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Analysis of California surface temperature trends based on observations.

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ANALYSIS OF CALIFORNIA SURFACE TEMPERATURE TRENDS BASED ON OBSERVATIONS

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ABSTRACT

ANALYSIS OF CALIFORNIA SURFACE TEMPERATURE TRENDS BASED ON OBSERVATIONS

by Wittaya Kessomkiat

Analysis of California surface temperature based on observations has been conducted using United States Historical Climatology Network (USHCN) stations and Cooperative Weather (COOP) stations throughout California to understand spatial and temporal changes in temperature. Monthly maximum and minimum temperatures (Tmax and Tmin) were used to calculate and analyze annual and seasonal trends over the last 86 years via statistical analyses. For annual trends, Tmin is warming faster than Tmax for both 1918-2006 and 1950-2006 time periods. Since 1970, both Tmax and Tmin, however, have increased at the same rate. For seasonal trends, interestingly, by far the largest warming trends are found during spring (March-May) in both Tmax and Tmin, particularly in Southern California since 1970. While Tmin reveals a strong coherent temperature variation statewide in both annual and seasonal temperatures, Tmax shows spatial and temporal variations in finer scales. Particularly in Southern California during winter and summer, cooling and warming trends are leveled in Tmax. These regional temperature changes must be caused by different forcing mechanisms.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

Various recent studies characterize the increase in global temperatures over the last 100 years. A recent surface temperature data set by Brohan et al. (2006) found that the temperature increase over the 20th century was significantly larger than its uncertainty and suggests a real warming of the planet. Vose et al. (2005) found that the global minimum temperature increased more rapidly than the global maximum temperature (0.20°C dec^{-1} vs. 0.14°C dec^{-1}) during 1950–2004, producing a significant negative diurnal temperature range (DTR) trend at -0.07°C dec^{-1}. However, from 1979–2004, global minimum and maximum temperatures increased at nearly the same rate (0.29°C dec^{-1}) with essentially no DTR trends. These results agree with the results of the Intergovernmental Panel on Climate Change (IPCC) that reported that global mean surface temperatures have increased by 0.74°C ± 0.18°C over the last 100 years (1906-2005) and that the warming rate over the last 50 years of the 20th century (0.13°C ± 0.03°C dec^{-1}) was almost twice as large as the warming during the first 50 years of the 20th century (0.07°C ± 0.02°C dec^{-1}) (IPCC 2007).

Although globally the planet is warming, at a regional scale the warming is not uniform. In the continental United States, Lund et al. (2001) found annual warming trends in the Northeast, Northern Midwest, and west coasts and cooling trends in the Southeast.

California has a wide range of climate regions, including the valleys, the mountains, and deserts. The diversity of Californian geography appears to affect climate variability and trends. In order to better understand California's climate, the Desert

Research Institute (DRI) partitioned California into 11 regions using climatological precipitation and temperature from Cooperative Weather (COOP) stations and Parameter-elevation Regressions on Independent Slopes Model (PRISM) data throughout California to group stations into similar climate zones (Abatzoglou *et al.* 2009). At present it is unclear how climate has changed in different climate zones during different seasons.

Various studies have been conducted to understand trends and variability in California. A recent study from LaDochy et al. (2007) using air temperature from 1950-2000 found that warming in minimum temperatures is stronger compared to mean and maximum temperatures for most regions. They also found that warming trends, especially in intensive urban areas, are larger compared to rural and non-agricultural regions. Their study shows a strong correlation between temperature variability, and Pacific sea surface temperatures, especially due to the Pacific Decadal Oscillation. Christy and Norris (2006) suggested that warming in minimum temperatures during summer nights in the Central Valley were primarily due to irrigation. However, later studies by Bonfils et al. (2006) and Bonfils and Lobell (2007) suggest that trends in the Central Valley are due to both irrigation and anthropogenic greenhouse gases (GHGs) and that the effects of irrigation still remain unclear due to other land use changes.

The aim of our study is to investigate the spatial and temporal structure of California surface temperature trends over the last 89 years in order to characterize how temperature has changed in California. The data used in this study, together with the methodology are described in Section 2. In Section 3, results are presented in 5 subsections: a) California temperature trends, b) Temperature trends for California climate regions, c) temperature trends at individual United States Historical Climatology Network (USHCN) stations, d) significant cooling and warming periods for USHCN stations in California, and e) comparison with California cooperative weather stations (COOP) network. In Section 4, summary and discussion are given.

2. Data and methodology

Monthly surface temperature data used in this study were obtained from the United States Historical Climatology Network (USHCN) based on 54 cooperative weather stations (COOP) throughout California and 4 high quality assured cooperative weather stations close to California from neighboring states (OR, NV, AZ) (Fig. 1). Monthly temperature data for maximum and minimum temperatures obtained from the National Climate Data Center (NCDC) were based on 272 cooperative weather stations throughout California (Fig. 2). Monthly temperature data for maximum and minimum temperatures obtained from the USHCN are of high data quality and are urban heat-adjusted (Williams et al. 2007).

Annual and seasonal averages were computed using data quality assurance methods described in Stafford et al. (2000) and Vose (2005). In particular, no month was used if more than 6 days of data were missing, no three-month seasons were used if at least 1 month was missing, no year was used if more than 1 month was missing, and no station was used if there was less than 80% complete of data during the time period or less than 4 years of data in each decade were missing.

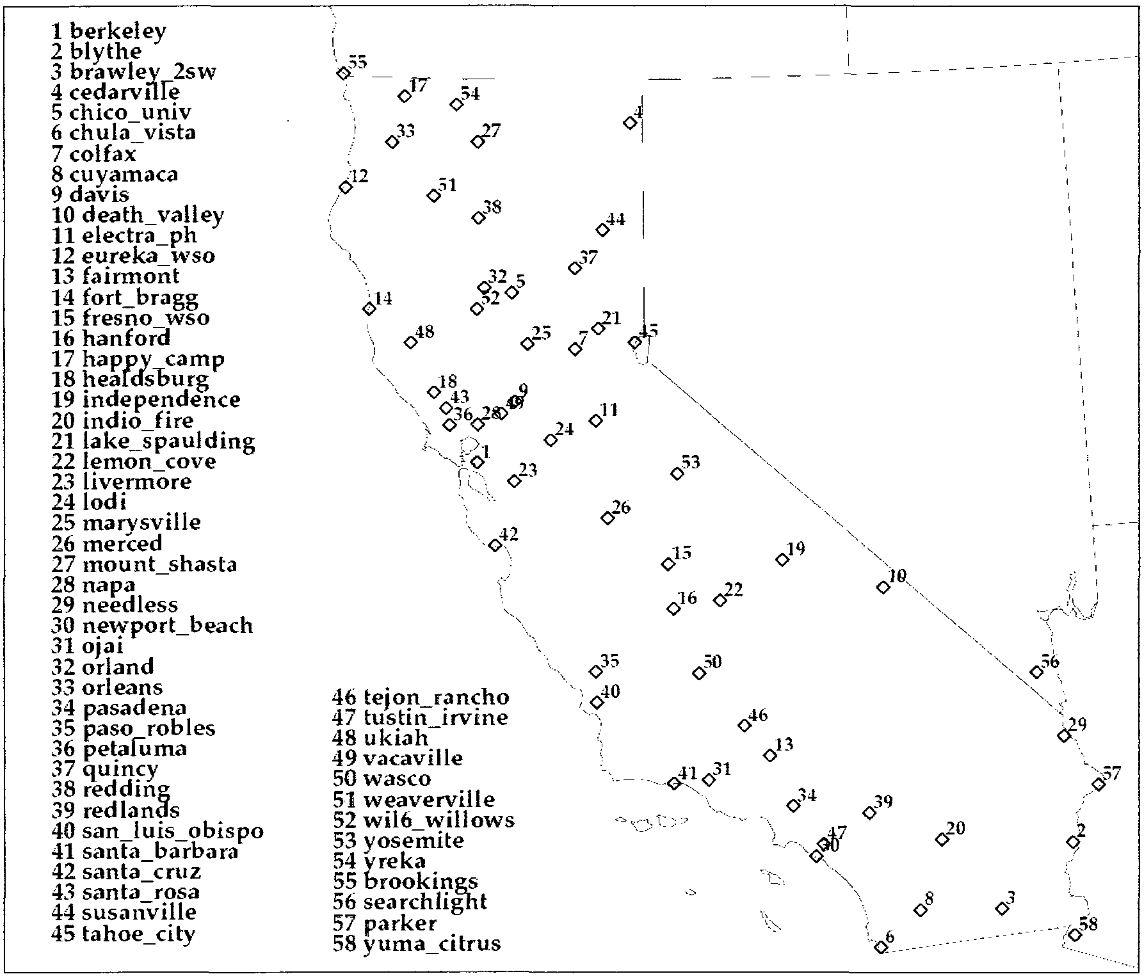


Fig. 1. Map of USHCN stations used in this study

Maximum and minimum monthly temperatures were analyzed in this study as these two climate variables show a high reliability and availability in climate records. Seasonal and annual averages were calculated using monthly averages, where seasons were defined using standard meteorological definitions: winter = DJF, spring = MAM, summer = JJA, and fall = SON. For each variable, monthly, seasonal, and annual trends were computed for different time periods during 1918-2006, 1950-2006, and 1970-2006 using a linear least-square regression. Those first two time periods are chosen where

