Teleconnection Influences on Extreme Daily Temperatures in California, 1950–2005

Gregory S. Bohr
California Polytechnic State University, San Luis Obispo

Abstract

Frequencies of extreme daily temperature events are compared between high and low phases of two teleconnection patterns that affect California—the Pacific/North America (PNA) pattern and the Southern Oscillation Index (SOI, representing ENSO). The positive phase of the PNA is associated with an increased number of hot extremes, especially in fall and winter, along with a decrease in winter and spring cold extremes. The positive phase of the SOI corresponds to an increased frequency of extreme events in both maximum and minimum temperatures, with the most effect on minimum temperatures in spring. Variations in these relationships with changes in the phase of the Pacific Decadal Oscillation (PDO) are also examined—the PNA pattern produces fewer cold extremes when the PDO is positive, and the difference is larger for the negative PNA. The positive SOI produces more spring hot events and fewer cold events when the PDO is also positive.

Introduction

THE ASPECTS OF WEATHER and climate that tend to be most noticeable to people, and which tend to have the most dramatic impacts on humans and the environment, are extreme events. Extreme temperatures in particular, both hot and cold, can have serious implications for health and mortality, agriculture, and energy usage (Curreiro et al. 2002; Colombo, Etkin, and Karney 1999; Downton and Miller 1993; Easterling, Meehl et al. 2000; Parmesan, Root, and Willig 2000; Wigley 1985; White et al. 2006). As global climates change and fluctuate, the frequency of extreme temperature events is likely to change. However, the probability of extreme values in a variable is not likely to change linearly with the mean of that variable; rather, extreme-event frequencies are a complex outcome of both the position (mean) and scale (variability) of a variable's probability distribution (Katz and Brown 1992; Mearns, Katz, and Schneider 1984; Wigley 1999; Wagner 1999; Liu et al. 2006). Furthermore, local and regional climates tend to vary in ways that are often different—and sometimes opposed—to global and hemispheric scale variations (Easterling, Karl et al. 2000; McGuffie et al. 1999; Stott et al. 2000). In order to understand the future likelihood of potentially disruptive extreme events, therefore, it is important to directly examine the mechanisms influencing extreme daily temperatures at the regional scale.

One mechanism that has been found to significantly influence regional climates, and which is reproducible in climate models, is the occurrence of recurrent, persistent, hemispheric-scale circulation patterns in the atmosphere known as teleconnections. These patterns are produced and influenced by a variety of factors, including sea surface temperatures (SSTs), snow cover, topography, and natural internal variability. The persistence of these patterns is generally on the order of days to months, but it is not uncommon for a particular phase of a teleconnection pattern to dominate for consecutive years. As a result, surface conditions in one part of the hemisphere are linked ("teleconnected") to conditions at another, often distant, location through the occurrence of particular mid-tropospheric flow patterns (Barnston and Livezey 1987; Cheng and Wallace 1993; Vega, Henderson, and Rohli 1995; Higgins, Leetmaa, and Kousky 2002; Mestas-Nunez and Miller 2006; Mori and Watanabe 2008). Many of these well-defined upper-level flow patterns have significant impacts on the surface climate of North America (as well as other regions), affecting such variables as the timing and intensity of precipitation (e.g., Henderson and Robinson 1994; Serreze et al. 1998; Jin et al. 2006), the magnitude, persistence, and variability of maximum and minimum temperatures (e.g., Wolter, Dole, and Smith 1999; Smith and Sardeshmukh 2000; Higgins, Leetmaa, and Kousky 2002; Bodri and Cermak 2003; Budikova 2005), or weather type frequencies (e.g., Sheridan 2003; Coleman and Rogers 2007). For the North American sector in particular, the Pacific/North American (PNA) pattern and the El Niño/Southern Oscillation (ENSO) influence temperature and precipitation at the monthly to annual scales, and the Pacific Decadal Oscillation (PDO) is correlated with climate at the decadal scale.

ENSO events have numerous linkages to extra-tropical surface weather conditions. For North America, these linkages result from alterations to tropospheric flow patterns initiated from the tropical Pacific, resulting in changes to storm tracks, temperature, and moisture advection into and across the U.S., particularly in winter and spring. During warm ENSO events (El Niño), the dominant circulation change is a strengthening of the southern branch of the

Pacific jet stream across the southern tier of the U.S., along with a reduction in the amount of cold air advecting southward from Canada due to a more zonal flow of the northern branch of the polar front jet. Cold phase (La Niña) events are characterized by increased meridionality in the flow across North America with frequent ridging over the eastern Pacific (Higgins, Leetmaa, and Kousky 2002; Yarnal 1985; Yu and Zwiers 2007). Cold phase events are associated with increases in the frequency of extreme wintertime cold days for much of the western U.S., while warm phase events are associated with decreases in the frequency of cold extremes (Higgins, Leetmaa, and Kousky 2002; Smith and Sardeshmukh 2000).

In this study, the strength and phase of the ENSO is represented by the Southern Oscillation Index (SOI), in which negative values indicate a warm-phase (El Niño) event. The monthly SOI is calculated by subtracting the standardized monthly sea level pressure anomaly at Darwin from the corresponding value for Tahiti. The resulting time series of monthly SOI values is itself standardized (CPC, 2008). Neutral conditions are represented by SOI values near zero, while values less than -1 or greater than 1 typically indicate warm and cold phase events, respectively. Values more extreme than +/-2 are uncommon and indicate particularly pronounced ENSO events. Since 1950, a handful of monthly values have exceeded -3, although fewer than 10% of the total values have been more extreme than +/- 2.

The PNA pattern is one of upper-level circulation characterized by, in its positive phase, ridging over the western portion of North America (approximately centered on the Rocky Mountains) and troughing over eastern North America. The negative phase of the teleconnection pattern is characterized by zonal flow over the continent or, in extreme cases, a reverse-PNA with troughing in the West and ridging over the eastern U.S. The mechanisms that lead to the establishment of a PNA flow pattern are complex—SSTs and convective activity in the tropical Pacific as well as surface temperatures over East Asia and the strength/position of the East Asian jet all play a role (Leathers and Palecki 1992; Mori and Watanabe 2008). In addition, the PNA pattern is correlated with ENSO events, with positive (negative) PNA index values common during warm (cold) ENSO events (Yarnal and Diaz 1986; Leathers and Palecki 1992; Vega, Rohli, and Henderson 1998). The PNA is not a major mode of Northern Hemisphere circulation in June and July, but it does show positive correlations with western U.S. temperatures in the other months of the year (e.g., Leathers, Yarnal, and Palecki 1991; Cayan 1996), as well as significant effects on synoptic weather type frequencies (Sheridan 2003).

The PNA index used here is calculated by combining 500 mb height anomalies (Z*) at four locations across North America as follows: *PNA = Z*(15°N-25°N,180-140°W)-Z*(40°N-50°N,180-140°W)+Z*(45°N-60°N,125°W-105°W)-Z*(25°N-35°N,90°W-70°W)* (CPC 2008).

Monthly PNA index values more extreme than +/- 1 indicate well-developed occurrences of the pattern. During the 1950–2005 period, fewer than 5% of the monthly PNA values exceeded +/- 2.

The Pacific Decadal Oscillation is a pattern in North Pacific SST variability that is somewhat similar to the El Niño pattern, although at a much longer time scale—PDO events persist for decades, as opposed to the months-to-years life span of an ENSO event. The PDO index is defined as the leading principal component of monthly sea surface temperature variability in the North Pacific (JISAO 2000), and index values more extreme than +/- 1 typically indicate positive or negative phases of the pattern (monthly values more extreme than +/- 2 occurred during fewer than 10% of the months in this study period). The basic pattern of a positive (warm phase) PDO event is warm SST anomalies along the west coast of the U.S., and cold anomalies in the central North Pacific. The negative (cold) phase of the PDO shows the opposite pattern. Over the past century, several long-term switches in the PDO time series are evident: the positive (warm) phase was dominant from 1925 through 1947, negative (cold) phase conditions then dominated until 1977, and positive values were common through the end of the century (Mantua et al. 1997; JISAO 2000). Negative values appeared to be regaining dominance in the late 1990s, but recent observations do not clearly indicate that another reversal has occurred. The positive phase of the PDO correlates with warmer wintertime temperatures on the west coast, including California, as well as reduced winter precipitation in the interior west (Mantua et al. 1997; LaDochy, Medina, and Patzert 2007).

