History of Pacific Northwest Heat Waves: Synoptic Pattern and Trends*

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ABSTRACT

A historical record of Pacific Northwest (defined here as west of the Cascade Mountains in Washington and Oregon) heat waves is identified using the U.S. Historical Climate Network, version 2, daily data (1901–2009). Both daytime and nighttime events are examined, defining a heat wave as three consecutive days above the 99th percentile for the maximum and minimum temperature anomalies separately. Although the synoptic characteristics of the daytime and nighttime heat events are similar, they do indicate some differences between the two types of events. Most notable is a stronger influence of downslope warming over the Cascade Mountains for the daytime events versus a more important role of precipitable water content for the nighttime events, presumably through its impact on downward longwave radiative fluxes. Current research suggests that the frequency and duration of heat waves are expected to increase in much of the United States, and analysis of the heat events reveals that a significant, increasing trend in the frequency of the nighttime events is already occurring in the Pacific Northwest. A heat wave occurred in 2009 that set all-time-record maximum temperatures in many locations and ranked as the second strongest daytime event and the longest nighttime event in the record.

1. Introduction

Western Washington and Oregon (hereinafter referred to as the PNW) typically experience a mild summer climate with few instances of extreme weather. Nevertheless, the PNW suffered a heat wave in July 2009 that set all-time-high temperature records throughout western Washington [e.g., Seattle–Tacoma International Airport reached 39.4°C (103°F)] and shattered single-day maximum temperature records from Medford, Oregon, to Bellingham, Washington. This event was notable in that overnight minimum temperatures were also high for over a week. We use this event as the impetus to explore the frequency and magnitude of PNW heat waves in the recent past. We examine the synoptic pattern of these events as well as the trends in the record.

Heat waves are expected to increase in both intensity and duration with global climate change (Clark et al. 2006; Kunkel et al. 2010; Meehl and Tebaldi 2004), and the frequency of hot days is virtually certain to increase (Allen et al. 2012). Heat waves have received worldwide attention in the last couple of decades, especially regarding major events in Chicago, Illinois, in 1995 (e.g., Kunkel et al. 1996), Europe in 2003 (e.g., Beniston 2004), and Russia in 2010 (e.g., Grumm 2011). Significant mortality was associated with all three of these events.

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Heat is among the top weather-related causes of mortality in the United States, responsible for 1500 deaths per year, on average (National Oceanic and Atmospheric Administration 2012). A study by Hoshiko et al. (2009), for example, found a statistically significant (95% confidence level) 6% increase in California deaths during the heat event of 2006. Despite this evidence, many people have incorrect perceptions of weather dangers and do not adequately prepare for these types of hazards (Changnon et al. 1996). Additionally, parts of the country that are historically not prone to extreme heat waves, such as the PNW, are likely to experience greater negative impacts on residents and increased mortality because of the relative rarity of occurrence (McGeehin and Mirabelli 2001; Meehl and Tebaldi 2004).

The vulnerability of PNW residents to heat waves is twofold: residents often lack effective cooling measures and are not acclimated to hot weather. The lack of home air conditioning (AC) units in western Washington (Jackson et al. 2010; Davis et al. 2003) and western Oregon is especially relevant considering the documented importance of AC as a protective factor in preventing heat-related sickness and death (e.g., Reid et al. 2009; Semenza et al. 1996; Naughton et al. 2002). However, it is important to recognize that the use of AC can bring an economic burden, particularly to the elderly who may be living on a fixed income (Luber and McGeehin 2008) and are already vulnerable because of their decreased tolerance for heat (Kovats and Hajat 2008). In a recent nationwide urban vulnerability study, Reid et al. (2009) took many of these factors into account and found that parts of Washington’s Puget Sound and Oregon’s Willamette Valley were highly vulnerable to heat and that Pierce County, Washington, was among the 13 census tracts with the highest heat vulnerability index values nationwide.

Understanding the impact of heat events on humans is important, even for the PNW where heat waves tend to be less severe than in many other parts of the country. A preliminary examination of western Washington heat-related hospitalizations (which were coded as “excessive heat due to weather”) since 1987 during the heat events that we define in this study revealed that the longest-lasting nighttime event (in 2009) and the warmest nighttime event (in 2006) had the most hospitalizations, suggesting that it is likely a combination of the intensity and duration of the event that yields the greatest impact on human health. Additionally, summers with heat events as defined here were accompanied by about a 50% increase in heat-related hospitalizations. Our analysis is by no means exhaustive but it does illustrate that the PNW does have measurable health impacts from heat, as has also been reported upon by Chestnut et al. (1998) and Jackson et al. (2010). The expectation that heat events will increase in the future coupled with the vulnerability of the PNW population to extreme heat means that heat waves should remain a prominent issue in local climate adaptation planning, primarily at the urban level.

