The Spatial Extent of California Heat Waves

By

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I. Introduction

Death, record-breaking energy consumption, and economic hardship are impacts felt by society during the event of a heat wave. The weather phenomenon known as the heat wave has been found to be the leading cause of weather-related mortalities among humans in the United States (Lipton, 2005; Davis, 2005). In the California 2006 heat wave alone, near 140 human lives were lost due to the extreme heat (Blier, 2006; Edwards, 2006). However, not only in California are the societal impacts from heat wave events felt, but throughout the rest of the nation and world as well. In the Western European heat wave of August 2003, close to 35,000 deaths were attributed to the heat, along with record-breaking temperatures (Lipton, 2005). Among the many lives that are taken by heat waves, the elderly are the most susceptible age group to losing their life in such an event (World Health Organization, 2003). Death rates aside, individuals are also susceptible to heat-related illnesses such as heat fatigue, heat exhaustion, and heat stroke (World Health Organization, 2003).

Mortality, an important and concerning effect, is not the only impact of heat waves. In the California 2006 heat wave mentioned above, the state of California also set an all-time high energy consumption record on 24 July, with a usage amount of 50,270 Megawatts. Simultaneously, more than one million customers experienced a loss of electrical power (Blier, 2006). These are examples of some of the effects of heat waves that directly impact the communities in which the events occur.

There is no universal definition to classify an event of extreme temperature as a heat wave. In studies that have been carried out concerning the subject, the definition of the weather phenomenon often varies from study to study, resulting in a situation that makes it difficult to compare the severity of separate events, notably those of the past and present (Robinson, 2001). Being able to define such an event, and therefore make such comparisons, would provide a better understanding of the trends and development of these weather phenomena.

Heat waves have been studied by many scientists and authors who have provided a better understanding on the subject, along with various ways in which to define such an event. Robinson (2001) discusses the need for a definition of a heat wave event and proposes one based on the National Weather Service (NWS) criteria for heat stress watches and warnings. Starting with the NWS criteria that requires the daytime high heat index to be greater than 40.6ºC (105ºF) and nighttime low heat index to be greater than 26.7ºC (80ºF) for 2 consecutive days, he proposes allowing for changes that reflect variations in local climate due to geography and location. In areas where there are many heat wave events taking place, such as the South and Southwest, thresholds are examined using percentile-based values. These values were made by determining the heat index value that was exceeded a specified percent of the time for both overnight low heat index values and daytime high heat index values. If these values are greater than NWS values, then they become candidates for being a heat wave threshold. The goal that was set and achieved by Robinson (2001) was to have a smooth spatial transition between areas using the NWS criteria and those using the percentile-based criteria (Robinson, 2001).

Based on the proposed heat wave definitions in Robinson (2001) and 1951-1990 temperature and humidity data from the Surface Airways dataset of the National Climatic Data Center (NCDC), 1.8 heat waves occur per decade nationwide, with the events displaying a regional pattern. The heat waves were observed to be most common in the

South, and rare in the Northwest and South Florida. The analysis showed that areas of current high heat wave frequency show a decrease in frequency, and those of current low heat wave frequency show an increase in frequency. The completion of the analysis provides a baseline climate description of heat waves for the United States (Robinson, 2001).

The heat index value used by Robinson (2001) takes both temperature and humidity into account and "approximates the environmental aspect of the thermal regime of a human body (Robinson, 2001)." Due to the fact that humidity levels are low in the Sacramento area and throughout California compared to most other regions, humidity is determined to be not as relevant as absolute temperatures for determining a heat wave event in the current thesis study, and therefore, only absolute temperatures are used.

However, temperatures and heat index are not the only measures that scientists have examined in attempting to identify and define heat waves. Lipton et al. (2005) discuss a procedure of forecasting heat waves using climatic anomalies. Their study examines particular anomaly fields of significant mid-latitude heat waves that have taken place in the United States and Western Europe. Upon studying the atmospheric synoptic scale patterns and anomaly variables, they find that similarities exist between the patterns that are characteristic of the extreme heat events in both countries (Lipton et al., 2005).

Lipton et al. (2005) examine the anomaly fields of 500hPa heights, 850hPa temperatures, 700hPa temperatures, and precipitiable water (PW) during the heat wave events. The patterns that were found among all heat wave events were: a 500hPa ridge, a midtropospheric anticyclone associated with a 594dm height contour, and positive 850hPa and 700hPa temperature anomalies. For the most extreme heat wave cases, and often those with the highest amount of heat-related fatalities, a positive PW anomaly was also present, with the anomalous area of PW being to the north of the ridge and the area with the maximum temperatures. The presence of PW is able to have such an impact on the severity of a heat wave because once humid air is in place, cooling during the night is limited and results in high temperatures at the start of the next day. The definition of a heat wave that was used in the Lipton et al. (2005) analysis to determine the heat wave events required that the daily maximum temperature of June through September months remain 2 standard deviations above normal (based on a 1970-2000, 30-year climatology) for at least 2 consecutive days (Lipton et al., 2005).

Lipton et al. (2005) also emphasize the importance of the use of anomalies. It is explained that while a certain temperature in one area of the United States may be considered normal, a lesser temperature in another area could be considered above-normal. Lipton et al. (2005) conclude that height anomaly fields are more successful in determining heat waves over absolute height fields.

An advantage of having a definition of a heat wave is to better compare the characteristics, structure, development, and changes between past heat waves and the heat waves that occur in the present. Meehl and Tebaldi (2004) investigate the changes in heat waves over the years and into the future with the use of a global coupled climate model and NCEP/NCAR reanalysis data. The 1995 Chicago and the 2003 Paris heat waves are chosen as example cases to examine the changes. The model and reanalysis data show that associated with an increase in the 500hPa heights, both the frequency (number of heat waves per year) and duration of heat waves in the future will increase in Chicago and Paris.