While the PDO has significant direct effects on North American weather, it may have more critical impacts through a modulating effect on both ENSO events and the PNA pattern. In general, warm-phase ENSO events have stronger North American impacts during the positive PDO phase, when the ENSO and PDO SST anomalies are synchronized, with weaker ENSO signals detected across North

America during the negative PDO. Conversely, La Niña conditions synergize with negative PDO events and thus have a stronger signal in North American climate; effects of La Niña conditions are dampened by the warm phase of the PDO (Gershunov and Barnett 1998; Gershunov, Barnett, and Cayan 1999; Yu and Zwiers 2007). Additionally, the positive phase of the PDO encourages a PNA-like flow pattern over the North American continent, with higher-than-normal upper-level geopotential heights over the western part of the continent, and lower-than-normal heights over the northern Pacific (Mantua et al. 1997; Yu and Zwiers 2007).

While relationships between teleconnection patterns and mean temperatures have been intensively studied, linkages between hemispheric-scale circulation and extreme events have been directly addressed less frequently. The objective of this study is to explore correlations between seasonal frequencies of anomalous hot and cold days in California and the ENSO and PNA indices, as well as to explore whether the phase of the PDO modifies these correlations. For the two shorter-term indices, the differences in the numbers of extreme events occurring during high versus low phases of the index are examined. Next, the impact of the PDO phase is addressed by computing the differences in extreme-event frequencies for a given phase of the PNA or ENSO, but comparing seasons classified by either the high or low PDO phase.

Data and Methods

The temperature data used in this study are the daily maximum and minimum temperatures observed at National Weather Service Cooperative Observer Program (COOP) sites from 1950 to 2005, obtained online from the National Climatic Data Center (NCDC). To qualify for inclusion, sites were required to have observations for both maximum (TMAX) and minimum (TMIN) temperature on at least 95% of the total days in the 56-year study period. Additionally, any individual month missing more than 10% of its daily observations for either variable was marked as missing, and sites were rejected if more than 10% (i.e., six or more) of any given calendar month was missing. A total of 90 COOP sites were sufficiently complete to be used in the study (Figure 1).

At each site, extreme events in TMAX and TMIN were defined as exceedances of the 90th and 10th percentiles (respectively) of all non-missing values for each individual day of the year. The 90th (10th) percentile for a given day will be exceeded by the five warmest (cool-

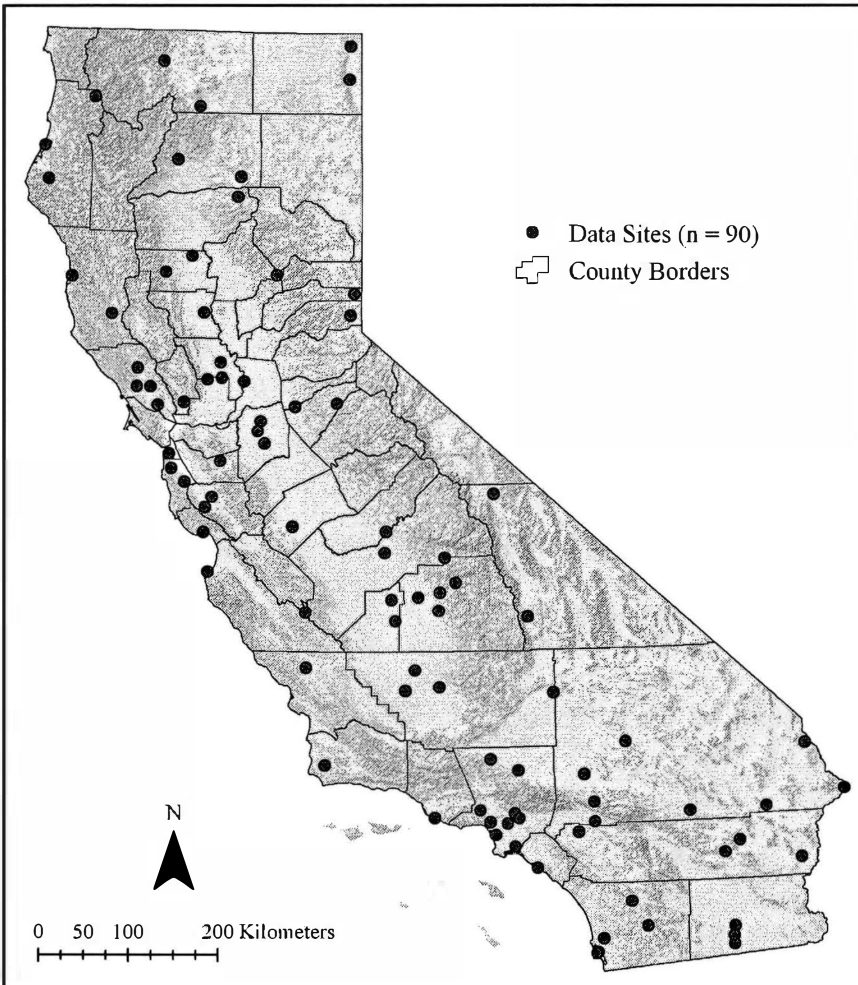

Figure 1.—Locations of 90 NWS COOP weather stations used in study.

est) observations for that date over the period of record. This method defines extreme events on a day-by-day basis and identifies unusually warm and unusually cold events throughout the year. Once each day was classified as extreme or not, the total number of each type of exceedance was summed by site for four seasons—winter (DJF), spring (MAM), summer (JJA), and fall (SON)—for years in which all three months were non-missing. The result of these calculations was 56-year time series of the seasonal frequencies of hot TMAX extremes and cold TMIN extremes at 90 sites across California.

Standardized monthly values for the PNA and SOI for 1950–2005 were obtained online from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/), and for the PDO from the Joint Institute for the Study of the Atmosphere and Ocean (http://jisao.washington.edu/pdo/). Seasonal values by year for each index were calculated as the average values for the same three-month periods used above. Positive and negative phases of the PNA and SOI were defined as seasonal values above 0.5 or below -0.5. Values between -0.5 and 0.5 were considered neutral. Although these cut-off values appear moderate compared to the range of monthly values observed in these teleconnection indices, they were chosen because they approximate the tercile values of the seasonal indices calculated here. The phases of the PDO were defined more broadly than the others: the positive and negative phases were defined as the top and bottom thirds of all 56 values for a given season, plus any additional values more extreme than +/- 0.5. Each season over the 56-year period was classified as high (positive), neutral, or low (negative) for each index. The three seasonal teleconnection indices are highly correlated (Table 1), with particularly strong relationships between the PDO and each of the others. This correlation created some difficulty in producing sufficiently large sample sizes of the various PNA/PDO and SOI/PDO combinations; the expanded definitions of the PDO phase was a response to this problem.

Table 1. Pearson's r correlations between the seasonal teleconnection indices, with correlations significant at the 0.05 level shown in bold.

	PNA/PDO	PNA/SOI	SOI/PDO
Spring	**0.52**	**-0.30**	**-0.54**
Summer	**0.32**	0.20	**-0.45**
Fall	0.26	-0.12	**-0.51**
Winter	**0.73**	**-0.36**	**-0.45**

To examine the relationships between the teleconnection patterns and extreme temperature events, the mean frequency of each type of extreme event was calculated for seasons classified as positive and for seasons classified as negative for each index. The difference between these values at each site (by season and index) was tested for significance using the non-parametric Wilcoxon rank-sum test in SAS software. Similar analyses were performed to test the effects of the PDO phase: the difference in the mean frequency of extremes during a single phase of the PNA or ENSO was compared between positive and negative phases of the PDO. For example, the mean number of extremes during the positive PNA/positive PDO combination was compared to the positive PNA/negative PDO condition. Significant differences in these values indicate that the specified phase of the shorter-scale pattern (PNA or ENSO) is associated with different frequencies of extreme events during different PDO phases.