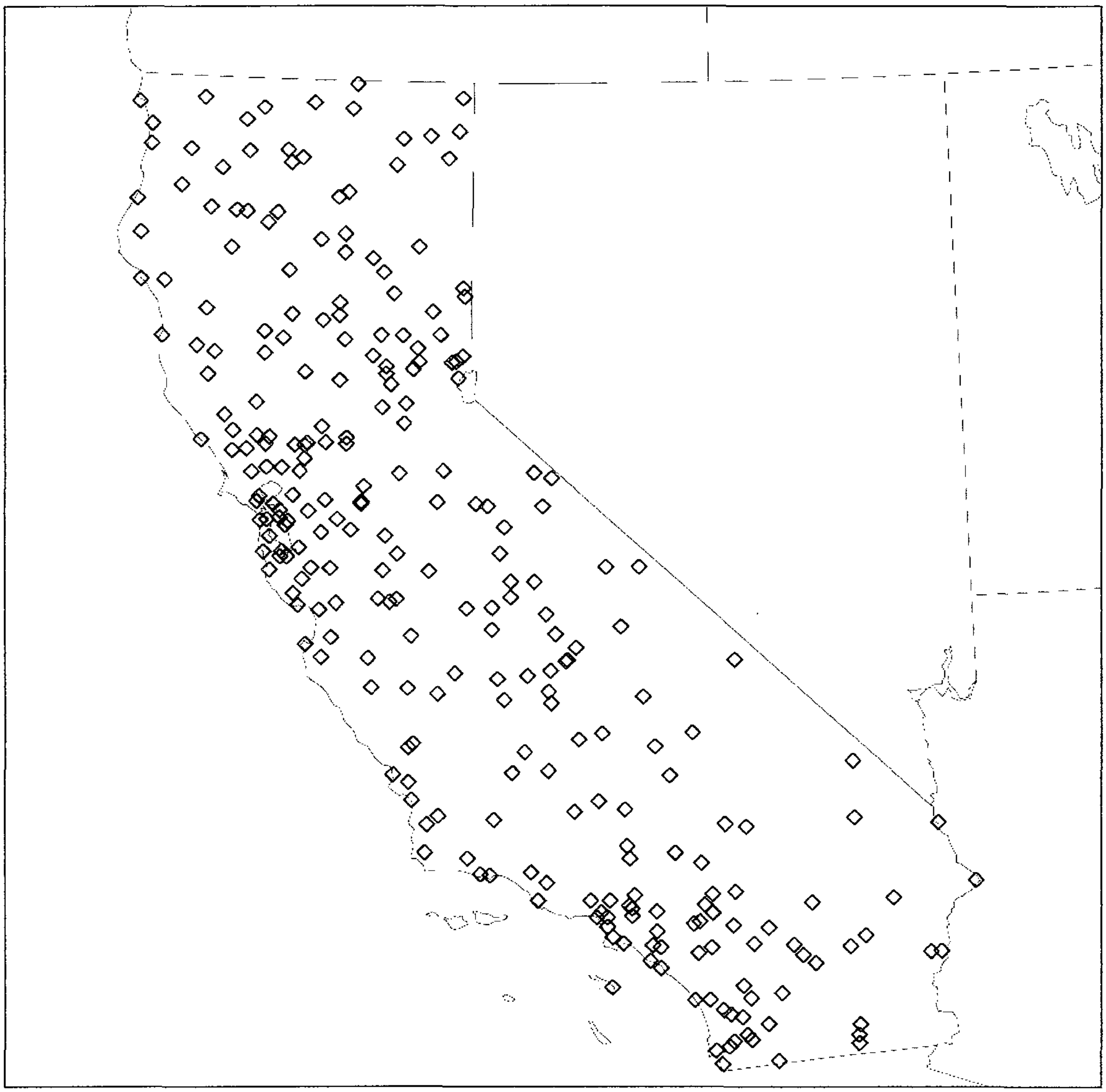


Fig. 2. Map of California COOP stations used in this study

most of USHCN and COOP stations can provide temperature data respectively while the period from 1970-2006 is where Tmax and Tmin are investigated in regional scale compared to global scale in which both Tmax and Tmin have increased at the same rate. Statistical significance in the trends was computed at 95% confidence level or better using the standard error where auto correlation has been taken into account. Auto correlation is included to correct standard error, in which effects the significance of trend and its confidence intervals, for the individual data points that are dependent. This is the case for most temperature data, where a value at a specific time often depends on values at previous time (Wigley 2006).

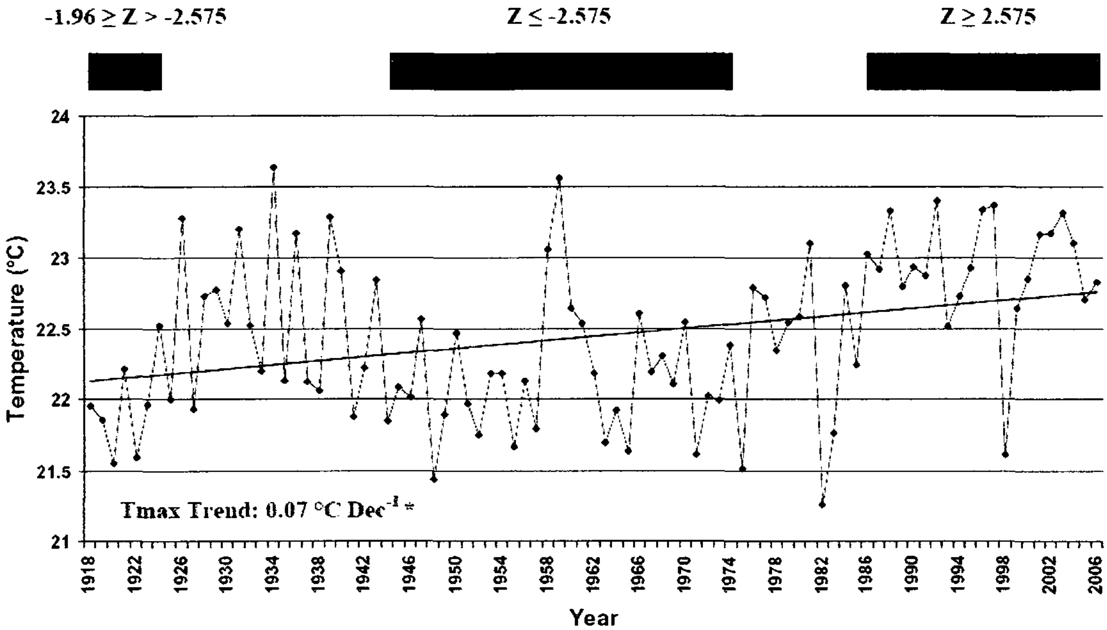
Based on where stations located within a region vary with one another, California is divided into 11 climate regions by DRI. They have used data from 195 COOP stations with at least 75% of observations during 1950-2005 and the PRISM dataset to compute a value for each monthly, seasonal, and annual temperature trend for each month for each station (Abatzoglou *et al.* 2009). For our study, data from 58 USHCN stations and from 272 COOP stations were used to compute seasonal and annual trends for both maximum and minimum temperatures at different time periods for the following geographical areas: California, Northern California, Southern California, and each California climate region.

Annual and seasonal temperature variations were then studied at each USHCN station between 1918-2006 using Mann-Whitney Z (MWZ) analysis method by Mauget (2003a, b). This approach ranks data values of selected time series, sample those ranking over moving time windows of 6-30 year duration, and then compute a Mann-Whitney U (MWU) statistic using each sample of rankings. Then MWZ can be calculated using the parameters of an appropriate MWU null distribution generated by the Monte-Carlo method described in (Mauget 2003a), to normalize the MWU statistics from sequences of ranked values of selected time series. Temperature rankings with significant positive (negative) MWZ values show significant warm (cool) years in a sample from a null hypothesis. Therefore warm and cool periods can be identified by the significant MWZ statistics from moving time windows and sampling windows of 6-30 years are used to repeat this process. Then non-overlapping time periods are identified by the largest positive or negative Z statistics from all the analyses. In Mauget (2003b), consistent patterns of significant variability in groups of time series can be graphically represented using this method.

3. Results

a. California Temperature Trends

Annual temperature trends between 1918-2006 were computed using the USHCN data for California, Northern California, and Southern California (Fig. 3 and 4). The annual temperature trends show statistically significant warming at the 95% confidence level for both maximum temperature (Tmax) and minimum temperature (Tmin) with larger warming in Tmin (0.17°C dec^{-1}) compared to Tmax (0.07°C dec^{-1}). A positive correlation (r=0.61) between Tmax and Tmin was computed using the Pearson's Correlation Coefficient and these results show that high (low) Tmax are likely to correspond with high (low) Tmin in a given year. A comparison of trends in Northern California versus Southern California show that while the annual Tmin values are essentially the same in both parts of the state, the Tmax trend is larger in Southern California (0.10°C dec^{-1}) compared to Northern California (0.05°C dec^{-1}).



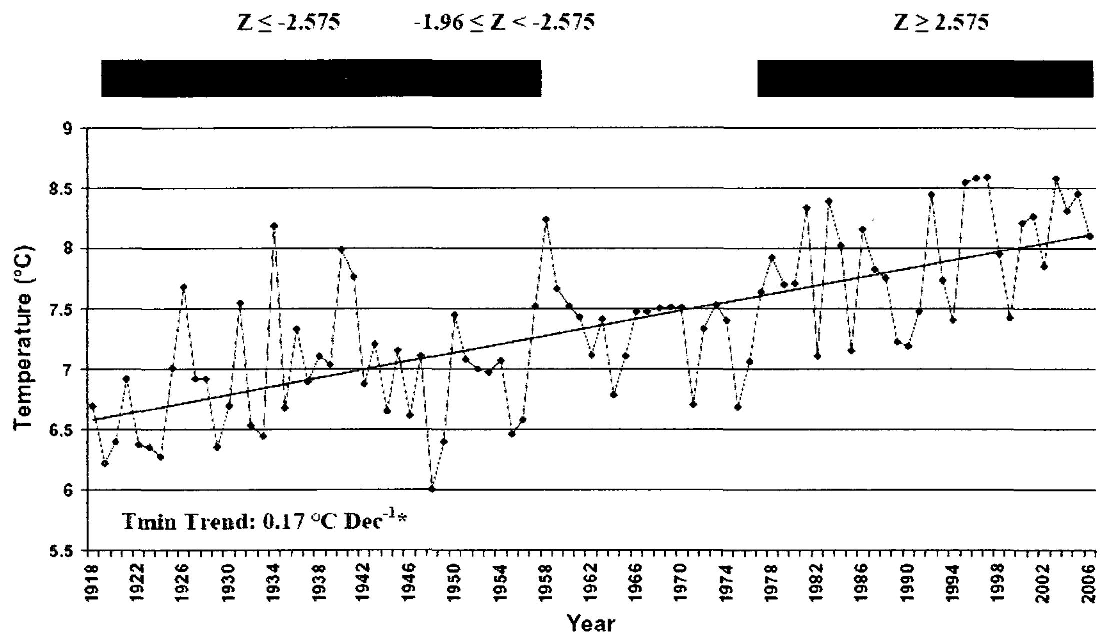


Fig. 3. California annual maximum (top) and minimum (bottom) temperatures computed from the USHCN network between 1918-2006. The linear trends (in °C dec^{-1}) are shown where an asterisk (*) indicates that the trend is statistically significant at 95% CL. Accompanying each statewide time series, statistically significant z values (at 95% and 99% CL for the MWU analysis are shown, where blue shading indicates cool periods and red shading indicates warm periods.