There is not a one-size-fits-all definition of a heat wave, although some combination of intensity and duration is typically involved. Solomon et al. (2007) define heat waves as temperature extremes of short duration. The approach to defining a heat wave varies in the literature (e.g., Davis et al. 2004; Hajat et al. 2006; Lyon 2009), and accepted definitions for PNW heat waves are lacking specifically. Both daytime and nighttime heat waves are considered in this paper; warm nighttime temperatures have been shown to have a greater influence on human health (e.g., Gershunov et al. 2011; Bohr 2009; Kalkstein and Davis 1989).

The next section of this paper describes the data used in this study, our definition of PNW heat waves, and our analysis methods. The characteristics (intensity, duration, and timing) and trends identified in the PNW heat events are presented in section 3. Section 4 reviews the synoptic pattern of the daytime and nighttime heat events, section 5 examines the relationship between our heat events and several climate indices, and section 6 includes concluding discussion.

### 2. Region and events defined: Data

Our analysis is based on daily values of warm-season (1 June–30 September; JJAS) maximum and minimum temperatures for Washington and Oregon for 1901–2009 from the U.S. Historical Climate Network, version 2 (USHCN v2), dataset (http://edc.ornl.gov/ftp/ushcn_daily/). Daily National Weather Service (NWS) Cooperative Observer Program (COOP) data from Seattle–Tacoma International Airport and Portland (Oregon) International Airport were added from the National Climatic Data Center’s (NCDC) quality controlled dataset. These two stations were added to account for the region’s two major population centers. The region of analysis was restricted to west of the Cascade Mountains in Washington (122°W) and Oregon (121°W), since it is relatively homogeneous in its climate and includes the bulk of the population in each state; further considerations on station selection in the western regions of the two states are described below. To define our heat events, summertime temperature anomalies were computed against the JJAS average for each station, and then those anomalies were averaged together for the whole region of study. This serves to minimize the impacts of the changes in the number of stations available over the period of analysis. Although fewer stations

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were included in the regional mean in the earlier part of the record, a test using only the stations with a full 1901–2009 record indicated that the heat events selected only differed slightly from those selected using all stations, regardless of the duration of the record.

The maximum and minimum temperatures were evaluated separately in order to define events as predominantly daytime (Tmax) or nighttime (Tmin) events. Although there are a variety of definitions of a heat event, the 99th percentile as a threshold for identifying extreme heat events has been used previously (e.g., Clark et al. 2006; Meehl and Tebaldi 2004). In addition, using the 99th percentile allowed us to restrict the analysis to the most extreme events but also included enough events for the composite results to be meaningful. Our specific definition of a heat wave is three or more consecutive days above the 99th percentile for the maximum [9.5°C (17.1°F)] or minimum [4.6°C (8.3°F)] temperature anomalies. These thresholds were found using the mean regional anomaly across all stations. Therefore, the 99th percentile anomaly corresponds to different temperature thresholds at each station, as shown in Fig. 1.

While an initial test of dividing the region into smaller subsets revealed that the strongest heat waves are manifested across the entire region, concern about local climate variations in the region, namely that the coastal portion of Oregon and Washington tends to be cooler than the inland portion, prompted further examination. For this exercise, we relaxed our heat-event threshold from the 99th percentile to the 95th percentile to get a larger set of hot days for the 41 USHCN stations and the 2 COOP stations (a total of 321 and 340 days for Tmax and Tmin days, respectively). We computed Pearson correlation coefficients $R$ for each station against the regional average anomaly of the 95th-percentile hot days. Four of the Tmin stations did not have statistically significant correlations (at the 99% confidence level) with the regional average. In other words, these stations did not consistently have warm anomalies when the rest of the region was warm. On the basis of these results, one coastal station in Washington (Long Beach, 454748), and three stations along the Oregon coast (Brookings, 351055; Newport, 356032, and North Bend, 356073) were removed from the dataset. The Tmax correlations for these four stations were statistically significant, but marginally so, and those stations were also excluded in the analysis of Tmax events for consistency between the two types. Our final regional heat wave analysis was based on 39 stations (Fig. 1).