Results and Discussion

Overall, the PNA pattern shows more widespread correlations with the frequency of both TMAX and TMIN than the SOI (Table 1). Throughout the year, the positive phase of the PNA is related to an increased frequency of unusually hot TMAX values, and a decreased number of cold TMIN events. Not surprisingly, this pattern shows little impact in summer, when it is not one of the primary modes of northern hemisphere circulation. The SOI, in contrast, is related to an increased frequency of both warm and cold extremes during the positive phase of the index (La Niña events), and a reduced frequency during negative phase (El Niño) events. Both indices appear to correlate slightly more strongly with minimum temperature events, based on the larger number of significant differences for TMIN; however, there are clear seasonal differences in the strength and direction of the teleconnection influences.

Table 2. Number of sites with significant ($\alpha = 0.05$) differences between the frequency of extreme daily temperatures between the high and low phases of the PNA and SOI. All comparisons have a possible total of 90 sites.

	PNA		SOI	
	TMAX	TMIN	TMAX	TMIN
Spring	11	41	1	26
Summer	2	2	15	2
Fall	19	10	4	14
Winter	46	75	12	4

The PNA has its most widespread impact on maximum temperatures during the fall and winter (SON, DJF). In both seasons, all statistically significant differences are increases in unusually warm events during the positive phase—these significant trends range from 5 to 10 additional warm events during positive PNA seasons, with an average increase of 7 days. This impact is unsurprising, as the positive PNA is characterized by ridging over the western U.S. and thus should be indicative of reduced northerly flow and warmer, clearer, anticyclonic conditions.

For fall, the sites with significant differences show a tendency to cluster in the half of the state north of the Bay Area. In the southernmost 10 counties, only four sites have significant fall differences between the two phases, and none of these sites are in the more populated coastal areas. This north-south division may be at least partially explainable by the generally earlier onset of winter weather in the north—during fall, winter conditions are delayed in the north by the positive PNA, but the difference is less noticeable in the south due to the generally later arrival of cold season conditions.

Half of the sites have significant differences in TMAX extreme frequency in winter between the high and low PNA phases. As in fall, these differences are clustered in the north, but there is also a strong tendency for coastal sites throughout the state to have more warm exceedances during positive PNA seasons (Figure 2). This effect may be partially explained by the negative correlation between the PNA and the SOI. The negative SOI (El Niño) is characterized by warmer SSTs offshore, which may contribute to warmer coastal conditions during positive PNA seasons.

The positive PNA is correlated with decreased numbers of extreme cold events across the state in spring and especially in winter, which is likely due to the enhanced ridging over the region during this phase, which blocks northerly flow and steers frontal systems away from the state. In spring, significant differences range from 5 to 11 fewer extreme cold events, with an average of 8 fewer days during this phase. For winter, the differences tend to be higher, with a range of 5 to approximately 14 fewer days, and an average of 9. A decrease in winter time extreme cold events during the positive PNA may be considered a beneficial impact, as these events have significant consequences for both human comfort and agriculture. Overall, the decrease in extreme cold events for the positive PNA is greater than the increase in extreme hot events, indicating the

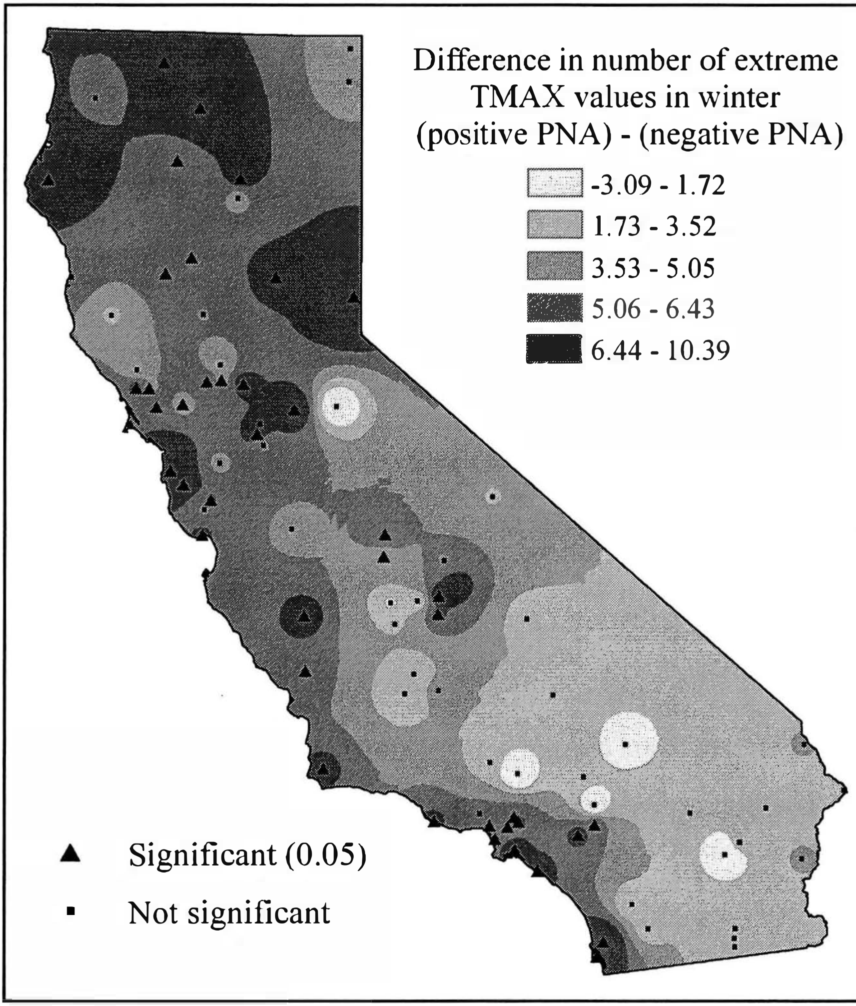

Figure 2.—Difference in the number of winter extreme TMAX events between high and low phases of the PNA (PNA+ minus PNA-). In this and all subsequent figures, an inverse distance weighted interpolation based on all 90 difference values was used.

importance of directly examining variations in the extreme tails of the temperature distribution.

Spatial patterns in the difference between TMIN extreme frequencies for the PNA are somewhat similar to the patterns for the TMAX events. In winter, the 75 sites with significant differences are widespread across the state, with no clear tendency for the larger differences to cluster in any area. In spring, however, the significant values tend to be found along the coast and in the northern half of the state (Figure 3). The strongest decreases in unusually cold spring events for the positive PNA are seen in the northwestern region, perhaps indicative of an earlier onset of warm-season patterns during this phase of the teleconnection.

The SOI shows fewer significant impacts on temperature extremes compared to the PNA, with the largest effect on TMIN in spring (Figure 4). During this season, 26 predominately coastal sites in central and southern California experience significant increases, ranging