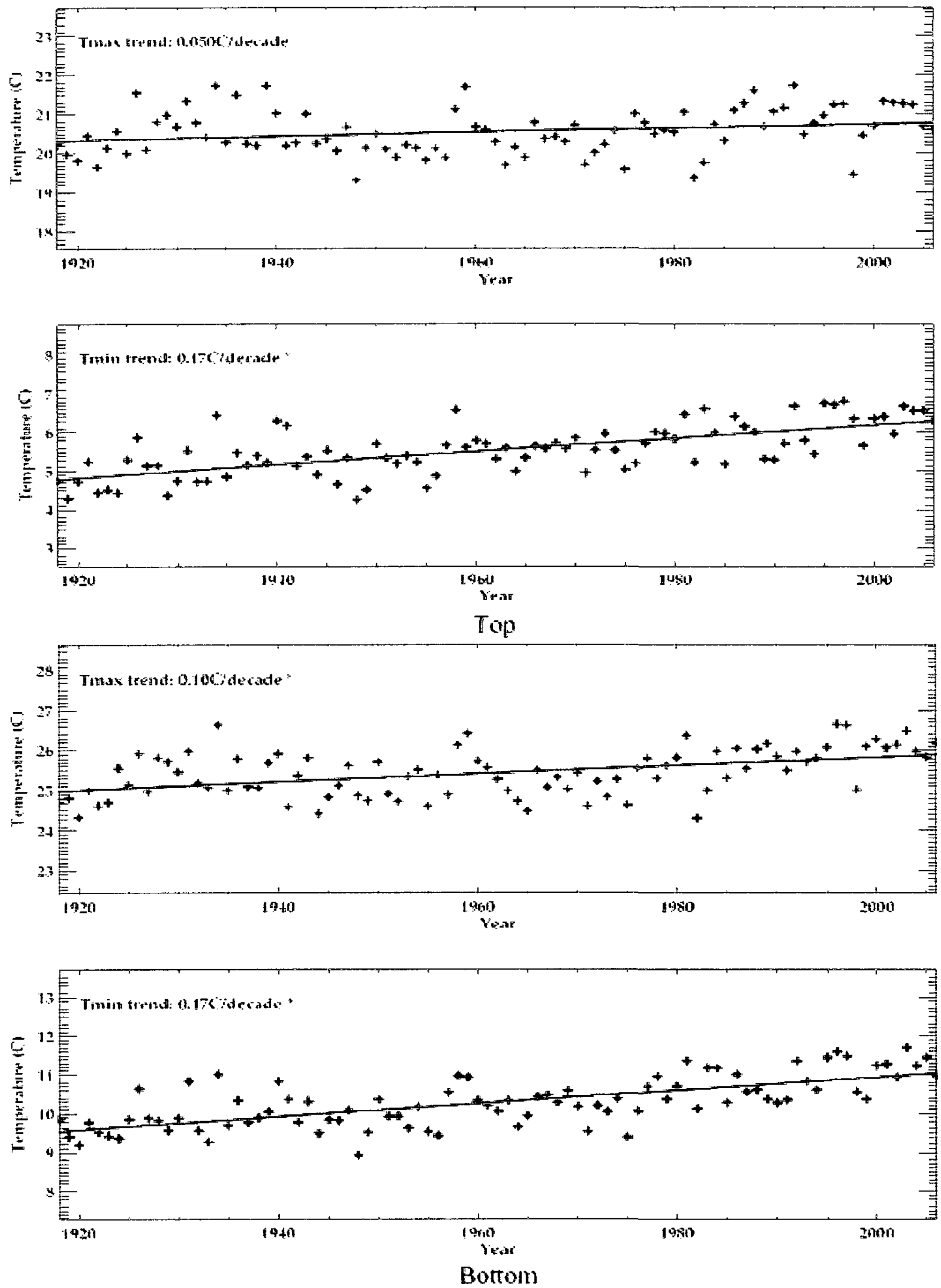
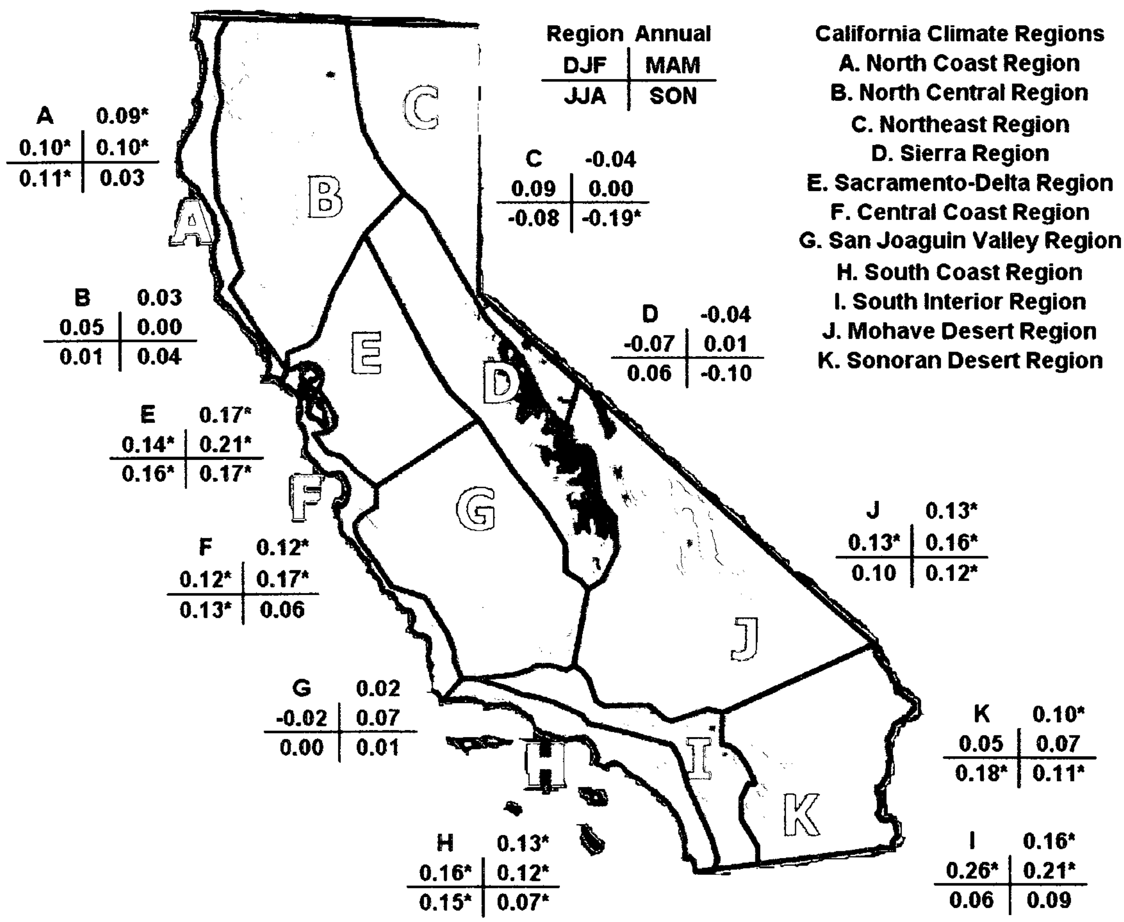
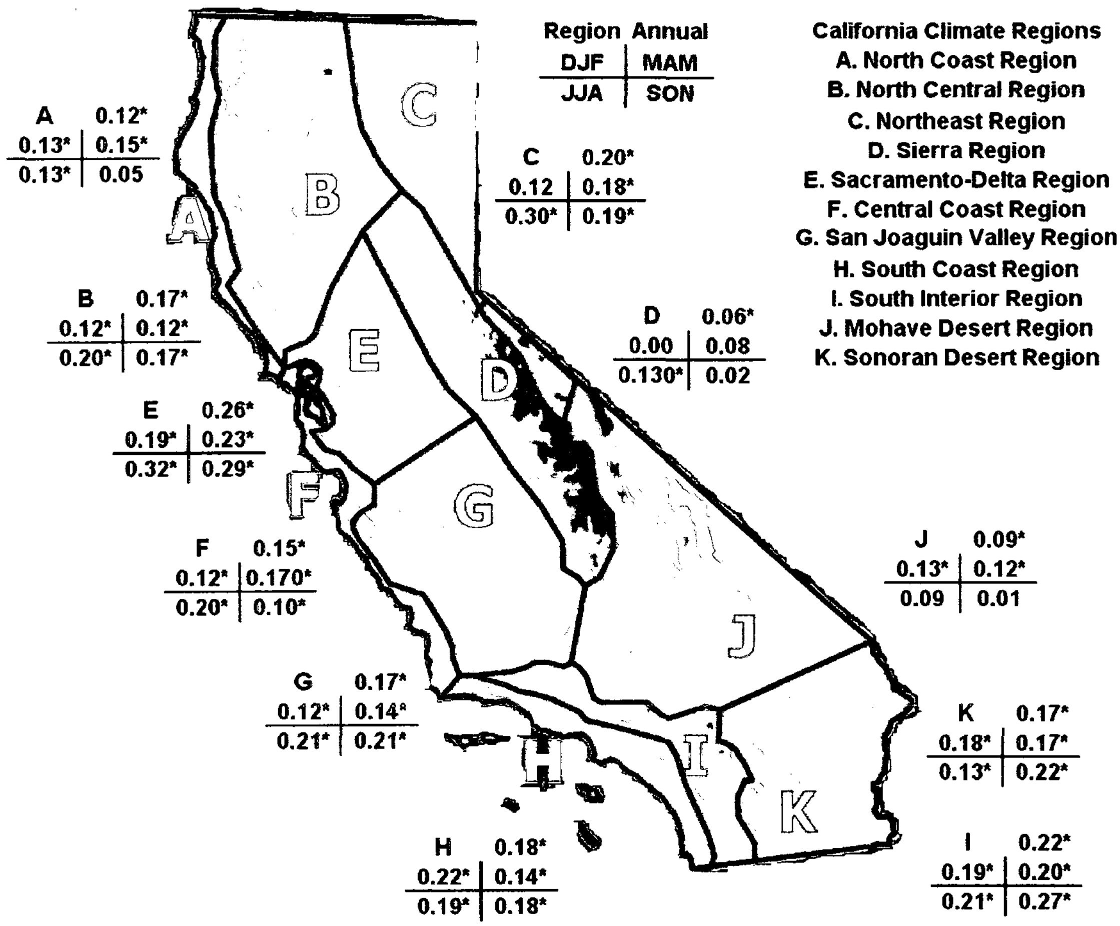


Fig. 4. Northern California (top) and Southern California (bottom) annual maximum and minimum temperatures computed from the USHCN network between 1918-2006. the linear trends (in °C dec^{-1}) are shown where an asterisk (*) indicates that the trend is statistically significant at 95% CL and where red color indicates maximum temperature and blue color indicates minimum temperature.

California seasonal temperature trends show statistically significant warming for Tmin varying from 0.14 (DJF)–0.21 (JJA) °C dec^{-1} (Fig. 5a and 5b). Although seasonal trends for Tmax show warming in all seasons, none of them is statistically significant.



(a)



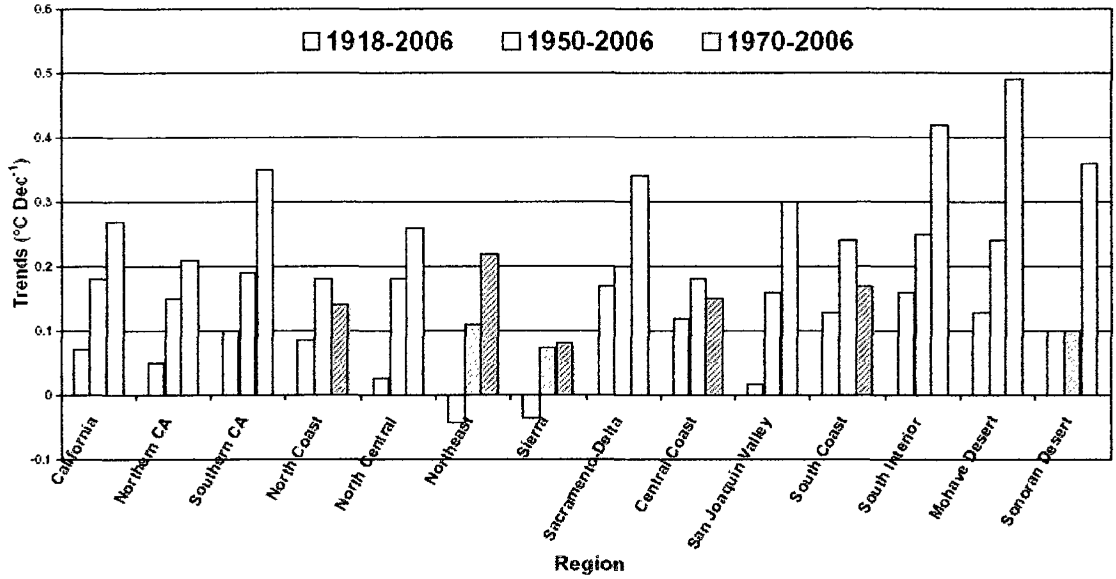
(b)

Fig. 5. Annual temperature trends (in °C dec^{-1}) for the 11 climate regions labeled A-K computed betwenn 1918-2006 for Tmax (a) and Tmin (b). Adjacent to each region label is the annual and seasonal trends for Tmax and Tmin, where the trends that are statistically significant at the 95% CL are indicated with an asterisk (*).

