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An Analysis and Summary of the July 2006 Record-Breaking Heat Wave Across the State of California

Daniel R. Kozlowski
HAS Meteorologist, California Nevada River Forecast Center

Laura M. Edwards
Assistant Research Climatologist, Western Regional Climate Center

Introduction:

A record-breaking heat wave affected much of the state of California during the period from Sunday, July 16 through Wednesday, July 26, 2006. Although numerous daily maximum temperature records were set, the aspect that made this event unique was the elevated overnight minimum temperatures at several reporting stations. This was especially true in the southern Sacramento Valley and much of the San Joaquin Valley. Along with the intensity of this heat wave, the duration of abnormally high maximum and minimum temperatures was particularly noteworthy. Previous studies have shown that the duration of a heat episode is an important factor to consider when determining its impact. Livezey and Tinker (1996) showed this was the case for the Chicago area during a heat wave event in July 1995. Additionally, they demonstrated that high minimum temperatures played a role in how hot the weather "felt" during this event. These factors, along with the meteorological synoptic situation, local effects and impacts, will be addressed in this study of the July 2006 California event.

Meteorological Synopsis:

The record-breaking heat wave that affected much of the state of California from Sunday, July 16 through Wednesday, July 26, 2006 can be attributed to the development of an amplified flow pattern across the northern hemisphere, and its effects on the typical summertime synoptic regime over the western United States and eastern Pacific Ocean. The following analysis will document the timeline of the event, and how each of the meteorological factors contributed to making this event noteworthy.

The primary feature noted in most heat wave events is the development of strong high pressure aloft, generating large scale descending air and compressional heating. Climatology of the 500mb heights (1968 – 1996) for the time period of this study (Fig. 1) indicates weak upper level ridging generally aligned along the crest of the Rocky Mountains with a center over New Mexico. Also, dry and broad west to southwest flow is situated along the west coast of the United States. During the 2006 heat wave episode, this semi-permanent summertime upper level high pressure ridge across the western United States strengthened and displaced westward with its center located over southern Utah (Fig. 2). This synoptic pattern adjusted flow across much of California with prevailing winds aloft from an easterly to southerly direction. This altered flow brought the advection of monsoonal moisture across much of California, increasing surface dew point temperatures and precipitable water values to above normal readings.

The building upper level high pressure ridge centered over southern Utah was part of an overall amplification of the general flow across the northern hemisphere (Fig. 3). This increased meridional flow resembled a wave number 5 pattern, with significant wave amplitudes given its occurrence during the summer season. In the week leading up to the July 2006 heat wave episode, an unseasonably deep upper level low pressure trough off the Kamchatka Peninsula of eastern Russia with its axis aligned over the western Pacific can be directly linked to the strengthening of the western United States upper level high pressure ridge. From July 9 through July 16, 2006, this disturbance propagated across the northern Pacific before splitting over the Gulf of Alaska (Fig. 4). A portion of system dissipated as it moved inland over British Columbia, while a secondary piece dug southward and developed an upper level low pressure trough along 150°W. The tendency for this system to split as it approached North America is evident in the upper level wind field during the week leading up to the heat wave. The 300mb wind field indicated an impressive summertime zonal jet stream across the Pacific Ocean between 40°N and 50°N reaching the North American coastline near the US-Canada border, but also showed a portion of the wind field diverging to the southeast as it crossed 150°W (Fig. 5). This deepening upper level low pressure trough along 150°W not only resulted in the strengthening of the subtropical upper level high pressure ridge north of Hawaii, but also resulted in its retrogression toward the International Data Line (180°). More importantly, this upper level low pressure trough resulted in a downstream adjustment of the synoptic scale flow, and the amplification of the western United States upper level high pressure ridge. This pattern shift signaled the beginning stages of the July 2006 heat wave event.

One distinct feature of the July heat wave that made it quite noteworthy and record-breaking was the prolonged nature of the event. In the southern Sacramento and northern San Joaquin Valleys, the record for most consecutive days reaching 100°F or greater was broken at the California State University – Sacramento and Modesto observation stations. The new record for the California State University – Sacramento gage is now eleven days, breaking the old record of nine days set four other times and most recently in 1996. In Modesto, the new record is currently twelve days, surpassing the previous record of ten days set back in 1960. An analysis of the daily averaged 500mb heights from July 16 through July 24, 2006 indicates the feature responsible for reinforcing the western United States upper level ridge of high pressure was another upper level short wave low pressure trough. This feature developed over the Kamchatka Peninsula of eastern Russia and began to shift eastward on July 16. After propagating across the northern Pacific Ocean, this system deepened between 150°W and 160°W developing an upper level low pressure trough (Fig. 6). This strengthening upper level low pressure trough over the east-central

Pacific Ocean caused a further adjustment of the downstream flow and enhanced the already anomalous western United States upper level high pressure ridge. This strengthening of the western United States upper level high pressure ridge coincided with the peak of the July 2006 heat wave.