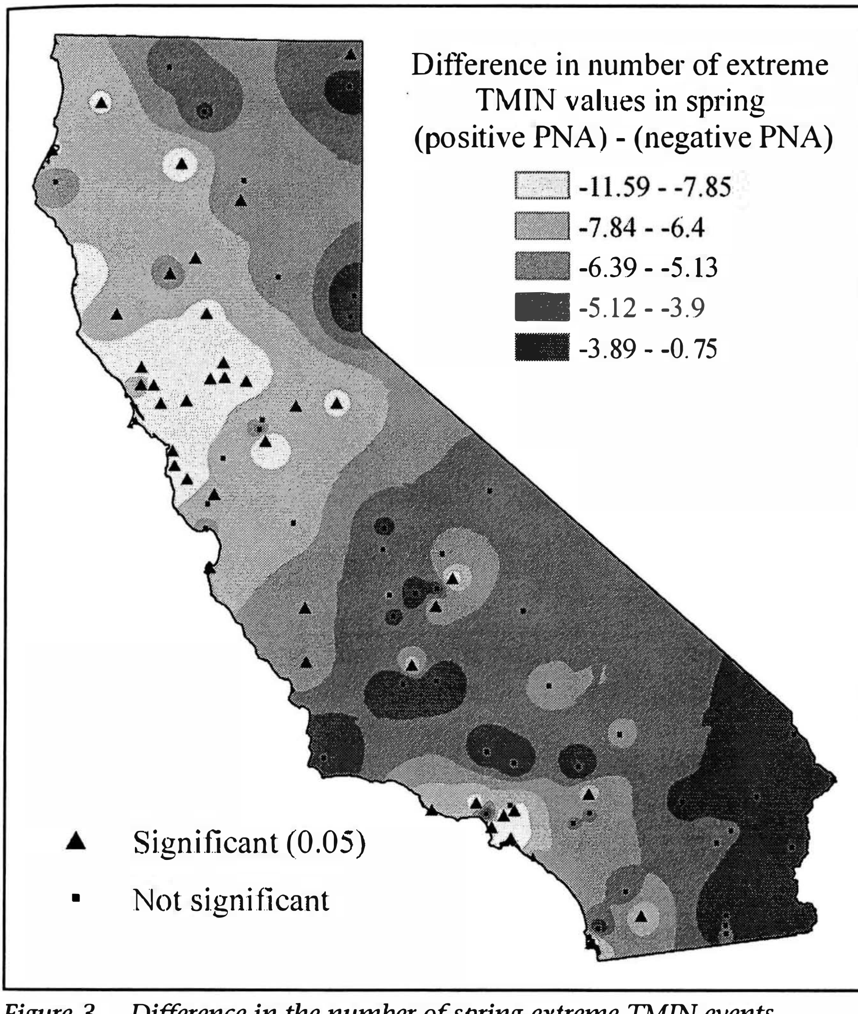

Figure 3.—Difference in the number of spring extreme TMIN events between high and low phases of the PNA (PNA+ minus PNA-).

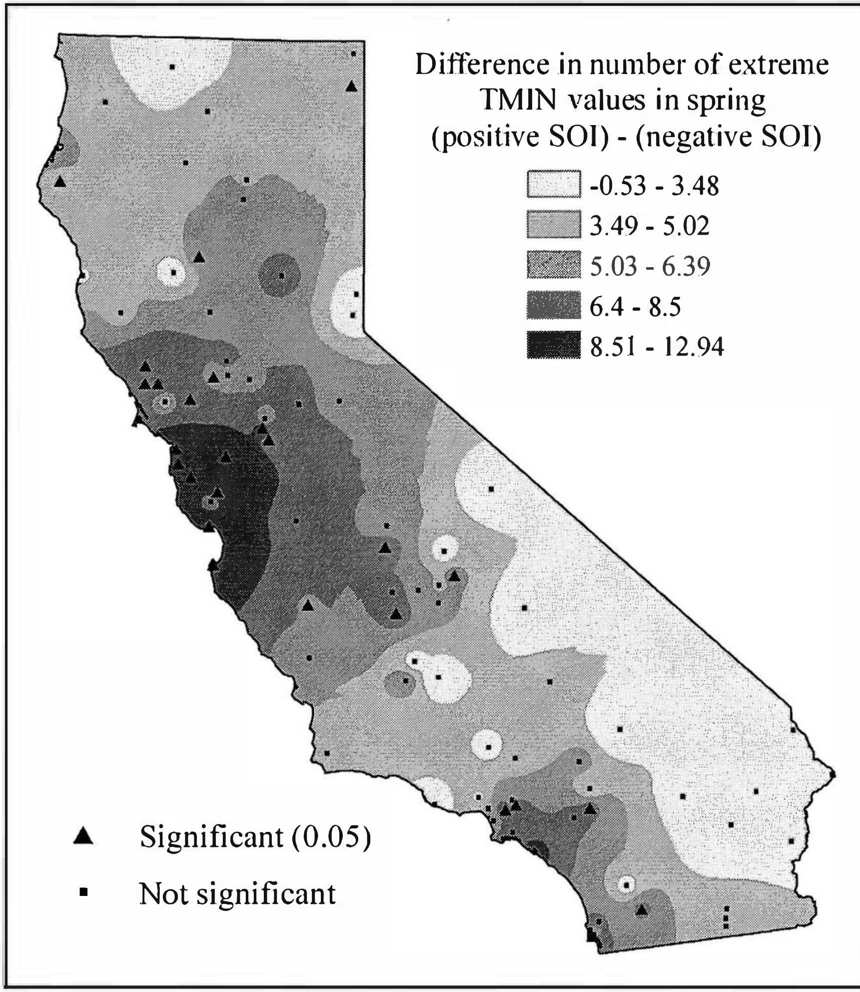

Figure 4.—Difference in the number of spring extreme TMIN events between high and low phases of the SOI (SOI+ minus SOI-).

from 5 to 13 with an average of 9, in the number of unusually cold days during the positive phase of the SOI (La Niña). This pattern is probably explainable by the increased northerly flow along the California coast during the cold phase, and possibly by an increase in radiative cooling due to the associated drier, clearer conditions. The converse of this is a decrease in the number of cold TMIN extremes during the El Niño pattern, likely due to the increased flow of moist subtropical air into the southern coast during the warm phase, as well as the warmer water offshore.

Summertime TMAX extremes are particularly noticeable to humans, and the SOI is positively related with increased frequencies of these events at 15 of the study sites. These sites are strongly clustered in the central part of the state (Figure 5) and show average differences of approximately 6 more hot JJA extremes during La Niña-type SOI patterns than during El Niño-type conditions. A possible reason for this is that La Niña events tend to lead to drier conditions in California, and the reduced moisture may allow increased sensible heating of the lower atmosphere in the interior regions.

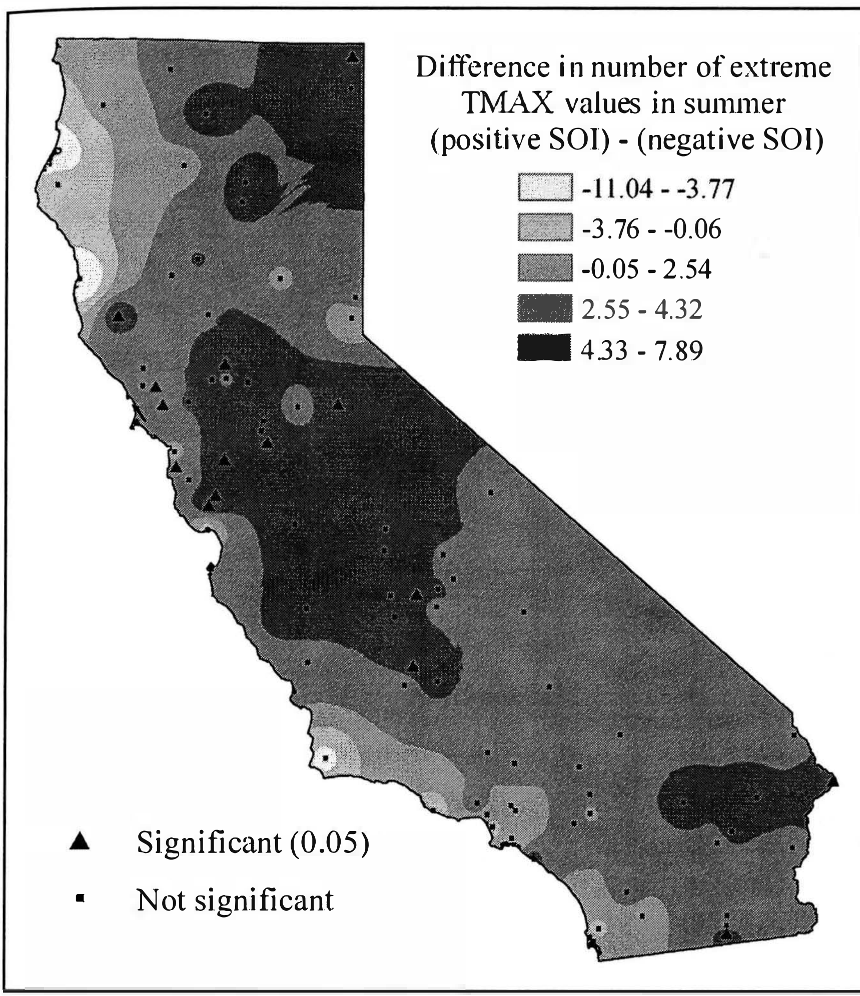

Figure 5.—Difference in the number of summer extreme TMAX events between high and low phases of the SOI (SOI+ minus SOI-).

As discussed above, the PDO is related in its own right to temperature patterns in North America and has also been found to encourage and enhance particular phases of the PNA and ENSO. Accordingly, the PDO can be expected to modify the relationships between these teleconnections and extreme events described here. This impact is examined by comparing the frequency of extreme temperature events between combinations of single phases of the shorter-term teleconnections (SOI and PNA) and the two phases of the PDO. Table 3 lists the numbers of sites that had significant differences in these comparisons for the PNA.