The atmospheric circulation observed during the heat waves examined in Meehl and Tebaldi (2004) is one represented by a semistationary 500hPa positive height anomaly. Subsidence, light winds, clear skies, warm air advection, and sustained high surface temperatures are, in turn, dynamically produced from the height anomaly. Model output shows an increase in the 500hPa height anomaly in the future time period, as well as with an increase in the 500hPa heights (Meehl and Tebaldi, 2004).

Two definitions of a heat wave are presented and explained in the Meehl and Tebaldi (2004) study, one of which is more qualitative, and the second of which uses the exceedence of specific thresholds to determine a heat wave. The first heat wave definition requires "several consecutive nights with no relief from very warm nighttime minimum temperatures (Meehl and Tebaldi, 2004)." The second, quantitative definition states that a heat wave is the longest period of consecutive days that satisfies the following three conditions: 1) The daily maximum temperature is greater than T1 for at least 3 days, where T1 (threshold 1) is equal to the 97.5th-percentile of the distribution of maximum temperatures in the observations and in simulated present day climate, 2) the average daily maximum temperature is greater than T1 for the entire period, where T2 (threshold 2) is equal to the 81st-percentile, and 3) the daily maximum temperature is greater than T2 for every day of the entire period. This definition is useful in determining frequency and duration of current and future heat waves. The model analysis suggests that regions in which current heat waves are very severe and also regions in which heat waves are not as severe will both have an increase in heat wave severity in the future, with the regions of current high severity having the largest increase (Meehl and Tebaldi, 2004).

Accompanying changes in the intensity of heat waves over the years and into the future is the related effect of human mortality. Davis et al. (2005) examine the relationship between heat waves and heat wave-related mortalities, using 1964-1998 mortality records in five United States cities (Davis et al., 2005). The heat event definition that Davis et al. (2005) use to determine significant events requires two or more consecutive day runs of above normal apparent temperatures (with normal defined by the 30-day moving average). In addition to this definition, heat waves are classified into the 4 categories of killer heat waves, non-killer heat waves, high mortality normal heat, and normal mortality normal heat (Davis et al., 2005).

Davis et al. (2007) also discuss and examine this relationship using mortality rates due to heat waves as a response variable, since there is no standard definition for a heat wave. The definition for a "heat event" in this analysis is a liberal one and requires "a maximum apparent temperature that exceeds one standard deviation calculated using a centered moving 5-year window (Davis et al., 2007)." It was shown that 3-4 days is the minimum time that is needed to instigate heat-related deaths. In regard to absolute versus relative heat waves, where absolute heat events are those defined based on absolute conditions and relative heat events are those defined based on deviations from normal, both were present, but absolute heat waves were larger in number than relative. The authors of the analysis suggest that the findings of the study could be involved in city planning and decision-making (Davis et al., 2007).

It can be seen from Table 1.1 below that the number of heat related fatalities in the United States, Puerto Rico, Guam, and the Virgin Islands has increased overall from 1986 to 2006. In addition, the 10-year average number of heat fatalities from 1997-2006 also outnumbers that of the 10-year average number of fatalities for floods, lightening, tornados, hurricanes, cold, winter storms, or wind (NWS).

Table 1.1. The yearly, total, and 10-year average number of fatalities due to heat, floods, lightening, tornados, hurricanes, cold, winter storms, and wind in the U.S., Puerto Rico, Guam, and Virgin Islands. Dash (-) indicates unavailable yearly data. Data from National Weather Service.

Year	Heat		Floods	Lightening	Tornados	Hurricanes	Cold	Winter Storms	Wind
1986	40		94	68	15	11	-	69	-
1987	38		70	88	59	0	-	30	-
1988	41		31	68	32	9	17	55	-
1989	6		85	67	50	38	121	63	-
1990	32		142	74	53	0	13	48	-
1991	36		61	73	39	19	13	45	-
1992	8		62	41	39	27	14	59	-
1993	20		103	43	33	2	18	66	-
1994	29		91	69	69	9	52	29	-
1995	1021		80	85	30	17	22	17	84
1996	36		131	53	26	37	62	86	54
1997	81		118	42	67	1	51	90	75
1998	173		136	44	130	9	11	68	65
1999	502		68	46	94	19	7	41	52
2000	158		38	51	41	0	26	41	51
2001	166		48	44	40	24	4	18	31
2002	167		49	51	55	53	11	17	45
2003	36		86	43	54	14	20	37	43
2004	6		82	31	34	34	27	28	42
2005	158		43	38	38	1016	24	43	25
2006	253		76	47	67	0	2	28	40
TOTAL	3007		7037	9045	6548	3296	515	978	607
10-year average (1997-2006)	**170**		**74**	**44**	**62**	**117**	**18**	**41**	**47**

In California, with a population of nearly 38 million people, the heat waves that affect the state, and their notable characteristics, are of much interest and concern. The residents of the Sacramento and San Joaquin Valleys, in particular, frequently experience high summer temperatures. Even though residents have learned to adapt to the uncomfortable conditions over the years, the intensity and effects of the events are still felt. The July 2006 heat wave that impacted the state in many ways has also been examined by scientists. Blier (2006) and Edwards et al. (2006) discuss the significance of the record-breaking heat wave and its synoptic meteorological conditions. Both note that the July 2006 heat wave in central California was historically significant in that it broke overnight and daytime high temperatures, most notably of these, the high overnight temperatures. Other important features of the July 2006 heat wave were the long duration of extreme heat lasting 11 days, unusually high dewpoints resulting in negative impacts on humans, and record-breaking energy consumption records (Blier, 2006; Edwards et al., 2006).

Blier (2006) affirms that a difference in the magnitude of the heat wave was also observed between the inland, low-level valleys of central California and the higher-elevation hills and mountains, where the magnitude and intensity was much greater and more significant in the valleys than at the higher-elevated areas. The large difference in temperatures between coastal and inland areas over a small spatial extent showed the existence of a shallow coastal marine layer, with the coastal temperatures not reaching nearly as high temperatures as inland valley temperatures or previously recorded record-high coastal temperatures (Blier, 2006).