The overall pattern of highly amplified flow resulting in the July 2006 heat wave event finally began to show signs of altering on July 24. A strengthening jet stream over the western Pacific began to shift east-northeast across the eastern Pacific, which resulted in a northward movement of the cooler air that had been displaced southward by the 155W upper level low pressure trough (Fig. 7). Consequently, 500mb heights rose over the east-central Pacific Ocean, and altered the downstream flow pattern over the western United States. By July 27, a deep long wave upper level low pressure trough developed over the western Pacific, and resulted in the strengthening of the subtropical upper level high pressure ridge north-northwest of Hawaii. This pattern change permitted a system developing over the Gulf of Alaska to dive southeast toward British Columbia and the Pacific Northwest. The overall pattern across the west coast of the United States shifted to a more climatologically dry west to southwest flow, signaling the end of the record-breaking July 2006 heat wave (Fig. 8).

A warm air mass associated with the upper level high pressure ridge settled across the western United States throughout the duration of the heat wave event. As was the case with the center of the upper level high pressure ridge being displaced westward over southern Utah, so was the core of the warmest air at 850mb. Climatology (1968 – 1996) suggests the core of the warm air mass at 850mb is normally centered over the Four Corners region of the southwest United States. Temperatures at the center of this summertime air mass typically run near 26°C. Readings across California warm from northwest to southeast and range from 16°C to 24°C respectively (Fig. 9). During the July 2006 heat wave episode, not only did the warmest air at 850mb shift west and reside over southern Nevada and southwest Utah, but this abnormally warm air mass encompassed a broader area extending westward to the coastal waters just off the western United States and northward into southwest Canada. The core of the 850mb temperatures through the duration of the heat wave averaged near 30°C (Fig. 10). Although the warmest temperatures at 850mb during the July 2006 heat wave were located to the east of California, the strongest anomalies associated with this air mass were found along the west coast, and in particular across northern and central California. Peak departures from climatology over the San Francisco Bay Area inland to the southern Sacramento and northern San Joaquin Valleys were near +7°C (Fig. 11).

A closer investigation of 850mb temperatures recorded from the soundings launched during the July 2006 heat wave at Oakland (KOAK), CA and Miramar Naval Air Station (KNKX) near San Diego, CA revealed 12-hourly fluctuations (Fig. 12). A rise in 850mb temperatures is noted early during the July 2006 heat wave episode, with an initial peak within the first two days near 27°C. Using Poisson's Equation,

$$T_{1000} = T_p\,(1000 / p)^{.286}$$

T_{1000}	*Temperature at 1000mb (in Kelvin)*
T_p	*Temperature at pressure level "p" (in mb)*
p	*Pressure level to calculate T_{1000}*

bringing 27°C down to near sea level dry adiabatically equates to an air temperature near 41°C (106°F). Air temperatures at 850mb began to slowly cool after this initial peak until late on July 19 to early on July 20. At this point, 850mb temperatures rose as a result of an amplification of the upper level high pressure ridge across the western United States. At the Oakland (KOAK) sounding location, 850mb temperatures peaked near 29°C, while farther south at the Miramar Naval Air Station (KNKX) sounding site 850mb temperatures topped out just over 30°C. Bringing these values down to near sea level (1000mb) dry adiabatically using Poisson's Equation, yield estimated air temperatures between 43°C (110°F) and 45°C (113°F). This methodology does not work for every heat wave event across the Sacramento and San Joaquin Valleys, or locations in coastal valleys. Factors that can alter the effectiveness of this method include: mixing height, wind speed, cloud cover, and mesoscale parameters (low level inversions, marine influences, and complex terrain). However, this procedure can be used as guidance in determining the potential of an impending heat wave event. In the July 2006 case, the extremely warm temperatures estimated by this method were realized. Numerous daily record maximum temperatures and even some all-time record maximum temperatures were broken. Both Stockton and Modesto, located in the San Joaquin Valley, surpassed their old all-time record maximum temperatures. In Stockton the maximum temperature on July 23 reached 115°F, breaking the old record of 114°F set back in July 1972. Farther south in Modesto, the maximum temperature topped out at 113°F on July 23 and July 24, which exceeded the old record of 112°F set back in August 1961.