Table 3. Number of sites (out of a possible 90) with significant differences in extreme events for the positive phase of the PNA, comparing positive and negative PDO seasons, and for the negative phase of the PNA compared between positive and negative PDO seasons.

	Positive PNA		Negative PNA	
	(PNA^+ / PDO^+)—(PNA^+ / PDO^-)		(PNA^- / PDO^+)—(PNA^- / PDO^-)	
	TMAX	TMIN	TMAX	TMIN
Spring	7	35	4	22
Summer	5	11	10	20
Fall	15	2	2	36
Winter	*	*	4	23

* Due to the correlation between the patterns, there were insufficient seasons in these categories to perform analysis.

When the PNA is positive, variations in the PDO have relatively minor effects on extreme temperatures. The exception is during spring, when more than a third of the sites have significantly fewer cold TMIN days when the PDO is also positive (Figure 6). Given that the positive PDO is associated with above-average sea level pressure and upper-level geopotential heights (ridging) along the western coast, it appears that the positive PDO amplifies and supports the positive PNA, leading to reduced cold events. These sites are distributed throughout the state, but there is a tendency for larger decreases to be found in the central and far southern areas. Overall, the statistically significant sites average 12 fewer TMIN extremes during the PNA^+/PDO^+ combination, compared to the PNA^+/PDO^- seasons. The PDO has shown indications of switching to a predominantly nega-

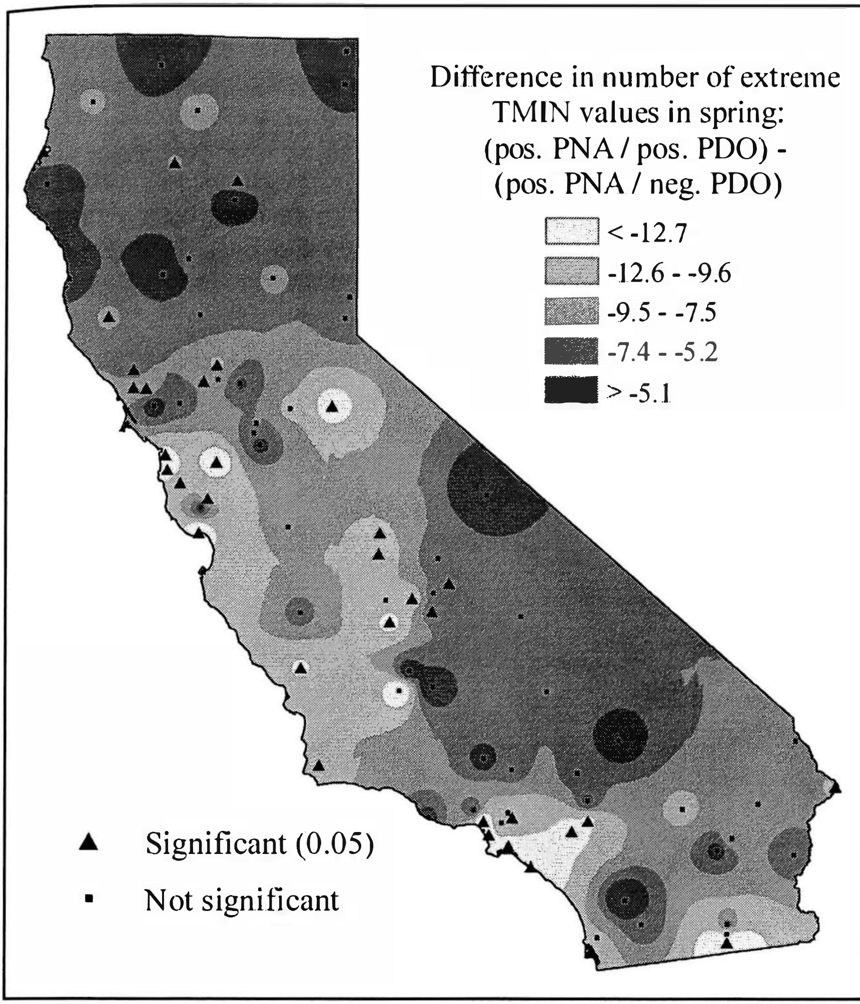

Figure 6.—Impact of the PDO on the frequency of extreme spring TMIN events during the positive PNA (PNA+/PDO+ minus PNA+/PDO-).

tive regime, which suggests a switch to an increased number of cold extremes during the positive PNA as the constructive interference between the two patterns is removed.

During the negative phase of the PNA, which is a generally zonal upper-level pattern across the U.S., variations in the PDO correspond to significant differences in the frequency of extreme cold events throughout the year. In winter, the 23 sites with significant differences average nearly 12 fewer cold TMIN days during years with the PNA^{-}/PDO^{+} combination than the seasons when the indices are in phase. The statistically significant differences are well distributed across California (Figure 7), but the southern half of the state shows a generally larger magnitude of change. As with the positive PNA, the PDO appears to augment the negative PNA when the two indices are in phase. The negative PDO corresponds to reduced geopotential heights and lower SLPs over the west coast—this pattern allows increased cold air intrusion from the north and more frequent cyclonic activity over the state. A switch toward a more negative PDO regime may result in an increased frequency of cold events during the negative PNA.

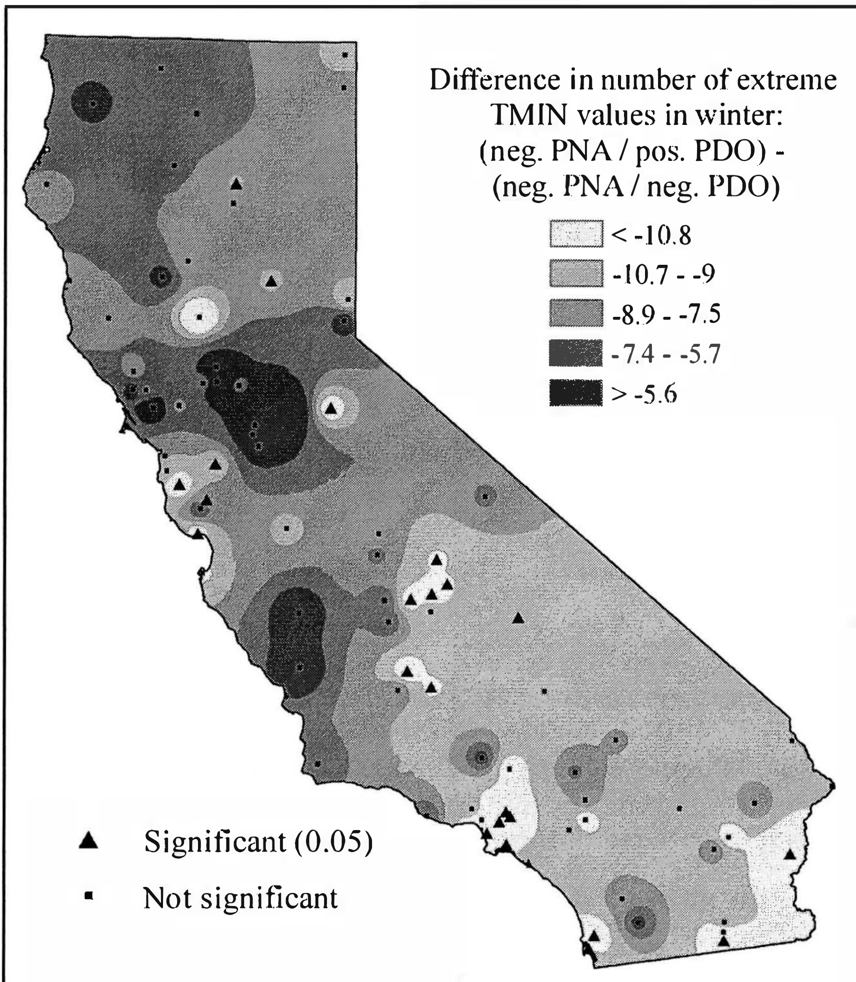

Figure 7.—Impact of the PDO on the frequency of extreme winter TMIN events during the negative PNA (PNA-/PDO+ minus PNA-/PDO-).