In Northern California, only the Tmin trends are statistically significant, again with JJA having the largest trends. In Southern California, both Tmin and Tmax have statistically significant warming trends, with MAM having the largest Tmax trends and essentially no seasonal variation in the warming Tmin trends. Global (Karl et al. 1993; Braganza et al. 2004; Vose et al. 2005) and regional (Karl et al. 1993; Bonfils et al. 2007) analysis found that Tmin increased faster than Tmax. It is unclear what exactly causes these asymmetric trends of Tmax and Tmin (Karl *et al.* 1993; Trenberth *et al.* 2007).

Similar trends from the USHCN data were then computed between 1950-2006 and 1970-2006 (Fig. 6). For both time periods, California annual temperature trends for both Tmax and Tmin show statistically significant warming in magnitudes larger than those in the 1918-2006 time period. Similar results are also found in Northern and Southern California for annual trends with larger warming in Tmin compared to Tmax for both different time periods except Tmin between 1970-2006. Unlike annual trends from 1918-2006, annual trends for both 1950-2006 and 1970-2006 are larger in Southern California compared to Northern California.

In the seasonal analysis, between 1950-2006 (Table 1), California temperature trends show statistically significant warming for all seasons in Tmin with greater magnitudes compared to trends from 1918-2006. However, both Tmax and Tmin show the largest trends in MAM with statistical significance. In Northern California and Southern California, seasonal trends also show statistically significant warming in Tmin except DJF in Northern California and both Tmax and Tmin show the largest trends in MAM with statistical significance. In contrast, in the seasonal analysis between 1970-2006 (Table 2), California temperature trends show warming without any statistical significance except for the MAM and JJA trends in Tmin. Unlike results from 1918-2006 and 1950-2006 in Southern California, seasonal trends in Tmax show warming in magnitudes larger than those in Tmin in all seasons except the MAM trend, with the largest trends in MAM for both Tmax and Tmin.



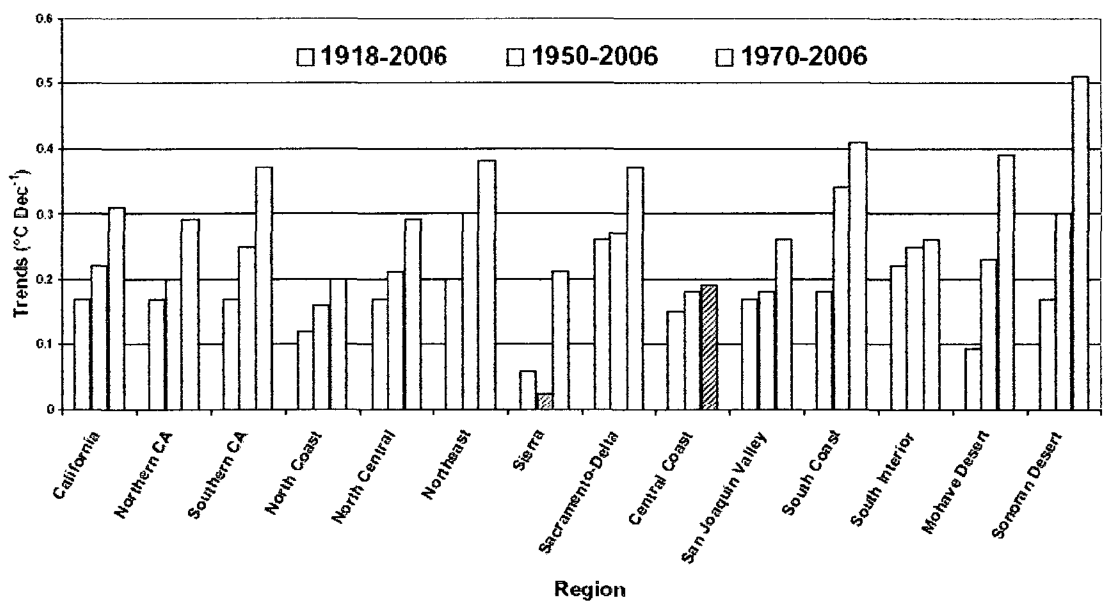


Fig. 6. A comparison of the statewide and regional annual Tmax (top) and Tmin (bottom) trends for 3 times periods, 1918-2006, 1950-2006, and 1970-2006, where the bars are solid when the computed trend is statistically significant at 95% CL and hashed when the trend is not statistically significant.

b. Temperature trends for California Climate Regions

In annual temperature analysis based on USHCN urban heat-adjusted data from 1918-2006, California annual temperature trends were computed for climate regions labeled A-K, as originally defined by the Desert Research Institute (DRI) and shown in Figure 5a and 5b. California annual temperature trends in Tmax show warming in 9 out of 11 regions with statistically significant trends in 5 out of 9 regions and cooling in 2 out of 11 regions but any significant trends. On the other hand, California annual temperature trends show statistically significant warming for all regions in Tmin. All regions in Southern California show significant warming trends in both annual Tmax and Tmin. In contrast, most annual trends for Tmax are not statistically significant in either the northern or the central parts of California.

For seasonal temperature analysis (Fig. 5a and 5b), in Tmax, while only approximately half of the 11 regions show statistically significant warming, most of the seasonal trends are statistically significant in Tmin. Only cooling trends are found in 2 of the 11 regions (Northeast and Sierra) and none of them is statistically significant, except the SON trend in the Northeast region. Though most of the regions show statistically significant trends in Tmin, only regions in central and southern parts of California show statistically significant trends in Tmax.

Table 1. Annual and seasonal trends (in °C dec^{-1}) for California, northern and southern California, and the 11 climate regions computed between 1950-2006 for Tmax and Tmin from the USHCN stations, where the trends that are statistically significant at the 95% CL are indicated with an asterisk (*).

SEASON	MAXIMUM	MINIMUM	SEASON	MAXIMUM	MINIMUM
California (58)			*E. Sacramento-Delta Region (7)*		
Annual	0.18*	0.22*	Annual	0.20*	0.27*
DJF	0.16	0.20*	DJF	0.21*	0.21*
MAM	0.27*	0.30*	MAM	0.29*	0.34*
JJA	0.20*	0.27*	JJA	0.16	0.33*
SON	0.082	0.13*	SON	0.13	0.22*
Northern California (33)			*F. Central Coast Region (3)*		
Annual	0.15*	0.20*	Annual	0.18*	0.18*
DJF	0.16	0.16	DJF	0.18*	0.15
MAM	0.24	0.28*	MAM	0.34*	0.25*
JJA	0.15	0.27*	JJA	0.14	0.25*
SON	0.07	0.11	SON	0.06	0.07
Southern California (25)			*G. San Joaquin Valley Region (7)*		
Annual	0.19*	0.25*	Annual	0.16*	0.18*
DJF	0.14	0.26*	DJF	0.15	0.12
MAM	0.29*	0.33*	MAM	0.22	0.23*
JJA	0.27*	0.27*	JJA	0.19*	0.23*
SON	0.07	0.15*	SON	0.07	0.14*
A. North Coast Region (3)			*H. South Coast Region (5)*		
Annual	0.18*	0.16*	Annual	0.24*	0.34*
DJF	0.22*	0.16	DJF	0.22*	0.40*
MAM	0.26*	0.28*	MAM	0.29*	0.41*
JJA	0.25*	0.23*	JJA	0.32*	0.36*
SON	-0.02	-0.01	SON	0.11	0.19*
B. North Central Region (12)			*I. South Interior Region (3)*		
Annual	0.18*	0.21*	Annual	0.25*	0.25*
DJF	0.17*	0.18	DJF	0.26*	0.22*
MAM	0.21	0.26*	MAM	0.38*	0.33*
JJA	0.19	0.24*	JJA	0.31*	0.28*
SON	0.13	0.12*	SON	0.06	0.19*
C. Northeast Region (3)			*J. Mohave Desert Region (4)*		
Annual	0.11	0.30*	Annual	0.24*	0.23*
DJF	0.11	0.19	DJF	0.13	0.28*
MAM	0.29	0.38*	MAM	0.38*	0.34*
JJA	0.10	0.46*	JJA	0.30*	0.24*
SON	-0.04	0.17*	SON	0.17	-0.03
D. Sierra Region (5)			*K. Sonoran Desert Region (6)*		
Annual	0.07	0.02	Annual	0.10	0.30*
DJF	0.03	-0.04	DJF	-0.013	0.32*
MAM	0.18	0.17*	MAM	0.22*	0.38*
JJA	0.11	0.11	JJA	0.24*	0.27*
SON	0.01	-0.13*	SON	-0.04	0.24*

Table 2. Annual and seasonal trends (in °C dec^{-1}) for California, northern and southern California, and the 11 climate regions computed between 1970-2006 for Tmax and Tmin from the USHCN stations, where the trends that are statistically significant at the 95% CL are indicated with an asterisk (*).

SEASON	MAXIMUM	MINIMUM	SEASON	MAXIMUM	MINIMUM
California (58)			*E. Sacramento-Delta Region (7)*		
Annual	0.27*	0.31*	Annual	0.34*	0.37*
DJF	0.13	0.28	DJF	0.25	0.33
MAM	0.33	0.40*	MAM	0.34	0.41*
JJA	0.26	0.32*	JJA	0.32*	0.38*
SON	0.34	0.24	SON	0.40*	0.34*
Northern California (33)			*F. Central Coast Region (3)*		
Annual	0.21*	0.29*	Annual	0.15	0.19
DJF	0.10	0.26	DJF	0.12	0.10
MAM	0.24	0.35*	MAM	0.31	0.30
JJA	0.18	0.32*	JJA	-0.03	0.24*
SON	0.32	0.2	SON	0.16	0.10
Southern California (25)			*G. San Joaquin Valley Region (7)*		
Annual	0.35*	0.37*	Annual	0.30*	0.26*
DJF	0.18	0.31	DJF	0.17	0.22
MAM	0.46*	0.49*	MAM	0.33	0.30
JJA	0.36*	0.33*	JJA	0.37*	0.25*
SON	0.35*	0.33*	SON	0.3	0.25
A. North Coast Region (3)			*H. South Coast Region (5)*		
Annual	0.14	0.20*	Annual	0.17	0.41*
DJF	0.16	0.20	DJF	0.16	0.44*
MAM	0.19	0.30	MAM	0.19	0.56*
JJA	0.22	0.28*	JJA	0.19	0.36*
SON	-0.06	0.01	SON	0.14	0.29*
B. North Central Region (12)			*I. South Interior Region (3)*		
Annual	0.26*	0.29*	Annual	0.42*	0.26*
DJF	0.11	0.31	DJF	0.17	0.20
MAM	0.22	0.33*	MAM	0.58*	0.42*
JJA	0.24	0.27*	JJA	0.45*	0.22
SON	0.43	0.21	SON	0.46*	0.21
C. Northeast Region (3)			*J. Mohave Desert Region (4)*		
Annual	0.22	0.38*	Annual	0.49*	0.39*
DJF	0.04	0.38	DJF	0.27	0.36*
MAM	0.34	0.43*	MAM	0.67*	0.52*
JJA	0.13	0.41*	JJA	0.43*	0.32*
SON	0.35	0.27	SON	0.56*	0.37*
D. Sierra Region (5)			*K. Sonoran Desert Region (6)*		
Annual	0.08	0.21*	Annual	0.36*	0.51*
DJF	-0.12	0.06	DJF	0.13	0.37*
MAM	0.14	0.35*	MAM	0.57*	0.68*
JJA	0.05	0.38*	JJA	0.35*	0.47*
SON	0.25	0.02	SON	0.37	0.54*

All coastal regions (North, Central, and South Coast) (Figs. 5a and 5b) show statistically significant warming in annual trends for both Tmax and Tmin and annual trends increase in magnitude from north to south ranging from 0.08-0.13°C dec^{-1} in Tmax and 0.12–0.18°C dec^{-1} in Tmin. For seasonal temperature trends, Tmin trends show statistically significant warming for all seasons in coastal regions except the SON trend in the North Coast region with the maximum trend 0.22°C dec^{-1} found in DJF in the South Coast region. Tmax trends also show statistically significant warming for a majority of all seasons in these regions. Interestingly, the weakest trends in all coastal regions are in SON for both Tmax and Tmin. In desert regions (Mohave and Sonoran), like coastal regions, most seasonal trends show statistically significant warming in both Tmax and Tmin.