The difference in the synoptic pattern between the warm days and warm nights was examined by
constructing composites for all of the days above the Tmax threshold (46 days) separately from composites for all of the days in our Tmin events (61 days). The 500-hPa geopotential height, 850-hPa temperatures, total precipitable water, and sea level pressure anomaly composites (with respect to the 1981–2008 climatology) were considered using data from version 2 of the Twentieth Century Reanalysis Project (Compo et al. 2006, 2011). The daily composites are the average of the 0000, 0600, 1200, and 1800 UTC values, meaning that the synoptic conditions for the given calendar day are, in local time, for 1700 Pacific daylight time (PDT) on the previous calendar day to 1100 PDT on that calendar day. To account for UTC time, the Tmin event composites begin on the actual calendar day of the heat event, but the Tmax events were shifted forward 1 day to match local PDT. Composite anomalies are considered statistically significant (at the 95% confidence level) where they exceed thresholds determined by \( t \) tests based on the pattern in standard deviation in daily values for July–August of 1951–2010, and assuming there is a single degree of freedom for each of the individual heat waves included in the composite. These thresholds were also used as a measure of the statistical significance of differences between composites for the Tmax and Tmin events. We constructed 850-hPa vector wind composites using the mean field, rather than anomalies, and determined the statistical significance as described above for the wind speed only. In addition to composites spanning the entire event, the synoptic patterns of evolution of the Tmax and Tmin heat events were examined by constructing composite images for the first day of the 13 (15) Tmax (Tmin) events as well as the day before, the last day, and the day after the event. Finally, we removed five events that were present in both the Tmax and the Tmin events and constructed the same composites described above without the overlapping events.

The number of pressure observations available to be assimilated in the Twentieth Century Reanalysis dataset increases with time over the period of record used here (Compo et al. 2011). This implies that the atmospheric fields used in our composites may include greater errors in the early part of the record. We do not expect that to compromise our results for two reasons. First, changes in errors over the course of the twentieth century appear to be modest for the Northern Hemisphere (e.g., Fig. 3a in Compo et al. 2011). Second, assuming the errors are quasi-independent, there will be substantial cancellation in their effects on composites because of the averaging. In addition, we constructed Tmax and Tmin composites for the events since 1948 using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) and found very similar differences between the types of events as shown using the Twentieth Century Reanalysis. These supplementary composites are not presented here.

Extreme events such as heat waves are rare by definition, which complicates an analysis of trends. Here, we use the Mann–Kendall (MK) test, a nonparametric rank-based test for monotonic trend in a time series lacking normal distribution. The MK test provides the direction of the trend by calculating a \( z \) value, and the sign indicates the direction of the trend (positive = increasing; negative = decreasing). A significance \( p \) value of 0.05 (95% confidence) was used to determine statistical significance (Kendall 1955). To calculate trends, each heat event must be quantified in a manner in which it can be ranked and there must be at least 10 temporally separate cases. Each event was assigned a magnitude score, defined as the mean temperature anomaly of the entire event, a duration score, and a chronology rank.

The change from liquid-in-glass thermometers to maximum–minimum temperature sensors (MMTS) in the mid-1980s and urban growth at many of the stations that make up the USHCN daily database have the potential to impact estimates of the trends (Quayle et al. 1991). In recognition of this issue, we applied the monthly USHCN temperature adjustments to our daily data according to the breakpoints identified by NCDC’s pairwise algorithm (Menne et al. 2009). The adjustments specifically take into account the instrument switch to the MMTS and any changes in microclimate surrounding the stations. The majority of the adjustments fell between \(-1^\circ\) and \(1^\circ\)C for Washington and Oregon with the largest adjustment on the order of 3\(^\circ\)C. We performed the trend analysis on the daily, adjusted dataset as well as the unadjusted data (both shown in Figs. 2 and 3). Elsewhere in the paper, only the unadjusted data were used.

We also examined the relationship between our heat events since 1950 and the strength of several climate indices, including El Niño–Southern Oscillation (ENSO), the Pacific decadal oscillation (PDO), and so on, to help determine the potential for anticipating heat events on longer time scales.

