mountains and highlands that feed the Colorado River and the Rio Grande. Watersheds in the region are currently over-allocated and any further stresses placed upon them could result in a crisis (Barnett and Pierce, 2008). Additionally, the majority of modelled scenarios for precipitation show the region receiving less precipitation in the future than it has in recent history (Christensen *et al.*, 2007; Seager *et al.*, 2007; Seager and Vecchi 2010). Hoerling *et al.* (2010) modelled precipitation change over regions around the globe from 1977 to 2006. The study linked SSTs in the Pacific Oceans to precipitation patterns in the American southwest, finding negative trends that agree with the majority of modelled future projections. The difference in time period studied directly influences the contrast in trend calculated due to sampling different phases of the PDO. It is important to note that long-term natural variability in precipitation may be masking the changes expected due to anthropogenic forcing of the climate, and calculated past trends cannot necessarily be expected to continue into the future (Hoerling *et al.*, 2010). Higher temperatures and projected decreases in precipitation will have a negative impact on soil moisture level, further increasing the demand for irrigation, and contributing to the desertification of some areas (Wilcox, 2010). Reservoir levels in the Colorado River system are currently hovering at an all-time low, running the risk of crippling hydroelectric generation and irrigation agriculture depended upon by millions living in the southwestern US (Barnett and Pierce, 2008). While best management practices may be able to mitigate the risk of widespread system failure (Rajagopalan *et al.*, 2009), current levels of development in arid areas of the region may be unsustainable, especially if warming trends continue to increase the stress on critical water resources.

6.6. California–Nevada

Trends indicate increasing daily minimum temperatures throughout the CNV region, which has experienced a substantial reduction of frost days (Figure 5(a)). The region displays the greatest amount of warming in WNA according to the TN90P index, with an annual average increase of 0.12% of days per year registering above the baseline 90th percentile (Table III; Figure 5(d)). The regional time series for TN90P (Figure 8(f)) shows a dramatic increase in minimum temperatures, as does the 1906–2005 trend for Ukiah, CA (Figure 9(f)). Stations across California show a slight significant increase in GSL, especially in central and northern areas (Figures 4(b)). The maximum temperature TX90P index is more varied spatially, and as such it did not report a significant regional trend. Warming trends are most apparent for this index in southern and northern California as well as in California's central valley, while the central coastal area seems to have experienced a slight lowering of maximum temperatures (Figure 4(c) and (d)).

Precipitation trends over CNV were weaker than in other regions, with a majority of stations reporting no statistically significant trend. However, an argument can be made in favour of increasing precipitation across the region as a whole if the sign of the individual trends is taken into account (Figure 6(d) and (e)). This notion is based on the fact that 36 out of 40 stations in the region reported positive sign trends with respect to PRCPT (Table II(f)), and the regional mean slope of 1.01 mm per year was found to be significantly different from zero at the $p < 0.001$ level (Table III). Similar spatial trends are found in R5MM whose regional mean is also significantly positive (Figure 7(b)). Although the majority of stations indicate positive trends in intensification, only a few stations in the region are reporting statistically significant trends for the intensity-based indices, and the regional means for the SDII and R95p indices were not found to be statistically significant.

The California–Nevada region is heavily populated and represents one of the most productive irrigation-based agricultural areas in North America. The substantial warming and lack of any significant increase in precipitation over the region may pose a serious threat to both agricultural operations and large population. Significant positive trends were found in the extreme temperature index TX90P at stations located in the vicinity of Los Angeles in southern California (Figures 4(c)). Demand for power will likely continue to increase as more people seek relief from the warming temperatures (Franco and Sanstad, 2008). An increase in the frequency and intensity of wildfires in the region as a whole has been tied to rising temperatures, especially in higher elevations (Fried 2008; Westerling and Bryant, 2008; Miller *et al.*, 2009). Modelled forecasts for the region predict that temperatures will continue to rise and precipitation will likely decrease as part of a larger trend affecting nearly all of southwest North America (Christensen *et al.*, 2007; Seager and Vecchi, 2010). During the study period, stations in northern California have become drier and warmer, representing the southern portion of a spatially coherent trend found over Oregon and southern Washington. Central California has also experienced a significant amount of warming. As in the other mountainous regions of WNA, the sharp decline in the number of frost days may have altered the hydrologic regime. Crops grown in the region place a very heavy demand on the water resources of the area. A decline in the availability of water supplies may make the current intensive agriculture industry in California's central valley unsustainable in the long term (Purkey *et al.*, 2008), and threaten hydropower operations that supply 15% of California's in-state electricity use (Vicuna *et al.*, 2008). It is clear from the results that the CNV region has already experienced substantial climatic change over the period 1950–2006.