A trend analysis between 1950-2006 and 1970-2006 (Fig. 6) was also computed to study the similarities and differences among the three periods. In general, both Tmax and Tmin trends show greater trends in magnitudes as time progresses for all regions. While most annual trends in Tmin show statistically significant warming, only half of annual trends in Tmax are found to be warming at a statistically significant level. Like results from 1918-2006, while 10 out of 11 regions for 1950-2006 and 1970-2006 show statistically significant warming in annual Tmin, statistically significant warming can only be only found 8 out of 11 regions for 1950-2006 and 6 out of 11 regions for 1970-2006 in annual Tmin.

In the seasonal temperature analysis (Tables 1 and 2), most of the seasonal trends in Tmin show statistically significant warming in 1950-2006 as also found in 1918-2006, with the MAM trends showing the largest trends not only in Tmin but also in Tmax for all regions. Interestingly, coastal regions (North, Central, and South Coast) show the increase in magnitude from north toward south in Tmin. In contrast, only ~20% (Tmax) and ~50% (Tmin) of trends show statistically significant warming during 1970-2006 with JJA Tmin showing statistically significant warming for all regions except South Interior region. Similar results to those found from 1950-2006 are also found in Tmax and Tmin between 1970-2006 for coastal regions with the increases in magnitude from north toward south in Tmin. In addition, Sonoran Desert region shows the largest individual significant trend with 0.68°C dec^{-1} in MAM Tmin while Mojave Desert region shows the largest individual trend with 0.67°C dec^{-1} in JJA Tmax during 1970-2006.

c. Temperature trends at individual USHCN stations

To further explore regional variations in trends, the 58 individual USHCN stations were also investigated. Annual and seasonal trends were computed for each individual USHCN station between 1918-2006 (Fig. 7), 1950-2006 (Fig. 8), and 1970-2006 (Fig. 9). Between 1918-2006, 26 statistically significant trends show warming in annual Tmax and 42 statistically significant trends show warming in annual Tmin.

However, between 1950-2006, all statistically significant trends show warming in annual Tmax and Tmin except 2 stations in Tmin showing cooling trends, one in the Sierra region and the other in the San Joaquin Valley region, with trends in Tmin having greater magnitude compared to Tmax in general.

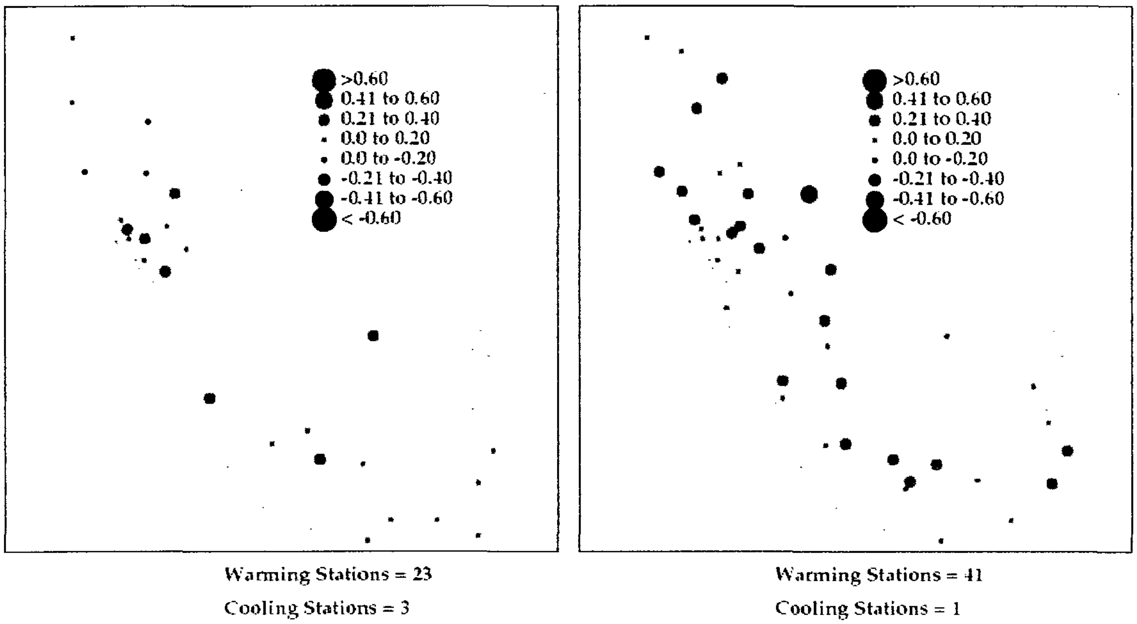


Fig. 7. Map showing statistically significant (95% CL) warming or cooling trends between 1918-2006 for annual Tmax (left) and Tmin (right) temperatures from the USHCN. Red circles denote warming trends and blue circles denote cooling trends, where the average warming or cooling trend is given at the bottom.

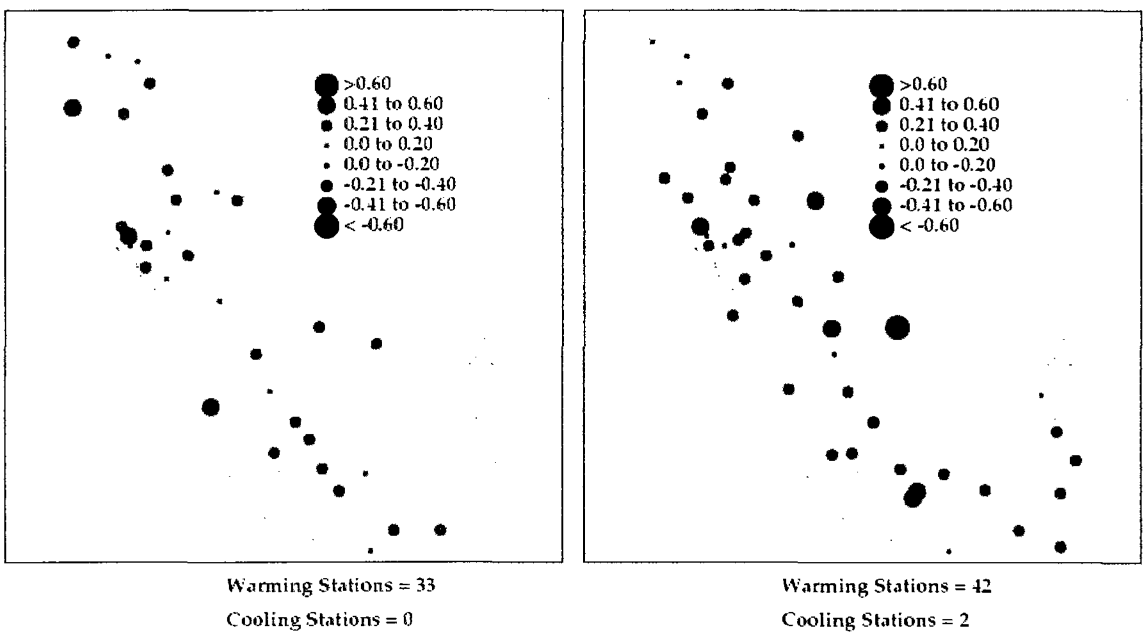


Fig. 8. Map showing statistically significant (95% CL) warming or cooling trends between 1950-2006 for annual Tmax (left) and Tmin (right) temperatures from the USHCN. Red circles denote warming trends and blue circles denote cooling trends, where the average warming or cooling trend is given at the bottom.