### 3. Identified events and trends

Using the 99th-percentile threshold described above, 13 Tmax events (Fig. 2, black and red dots) and 15 Tmin events (Fig. 3, black and red dots) were identified from 1901 to 2009. The Tmax and Tmin events occur exclusively in July and August. The earliest Tmax (Tmin) event began on 30 June (1 July) in 1942; the latest Tmax event began on 10 August (1977), and the latest Tmin
event began on 27 August (1935). The average start dates for the Tmax and Tmin events were near the end of July: 23 July and 26 July, respectively. Five of the heat waves (in 1941, 1942, 1981, 2006, and 2009) were in both the Tmax and Tmin sets; the other 18 individual events were of just one type.

The severity of each event can be categorized in several ways. Here, we rank each event both by average anomaly and by duration (Tmax and Tmin events are shown in the top and bottom of Table 1, respectively). On average, the nighttime events (4 days) persisted 0.5 days longer than the daytime events (3.5 days). For Tmax events, the 1981 event was the top ranked in terms of intensity and duration. It is worth noting that the 2006 event, ranking as the most intense nighttime event but only tying for ninth in terms of daytime intensity, occurred on the same dates as the California and Nevada heat wave that was studied by Gershunov et al. (2009) and Hoshiko et al. (2009), among others. The longest-lasting Tmin event, in 2009, had eight consecutive days with minimum temperatures above the threshold. The 2009 event was also notable for its high ranking in both the Tmax and Tmin categories.

As seen in Figs. 2 and 3, applying the NCDC adjustments to each individual station results in only slightly different sets of heat events. The 99th-percentile threshold anomaly for both the Tmax and Tmin events remained the same, and most of the events identified overlapped when using the two separate datasets. A statistically significant ($p = 0.05$) increasing trend in frequency was found for both the unadjusted and adjusted Tmin events for the period of record. On the other hand, no statistically significant trend was identified for either the unadjusted or adjusted Tmax events. Trends in magnitude or duration were also not statistically significant for either the Tmax or Tmin events.

4. Synoptic weather patterns

Five meteorological fields were considered toward the characterization of the regional circulation associated with PNW heat waves. Our focus is on the periods of extreme event, (i.e., the Tmax and Tmin days), and discussion is also included on the typical evolution in the fields over the course of the events.

a. 500-hPa geopotential heights

The 500-hPa geopotential height $Z$ anomaly composite for all of days in the Tmax events is shown on the left-hand side (lhs) of Fig. 4a and is very similar to its counterpart for all of the Tmin days in shape and pattern (rhs of Fig. 4a). The difference is in the amplitude of the 500-hPa $Z$ anomalies: Tmax events have a higher-amplitude ridge with a large area of anomalies greater than 100 m and a peak amplitude greater than 120 m. The Tmin events are associated with a smaller region of anomalies exceeding 100 m. The differences in heights between the Tmax and Tmin events during the entire duration of the event are near the $\sim$20-m threshold of statistical significance but are not quite over the threshold for the sets to be statistically distinct from one another. Still, the stronger 500-hPa ridge might be expected to promote greater subsidence on the west side of the Cascade Mountains for the Tmax events, relative to the Tmin events. Stronger subsidence was indeed found in the 700-hPa omega anomaly composite for all of the Tmax
days relative to the Tmin days (not shown). The strongest anomalous sinking motion occurred through central and northern Puget Sound extending north to British Columbia, Canada, for the Tmax events (between 0.075 and 0.135 Pa s\(^{-1}\)) whereas the Tmin days had lower omega anomaly values in that same region (between 0.03 and 0.105 Pa s\(^{-1}\)). There was not any anomalous sinking motion in western Oregon for the Tmax events (between 0.015 and 0.045 Pa s\(^{-1}\)).

The evolution of the 500-hPa Z anomalies also shows a consistently stronger 500-hPa ridge for the Tmax events (Fig. 5). Even the day before the start of the daytime event has Z anomalies between 140 and 160 m (Fig. 5a), and these anomalies strengthen on the first day of the event (not shown). For the Tmin event, the day before the start of the event has considerably weaker anomalies averaging between 100 and 120 m (Fig. 5b), making the difference between the Tmax and Tmin events statistically significant. The Z anomalies do strengthen on the first day of the Tmax events (between 120 and 140 m), but they are weaker and cover a smaller area than the Tmax Z anomalies, resulting in statistically significant differences between the two types of events (not shown).

Table 1. The start date, average temperature anomaly (°C), and total duration (days) for the Tmax and Tmin events. A ranking for the intensity and duration for each event is also listed.