7. Summary and conclusions

- Across the western half of North America, climate change is already well under way. Significant historical trends were found in all indices tested, although it is clear that different regions have changed in different ways over the last half century.
- Many regions have experienced similar changes for the indices tested, but for no index has the amount of change been uniform across WNA. One area that stands out is the Gulf region, where the calculated mean trends are significantly different from all other regions in 7 out of 10 indices. Increasing precipitation in the Gulf region during the study period has driven this separation from the other regions.
- The regions that make up the western cordillera have experienced significant trends for temperature-based indices. If they continue as projected by most future models, warming trends in mountainous regions will continue to substantially alter the climatology and hydrology of the Cordillera and the Great Plains.
- The problems identified in this study will likely become exacerbated in the near future, with temperatures projected to continue increasing throughout the 21st century due to anthropogenic forcing. As the climatic zones of North America shift due to changing temperature and precipitation patterns, society must adapt in order to achieve a more sustainable future.

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References

Ahrens CD. 2008. *Essentials of Meteorology: an invitation to the atmosphere, 5th (Instructor's) edn*. Thompson Learning Inc: Belmont, CA.

Akinremi OO, McGinn SM, Cutforth HW. 1999. Precipitation trends on the Canadian Prairies. *Journal of Climate* **12**: 2996–3003.

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Kumar R, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* **111**: D05109, DOI: 10.1029/2005JD006290.

Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**(17): 303–309, DOI: 10.1038/nature04141.

Barnett TP, Pierce DW. 2008. When will Lake Mead go dry? *Water Resources Research* **44**: W03201, DOI: 10.1029/2007WR006704.

Cayan DR, Redmond KT, Riddle LG. 1999. ENSO and Hydrologic Extremes in the Western United States. *Journal of Climate* **12**: 2881–2893, DOI: 10.1175/1520-0442(1999)012<2881:EAHEIT>2.0.CO;2.

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli KK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P. 2007. Regional Climate Projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY.

Dore MHI. 2005. Climate change and changes in global precipitation patterns: what do we know? *Environment International* **31**: 1167–1181, DOI: 10.1016/j.envint.2005.03.004.

Easterling DR. 2002. Recent changes in frost days and the frost-free season in the United States. *Bulletin of the American Meteorological Society* **83**(9): 1327–1332.

Elsner JB, Kossin JP, Jagger TH. 2008. The increasing intensity of the strongest tropical cyclones. *Nature* **455**: 92–95, DOI: 10.1038/nature07234.

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank A, Peterson T. 2002. Observed coherent changes in climatic extremes during second half of the twentieth century. *Climate Research* **19**: 193–212.

Fried JS. 2008. Predicting the effect of climate change on wildfire behavior and initial attack success. *Climatic Change* **87**(1): 251–264, DOI: 10.1007/s10584-007-9360-2.

Franco G, Sanstad AH. 2008. Climate change and electricity demand in California. *Climatic Change* **87**(1): 139–151, DOI: 10.1007/s10584-007-9364-y.

Gleick PH *et al*. 2010. Climate change and the integrity of science. *Science* **328**(5979): 689–690, DOI: 10.1126/science.328.5979.689.

Groisman PY, Knight RW, Easterling DR, Karl TR, Hegerl GC, Razuvaev VN. 1999. Changes in the probability of heavy precipitation: important indicators of climate change. *Climatic Change* **42**: 243–283.

Groisman PY, Knight RW, Karl TR, Easterling DR, Sun B, Lawrimore JH. 2004. Contemporary changes of the hydrologic cycle over the contiguous United States: trends derived from in situ observations. *Journal of Hydrometeorology* **5**: 64–84.

Hoerling M, Eischeid J, Perlwitz J. 2010. Regional precipitation trends: distinguishing natural variability from anthropogenic forcing. *Journal of Climate* **23**: 2131–2145. DOI: 10.1175/2009JCLI3420.1.

Hughes MK, Diaz HF. 2008. Climate variability and change in the drylands of Western North America. *Global Planetary Change* **64**: 111–118, DOI: 10.1016/j.gloplacha.2008.07.005.

IPCC. 2007. Climate Change 2007. Solomon S, Qin D, Manning M, Chen Z, Marquis M, 586 Averyt KB, Tignor M, Miller HL. (eds), *The Physical Science Basis.* 587 *Contribution of Working Group 1 to the Fourth Assessment Report of the* 588 *Intergovernmental Panel on Climate Change.* Cambridge University Press: Cambridge, United Kingdom and New York, 996.

Johnston K, Ver Hoef JM, Krivoruchko K, Luca N. 2001. Using ArcGIS Geostatistical Analyst. ESRI: Redlands, CA, USA. 300 pp.

Karl TR, Koss WJ. 1984. Regional and national monthly, seasonal, and annual temperature weighted by area 1895–1983. *National Climatic Data Center Tech. Rep.* Historical Climatology Series 4–3: 33 pp.

Karl TR, Trenberth KE. 2003. Modern global climate change. *Science* **302**: 1719–1723, DOI: 10.1126/science.1090228.

Klein Tank AMG, Können GP. 2003. Trends in indices of daily temperature and precipitation extremes in Europe, 1946-99. *Journal of Climate* **16**: 3665–3680, DOI: 10.1175/1520-0442(2003)016<3665:TIIODT>2.0.CO;2.

Kunkel KE. 2003. North American trends in extreme precipitation. *Natural Hazards* **29**: 291–305.