The position of the surface thermal trough played a key role in this heat wave event. Climatology for July 16 through July 26 indicates a thermally induced thermal surface low pressure center (approximately 1011mb) located just south of Yuma, Arizona over northwest Mexico. A thermal surface trough extends northward through the Great Basin from this surface low pressure center. For the most part the thermal surface trough is aligned along the Nevada and Utah border (Fig. 13). Also of note is the quasi-stationary broad area of surface high pressure located across the eastern Pacific Ocean, generating northwesterly winds and upwelling of cooler water over the coastal waters of the western United States. During the July 2006 heat wave, the thermal surface low pressure center (approximately 1009mb) and weak surface trough were situated in a similar location as compared to climatology. However, a deeper thermally induced surface trough developed along the west coast of California (Fig. 14). This resulted in the reversal of the typical westerly onshore flow pattern, with weak easterly surface winds. The marine layer along the west coast, which normally shifts inland during the overnight hours, was unable to penetrate inland and remained along the immediate coast during the July 2006 heat wave episode. Also, the development of the thermal trough reduced the persistent summertime northwesterly surface pressure gradient over the coastal waters, calmed winds at buoys, and decreased the upwelling of cooler ocean waters. As a result of the reduced upwelling along the coast of California, sea surface temperature anomalies increased through the duration of the event, with a peak occurring just after the maximum air temperatures were recorded inland (Fig. 15). During the seven day period leading up to the July 2006 heat wave event, sea surface temperature anomalies from San Francisco to the United States and Mexico border ranged from near 0.0°C to +2.5°C with the greatest departure from normal in the coastal waters from Santa Barbara, CA to San Diego, CA. At the peak of the sea surface temperature anomalies, which occurred in the weeks of July 23 through July 29 as well as July 30 through August 5, anomalies jumped the greatest in the coastal waters from Santa Barbara, CA to San Diego, CA and to a lesser extent off the coast of San Francisco. During this week, positive anomalies of +0.5°C to +3.5°C were recorded. This indicated an approximate 1°C rise in ocean temperatures in this location during the July 2006 heat wave episode with locally higher increases. It is evident that this increase in sea surface temperatures was the result of the slackening northwesterly surface pressure gradient over the coastal waters of California, but it is not clear as the direction or magnitude of the feedback that elevated ocean temperatures had on inland air temperatures during the heat wave. As northwesterly winds once again increased over the coastal waters of California during early August, sea surface temperature anomalies began to diminish during the week of August 6 through August 12.

The aspect of the July 2006 heat wave event that made it especially noteworthy was the advection of monsoonal moisture over central and southern California. This resulted in elevated overnight minimum temperatures, allowing for little recovery from the intense daytime record-breaking heat. The monsoon season across portions of the southwestern United States normally runs from early July through the middle of September, as developing south to southeast flow transports lower latitude tropical moisture from the Pacific Ocean, the Gulf of California, and even the Gulf of Mexico. Under the influence of dry west to southwest flow, California generally remains to the west of this monsoonal moisture plume. However, during the July 2006 heat wave event, the typical climatological flow across California shifted to the east and south, allowing an influx of monsoonal moisture across the region. This increase in monsoonal moisture was observed in both surface dew point temperatures and precipitable water values recorded across the region.

One notable piece of information was the minimal change in relative humidity values during the heat wave as compared to the days leading up to and after the event. Only the typical diurnal fluctuations were observed with little day to day variations. Ground-based meteorology observation stations located at Chowchilla in the north-central San Joaquin Valley and Lincoln in the southern Sacramento Valley depict the measurement of these three moisture parameters (Fig. 16 and Fig. 17).

Surface dew point temperatures average near 50°F through the southern Sacramento and northern San Joaquin Valleys during the month of July. The advection of monsoonal moisture across the region resulted in an increase in dew point temperatures well above the 50°F mark for much of the duration of the July 2006 heat wave. During the peak of the episode on July 23, dew point temperatures rose nearly 15°F to 20°F. Both the Chowchilla and Lincoln stations recorded surface dew point temperatures near 70°F, considered extreme for this region. As expected, precipitable water values increased along with the dew point temperatures as monsoonal moisture advected across the region from the southeast. The integrated precipitable water values recorded at both Chowchilla and Lincoln were above 1.0 inch through much of the event. As dew point temperatures peaked near 70°F on July 23, integrated precipitable water readings topped out just over 1.5 inches. These maximum dew point temperatures even surpassed the climatological peak of dew point temperatures during the monsoon months at Tucson, Arizona (KTUS) where a value near 60°F is expected during late July and early August (2006).