The meteorological conditions that were representative of the California 2006 heat wave included a retrograding 500hPa height anomaly pattern. The westward shift of the height anomaly caused a large-scale upper-level high to position itself over the Great Basin. A shift in mid-level 500hPa winds caused winds to blow from the east-southeast into California, causing monsoonal moisture from lower latitudes to be transported to California, resulting in high upper-level moisture over the southwest United States which allowed higher overnight lows, and, in turn, higher daytime humidity the following day.

The higher overnight lows that were observed resulted in part from the combination of high dewpoint temperatures and calm winds (Blier, 2006; Edwards et al., 2006). No heat wave definition was explained or proposed in Blier (2006) or Edwards et al. (2006).

Moisture is not used as a variable in this thesis study. However, if moisture from southern latitudes moved north into California at any point during a heat wave due to a shift in winds, as was the case in the 2006 heat wave in California, the intensity of the event could potentially increase due to the moister air. Therefore, the addition of moisture as a variable in order to investigate its effect on heat waves could be a worthwhile area to investigate further.

Finally, Grotjahn and Fauare (2007) discuss how to forecast significant weather events in the Sacramento area by using historical analogs. Heat waves are included among the significant weather events covered. Grotjahn and Faure (2007) focus on examining the geopotential, pressure, temperature, and wind fields at the beginning and end times of heat waves in the Sacramento area. Their study builds on the study of Staudenmaier (1995), which attempted to familiarize forecasters with the synoptic patterns of significant weather events in the Sacramento area. Concerning heat waves, Staudenmaier (1995) concluded that high heights measuring above 5920m at the 500hPa level over Nevada, along with a high located off of the coast of California at the 850hPa level with a weak northerly gradient across California, signaled maximum heating in the area. Grotjahn and Faure (2007) improve upon Staudenmaier’s study by 1) using data that covers a larger area, 2) looking at the times prior to the event onset, 3) using better data that consisted of NCEP/NCAR Reanalysis data, 4) introducing statistical tests to examine the statistical reliability of the findings, and 5) using more variables at more levels. Grotjahn and Faure (2007) capture 15 heat wave event occurrences in the June to September months from 1979-1999 by using the definition of a heat wave event to be at least three consecutive days during which the daily maximum temperatures are above 100ºF (38ºC), with the temperature of at least one day being above 105ºF (40.5ºC). Grotjahn and Faure (2007) observe that the end of a heat wave is 1) hard to forecast due to the temperatures that remain elevated until the end of the event, and 2) brought about by the delta breeze, an onshore flow of cool, moist air from the San Francisco Bay area inland towards the Central Valley. Of important note in their study is the fact that both the 300hPa and 850hPa ridges at the west coast of California are linked to larger-scale patterns and cover several southwestern states. This observation is very informative of the nature and structure of heat waves in that it shows heat waves, due to their relationship to larger-scale atmospheric patterns, are in turn, widespread events that are able to affect large areas (Faure and Grotjahn, 2001). The 850hPa temperature field at the event onset is the most relevant synoptic pattern to this thesis study.

In Figure 1.1 below is the 850hPa mean air temperature and significant temperature anomalies, from Grotjahn and Faure (2007), recorded at the onset of the hottest heat waves that occurred in Sacramento. Of important note, and the focus for this project, is the large area of positive anomalies along the western coast of North America. This area of highly significant anomalies, with the majority being greater than 98.5% significant, is centered along the western seaboard and extends as far north to 52.5˚N latitude, north of Washington state, and south to 32.5˚N latitude on the coast to near the California state and Mexico border. The area extends as far west over the Pacific Ocean to 135˚W longitude and east over California to 117.5˚W longitude into western Nevada, at its middle, and also extends to 112.5˚W longitude into Canada, at its northern points, and to 115˚W longitude at its southern points. These coordinates encompass the majority of the states of California, Oregon, Washington, and western Nevada, therefore, extending more in the north and south directions, than eastwards.

850hPa Mean Air Temperature

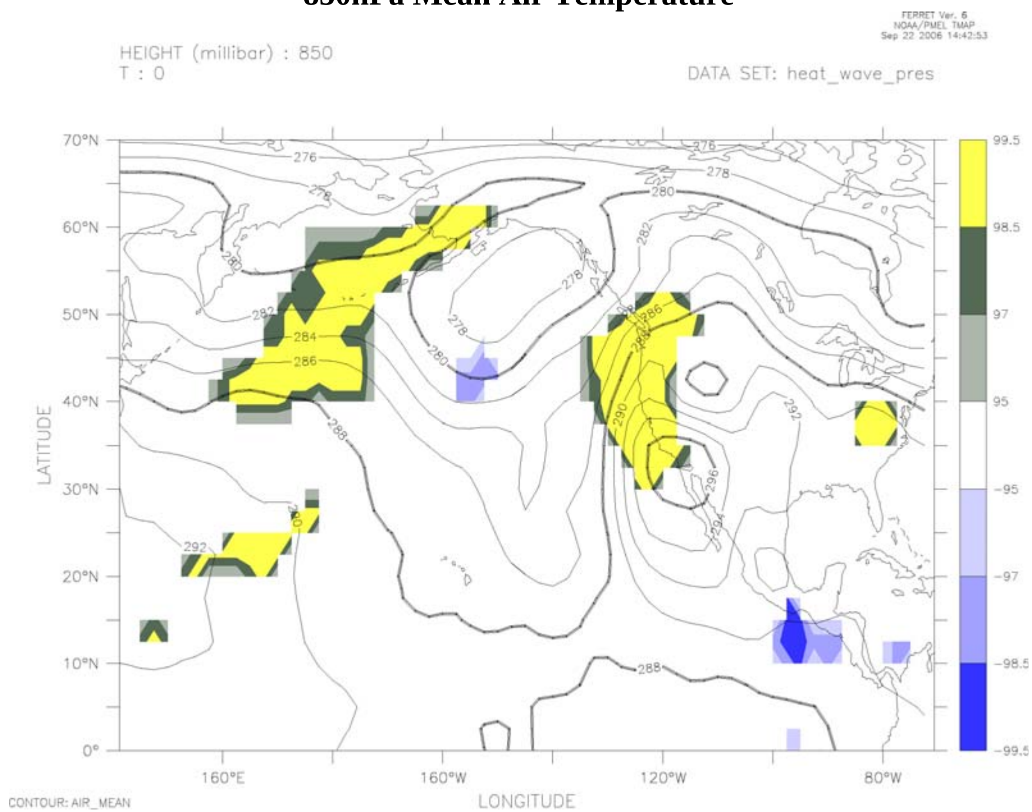

Figure 1.1. 850hPa Mean Air Temperature. Contours represent mean air temperature (Kelvin), and shading represents areas having positive (negative) temperature anomalies with significance greater than (less than) 95% (-95%). Of important note is the area of positive anomalies centered along the western coast of the United States. Plot produced by Grotjahn and Faure (2007).