The fall season experiences the most widespread difference in cold event frequencies between the PNA/PDO phase combinations, with significant differences averaging approximately 10 fewer cold extremes during the PNA⁻/PDO⁺ combination at 36 sites. These sites are distributed along the coastal half of the state from north of the Bay Area to the southern border, with a cluster of large differences in the southern Central Valley (Figure 8). Spatially, the spring pattern is similar to the fall pattern, except that fewer sites have significance.

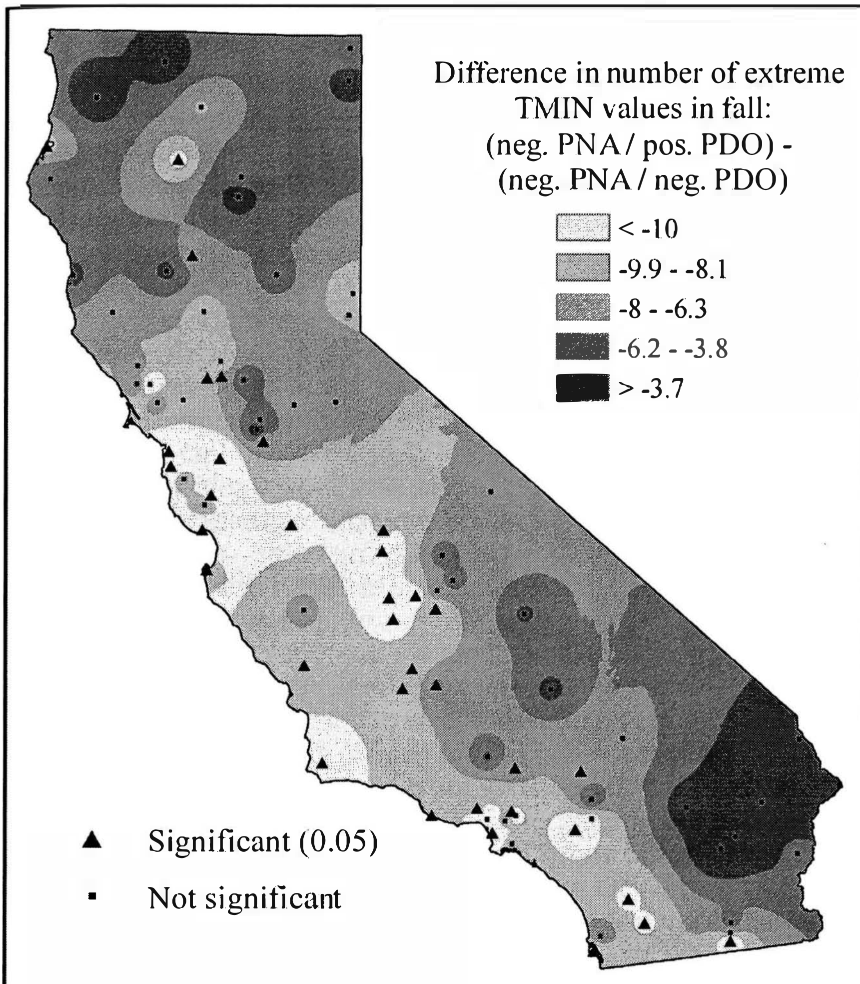

Figure 8.—Impact of the PDO on the frequency of extreme fall TMIN events during the negative PNA (PNA-/PDO+ minus PNA-/PDO-).

As with the PNA, the phase of the PDO has been found to augment or interfere with the patterns produced by variations in the SOI. In general, the positive phase of the PDO enhances the North Pacific troughing associated with the negative (warm) phase of the SOI, while the negative phase of the PDO interferes with the warm SOI pattern. Conversely, the positive (cold) SOI is enhanced by the negative PDO. Significantly, the west coast ridging associated with cold-phase (La Niña) SOI patterns appears to be shifted westward and offshore during negative PDO phases (Gershunov and Barnett 1998; Yu and Zwiers 2007).

The numbers of sites that have significant differences in extreme-event frequencies between the positive/negative SOI and PDO combinations are shown in Table 4. For both phases of the SOI, variations in the PDO predominantly affect extremes in the spring, with few significant differences in the rest of the year. The positive (La Niña) phase of the SOI experiences particularly widespread modification by the PDO during spring; half of the sites have significantly more spring TMAX extremes (13 more days/season, on average) when the SOI and PDO are in phase (Figure 9). This is likely due to the enhanced ridging directly over the region during this teleconnection combination. The largest differences are found in the southern quarter of the state and all the way up the coast—the central valley and eastern portions of the state show only small and insignificant differences. Also in spring, a third of the sites show significant decreases in the frequency of extreme cold events during the SOI^{+}/PDO^{+} combination compared to when the PDO is negative—these differences are larger than the concurrent increase in TMAX extremes, averaging approximately 16 fewer days per season, and are concentrated in the western half of the state from the Bay Area to the south coast. When the PDO is negative, the offshore shift of the ridge during La Niña events allows an increased flow of cold air from the north and thus an increase (decrease) in cold (warm) extremes. Given that the PDO has been mainly positive for the past few decades, this result suggests that the impact of La Niña events on extreme events has been skewed in the warm direction—a regime change in the PDO may allow cold ENSO patterns to produce more spring cold events and fewer spring hot days.

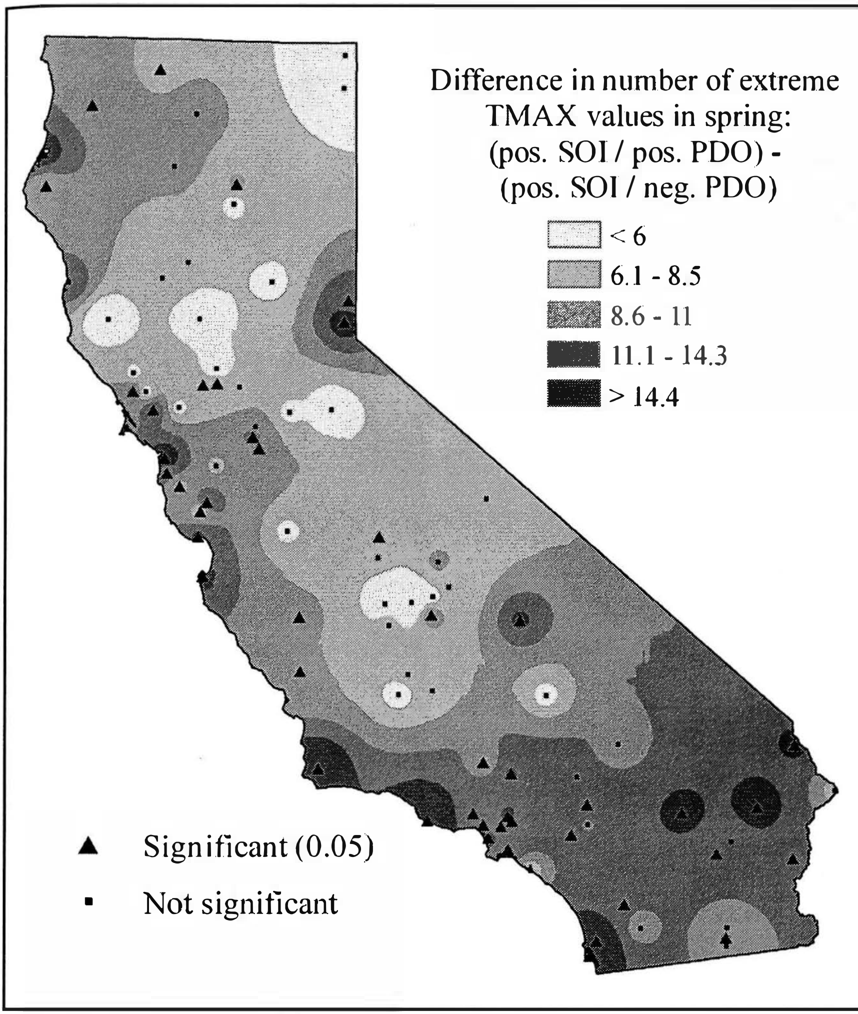

Figure 9.—Impact of the PDO on the frequency of extreme spring TMAX events during the positive SOI (SOI+/PDO+ minus SOI+/PDO-).