When looking specifically at surface relative humidity, there was no strong signal to indicate the presence of the monsoonal moisture. Other than the typical diurnal fluctuation, day to day variations were rather small. As a result, the calculated heat index did not completely represent the "discomfort" factor. This was true because the heat index uses relative humidity and dry air temperature to calculate the "feels like" temperatures. When afternoon air temperatures rose well above 100°F and relative humidity readings dropped to near 20 percent, the monsoonal moisture that brought extremely high dew point temperatures and precipitable water values were not reflected in the heat index values.

Precipitable water values recorded at the Oakland (KOAK) sounding site during afternoon launches also indicated the increase in monsoonal moisture through the heat wave event, peaking between July 21 and July 23 with readings near 1.3 inches (Fig. 18). This peak in moisture correlated well with the elevated overnight minimum temperatures, which reached their highest readings on July 23 through the southern Sacramento and San Joaquin Valleys. Numerous all-time record high minimum temperatures were exceeded during this peak. These records are listed in Table 1 below.

Table 1
All-Time Record High Minimum Temperature (°F) – July 2006 Heat Wave

Station Name	***Date***	***T (°F)***	***Old Record ****
California State University - Sacramento	July 23	84	06/23/1909 – 78 **
Sacramento Executive Airport	July 23	78	07/12/1999 – 75 **
Stockton	July 23	82	07/25/1974 – 80 **
Modesto	July 22	84	07/13/1990 – 80
Fresno	July 23	90	08/01/1908 – 86

* All-time record high minimum temperatures occurred on back-to-back days (July 22 and 23) at California State University – Sacramento, Sacramento Executive Airport, and Stockton. Old records represent values before the July 2006 heat wave.

** Old records have several occurrences. Dates represent the most recent occurrence.

At the California State University – Sacramento, Sacramento Executive Airport, and Stockton, all-time record high minimum temperatures were also recorded on July 22 only to be surpassed one day later. The previous records at both the California State University – Sacramento and Fresno went back almost 100 years, dating back to June 23, 1909 and August 1, 1908 respectively!

These elevated overnight minimum temperatures were also the direct result of reduced outgoing long wave radiation due to periodic cloud cover and the monsoonal air mass. Short wave troughs rotating along the periphery of the western United States upper level high pressure ridge generated rounds of shower and thunderstorm activity during the July 2006 heat wave event. Much of the scattered precipitation was confined to the higher terrain of the Sierra Nevada and coastal mountain ranges, however a few stray showers did move through the Sacramento and San Joaquin Valleys. Sacramento Executive Airport reported a trace amount of precipitation on July 19, while Modesto recorded a trace amount on July 18 and .08 inch on July 19. More importantly the cloud cover generated from the short wave troughs reduced the amount of outgoing long wave radiation and increased ambient humidity levels thereby keeping overnight minimum temperatures elevated.

Finally, as the general flow across the west coast of the United States returned to a seasonable dry west to southwest direction at the tail end of the July 2006 heat wave event, monsoonal moisture decreased allowing minimum temperatures to return closer to normal. As previously mentioned, this pattern shift signaled the end of the prolonged heat.

Local Effect:

During the eleven day stretch of the heat wave, the already elevated minimum temperatures were exacerbated in developed areas due to a phenomenon known as the urban heat island. According to the United States Environmental Protection Agency (2006), temperatures recorded in urban and suburban areas are typically 2°F to 10°F warmer than nearby rural areas.

The urban heat island played a key role in generating localized areas where daily minimum temperatures reached unprecedented levels. To examine the effects of the urban heat island during the July 2006 heat wave event, the overnight minimum temperatures were analyzed for three locations around the Sacramento region. These observation stations include Sacramento International Airport, Sacramento Executive Airport, and California State University – Sacramento (Fig. 19). The Sacramento International Airport is located outside of the urban boundary to the northwest in a rural setting. The Sacramento Executive Airport is located near the edge of the urban boundary on the southwest corner of the region and the California State University – Sacramento is located near the center of the urban region.