Figure 1.1 highlights the important observation that the anomalous temperatures of a heat wave event that takes place in Sacramento spreads across surrounding areas at substantial distances, especially northwards and southwards. The anomaly pattern in the figure shows that these heat waves are not just a local weather event to Sacramento, but are part of a large-scale synoptic pattern.

In Table 1.2 below, the heat wave event definitions and their corresponding sources can be seen for the studies discussed above.

Table 1.2. Heat wave definitions and their sources.

Source	Definition
Robinson (2001)	A period of at least 48 hours during which neither the overnight low nor the daytime heat index (H_i) falls below the NWS heat stress thresholds (80ºF (26.7ºC) and 105ºF (40.5ºC)). At stations where more than 1% of both the high and low H_i observations exceed these thresholds, the 1% values are used as the heat wave thresholds
Lipton et al. (2005)	Daily maximum high temperature remains 2 standard deviations above normal for at least 2 consecutive days
Meehl and Tebaldi (2004)	**1)** *Qualitative*: Several consecutive nights with no relief from very warm nighttime minimum temperatures **2)** *Quantitative*: The longest period of consecutive days satisfying the following 3 conditions: i. Daily maximum temperature > T1 for at least 3 days ii. Average daily maximum temperature > T1 for entire period iii. Daily maximum temperature > T2 for every day of entire period, where T1 (threshold 1) = 97.5th %-ile of distribution of maximum temperatures in the observations and in simulated present day climate T2 = 81st %-ile
Davis et al. (2005)	Two or more consecutive day runs of above normal apparent temperatures (with normal defined by the 30-day moving average)
Davis et al. (2007)	A maximum apparent temperature that exceeds one standard deviation, calculated using a centered moving 5-year window
Grotjahn and Faure (2007)	At least 3 consecutive days during which the daily maximum temperatures are above 100ºF (38ºC), with at least one above 105ºF (40.5ºC)

It should be noted that the quantitative definition of Meehl and Tebaldi (2004) in the table above is based on the definition of Huth et al. (2000), in which gridded data is used rather than station data. This is important to point out because when using absolute temperature as a criteria, the source of the data and observations (such as point data or grid-box averaged data) may be important. The difference in the types and resolutions of the data can possibly result in different values. The qualitative definition of Meehl and Tebaldi (2004) in the table is based on the definition of Karl et al. (1997), which uses station data. Meehl and Tebaldi (2004) also reference Schar et al. (2004) and Palecki et al. (2001) as having alternative definitions of heat waves, where Schar et al. (2004) also uses gridded data.

It can be seen from the above studies that heat waves are a weather phenomenon of importance and concern due to their largely-felt impacts across the state of California. It has been shown that 1) mortality, health related-illnesses, and economic loss have been associated with heat waves, 2) there exists variety in heat wave definitions, and 3) there is a large-scale synoptic pattern associated with heat wave events. This study will focus on the latter two observations by building upon the finding of Grotjahn and Faure (2007) that heat wave events exhibit large-scale synoptic patterns by observing the spread of California heat waves that affect Sacramento. This will be done by identifying heat waves in California and surrounding states by using a specified definition of a heat wave event and performing a matching scheme on the top ranked events. Absolute and anomalous temperature data from 30 stations in California and surrounding states will be used. The goal of the study and its results is to build a better understanding of the extent to which Sacramento heat waves are shared by other regions within and outside of the state. The methodology of data choice, event identification, and station comparisons will be discussed in Section II of the paper. The results of the matching scheme, correlations, and other findings from the study will be discussed in Section III, and the summary and conclusions of the study will be discussed in Section IV.

II. Methodology

A. The Data

Cities were chosen in order to represent spatially the inland Sacramento and San Joaquin valleys, the California coast, and the surrounding states of Washington, Oregon, and Nevada. The 10 cities chosen to represent the Central Valley were Redding, Red Bluff, Colusa, Sacramento, Stockton, Modesto, Merced, Fresno, Visalia, and Bakersfield. The 10 cities selected to represent the coastline were Crescent City, Eureka, Covelo, Graton, San Francisco, Monterey, San Luis Obispo, Santa Barbara, Santa Ana, and Vista. The 10 cities representing the three surrounding states were Seattle, Spokane, and Yakima, Washington; Portland, Eugene, Medford, Pendleton, and Baker City, Oregon; and Reno and Tonopah, Nevada.

The topography of California and the surrounding states is useful to know when the different stations are discussed. California, Oregon, Washington, and Nevada have many mountain ranges, and therefore, some of the stations mentioned above are located close to these ranges. Portland, OR, is nestled in between the Coast and the Central Cascade Ranges; Pendleton, OR, is to the immediate north of the Blue Mountains; Baker City, OR, lies in between the Blue and the Wallowa Mountains; Seattle, WA, is located on the Puget Sound in between the Olympic Mountains and the Northern Cascade Range; Reno, NV, lies directly east of the Northern Sierra Nevada Mountains; and Tonopah, NV, lies to the east of the Central Sierra Nevada Mountains and also among ranges in Nevada. Crescent City and Eureka are located along the Pacific coast at the western edge of the Klamath Mountains. Another characteristic topographic feature of California is the Central Valley, which is approximately 450 miles long and is located in between the

Coast Ranges and the Sierra Nevada Mountains, and is where ten of the 30 stations, including Sacramento, are located.