<table>
<thead>
<tr>
<th>Year</th>
<th>Start date</th>
<th>Avg anomaly (°C)</th>
<th>Intensity rank</th>
<th>Duration (days)</th>
<th>Duration rank</th>
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<td>15 Jul</td>
<td>10.5</td>
<td>11</td>
<td>3</td>
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<tr>
<td>1926</td>
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<td>10.6</td>
<td>9</td>
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<td>11.0</td>
<td>6</td>
<td>4</td>
<td>3</td>
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<tr>
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</table>

days relative to the Tmin days (not shown). The strongest anomalous sinking motion occurred through central and northern Puget Sound extending north to British Columbia, Canada, for the Tmax events (between 0.075 and 0.135 Pa s\(^{-1}\)) whereas the Tmin days had lower omega anomaly values in that same region (between 0.03 and 0.105 Pa s\(^{-1}\)). There was not any anomalous sinking motion in western Oregon for the Tmax events, and there was modest anomalous sinking motion there for the Tmax events (between 0.015 and 0.045 Pa s\(^{-1}\)).

The evolution of the 500-hPa Z anomalies also shows a consistently stronger 500-hPa ridge for the Tmax events (Fig. 5). Even the day before the start of the daytime event has Z anomalies between 140 and 160 m (Fig. 5a), and these anomalies strengthen on the first day of the event (not shown). For the Tmin event, the day before the start of the event has considerably weaker anomalies averaging between 100 and 120 m (Fig. 5b), making the difference between the Tmax and Tmin events statistically significant. The Z anomalies do strengthen on the first day of the Tmax events (between 120 and 140 m), but they are weaker and cover a smaller area than the Tmax Z anomalies, resulting in statistically significant differences between the two types of events (not shown).

Further analysis was carried out on the relationship between the magnitudes of the 500-hPa Z anomalies and the surface temperature anomalies on the first day of the Tmax and Tmin events. An index for the former was created by determining the maximum 500-hPa Z anomaly in the area with the largest signal in the composite anomaly patterns (49°–55°N, 131°–125°W). A positive relationship was found between the value of the highest 500-hPa Z anomaly and the average regional maximum temperature anomaly (R-squared value of ~0.32). Essentially no relationship (R-squared value of ~0.02) was found between the 500-hPa Z and the temperatures for the Tmin events. In other words, variations in the exact location and amplitude of the 500-hPa Z anomalies do not play as strong of a role in determining the intensity of the Tmin events.

**b. 850-hPa temperatures**

The 850-hPa temperature anomaly composite for all of the days in the Tmax events features a peak value of about 8°C as compared with about 6°C for the Tmin events (Fig. 4b). The 2°C difference between the two types of events is at or slightly below the threshold of statistical significance. The distinctions between the 850-hPa temperatures tend to be greater on the day before the start of the heat waves (Fig. 6), during which the peak anomalies on average are 3°C greater for the Tmax events than for the Tmin events (significant). This difference tends to decrease over the course of the heat waves and is not statistically significant by the last day of the events.

**c. Total precipitable water**

The total precipitable water (PW) anomalies for all of the days composing the Tmax events (lhs of Fig. 4c) are positive over most of Oregon and negative over Washington. Only a small area of the positive PW anomalies, mainly over southern Oregon, is statistically significant, however. On the other hand, the composite for all of the Tmax days (rhs of Fig. 4c) includes statistically significant positive anomalies over a larger area of western Oregon and positive anomalies over the study region as a whole. These PW differences between the Tmin and Tmax events are marginal; composite anomalies are significant at magnitudes of about 1.5–2 kg m\(^{-2}\), and the differences between the Tmax and Tmin composites are less than that.
FIG. 4. Composite anomalies of (left) all Tmax event days and (right) all Tmin event days for (a) 500-hPa geopotential heights (m), (b) 850-hPa temperatures (K), (c) total PW (kg m$^{-2}$), and (d) SLP (Pa). Shaded areas show where the $t$ statistic for the composite mean indicates anomalies that are significantly different from zero at the 95% confidence level, assuming a single degree of freedom for each heat wave.
The composites showing the evolution of the events indicate greater PW in general for the Tmin events than for the Tmax events (Fig. 7) and are significantly different from each other on the day before the start of the event and on the last day of the event. The PW anomalies are negative for the Tmax events on the day before the event throughout Washington and Oregon (from $-1$ to $-4$ kg m$^{-2}$; Fig. 7a) and are statistically significant. This pattern remains similar for the first day of the event (from $-1$ to $-3$ kg m$^{-2}$ anomalies over western Washington and northern Oregon; not shown), but with a smaller area of statistical significance on the border of Washington and Oregon extending off the coast. For the Tmin events, positive PW anomalies exist off the coast of the study area and in southern Oregon on the day prior to the Tmin events (1–2 kg m$^{-2}$; Fig. 7c), although only the positive anomalies farther off the coast are significant. Positive PW anomalies do develop over the study area for the Tmax events on the last day, and a small area of those anomalies is statistically significant in western Oregon and in southern British Columbia (Fig. 7b). The termination of the Tmin events is associated with greater moisture totals with a larger area of statistical significance (Fig. 7d). For both types of heat waves, there is in general moistening over the course of the events.