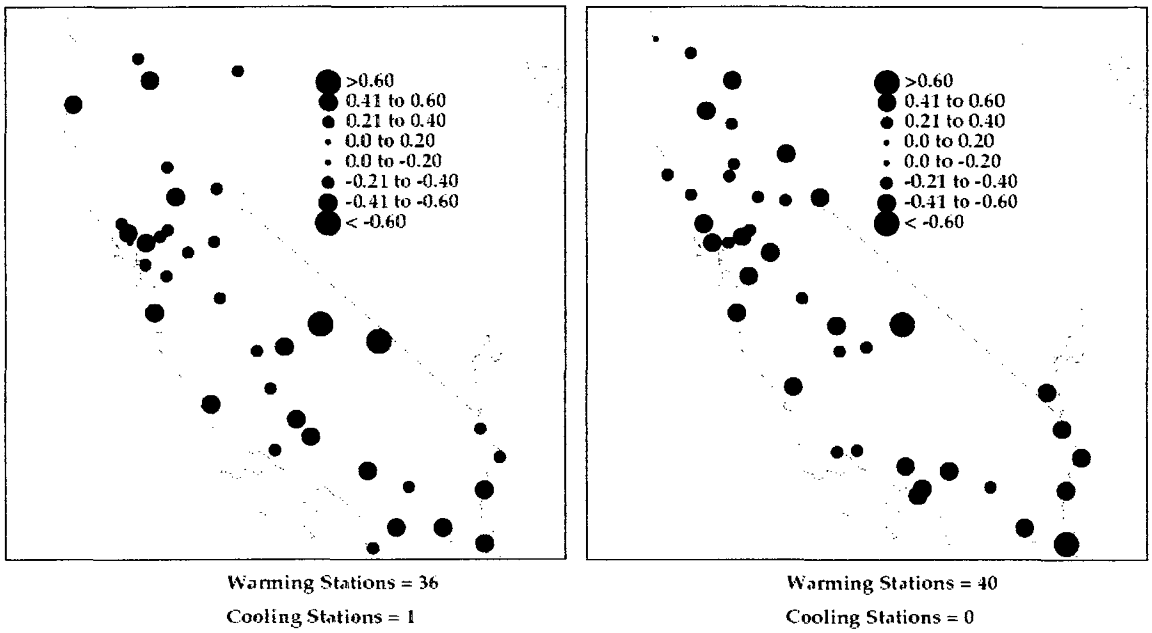


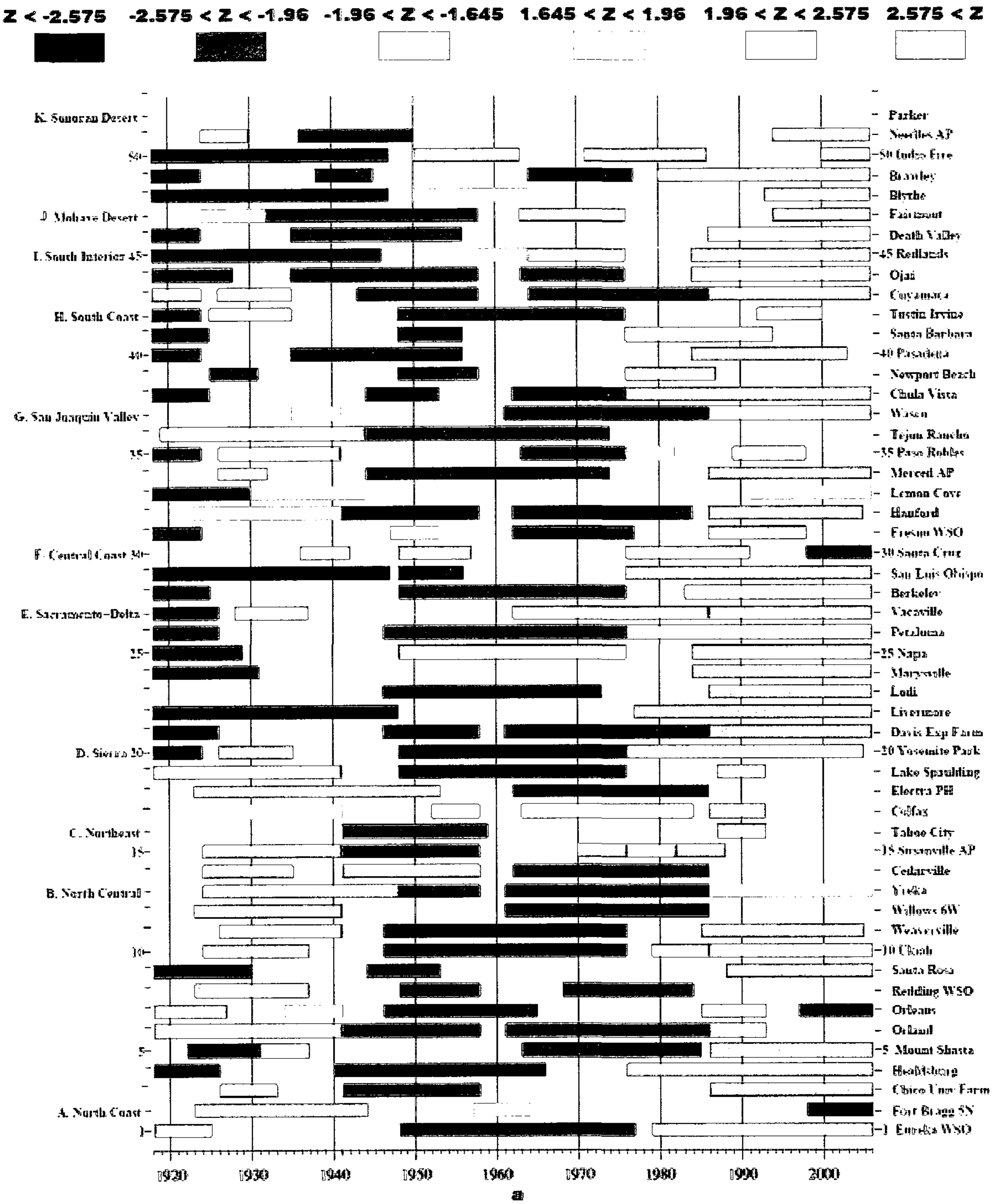
Fig. 9. Map showing statistically significant (95% CL) warming or cooling trends between 1970-2006 for annual Tmax (left) and Tmin (right) temperatures from the USHCN. Red circles denote warming trends and blue circles denote cooling trends, where the average warming or cooling trend is given at the bottom.

d. Significant cooling and warming periods for USHCN stations in California

Each individual USHCN station in California was investigated for significant warming and cooling periods between 1918-2006 using Mann-Whitney U statistics. As shown in Figure 10a and 10b, although annual Tmax and Tmin in general appear to have different warming and cooling patterns, they both show the same warming periods from ~1985-2006. For annual Tmax (Fig. 10a), most stations show significant cooling periods during ~1945-1975 except most stations in the Northeast region and half of all stations in the Sierra region. Interestingly, two significant warming periods can be found during ~1925-1942 by approximately 50% of all stations and during ~1985-2006 by approximately 80% of all stations. In contrast, for annual Tmin (Fig. 10b), it is clearly found by 90% of all stations that there are significant cooling periods during ~1918-1958 and significant warming periods during ~1976-2006 with a transition period during ~1959-1975 in between those two significant periods by 90% of all stations.

In terms of seasonal temperatures, for Tmax (Fig. 11a), like annual Tmax, the cooling period between ~1945-1970 is found in all seasons except in SON where the cooling period appears between ~1975-1985 instead. DJF and MAM show significant warming periods during ~1980-2006 by a majority of all stations, while ~50% of the stations show a warming period between ~1990-2006 in SON. In JJA, however, the warming period appears to be from 2000-2006 by a majority of the stations. For Tmin (Fig. 11b), while JJA and SON appear to have the warming and cooling patterns as shown in annual Tmin, MAM also seems to have similar patterns except for the cooling period which is from ~1940-1970 instead. In DJF, there are no significant patterns between 1918-1980, however the significant warming period is found between ~1980-2006.

In general, all seasonal temperatures for both Tmax and Tmin show a significant warming pattern during ~1980-2006. Similar results are also found in annual trends for both Tmax and Tmin. However, Tmax and Tmin show cooling patterns at different time periods. Those differences are possibly caused by climate forcings and large-scale dynamics. In addition, it seems that the beginning of the significant warming period for both Tmax and Tmin (~1980) appears to match the beginning of the warming period of the Pacific Decadal Oscillation (PDO) which affects sea and surface temperatures along the Pacific coastal regions (LaDochy et al. 2007).



Z < -2.575
-2.575 < Z < -1.96
-1.96 < Z < -1.645
1.645 < Z < 1.96
1.96 < Z < 2.575
2.575 < Z
K. Sonoran Desert
J. Mohave Desert
I. South Interior
H. South Coast
G. San Joaquin Valley
F. Central Coast
E. Sacramento-Delta
D. Sierra
C. Northeast
B. North Central
A. North Coast
Parker
Blythe
Death Valley
Redlands
Ojai
Santa Barbara
Pasadena
Newport Beach
Chula Vista
Paso Robles
Merced AP
Lemon Cove
Hanford
Fresno WSO
Santa Cruz
San Luis Obispo
Berkeley
Vacaville
Petaluma
Napa
Marysville
Lodi
Livermore
Davis Exp Farm
Yosemite Park
Lake Spaulding
Electra PH
Colfax
Tahoe City
Susanville AP
Cedarville
Yreka
Willows 6W
Weaverville
Ukiah
Santa Rosa
Redding WSO
Orleans
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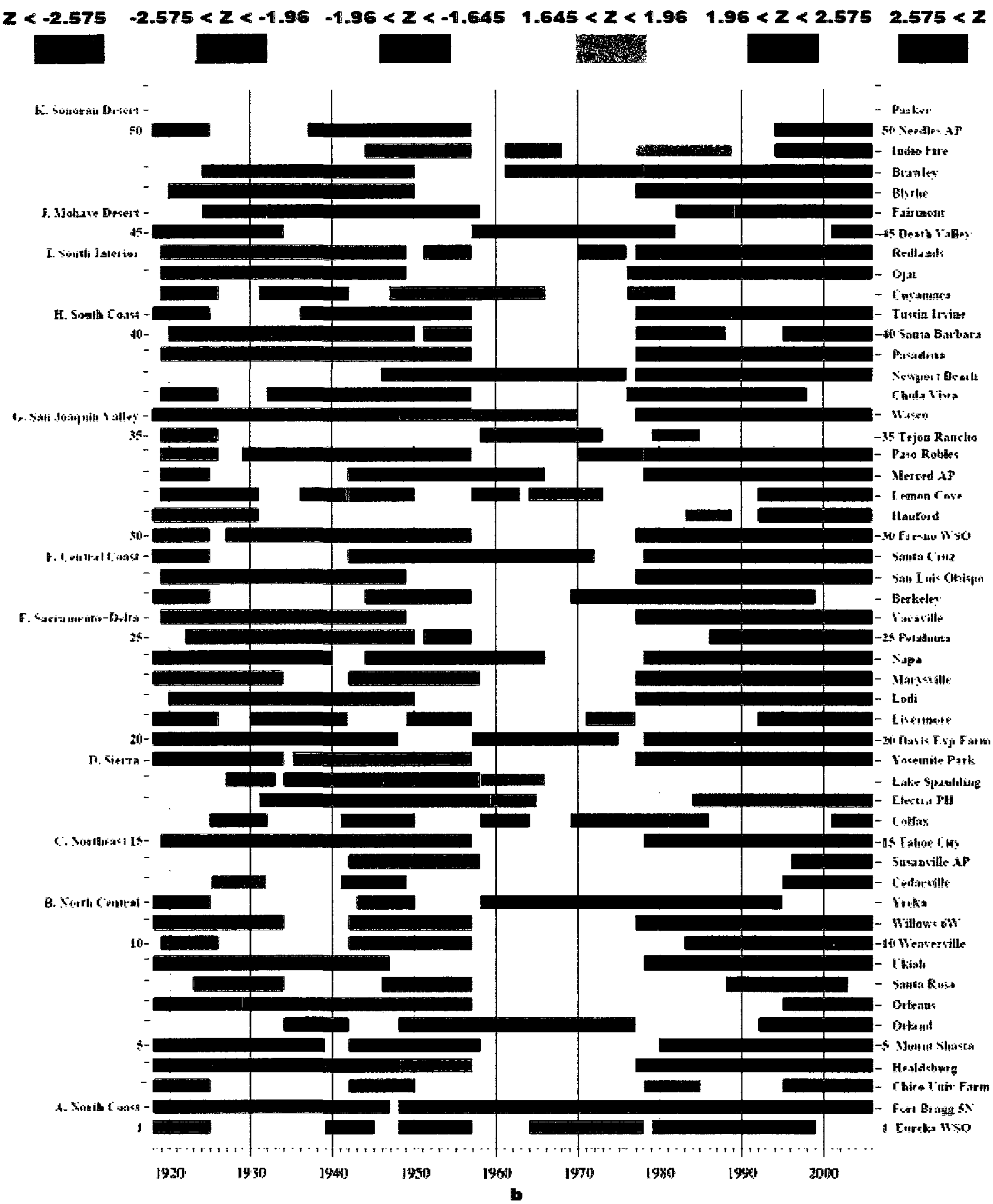
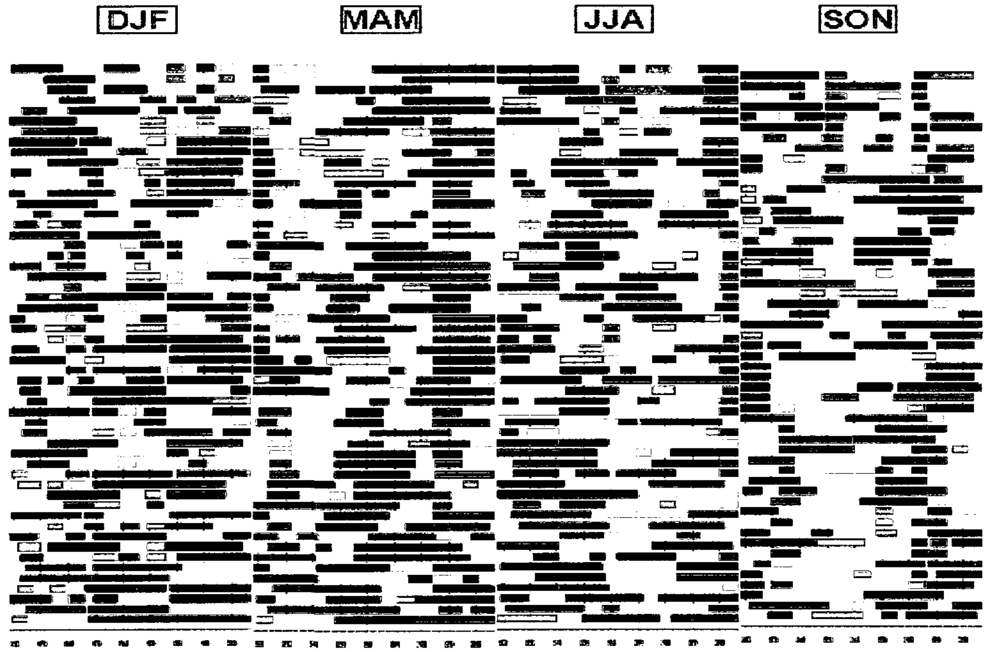
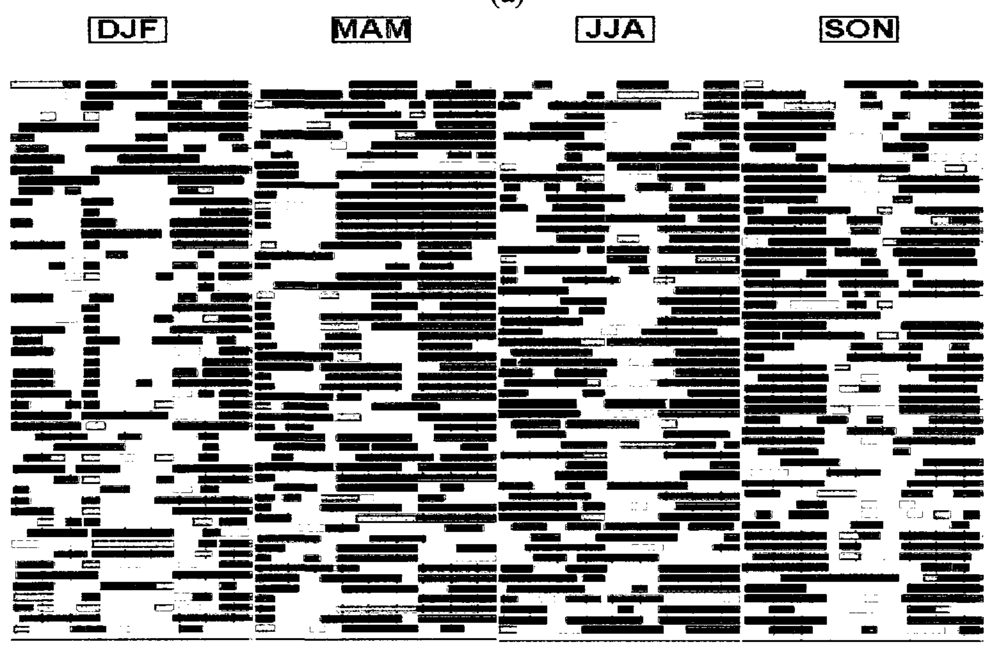