Overnight minimum temperatures at all three locations were elevated; however, the urban heat island effect was noted at the California State University – Sacramento observation site (Fig. 20). The average overnight minimum temperature was approximately 5°F warmer than at the Sacramento International and Executive Airports. The difference between the Sacramento International and Executive Airports in terms of average overnight minimum temperature during the eleven day period was only .09°F.

One might not anticipate the Sacramento Executive Airport to be similar to the Sacramento International Airport, and expect it to fall closer in line with the California State University – Sacramento site. However, after understanding the local wind pattern and the land use upwind, the results become clearer. With light winds from the southwest during the overnight, slightly cooler air advected over the Sacramento Executive Airport from the Sacramento River Delta. Land use in this area is limited to small rural towns surrounded by agriculture and open space. This allowed temperatures to slightly modify cooler at the Sacramento Executive Airport, while this air never penetrated farther inland to the California State University – Sacramento given the weak nature of the overnight winds. Given the supporting minimum temperature data at these three locations throughout the Sacramento region, it can be concluded that overnight minimum temperatures were locally exacerbated by the urban heat island effect.

Records and Data:

As would be expected during any period of intense heat, numerous records were surpassed across the state of California during July 2006. The most obvious records susceptible to being broken during a heat wave event are the daily maximum temperatures. In fact, not only were a large number of daily maximum temperature records set at several climate stations across the region, but a number of these locations also recorded their all-time record maximum temperature. This was one aspect that pointed to the strength of this heat wave episode. Table 2 (below) depicts locations that set their all-time record maximum temperature.

Table 2
All-Time Record Maximum Temperature (°F) – July 2006 Heat Wave

Station Name	***Date***	***T (°F)***	***Old Record***
Woodland Hills	07/22	119	08/24/1985 – 116
Stockton	07/23	115	07/14/1972 – 114
Wild Animal Park	07/22	114	07/01/1985 & 08/29/1998 – 112
Modesto	07/24 *	113	06/15/1961 – 112
El Cajon	07/22	113	09/02/1982, 09/03 & 09/04/1988 - 109
Escondido	07/22	112	07/01/1985 & 08/12/1994 – 109
La Mesa	07/22	109	09/03/1988 – 109

* All-time record maximum temperatures occurred on back-to-back days (July 23 and 24) at Modesto with an observed value of 113°F.

Another data set that pointed to the magnitude of the July 2006 heat wave was the elevated overnight minimum temperatures. Along with the already warm air mass, the advection of monsoonal moisture across the region contributed to the warm nighttime temperatures experienced. At the Los Angeles (University of Southern California) observation station, the temperature remained at or above 70°F for 16 straight days. Only September 1984 saw a longer string of warm nighttime temperatures. Just to the north, Burbank experienced temperatures greater than or equal to 70°F for 17 consecutive days, one more than Los Angeles. These elevated temperatures were felt outside of California as well. Under the influence of this strong upper level high pressure ridge, Reno, NV recorded a temperature above 65°F for 13 straight days. This easily broke the old record of 8 days set back in both July 2003 and July 2005.

Along with these prolonged elevated temperature streaks, numerous all-time record high minimum temperatures were set across the region. These warm overnight temperatures were another factor that made the July 2006 heat wave extremely noteworthy. In fact, several of these old records were easily surpassed, while others dated back almost 100 years. A list of selected locations is included in Table 3 below.

Table 3
All-Time Record High Minimum Temperature (°F) – July 2006 Heat Wave

Station Name	***Date***	***T (°F)***	***Old Record***
Needles	07/22	100	06/30/2001 – 100
Imperial	07/22	93	07/14/1942 & 08/10/1946 – 90
Fresno	07/23	90	08/01/1908 – 86
Calif. State Univ. - Sacramento	07/23	84	06/23/1909 – 78 *
Modesto	07/22	84	07/13/1990 – 80
Madera	07/23	83	07/13/1999 – 81
Stockton	07/23	82	07/25/1974 – 80 *
Riverside	07/23	79	08/14/1994 – 77
Sacramento Executive Airport	07/23	78	07/12/1999 – 75 *
San Jose	07/22	74	07/25/1974 – 73
Campo	07/23	74	09/03/1950 – 73

* All-time record high minimum temperatures occurred on back-to-back days (July 22 and 23) at California State University – Sacramento, Sacramento Executive Airport, and Stockton. Old records represent values before the July 2006 heat wave.