d. Sea level pressure

Both Tmax and Tmin events are characterized by positive sea level pressure (SLP) anomalies over the continental United States and Canada and negative anomalies for the PNW extending westward over the Pacific Ocean, as shown in the composites for all of the Tmax days versus all of the Tmin days (Fig. 4d). This setup brings about a low-level flow of warm, continental air to western Washington and Oregon. There are discernible differences between the two types of events. In particular, the negative SLP anomalies over the Pacific Ocean through the study area, and the positive anomalies inland, are stronger in the Tmax versus Tmin events over their lifetimes as a whole. The magnitudes of these differences are about 1 hPa, which is below the
threshold (about 2 hPa) for statistical significance. The nature of these SLP dipoles and the differences between types of events continue throughout the evolution of the event (not shown). On the day before the start of the event and on the first day, the Tmax positive SLP anomalies over British Columbia are significantly larger (greater than 2 hPa) than the Tmin positive anomalies in the same region. On the last day of the event, the Tmax negative SLP anomalies throughout Washington and northwestern Oregon are significantly larger than those for the Tmin events. More information on the thermally induced low pressure that can develop in the coastal region of the PNW is provided by Brewer et al. (2012).

e. 850-hPa vector wind

The mean composites for all of the Tmax days versus all of the Tmin days for the 850-hPa vector wind (Fig. 8) reveal similar wind directions (northeasterly over Washington and Oregon) for both types of events. There are stronger winds off the coast and over Oregon for the Tmax events. These differences are marginal in most locations averaged over the course of the events, with a difference between 0.8 and 1 m s$^{-1}$ needed for statistical significance. As with the SLP anomalies, the distinctions in the strength of the 850-hPa flow anomalies between the Tmax and Tmin events tend to be greater near the start and lesser near the end of the events. The 850-hPa flow is statistically significantly stronger for the Tmax events on the day before the start of the event and on the first day of the event, by 2–2.5 and 1–2 m s$^{-1}$, respectively. Both types of events feature a transition to anomalous northwesterly flow by the last day. The moistening that occurs at that time (as illustrated in Fig. 7) appears to be due in general to the cessation of strong sinking motion rather than the low-level advection of relatively moist air from the south.
f. Composites without overlapping events

To draw out the distinctions between the Tmax and Tmin heat events, the five overlapping events (1941, 1942, 1981, 2006, and 2009) are removed, resulting in composites of all of the days in the remaining 8 (Tmax) and 10 (Tmin) events. Note that the events removed were the strongest (Table 1), resulting in weaker composite fields in many cases. The 500-hPa $Z$, for example, showed weaker $Z$ anomalies for both the Tmax and Tmin composites but retained the difference between the Tmax and Tmin events at $\sim 20$ m (not shown).

There were some notable differences, and the composites for the PW (Figs. 9a,c) and SLP (Figs. 9b,d) without the five overlapping events are presented here. For PW, the Tmax events are drier over Washington by 1–2 kg m$^{-2}$ relative to the composite that uses all of the events (Fig. 9a). This is not statistically significant, in part because the smaller sample size of eight means the signal must be larger to reach the 95% confidence level, but does show an increase in the magnitude and area of negative PW anomalies relative to the composite including the overlapping events. For the Tmin events, the magnitude of the positive PW anomalies is 2–3 kg m$^{-2}$ greater over Oregon and the extent of the statistically significant anomalies is larger as well (Fig. 9c).

The differences in the SLP anomalies without the overlapping events can help explain the changes in the PW fields. Relative to the composites with all of the events, the Tmax events exhibit much stronger positive SLP anomalies inland with statistical significance extending farther west (Fig. 9b). This is lacking in the Tmin events, and the inland high is much weaker (Fig. 9d). The stronger Tmax gradient in the SLP anomalies is consistent with stronger downslope warming at low levels (also reflected in the Tmax 850-hPa temperatures; not shown) as compared with the Tmin events where the SLP gradient is much weaker.