The geographic locations and 3 letter codes of the selected stations can be seen in Figure 2.1 and Table 2.1 below.

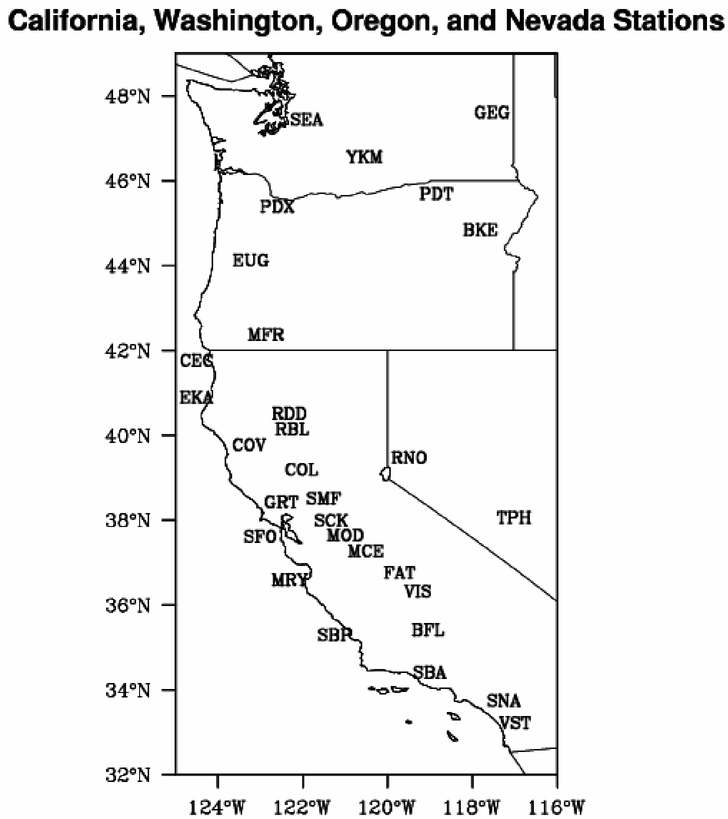

Figure 2.1. The geographic locations of the 30 selected California, Washington, Oregon, and Nevada stations.

Table 2.1. The station codes and names for the selected 30 stations, separated by their geographic regions.

Central Valley Stations		**Coastal Stations**		**Surrounding State Stations**	
Redding	RDD	Crescent City	CEC	Seattle	SEA
Red Bluff	RBL	Eureka	EKA	Spokane	GEG
Colusa	COL	Covelo	COV	Yakima	YKM
Sacramento	SMF	Graton	GRT	Portland	PDX
Stockton	SCK	San Francisco	SFO	Eugene	EUG
Modesto	MOD	Monterey	MRY	Medford	MFR
Merced	MCE	San Luis Obispo	SBP	Pendleton	PDT
Fresno	FAT	Santa Barbara	SBA	Baker City	BKE
Visalia	VIS	Santa Ana	SNA	Reno	RNO
Bakersfield	BFL	Vista	VST	Tonopah	TPH

The maximum and minimum daily air temperature data for all California stations used in this project were obtained from the University of California Statewide Integrated Pest Management Program (UC IPM) database of information accessible online (University of California, 2007), which is a provider of weather data and products to the public. Temperature data were chosen by county and specific station site at which the readings took place. Among the data available were current daily and hourly data, and long-term data that were available from climate stations. Climate station data were selected for this project, providing data that spanned a longer time period. For each selected station, the observer, location, recorded variable, sensor height, backup stations, and percentage of values stored for certain time periods were provided.

At the time of data retrieval, the available records for the 10 valley stations contained UC IPM database records spanning 1 January 1950 to about January 2007 and measured temperature data at a sensor height of five feet (1.5 m). The available records for the 10 coastal observation sites contained UC IPM database records that spanned from 1 January 1951 to about January 2007, except for the Graton and Vista observation sites, whose records spanned from 1 July 1948 to about January 2007, and 1 May 1962 to about January 2007, respectively. Temperature measurements for all coastal stations were measured at a sensor height of five feet (1.5 m).

The data for the Washington, Oregon, and Nevada stations were obtained from the Global Summary of the Day (GSOD) provided by the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center's (NCDC) Climate Data Online (National, 2007). The location, observer, and elevation were provided for all stations. Tables 2.2, 2.3, and 2.4 below list the information for the selected 30 stations.

Table 2.2. California Central Valley Station Information. NWS = National Weather Service, FAA = Federal Aviation Administration, ASOS = Automated Surface Observation Stations

City	Station Site (if known)	County	Latitude	Longitude	Elevation (meters)	Observer (if known)
Redding		Shasta	40º 31´´N	122º 19´´W	153	NWS
Red Bluff	Red Bluff Municipal Airport	Tehama	40º 9´´N	122º 15´´W	106	
Colusa		Colusa	39º 12´´N	122º 1´´W	15	City of Colusa
Sacramento	Sacramento Executive Airport	Sacramento	38º 31´´N	121º 30´´W	5	FAA-Flight Service Station
Stockton	Stockton Fire Station #4	San Joaquin	38º 0´´N	121º 19´´W	4	
Modesto		Stanislaus	37º 39´´N	121º 0´´W	28	Modesto Irrigation District
Merced		Merced	37º 17´´N	120º 31´´W	47	Merced Fire Department
Fresno	Fresno Yosemite Internation al Airport	Fresno	36º 46´´N	119º 43´´W	101	NWS-ASOS
Visalia		Tulare	36º 20´´N	119º 18´´W	99	Visalia Fire Department
Bakersfield	Bakersfield WSO Airport	Kern	35º 25´´N	119º 3´´W	149	NWS-ASOS

Table 2.3. California Coastal Stations Information. NWS = National Weather Service.