Fig. 10. Z values computed using running Mann-Whitney U statistics for annual temperatures during 1918-2006 for (a) Tmax and (b) Tmin from the USHCN stations. Red colors denote warming temperatures while blue colors denote cooling temperatures, with the shading from darkest to lightest indicating statistical significant at the 99%, 95%, and 90% CL respectively. Ecah of the individual station names is given in the right, while the corresponding regions are indicated on the left.



(a)



(b)

Fig. 11. Z values computed using running Mann-Whitney U statistics for seasonal temperatures during 1918-2006 for (a) Tmax and (b) Tmin from the USHCN stations. Red colors denote warming temperatures while blue colors denote cooling temperatures, with the shading from darkest to lightest indicating statistical significant at the 99%, 95%, and 90% CL respectively. Each of the individual station names is given in the right, while the corresponding regions are indicated on the left.

e. Comparison with California COOP network

Although USHCN data are of a higher quality than data from COOP stations because of their urban heat-adjustments, the USHCN data have less coverage throughout California compared to COOP stations. Given more stations throughout California, on the other hand, COOP data provide more details and information for our analysis. This trend analysis is now repeated using the 272 COOP stations between 1950-2005 and 1970-2005. Overall in California between 1950-2005 (Table 3), we find similar results, not only with annual temperatures but also with the seasonal temperature trends compared to the USHCN results. For the same time period, we find statistically significant warming in Tmin for both annual and seasonal trends with 0.23°C dec^{-1} for the annual trend and ranging from 0.13–0.31°C dec^{-1} for seasonal trends. Annual temperature trends also show statistically significant warming in Tmin for both Northern and Southern California with the larger trend in Northern California compared to that in Southern California. Seasonal temperature trends as well show statistically significant warming in Tmin for both Northern and Southern California for all seasons with the largest trends again in MAM as found in the results from USHCN between 1950-2006. In contrast, there are no statistically significant trends found in annual and seasonal trends statewide in Tmax but MAM is still the largest trend as shown in Tmin.

On a regional scale during 1950-2005 (Table 3), statistically significant warming trends are also found in annual Tmin for almost all regions and for a few regions in annual Tmax. However, more statistically significant trends are found for regional scales in Tmin and Tmax from USHCN results between 1950-2006. For seasonal temperature

Table 3. Annual and seasonal trends (in °C dec^{-1}) for California, northern and southern California, and the 11 climate regions computed between 1950-2005 for Tmax and Tmin from the COOP stations, where the trends that are statistically significant at the 95% CL are indicated with an asterisk (*).

SEASON	MAXIMUM	MINIMUM	SEASON	MAXIMUM	MINIMUM
California (272)			*E. Sacramento-Delta Region (31)*		
Annual	0.06	0.23*	Annual	0.11*	0.30*
DJF	0.05	0.22*	DJF	0.13	0.25*
MAM	0.19	0.31*	MAM	0.21	0.40*
JJA	0.04	0.22*	JJA	0.03	0.33*
SON	-0.07	0.13*	SON	0.05	0.25*
Northern California (156)			*F. Central Coast Region (29)*		
Annual	-0.03	0.24*	Annual	0.12*	0.24*
DJF	0.06	0.20	DJF	0.06	0.19*
MAM	0.19	0.33*	MAM	0.25*	0.32*
JJA	0.02	0.25*	JJA	0.24*	0.27*
SON	-0.04	0.16*	SON	-0.04	0.12*
Southern California (116)			*G. San Joaquin Valley Region (24)*		
Annual	0.07	0.22*	Annual	0.05	0.21*
DJF	0.06	0.25*	DJF	0.10	0.21*
MAM	0.24*	0.33*	MAM	0.18	0.30*
JJA	0.07	0.19*	JJA	-0.07	0.23*
SON	-0.06	0.17*	SON	-0.05	0.17*
A. North Coast Region (9)			*H. South Coast Region (31)*		
Annual	0.150*	0.05	Annual	0.03	0.39*
DJF	0.13	0.04	DJF	0.08	0.38*
MAM	0.25*	0.18*	MAM	0.16	0.44*
JJA	0.20*	0.10*	JJA	0.03	0.30*
SON	-0.01	-0.14*	SON	-0.10	0.32*
B. North Central Region (39)			*I. South Interior Region (20)*		
Annual	0.06	0.10*	Annual	0.24*	0.29*
DJF	0.12	0.14	DJF	0.05	0.19*
MAM	0.13	0.22*	MAM	0.36*	0.36*
JJA	-0.05	0.10	JJA	0.23*	0.28*
SON	0.00	0.03	SON	-0.01	0.15*
C. Northeast Region (24)			*J. Mohave Desert Region (17)*		
Annual	0.02	0.19*	Annual	0.02	0.14*
DJF	0.01	0.18	DJF	-0.03	0.24*
MAM	0.10	0.28*	MAM	0.18	0.26*
JJA	0.04	0.24*	JJA	0.08	-0.27
SON	-0.09	0.07	SON	-0.05	0.14
D. Sierra Region (33)			*K. Sonoran Desert Region (15)*		
Annual	-0.06	0.28*	Annual	0.06	0.19*
DJF	-0.06	0.26*	DJF	0.04	0.25*
MAM	0.07	0.35*	MAM	0.21	0.31*
JJA	-0.09	0.29*	JJA	0.14	0.11
SON	-0.20	0.18*	SON	-0.09	0.11

trends, most of trends in Tmin again show statistically significant warming and MAM trends in both Tmax and Tmin are the greatest compared to other seasonal trends as shown in results from USHCN data between 1950-2006. On the other hand, MAM trends are not the largest trends at the regional scale for both Tmax and Tmin from USHCN results between 1918-2006.

Statistically significant trends for annual Tmax and Tmin between 1950-2005 are shown in Fig. 12 for individual COOP stations throughout California. While 81% of all significant trends in Tmax are warming, 19% of them show cooling and most of the cooling trends are in the Sierra area. Like Tmax, ~95% of all significant trends in Tmin show warming and only ~5% show cooling. In addition, more statistically significant trends are found in Tmin compared to Tmax and ~90% of them are in central and southern California. For seasonal Tmax and Tmin (Table 3), again Tmin show more significant trends compared to Tmax with MAM in Tmin the largest among all seasons. However, cooling trends are found more in Tmax, especially in SON with a larger number of cooling trends compared to warming trends and most of SON cooling trends are in the Sierras, the Central Valley and along the Pacific coast.

For annual Tmax and Tmin between 1970-2005 (Fig. 13), ~80% of all statistically significant trends in Tmax show warming and these are distributed throughout the state. Of the ~20% that show cooling, most of these trends are located along the Pacific coast.

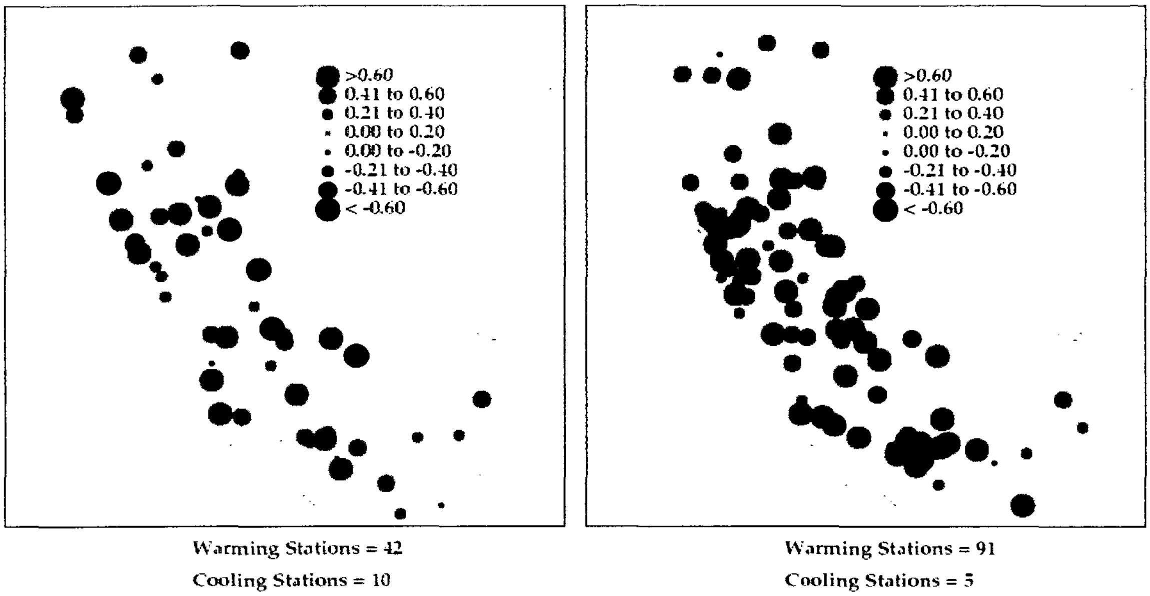


Fig. 12. Map showing statistically significant (95% CL) warming or cooling trends between 1950-2005 for annual Tmax (left) and Tmin (right) temperatures from the COOP. Red circles denote warming trends and blue circles denote cooling trends, where the average warming or cooling trend is given at the bottom.