Table 4. Number of sites with significant differences in extreme events for the positive phase of the SOI, comparing positive and negative PDO seasons, and for the negative phase of the SOI compared between positive and negative PDO seasons.

	Positive SOI		Negative SOI	
	(SOI^+ / PDO^+)—(SOI^+ / PDO^-)		(SOI^- / PDO^+)—(SOI^- / PDO^-)	
	TMAX	TMIN	TMAX	TMIN
Spring	48	30	1	28
Summer	8	14	2	13
Fall	5	10	3	0
Winter	0	3	4	10

The phase of the PDO has less of an impact on extreme-event frequencies during the negative (El Niño) phase of the SOI. The only widespread impacts are in spring, when almost a third (28) of the sites have significantly fewer (by approximately 8 days/season) cold TMIN events during the SOI^-/PDO^+ combination. The mechanism for this result is likely the lower-than-normal sea-level pressures in the North Pacific when the positive PDO is augmenting the El Niño pattern, which would result in an enhanced flow of warm subtropical air, especially into the southern half of the state. These sites are heavily concentrated in the coastal half of the state between Sonoma and San Luis Obispo counties (Figure 10), with a few sites grouped on the north coast. Again, a negative shift in the PDO may result in more cold spring days during warm ENSO events, as this constructive interference is reduced.

Summary

The phase of teleconnection indices such as the PNA and SOI has been found to be significantly related to the frequency of occurrence of extreme temperature events, to a degree that varies both spatially and seasonally. Both indices predominantly affect the frequency of extreme cold (TMIN) events, particularly in the cold season.

The PNA is generally associated with a change in extreme-event frequencies that is commensurate with an upward shift in the overall temperature distribution during its positive phase. Throughout the

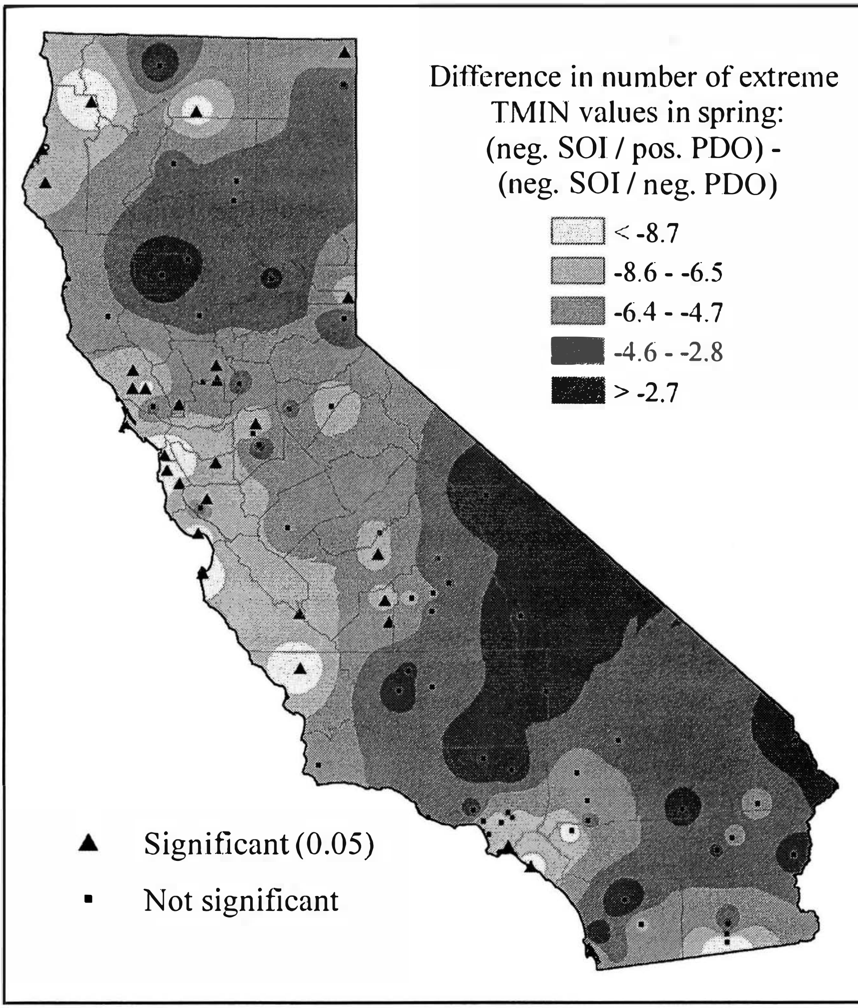

Figure 10.—Impact of the PDO on the frequency of extreme spring TMIN events during the negative SOI (SOI-/PDO+ minus SOI-/PDO-).

cold season, but especially in winter, the positive PNA produces an increased frequency of anomalously warm events and a decreased frequency of extreme cold events. The primary mechanism behind this relationship is likely the enhanced ridging over the region during the positive PNA, which steers cold northern air around the region and allows southerly flow and anticyclonic warming to dominate. The SOI significantly influences extreme-event frequencies at fewer sites than the PNA, and it differs in that the positive SOI (La Niña) produces an increased frequency of both hot and cold events, albeit at different times of the year. The impact on cold events is mainly seen in the spring, when clear conditions and northerly flow encourage colder nights during La Niña, while the smaller increase in hot events shows up in the summer.

The concurrent phase of the PDO appears to influence the effects that the other two teleconnections have on extreme temperatures in California. In particular, the PDO modifies the frequencies of extreme TMAX and TMIN events in spring during positive (La Niña) SOI events, with more hot events and fewer cold events when the indices are in phase. Both phases of the SOI are associated with fewer spring cold events when the PDO is positive compared to the negative PDO.

The PDO appears to enhance the impacts of the PNA when the indices are in phase, and counter the PNA impacts when out of phase. For the negative PNA, there tends to be a reduction in extreme cold days throughout the year when the PDO is positive. As the PDO is currently due for a switch back to the negative, these findings suggest that the negative PNA and both warm and cold ENSO events may be a source of more frequent cold days in the future. Overall, the PDO appears to have broader impacts on the positive phase of the SOI and the negative phase of the PNA than on the other phases.

An important caveat that applies to these results is that the climate processes addressed here do not operate in isolation. Extreme temperature events are influenced by a variety of factors, including other simultaneously operating teleconnection patterns, long-term trends in global/regional climate, and land cover changes at the observation sites. A particular concern is that the time period of this study overlaps with only one complete cycle of the PDO, which means that most of the positive PDO seasons are toward the end of the record. This is cause for caution, as any long-term trends in temperature (and extreme-event frequencies) from sources not associated with the PDO will be spuriously and unavoidably combined with the PDO impacts. Despite these issues, the results presented here should provide insight into the spatial and seasonal patterns of extreme temperatures that may be expected as the dominant modes of circulation in North America and the Pacific vary in phase. These findings may be of particular importance if/when the PDO completes its transition back to predominantly negative condition. Considering that extreme events tend to be potentially damaging and disruptive weather phenomena, understanding the mechanisms that influence their occurrence should prove beneficial as the regional climates of the west coast vary in the coming century.

References

Barnston, Anthony G. and Robert E. Livezey. 1987. "Classification, Seasonality, and Persistence of Low-Frequency Atmospheric Circulation Patterns." *Monthly Weather Review* 115:1083–1126.

Bodri, L. and V. Cermak. 2003. "High Frequency Variability in Recent Climate and the North Atlantic Oscillation." *Theoretical and Applied Climatology* 74:33–40.

Budikova, Dagmar. 2005. "Impact of the Pacific Decadal Oscillation on relationships between temperature and the Arctic Oscillation in the USA in winter." *Climate Research* 29:199–208.

Cayan, Daniel R. 1996. "Interannual Climate Variability and Snowpack in the Western United States." *Journal of Climate* 9:928–948.

Cheng, Xinhua and John M. Wallace. 1993. "Cluster Analysis of Northern Hemisphere Wintertime 500-hPa Height Field: Spatial Patterns." *Journal of the Atmospheric Sciences* 50 (16):2674–2696.

Climate Prediction Center. 2008. *Monthly Atmospheric & SST Indices* (Web page). NOAA/National Weather Service (CPC) (cited Sept. 2008). Available from http://www.cpc.ncep.noaa.gov/.