City	Station Site (if know)	County	Latitude	Longitude	Elevation (meters)	Observer
Crescent City		Del Norte	41º 46´´N	124º 12´´ W	12	Mrs. Leslie Disrude
Eureka	Eureka WSO, Woodley Island	Humboldt	40º 48´´ N	124º 10´´ W	6	NWS
Covelo	Round Valley Airport	Mendocino	39º 47´´ N	123º 15´´ W	436	William B. Cook
Graton		Sonoma	38º 26´´ N	122º 52´´ W	61	Mrs. Louise Hallberg
San Francisco	San Francisco WSO Airport	San Mateo	37º 37´´ N	122º 23´´ W	2	NWS
Monterey		Monterey	36º 36´´ N	121º 54´´ W	117	Mr. Robert J. Renard
San Luis Obispo		San Luis Obispo	35º 18´´ N	120º 40´´ W	96	California Polytechnic State University
Santa Barbara		Santa Barbara	34º 25´´ N	119º 41´´ W	2	City of Santa Barbara
Santa Ana	Santa Ana Fire Station	Orange	33º 45´´ N	117º 52´´ W	41	Santa Ana Fire Department
Vista	Fire Station #3	San Diego	33º 14´´ N	117º 14´´W	155	Vista Fire Department

Table 2.4. Washington, Oregon, and Nevada Station Information. ASOS = Automated Surface Observation Stations, NWS = National Weather Service, COOP = Cooperation Stations, AC = Cooperative Aviation, NEXRAD = NEXt generation RADar, FAA = Federal Aviation Administration, AAF = Army Air Field.

City	Station Site	County	Latitude	Longitude	Elevation (meters above sea level)	Observer
Seattle, WA	Seattle Tacoma International Airport	King	47º 27´´N	122º 19´´W	113	ASOS-NWS COOP ASOS
Spokane, WA	Spokane International Airport	Spokane	47º 37´´N	117º 32´´ W	717	Air Sampling Station ASOS-NWS ASOS COOP
Yakima, WA	Yakima Air Terminal	Yakima	46º 34´´N	120º 33´´ W	324	ASOS ASOS-NWS COOP
Portland, OR	Portland International Airport	Multnomah	45º 35´´N	122º 36´´ W	6	COOP ASOS ASOS-NWS
Eugene, OR	Eugene Mahlon Sweet Airport	Lane	44º 08´´ N	123º 13´´ W	108	ASOS COOP ASOS-NWS
Medford, OR	Medford Rogue Valley Airport	Jackson	42º 23´´ N	122º 52´´ W	395	ASOS-NWS ASOS COOP
Pendleton, OR	Pendleton E Or Rgnl Airport	Umatilla	45º 42´´ N	118º 51´´ W	453	ASOS-NWS ASOS COOP NEXRAD
Baker City, OR	Baker City Municipal Airport	Baker	44º 51´´ N	117º 49´´ W	1024	ASOS-NWS ASOS ASOS-FAA COOP
Reno, NV	Reno Tahoe International Airport	Washoe	39º 29´´ N	119º 46´´ W	1344	ASOS ASOS-NWS COOP
Tonopah, NV	Tonopah AAF	Nye	38º 04´´ N	117º 01´´ W	1650	AAF

Temperature data were extracted from the websites and put into a comma-delimited data file for the 28-year time period of 01 January 1979 to 30 September 2006, for each station. Due to the utilization of satellites in 1979, dates after 1979 were chosen to assure consistent data when creating the 850mb temperature anomaly field plots discussed later. A 28-year long time period was determined to be a reasonable amount of time to observe at least a dozen severe heat wave events. The summer months of June, July, August, and September (JJAS) were considered for heat waves because they are the months in which heat waves most frequently occur. These data files were then saved into a Wordpad text file. This external data was imported into Microsoft Excel, and read into the created event identification program, IPM.ncl, of which most parts can be seen in Appendix C. Each station file consisted of 10,135 times, maximum daily temperatures, and minimum daily temperatures which corresponded to one reading for each day between 01 January 1979 and 30 September 2006.

B. Event Identification

NCAR Command Language (NCL), a program language designed for analyzing and graphing scientific data, was used to analyze the data. The programs, which will be individually referenced later, are in Appendix C.

The steps taken to determine the spatial extent of Sacramento heat waves included selecting JJAS dates and temperatures from the entire dataset of maximum and minimum atmospheric temperature data, creating long term daily means and anomalies, selecting heat wave events based on certain criteria, correlating temperature data, ranking heat wave events based on certain criteria, matching the top heat wave event dates between cities, using bootstrap resampling statistical methods to derive certain sample statistics, and creating 850hPa level maximum temperature and anomaly field plots. Other graphs and plots were also created in order to display information about the data. This graphical output aided in identifying and understanding trends, similarities, and differences of the temperatures and heat wave events across the stations. Determination of heat wave events was performed using both unfiltered and filtered temperature data. Filtering was done in order to smooth the extreme peaks and valleys in the daily raw temperature data so that the lengths of the heat waves could be more reliable. A heat wave event that appears as two separate events due to a low-valued maximum temperature that does not surpass the threshold criteria, could possibly be considered one event after the filtering is performed. Filtering of daily data used a low-pass Lanczos filter with 51 weights and a cut-off period of 3. The filtering program, filter.ncl, is in Appendix C. Each task mentioned above will be explained in further detail.

Once JJAS times and temperature data are selected, long term daily means (LTDM) for maximum and minimum temperatures are computed for each date. For example, the LTDM maximum temperature for 01 June would be equal to that of the sum of the 01 June maximum temperatures from each year divided by the total number of years in the dataset, 28. Therefore, a total of 122 LTDMs, one for each day in JJAS, are computed. The LTDM is then used to compute the maximum and minimum anomalies for each date, for every year, by subtracting the LTDM temperature from the observed temperature recorded on that specific date.