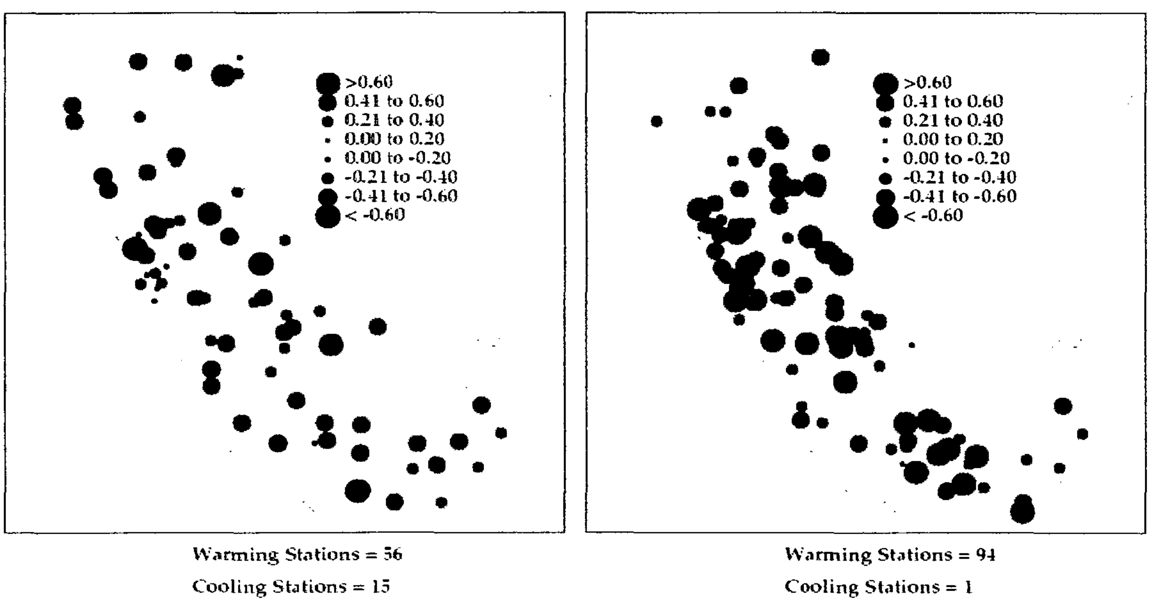


Fig. 13. Map showing statistically significant (95% CL) warming or cooling trends between 1970-2005 for annual Tmax (left) and Tmin (right) temperatures from the COOP. Red circles denote warming trends and blue circles denote cooling trends, where the average warming or cooling trend is given at the bottom.

A larger number of warming trends are found in Tmin similar to the results in Tmin between 1950-2005. For seasonal Tmax and Tmin (Table 4), interestingly, the number of statistically significant cooling trends in Tmax are about 2 times greater than warming trends during DJF (3 warming; 6 cooling) and about 1.5 times greater than warming trends during JJA (15 warming; 23 cooling) (Fig. 14). The cooling DJF Tmax trends occurred widely throughout the state, while most of the cooling JJA Tmax trends are located along the Pacific coast. It is likely that the effect of natural variability in the winter could be a reason causing the cooling trends in DJF Tmax. For cooling JJA Tmax trends, Lebassi et al. (2009) found cooling trends in the San Francisco Bay area and the Los Angeles basin in JJA Tmax. They suggested these trends were caused by an enhanced sea-breeze circulation due to additional warming in the interior.

Although USHCN data provide more accurate and quality for trends, COOP data clearly give us an advantage to explore and identify spatial and temporal temperature variations on a smaller scale because of the larger number of stations throughout California.

Table 4. Annual and seasonal trends (in °C dec^{-1}) for California, northern and southern California, and the 11 climate regions computed between 1970-2005 for Tmax and Tmin from the COOP stations, where the trends that are statistically significant at the 95% CL are indicated with an asterisk (*).

SEASON	MAXIMUM	MINIMUM	SEASON	MAXIMUM	MINIMUM
California (272)			*E. Sacramento-Delta Region (31)*		
Annual	0.14	0.30*	Annual	0.15	0.40*
DJF	-0.02	0.27	DJF	0.09	0.40
MAM	0.30	0.43*	MAM	0.22	0.51*
JJA	0.01	0.20*	JJA	-0.02	0.36*
SON	0.20	0.23	SON	0.26	0.36*
Northern California (156)			*F. Central Coast Region (29)*		
Annual	0.14	0.33*	Annual	0.14	0.27*
DJF	-0.04	0.29	DJF	0.02	0.21
MAM	0.23	0.41*	MAM	0.23	0.38*
JJA	0.03	0.25*	JJA	-0.01	0.24*
SON	0.23	0.24	SON	0.07	0.13
Southern California (116)			*G. San Joaquin Valley Region (24)*		
Annual	0.16	0.25*	Annual	0.17	0.35*
DJF	0.02	0.25	DJF	0.13	0.34
MAM	0.41	0.44*	MAM	0.32	0.45*
JJA	-0.01	0.15	JJA	0.00	0.29*
SON	0.18	0.23	SON	0.20	0.26
A. North Coast Region (9)			*H. South Coast Region (31)*		
Annual	0.12	0.11	Annual	-0.10	0.33*
DJF	0.06	0.14	DJF	0.00	0.31*
MAM	0.22	0.30	MAM	0.16	0.53*
JJA	0.24*	0.11	JJA	-0.21	0.20
SON	0.06	-0.11	SON	-0.12	0.30*
B. North Central Region (39)			*I. South Interior Region (20)*		
Annual	0.14	0.22*	Annual	0.28*	0.32*
DJF	-0.08	0.24	DJF	-0.01	0.20
MAM	0.24	0.31*	MAM	0.51	0.43*
JJA	0.01	0.08	JJA	0.10	0.20
SON	0.29	0.17	SON	0.35	0.24
C. Northeast Region (24)			*J. Mohave Desert Region (17)*		
Annual	0.16	0.35*	Annual	0.30*	0.15
DJF	-0.05	0.47	DJF	-0.04	0.19
MAM	0.30	0.52*	MAM	0.63	0.42
JJA	0.06	0.24*	JJA	0.17	0.11
SON	0.22	0.19	SON	0.28	0.25
D. Sierra Region (33)			*K. Sonoran Desert Region (15)*		
Annual	0.09	0.35*	Annual	0.27*	0.34*
DJF	-0.18	0.24	DJF	0.09	0.31
MAM	0.22	0.43*	MAM	0.54*	0.59*
JJA	-0.02	0.19	JJA	0.11	0.17
SON	0.19	0.29	SON	0.35	0.40*

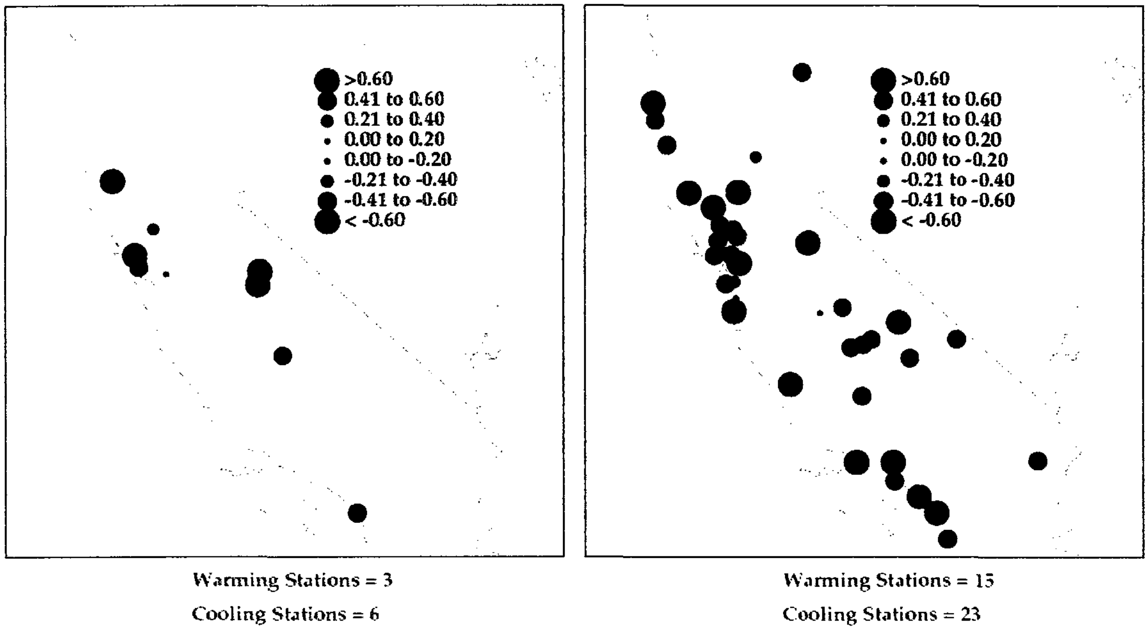


Fig. 14. Map showing statistically significant (95% CL) warming or cooling trends between 1970-2005 for DJFl Tmax (left) and JJA Tmax (right) temperatures from the COOP. Red circles denote warming trends and blue circles denote cooling trends, where the average warming or cooling trend is given at the bottom.

4. Summary and discussion

Significant changes in spatial and temporal variation of California temperature have been found over the last 89 years (1918-2006). Statewide, both Tmax and Tmin between 1918-2006 have been increasing with a greater magnitude in Tmin compared to Tmax. Although annual Tmin trends seem to be consistent throughout the state, annual Tmax trends are warming faster in Southern California than in Northern California. Both annual Tmax and Tmin were also found to be increasing in magnitude as time progresses. Seasonal Tmin again appear to be uniform throughout Southern California for all seasons. Furthermore, seasonal trends for both Tmax and Tmin during 1950-2006 and

1970-2006 show that MAM trends are the largest trends among all seasons with Southern California having larger trends than Northern California. In addition, the number of stations with significant trends is greater in Tmin compared to Tmax and the larger variability contributing to Tmax is likely to be one of the reasons. There is a possibility that climate forcings also have an effect on that variation.

For California climate regions, results between 1918-2006 in general show statistically significant warming in annual Tmin for all regions. However in annual Tmax, only half of all regions show statistically significant increases. In seasonal temperatures, we still find that most of seasons show statistically significant warming in Tmin compared to Tmax increases. Between 1950-2006 and 1970-2006, similar results statewide show the largest trends in MAM. However, increasing in magnitude is also found from north to south for the coastal regions. In addition, results from COOP data between 1950-2005 and 1970-2005 also show an agreement with the results above. However, between 1970-2005, interesting seasonal variations are found in DJF and JJA in Tmax with the former showing the number of cooling stations are as twice as warming stations (3:6) and the latter showing a slight differences in the ratio of the number of warming versus cooling stations (15:23).

Based on the analysis of several significant periods of time, although both annual Tmax and Tmin show agreement in a significant warming period from approximately 1985-2006, Tmax and Tmin have different annual and seasonal variation patterns. While Tmax show significant cooling periods during ~1950-1970 and continue with significant warming periods during ~1985-2006, Tmin show a strong cooling period during ~1918-

1957 and a warming period during ~1980-2006 with a transition period in between. Like wise, seasonal Tmin also show the same pattern as annual Tmin, for the months of JJA and SON in particular. In contrast, only MAM shows the same pattern between seasonal and annual Tmax. Annual and seasonal variations in Tmax and Tmin appear to have different effects probably as a result of climate forcings. Further investigation is required and climate models could be a useful tool to explore those effects from climate forcings.

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