5. Teleconnections

Here, we examine the linkages between PNW heat waves and large-scale, long-term (monthly and longer) aspects of the atmospheric circulation. Forecasts of the latter are being made by general circulation models for seasonal weather prediction of mean temperature and precipitation, and in principle there is the potential to provide information on the relative odds of heat waves for an upcoming summer season. A full investigation of the feasibility of making seasonal predictions of heat waves is outside the scope of the present study, but we have taken a first step in assessing the strength of relationship(s) between the episodic, extreme events represented by PNW and the state of the climate system.

Our approach involved determining the mean and standard deviation in the state of various climate indices during the months in which our heat waves occurred (since 1950). Our results represent simple composites for our extreme events as opposed to a regression-based analysis used by Guirguis et al. (2011) in a study of the relationships between both warm and cold events in winter with a variety of climate modes. The indices considered here are as follows: ENSO, PDO, the Arctic Oscillation (AO), the Pacific–North American pattern (PNA), the North Pacific Gyre Oscillation (NPGO), and the east Pacific–North Pacific pattern (EP–NP). Each of these indices is standardized to zero. The first four indices have been used in a large variety of studies for characterizing the climate variability of the PNW. The latter two may not be as familiar to most readers but they do project on atmospheric variables in the region of interest. A description of the NPGO is provided by DiLorenzo et al. (2008), and the EP–NP is
described by Bell and Janowiak (1995) and Barnston and Livezey (1987). The results are summarized in Table 2.

PNW heat waves are in general related more strongly to the EP–NP index than to the other climate indices tested. This is especially the case for Tmax events, during which the EP–NP was 0.86 in the mean. In comparison the mean value of the EP–NP was 0.44 for the Tmin events. The positive phase of EP–NP features positive midtropospheric $Z$ anomalies over Alaska and western Canada and an enhanced anticyclonic circulation pattern over western North America, similar to the synoptic pattern identified with our events. Furthermore, warmer-than-normal temperatures along the west coast of the United States are associated with this pattern. There was less correspondence between the other indices and the occurrence of our heat events. There has been a tendency for the AO to be negative during heat waves, but only marginally so, especially during Tmin events. The mean values of the PDO, PNA, and NPGO

![Fig. 9. The composite (a),(c) PW and (b),(d) SLP anomalies for all of the (left) Tmax days and (right) Tmin days excluding the five overlapping Tmax and Tmin events. Shading is as described in Fig. 4.](image)

<table>
<thead>
<tr>
<th>Niño-3.4</th>
<th>PDO</th>
<th>AO</th>
<th>PNA</th>
<th>NPGO</th>
<th>EP–NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmax</td>
<td>0.08 (0.74)</td>
<td>−0.19 (0.68)</td>
<td>−0.31 (0.74)</td>
<td>0.00 (1.31)</td>
<td>0.37 (0.72)</td>
</tr>
<tr>
<td>Tmin</td>
<td>0.13 (0.44)</td>
<td>0.36 (1.19)</td>
<td>−0.08 (0.29)</td>
<td>0.55 (1.13)</td>
<td>0.00 (1.24)</td>
</tr>
</tbody>
</table>
indices were markedly different in a relative sense for the Tmax and Tmin events. Since the characteristic atmospheric circulation patterns for the two kinds of heat waves are not that different from one another, this lack of consistency suggests these modes, at least on a monthly time scale, are unlikely to provide reliable information about the prospects of PNW heat waves. On the other hand, our results provide tentative evidence that forecasts of lower or higher odds of their occurrence may be practicable on the basis of projections of the EP–NP or associated circulation anomalies on monthly to seasonal time scales.

6. Discussion and conclusions

The composite patterns of atmospheric properties associated with the Tmax and Tmin categories of heat waves share many commonalities in the overall synoptic pattern. For example, it is well appreciated by the local forecasting community that PNW heat waves are associated with prominent ridges in 500-hPa Z. On the other hand, there were distinctions between the two categories in terms of their mean atmospheric anomaly patterns. In general, the differences between the two types of the events were either not significant or only marginally so when considering all of the days of the event, but statistically significant differences were found in the evolution composites, especially for the early stages of the events. The stronger 850-hPa winds, higher 500-hPa geopotential heights, and larger SLP gradient over the region for the Tmax events all support the idea that downslope warming over the west side of the Cascade Mountains is more important for the daytime events. The positive relationship between the strength of the 500-hPa Z anomalies and the magnitude of the Tmax regional anomalies also supports this finding.