Kunkel K, Easterling DR, Hubbard K, Redmond K. 2004. Temporal variations in the frost free season in the United States: 1895–2000. *Geophysical Research Letters* **31**(3): L03201.

Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L. 2008. Mountain pine beetle and forest carbon feedback to climate change. *Nature* **452**(24): 987–990.

Lapp S, Byrne JM, Kienzle S, Townshend I. 2002. Linking global circulation model synoptic and precipitation for western North America. *International Journal of Climatology* **22**: 1807–1817, DOI: 10.1002/joc.851.

Lapp S, Byrne J, Townshend I, Kienzle S. 2005. Climate warming impacts on snowpack accumulation in an alpine watershed. *Int. J. Climatol* **25**: 521–536.

Liu W, Zhang Z, Wan S. 2009. Predominant role of water in regulating soil and microbial respiration and their responses to climate change in a semiarid grassland. *Global Change Biology* **15**: 184–195.

MacDonald RJ, Byrne JM, Kienzle S, Larson RP. 2011. Assessing the potential impacts of climate change on mountain snowpack in the St. Mary River watershed, Montana. *Journal of Hydrometeorology* **12**(2): 262–273. DOI: 10.1175/2010JHM1294.1.

Meehl GA, Tebaldi C, Walton G, Easterling D, McDaniel L. 2009. Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S. *Geophysical Research Letters* **36**: L23701, DOI: 10.1029/2009GL040736.

Mekis E, Hogg WD. 1999. Rehabilitation and analysis of Canadian daily precipitation time series. *Atmosphere-Ocean* **37**(1): 53–85.

Miller JD, Safford HD, Crimmins MA, Thode AE. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA. *Ecosystems* **12**: 16–32.

Moore RD, Fleming SW, Menounos B, Wheate R, Fountain A, Stahl K, Holm K, Jakob M. 2009. Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes* **23**: 42–61, DOI: 10.1002/hyp.7162.

Peel MC, Finlayson BL, McMahon TL. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences* **11**: 1633–1644.

Peterson TC. 2005. Climate change indices. *World Meteorological Organization Bulletin* **54**(2): 83–86.

Portman RW, Solomon S, Hegerl GC. 2009. Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. In *Proceedings of the National Academy of Sciences of the United States of America* **106**(18): 7324–7329.

Pryor SC, Howe JA, Kunkel KE. 2009. How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? *International Journal of Climatology* **29**: 31–45.

Purkey DR, Joyce B, Vicuna S, Hanemann MW, Dale LL, Yates D, Dracup JA. 2008. Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley. *Climatic Change* **87**(1): 109–122, DOI: 10.1007/s10584-007-9375-8.

Rajagopalan B, Nowak K, Prairie J, Hoerling M, Harding B, Barsugli J, Ray A, Udall B. 2009. Water supply risk on the Colorado River: Can management mitigate? *Water Resources Research* **45**: W08201, DOI: 10.1029/2008WR007652.

Running SW. 2006. Is global warming causing more larger wildfires? *Science* **313**: 927–928.

Seager R, Ting M, Held I, Kushnir Y, Lu J, Vecchi G, Huang HP, Harnik N, Leetmaa A, Lau NC, Li C, Velez J, Naik N. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* **316**: 1181–1184.

Seager R, Vecchi GA. 2010. Greenhouse warming and the 21st century hydroclimate of southwestern North America. In *Proceedings of the National Academy of Sciences of the United States of America* **107**(50): 21277–21282, DOI: 10.1073/pnas.0910856107.

St Jacques JM, Sauchyn DJ, Zhao Y. 2010. Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability? *Geophysical Research Letters* **37**: L06407, DOI: 10.1029/2009GL042045.

Vicuna S, Leonardson R, Hanemann MW, Dale LL, Dracup JA. 2008. Climate change impacts on high elevation hydropower generation in California's Sierra Nevada: a case study in the Upper American River. *Climatic Change* **87**(1): 123–137, DOI: 10.1007/s10584-007-9365-x.

Vincent LA, Mekis E. 2006. Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. *Atmosphere-Ocean* **44**(2): 177–193.

Westerling AL, Bryant BP. 2008. Climate change and wildfire in California. *Climatic Change* **87**(1): 231–249, DOI: 10.1007/s10584-007-9363-z.

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* **313**: 940–943.

Wilcox BP. 2010. Transformative ecosystem change and ecohydrology: ushering in a new era for watershed management. *Ecohydrology* **3**: 126–130, DOI: 10.1002/eco.104.

Williams CN, Menne MJ, Vose RS, Easterling DR. 2006. United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data. *USHCN ORNL/CDIAC-118 NDP-070*. http://cdiac.ornl.gov/epubs/ndp/ushcn/ndp070.html

Zhang X, Hogg WD, Mekis E. 2001. Spatial and temporal characteristics of heavy precipitation events over Canada. *Journal of Climate* **14**: 1923–1936.

Zhang X, Vincent LA, Hogg WD, Nitsoo A. 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean* **38**(3): 395–429.

Zhang X, Yang F. 2004. RClimDex (1.0) User's Manual. *Climate Research Branch Environment Canada*. http://cccma.seos.uvic.ca/ETCCDMI/software.shtml