Now that the correct data have been selected, and certain initial calculations made, the heat wave events are now identified based on certain criteria. Therefore, a definition of a heat wave must be created or chosen to implement into the program. It was decided to base the definition of a heat wave on the temperature anomaly data. Using temperature anomalies to define a heat wave would base the event on its deviation from normal on those particular days of the event, rather than absolute temperatures. Using a specified absolute temperature across the board could result in some cities reaching that determined threshold many of the times, because that city frequently experiences high temperatures, while other cities may never reach the threshold, yet at the same time may be experiencing very high temperatures relative to that city's normal temperatures for that day. A temperature of 100ºF (38ºC)may be a normal occurrence for some cities in the Central Valley, and not anomalous on some dates, while for cities at the coast, a lower temperature would be anomalous and very warm compared to what is normally observed for that region. It was decided to define a heat wave event as at least three consecutive days with temperature anomalies greater than a specified threshold for every day and at least one day where the temperature anomaly exceeded an even higher threshold. The structure of the definition stems from Grotjahn and Faure's (2007) definition, but using temperature anomalies rather than absolute temperatures.

In order to execute such a definition, a maximum and minimum anomaly threshold must be selected. Once thresholds are chosen, all dates in the historical record having anomalous temperatures that exceed the minimum anomaly threshold for three consecutive days are searched for and selected. Once these candidate dates are selected, the historical record is searched again for those dates that satisfy the criteria of at least one of these consecutive dates having a maximum temperature anomaly that exceeds the maximum temperature anomaly threshold. If no dates are found that satisfy this second requirement, then that candidate event is no longer considered.

In order to determine the appropriate minimum and maximum anomaly thresholds, different combinations of thresholds were tested. Threshold pairs 5 degrees apart were chosen, once again mimicking the definition of Grotjahn and Faure (2007). Examples tested included 8 and 13, 9 and 14, 10 and 15, and 11 and 16 degrees Fahrenheit. The anomaly threshold pair was chosen to obtain, at the most, 20 to 30 heat wave events in Sacramento for the 28 years being reviewed. This would be roughly equal to about 1 heat wave event per year. It was found that a minimum anomaly threshold of 10 and a maximum anomaly threshold of 15 was the most suitable pair to deliver these results. Higher anomaly threshold pairs that were tested resulted in too few events for some cities, while smaller anomaly threshold pairs resulted in too many events in other cities. Events would not be considered extreme if a very large number of events took place at one station. The criteria for this first definition of a heat wave event can be seen in Table 2.5 below.

Table 2.5. Criteria for the first definition of a heat wave.

	Criteria
1	At least 3 consecutive days where maximum temperature anomaly ≥ 10
2	At least 1 day where maximum temperature anomaly ≥ 15

Once the candidate heat wave events were identified, it was found that some of the selected heat wave events included maximum temperatures that were perhaps too low to be considered as a heat wave, despite the fact that they were sufficient in exceeding the anomaly threshold. For example, a 10ºF anomaly could be as low as 96ºF (36ºC) at some of the Central Valley cities. Although a warm temperature, it was felt that temperatures near this range were not hot enough to be included in an extreme event such as a heat wave in the Central Valley. While anomalies are very important in the examination of weather patterns and unusual events on weather maps, absolute temperatures are also important when considering the severity and impacts of a heat wave. It is the heat intensity that effects the people and economy of a particular community, and therefore, it is important to also examine the absolute temperatures. Thus, another criterion was developed to include in the heat wave definition that required the average maximum temperature of a heat wave event to also equal or exceed 100ºF (38ºC). The criteria for the second definition of a heat wave event can be seen in Table 2.6 below.

Table 2.6. Criteria for the second definition of a heat wave.

	Criteria
1	At least 3 consecutive days where maximum temperature anomaly ≥ 10
2	At least 1 day where maximum temperature anomaly ≥ 15
3	Average maximum temperature of event ≥ 100ºF (38ºC)

C. Comparing Stations (Rankings and Matchings)

After heat wave events were selected based on the two definitions above, the heat wave events for each station were ranked, first, based on the maximum temperature of each event and, second, based on the highest consecutive 3-day average of maximum temperature anomalies within each event. The top 15 events of each city were selected for each ranking method. For the first ranking method, the date with the largest daily maximum temperature within each event was searched for and selected. The heat wave with the largest maximum temperature was determined to be the "hottest" or "most intense" heat wave of that city's record and the heat wave with the smallest maximum temperature was determined to be the "least hot" or "least intense" heat wave of that city's record.

For the second ranking method based on the highest consecutive 3-day average of maximum temperature anomalies, three days was chosen as the time interval of which to take the average because all heat waves, according to the implemented definition, had to be at least 3 days in duration. All heat waves would have an averaged value. The heat wave with the highest average was considered the most intense event and the event with the lowest average was considered the least intense.

The two methods of ranking the hottest heat wave events at each station resulted in differing event lists. The events were ranked according to both maximum temperature and 3-day averages of anomalies because each method highlights different and important features of heat waves. Ranking by the highest maximum temperature of the events highlights the "absolute" or "peak" intensity of the heat wave event. The events that have the highest temperatures will be considered the most intense heat waves. Under this ranking method, coastal stations will not have as many heat events as, say, Central Valley stations, because high temperatures reaching into the 100s do not occur as often at the coast as they do in the Central Valley. Since this ranking scheme identifies areas experiencing the worse "absolute" heat intensity, that knowledge identifies cities whose population and economy might suffer hardship from negative effects of the high temperatures.

When ranked by the highest 3-day average of maximum temperature anomalies, temperature anomalies and anomalous weather patterns are the highlighted features of the events. The latter is highlighted because the event is ranked in part due to the persistence of the high temperatures. Under this ranking method, events are at stations that experience similar anomalous strength of a heat wave relative to the mean local climate of each station, but not necessarily the same high absolute temperatures. Therefore, even if a city does not observe temperatures as high as Sacramento, its anomalous strength and deviation from its local mean can still be compared. For example, because anomalies do not have a seasonal trend, when a heat wave event occurs in September when it is generally cooler, rather than in July, maximum temperatures may not reach the event thresholds, though the large-scale weather pattern may be similar. Once identified, the anomalous weather pattern can be used in the future to indicate other extreme events such as heat waves. So, another purpose of using anomalies is to even out the season and to create a longer record with which to work, which results in more samples and, thus, better statistics.