Conversely, the Tmin events had a weaker 500-hPa ridge throughout the event in addition to weaker 850-hPa easterly winds, a weaker SLP gradient, and no relationship between the strength of the 500-hPa Z anomalies and the regional anomaly. The PW, however, was higher in the Tmin events than in the Tmax events, suggesting that the Tmin events are more related to downward longwave fluxes, as mediated by moisture (and temperatures) aloft. This hypothesis is supported by the relationship between PW and infrared sky temperature measured by an IR thermometer (Mims et al. 2011). While this relationship was not statistically significant in the composites that included all of the days in the event, the evolution composites indicated statistically significant differences in PW between the Tmax and Tmin events, and the composites that removed the overlapping events showed a greater distinction in moisture between the two types. Note that more drastic moisture differences between daytime and nighttime heat events were found in California and Nevada (Gershunov et al. 2009). The weaker 850-hPa temperatures for the Tmin events relative to the Tmax events is further evidence that the nighttime events tend to be associated with more than just a strong ridge and warm temperatures aloft to be consequential.

Most of the statistically significant differences between the two types of events occurred on the day before the event and on the first day for all of the variables, suggesting some implications for operational forecasting. The output from model output statistics (MOS) has comparable skill to that of NWS human forecasters during typical weather, but that is not generally the case for extreme events (Baars and Mass 2005). Successful forecasts for the latter require recognition of the characteristic patterns in key atmospheric variables; the fields described here may be especially valuable in an operational setting for discriminating between Tmax (e.g., stronger ridge and lack of moisture) and Tmin (e.g., higher humidity and weaker SLP gradient) events.

While we focused on the synoptic patterns of the daytime and nighttime events here, we do recognize that there is mesoscale variability from event to event. For example, there may be terrain-driven downsloping differences between events that are not apparent in our composite analysis. Mesoscale differences were used, in part, to determine the region to include in our analysis; namely, the coastal range in Washington and Oregon often acts as a barrier to the interior heat and hence several coastal stations were not included. When those temperatures do rise around coastal Washington, it is typical for the coast to cool down more quickly while the Puget Sound region usually stays hot for an additional 1–2 days.

Over the historical record of heat waves in western Oregon and Washington, the 2009 event stands out in terms of the duration of minimum temperatures. The 2009 event was the only event in the record with eight consecutive days above the 99th-percentile Tmin threshold (Fig. 3). Prolonged events have been shown to increase the impacts on human health (e.g., Sheridan and Kalkstein 2004), making the 2009 event more significant for our region. Despite this extreme, recent event, the typical duration of a Tmax event has not systematically changed over the period of record.

Our trend analysis revealed that the increase in the frequency of Tmin events is the only significant trend with respect to heat waves in the PNW. This finding, together with the results of Gershunov et al. (2009), suggests that this result holds for at least the west coast of the United States. Trends in nighttime heat events
are consistent with minimum temperatures increasing throughout the twentieth century globally (e.g., Vose et al. 2005) and in the region (Office of the Washington State Climatologist 2012). It is therefore not surprising to find this trend given that we used a constant threshold for defining a heat wave in a nonstationary climate. Perhaps more interesting then, is the lack of a significant trend in magnitude or frequency among the Tmax events. The most recent event in 2009 was the second strongest event in terms of magnitude, which may lead to a public misperception that daytime heat events are increasing. It is premature to make that assertion for the PNW based on the historical record presented here, even though climate model simulations indicate future increases in Tmax events in general (e.g., Clark et al. 2006; Meehl and Tebaldi 2004).

The focus of this study has been on historical heat waves, but our results are also applicable to considerations of future PNW heat waves. While it is beyond the scope of the present work, it would be interesting to examine whether the simulated historical record from global and regional climate models replicates the observed properties of the regional atmospheric circulation associated with PNW heat waves. Their forecasts of future regional patterns could answer questions about the probable changes in the nature of these events. For example, are these events likely to increase more in frequency or in magnitude? Will future circulation patterns favor more Tmax- or Tmin-type events? A characterization based on the regional atmospheric circulation, which in principle can be simulated by global-scale models, would be complementary to a dynamical-downscaling approach using high-resolution NWP models (e.g., Salathé et al. 2008) or regional climate modeling efforts for the western United States.

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