Coleman, Jill S. M. and Jeffrey C. Rogers. 2007. "A Synoptic Climatology of the Central United States and Associations with Pacific Teleconnection Pattern Frequency." *Journal of Climate* 20:3485–3497.

Colombo, Andrew F., David Etkin, and Bryan W. Karney. 1999. "Climate Variability and the Frequency of Extreme Temperature Events for Nine Sites across Canada: Implications for Power Usage." *Journal of Climate* 12:2490–2502.

Curreiro, Frank C., Karlyn S. Heiner, Jonathan M. Samet, Scott L. Zeger, Lisa Strug, and Jonathan A. Patz. 2002. "Temperature and Mortality in 11 Cities of the Eastern United States." *American Journal of Epidemiology* 155 (1):80–87.

Downton, Mary W. and Kathleen A. Miller. 1993. "The Freeze Risk to Florida Citrus, Part II: Temperature Variability and Circulation Patterns." *Journal of Climate* 6:364–372.

Easterling, David R., Thomas R. Karl, Kevin P. Gallo, David A. Robinson, Kevin E. Trenberth, and Aiguo Dai. 2000. "Observed Climate Variability and Change of Relevance to the Biosphere." *Journal of Geophysical Research* 105 (D15):20,101–20,114.

Easterling, David R., Gerald A. Meehl, Camille Parmesan, Stanley A. Changnon, Thomas R. Karl, and Linda O. Mearns. 2000. "Climate Extremes: Observations, Modelling, and Impacts." *Science* 289:2068–2074.

Gershunov, Alexander and Tim P. Barnett. 1998. "Interdecadal Modulation of ENSO Teleconnections." *Bulletin of the American Meteorological Society* 79 (12):2715–2725.

Gershunov, Alexander, Tim P. Barnett, and Daniel R. Cayan. 1999. "North Pacific Interdecadal Oscillation Seen as Factor in ENSO-Related North American Climate Anomalies." *Eos* 80 (3):25–30.

Henderson, Keith G. and J. Peter Robinson. 1994. "Relationships between the Pacific/North American Teleconnection Patterns and Precipitation Events in the South-Eastern USA." *International Journal of Climatology* 14:307–323.

Higgins, R. W., A. Leetmaa, and V. E. Kousky. 2002. "Relationships between Climate Variability and Winter Temperature Extremes in the United States." *Journal of Climate* 15:1555–1572.

Jin, Jiming, Norman L. Miller, Soroosh Sorooshian, and Xiagong Gao. 2006. "Relationship between atmospheric circulation and snowpack in the western USA." *Hydrological Processes* 20:753–767.

Joint Institute for the Study of the Atmosphere and Ocean. 2004. *The Pacific Decadal Oscillation (PDO)* (Web page). JISAO 2000 (cited Sept. 2008). Available from http://jisao.washington.edu/pdo/.

Katz, Richard W. and Barbara G. Brown. 1992. "Extreme Events in a Changing Climate: Variability Is More Important than Averages." *Climatic Change* 21:289–302.

LaDochy, Steve, Richard Medina, and William Patzert. 2007. "Recent California Climate Variability: Spatial and Temporal Patterns in temperature Trends." *Climate Research* 33:159–169.

Leathers, Daniel J. and Michael A. Palecki. 1992. "The Pacific/North American Teleconnection Pattern and United States Climate. Part II: Temporal Characteristics and Index Specification." *Journal of Climate* 5:707–716.

Leathers, Daniel J., Brent Yarnal, and Michael A. Palecki. 1991. "The Pacific/North American Teleconnection Pattern and United States Climate. Part I: Regional Temperature and Precipitation Associations." *Journal of Climate* 4:517–528.

Liu, X. D., Z. Y. Yin, X. M. Shao, and N. S. Qin. 2006. "Temporal trends and variability of daily maximum and minimum, extreme temperature events, and growing season length over the eastern and central Tibetan Plateau during 1961–2003."

Journal of Geophysical Research-Atmospheres 111 (D19):D19109, doi:10.1029/2005JD006915.

Mantua, Nathan J., Steven R. Hare, Yuan Zhang, John M. Wallace, and Robert C. Francis. 1997. "A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production." *Bulletin of the American Meteorological Society* 78 (6):1069–1079.

McGuffie, K., A. Henderson-Sellers, N. Holbrook, Z. Kothavala, O. Balachova, and J. Hoekstra. 1999. "Assessing Simulations of Daily Temperature and Precipitation Variability with Global Climate Models for Present and Enhanced Greenhouse Climates." *International Journal of Climatology* 19:1–26.

Mearns, Linda O., Richard W. Katz, and Stephen H. Schneider. 1984. "Extreme High-Temperature Events: Changes in their Probabilities with Changes in Mean Temperature." *Journal of Climate and Applied Meteorology* 23:1601–1613.

Mestas-Nunez, Alberto M. and Arthur J. Miller. 2006. "Interdecadal variability and climate change in the eastern tropical Pacific: a review." *Progress in Oceanography* 69:267–284.

Mori, Masato and Masahiro Watanabe. 2008. "The Growth and Triggering Mechanisms of the PNA: A MJO-PNA Coherence." *Journal of the Meteorological Society of Japan* 86 (1):213–236.

Parmesan, Camille, Terry L. Root, and Michael R. Willig. 2000. "Impacts of Extreme Weather and Climate on Terrestrial Biota." *Bulletin of the American Meteorological Society* 81 (3):443–450.

Serreze, Mark C., Martyn P. Clark, David L. McGinnis, and David A. Robinson. 1998. "Characteristics of Snowfall over the Eastern Half of the United States and Relationships with Principal Modes of Low-Frequency Atmospheric Variability." *Journal of Climate* 11:234–250.

Sheridan, Scott C. 2003. "North American Weather-Type Frequency and Teleconnection Indices." *International Journal of Climatology* 23 (1):27–45.

Smith, Catherine A. and Prashant D. Sardeshmukh. 2000. "The Effect of ENSO in the Intraseasonal Variance of Surface Temperatures in Winter." *International Journal of Climatology* 20:1543–1557.

Stott, Peter A., S. F. B. Tett, G. S. Jones, M. R. Allen, J. F. B. Mitchell, and G. J. Jenkins. 2000. "External Control of 20th Century Temperature by Natural and Anthropogenic Forcings." *Science* 290:2133–2137.

Vega, Anthony J., Keith G. Henderson, and Robert V. Rohli. 1995. "Comparison of Monthly and Intramonthly Indices for the

Pacific/North American Teleconnection Pattern." *Journal of Climate* 8 (8):2097–2103.
Vega, Anthony J., Robert V. Rohli, and Keith G. Henderson. 1998. "The Gulf of Mexico Mid-Tropospheric Response to El Niño and La Niña Forcing." *Climate Research* 10:115–125.
Wagner, Dieter. 1999. "Assessment of the Probability of Extreme Weather Events and Their Potential Effects in Large Conurbations." *Atmospheric Environment* 33:4151–4155.
White, M. A., N. S. Diffenbaugh, G. V. Jones, J. S. Pal, and F. Girogi. 2006. "Extreme heat reduces and shifts United States premium wine production in the 21st century." *PNAS* 103 (30):11217–11222.
Wigley, T. M. L. 1985. "Impact of Extreme Events." *Nature* 316:106–107.
———. 1999. *The Science of Climate Change: Global and U.S. Perspectives.* Arlington, VA: Pew Center on Global Climate Change.
Wolter, Klaus, Randall M. Dole, and Catherine A. Smith. 1999. "Short-Term Climate Extremes over the Continental United States and ENSO. Part I: Seasonal Temperatures." *Journal of Climate* 12:3255–3272.
Yarnal, Brent. 1985. "Extratropical teleconnections with El Niño/ Southern Oscillation (ENSO) events." *Progress in Physical Geography* 9 (3):315–352.
Yarnal, Brent and Henry F. Diaz. 1986. "Relationships between Extremes of the Southern Oscillation and the Winter Climate of the Anglo-American Pacific Coast." *Journal of Climatology* 6:197–219.
Yu, B. and F. W. Zwiers. 2007. "The impact of combined ENSO and PDO on the PNA climate: a 1,000-year climate modeling study." *Climate Dynamics* 29:837–851.