Once the top 15 heat wave events for each station were ranked, the heat wave event dates of these events from each valley, coastal, and surrounding state station were compared with the top 15 event dates found in Sacramento using a matching scheme. The matching scheme program, IPM_Stats.ncl, can be seen in Appendix C. If an event date from one of the stations matched the date of a Sacramento heat wave event date, then this date was selected and considered a "match." The number of overlapping heat wave events was then determined and counted. The number of event overlap matches for each station was divided by 15 to obtain the percentage of Sacramento's most intense heat wave events experienced by that station. This matching scheme was performed on both the top heat wave event set ranked by maximum temperature and the set ranked by the highest 3-day average of maximum temperature anomalies, for both unfiltered and filtered data, using both heat wave definitions. This method of matching was developed in order to assess how widespread a heat wave in Sacramento can be by indicating into what surrounding areas it spreads.

The expected number of the top 15 event dates that match by 'chance' is also estimated. Chance is defined as the same frequency as the ratio of the number of total heat wave days in the top 15 events at a particular station to the number of total dates in the period, N. There are JJAS days for 28 years, or N=122x28=3416, total dates. The total number of Sacramento heat wave days in the top 15 events is defined as n1.

Likewise, the total number of heat wave days in the top 15 events at each other station is defined as n2. The observed number of top event date matches is defined as m. The expected number of matches due to 'chance' would be n2/3416 = X/n1. As an example, for the scenario using filtered data and the first definition of a heat wave ranked by 3-day anomaly averages, n1=76 and n2 (Bakersfield)=50. Therefore, 50/3416 = X/76. This gives X=1.112, or, a little more than 1 match. m=21 top event date matches were observed at the Bakersfield station. This is more than 18 times the expected number of matches due to chance. Similar estimations were made for each station. Since rare weather events such as heat waves are being examined, the total number of observed matches may be small, but might be quite larger than the expected number of matches due to chance.

D. Correlations and Statistics

Correlations were calculated between stations for the temperature data. The first set of correlations performed correlated Sacramento JJAS temperatures with temperatures at the other stations on those corresponding dates. This correlation was performed in order to observe the relationship between daily maximum temperatures within all of JJAS, and not just heat wave events.

The second set of correlations consisted of lag correlations of temperature data. First, correlations of all JJAS Sacramento temperatures with the JJAS temperatures of each of the other cities were performed with lag times of 0 through 10 days (with 0 lag time being equal to the correlations performed above). These lag correlations were calculated in order to identify the relative timing of the temperature data between the different stations during summer months, and therefore, to better understand the progression of the weather events.

Another comparison was made between stations that used normalized maximum temperature anomalies. The standard deviation of all JJAS maximum temperatures was found for each station. The anomaly value on each date was then divided by this standard deviation value in order to obtain a normalized anomaly, one for each date. The normalized anomalies on all the dates of heat waves identified for that station were then averaged to obtain an average normalized anomaly for each station. This value could then be used to compare the strength of the maximum temperatures on all the identified heat wave dates at each station. The strength of this number represents the average number of standard deviations that the maximum temperature on those particular event dates is away from that station's long-term daily mean. Different stations will have different amounts of variation, and, thus, different standard deviations. This comparison assesses how unusual the temperatures on the target dates are for that particular city, based on that city's local climate, and allows for direct comparison between different stations having this different variability.

A second comparison was made using the normalized maximum temperature anomalies that averaged these values only on the dates that were part of the highest 3-day temperature anomaly averages for each of the top 15 ranked events experienced in Sacramento. The normalized anomalies on those same dates were averaged together for each of the other stations, resulting in one averaged normalized value for each station. These values represent the averaged anomalous temperature strength of each city on the dates that Sacramento experienced its most intense anomaly averages of its 15 most intense heat events. So, the dates used at the station were not necessarily matching event dates identified for that station. These resulting values give an indication of the sign and size of the maximum temperature anomalies outside of Sacramento on days when Sacramento had its strongest heat waves.

E. Bootstrap Resampling

The statistical significance of the onset dates of the hottest 15 heat wave events in Sacramento was tested using bootstrap resampling. The Bootstrap is a method used for estimating the distribution of a property of groups, or ensembles, drawn from a population. The Bootstrap method used here constructs each ensemble by sampling randomly and with replacement from the days in JJAS for the 28 years. A frequency distribution from the statistical property of each ensemble can then be created and compared to the statistical property of a specified target ensemble. A target ensemble might be the dates satisfying the criteria for a heat wave in Sacramento. The statistical property might be the mean of the maximum temperatures in the ensemble.

For each station, the maximum temperatures at that station on the top 15 onset dates of Sacramento heat waves, ranked according to the highest consecutive 3-day anomaly average, were averaged together and termed the ‘target’ ensemble average for that station. That ensemble average was then compared with the ensemble averages of 1,000 randomly generated 15-member mean ensembles of maximum temperatures during JJAS at that station. The 1,000 randomly generated ensemble averages and the target mean ensemble were plotted using a histogram in order to see the frequency distribution of the ensemble averages. The 99.5% significance threshold of each station was determined and the target ensemble was compared to that threshold. This procedure provides another way to assess how unusual the maximum temperatures are at different stations on the same days that Sacramento experiences stronger heat waves, for example, or the onset of a heat wave, for another example. For the stations whose target ensemble mean did not exceed the 99.5% significance threshold, new target ensemble means were created using the dates corresponding with the lag of its highest correlation with Sacramento temperatures. For example, if Seattle has the highest correlation with Sacramento temperatures at a lag time of 2 days, then a new target ensemble mean would be created for Seattle using the dates 2 days after the dates that Sacramento experienced its strongest events. The bootstrap program, rngen.ncl, is in Appendix C.

F. 850hPa Plots

Plots were created for the 850hPa level anomalous temperature and maximum temperature fields on the onset dates of the highest 3-day anomaly averages of the top 15 heat wave events in Sacramento. One plot was created for each event, along with a mean plot of the events for each field, totaling 16 plots. The purpose of the plots was to observe the large-scale structure of the most intense heat waves, and to assess how consistent this pattern is between the mean plot and the individual event plots.