One of the most debilitating aspects of the July 2006 heat wave was its duration. At the California State University – Sacramento observation station, the temperature reached 100°F or greater for 11 consecutive days. This surpassed the previous record of 9 set four times with the most recent in 1996. Modesto recorded temperatures that reached 100°F or greater for 12 consecutive days, which surpassed the old record of 10 days set back in 1960. Along with these locations, it was 100°F or higher for 15 consecutive days at Bakersfield and 14 consecutive days at Fresno. Farther south, the Woodland Hills (Pierce College) observation site near Los Angeles saw temperatures of at least 100°F for

21 consecutive days, which is the longest such streak since records began in 1949. The previous record was 15 consecutive days, set back in 1998.

As expected, with this record-breaking heat wave affecting California during July 2006, average maximum and average minimum temperatures for the entire month exhibited above normal conditions (Fig. 21). With both maximum and minimum temperatures running above normal, the monthly average temperature depicted warm anomalies as well (Fig. 22). Peak readings ranged from 6°F to 8°F above normal. As a result of these rather anomalous conditions, several observation stations saw their highest average temperature for the month of July on record. Most of the stations were located across southern California, given the relatively cooler temperatures experienced across northern California during the beginning of July that were not felt across the Southland. A list of selected locations is listed in Table 4 below.

Table 4
Record High July Average Temperature (°F) – July 2006 Heat Wave

Station Name	***T (°F)***	***Old Record***
Palm Springs	97.2	2003 – 96.0
Borrego Desert Park	96.0	2003 – 95.2
Fresno	87.8	1931 – 87.6
Woodland Hills	83.8	1985 – 81.0
Burbank	82.0	1984 – 79.7
Los Angeles (Univ. of Southern Calif.)	79.9	1985 – 79.2
Paso Robles	78.9	1967 – 78.0
Long Beach	77.5	1984 – 76.6
Univ. of Calif. – Los Angeles	74.9	1984 – 72.6
Camarillo	71.2	2003 – 70.1

Although marine influences were tempered for much of July 2006, immediate coastal locations primarily did experience relatively cooler conditions as compared to their inland counterparts. Also, elevation was a factor in determining daily temperatures with the higher terrain cooler than lower elevation locations, except along the immediate coast where areas were affected by the marine layer.

As expected, the number of days with temperatures exceeding 90°F, 95°F, and 100°F during July 2006 varied by location with the greatest total over inland valleys and deserts (Fig. 23). Table 5 below summarizes a list of selected stations with temperatures above 90°F, 95°F, and 100°F.

Table 5
Number of Days During July 2006 Above 90°F, 95°F, and 100°F

StationName	***# Days >90°F***	***# Days >95°F***	***# Days >100°F***
Eureka	0	0	0
Yreka	25	17	7
Alturas	28	15	5
Mount Shasta	13	4	1
Shasta Dam	28	22	13
Burney	19	14	4
Redding	31	24	19
Red Bluff	30	23	17
Quincy	19	11	1
Marysville	29	22	11
Ukiah	23	15	11
Santa Rosa	10	6	2
Napa	15	10	3
Sacramento Executive Airport	19	14	10
California State University – Sacramento	25	19	12
SFO International Airport	1	1	0
San Jose	10	5	2
Stockton	27	22	14
Gilroy	18	14	7
King City	17	13	7
Paso Robles	26	22	13
Madera	30	23	15
Coalinga	31	31	22
Fresno	31	28	20
Yosemite	7	3	0
Porterville	31	25	15
Bakersfield	31	24	17
San Luis Obispo	4	0	0
Santa Barbara	1	0	0
Los Angeles / USC	14	5	1
Burbank	21	8	2
Anaheim	23	13	7
Riverside Citrus	28	27	17
Lancaster	28	27	20
San Diego	1	1	0
El Cajon	21	12	5
Campo	27	22	9
Daggett Airport	31	31	29

Inyokern	31	31	29
Twentynine Palms	31	31	24
Thermal Airport	31	31	31
Palm Springs	31	31	30
Needles Airport	31	31	31
Imperial	31	31	31
Blythe	31	31	30
Bishop	31	26	13

Evidence of temperature and relative humidity differences are apparent in a comparison of two coastal locations, Highlands Peak and Whale Point (Fig. 24 and Fig. 25). These two stations are along the central California coast near the Big Sur area, and are approximately one mile apart in a straight line. However, the elevation difference between Highlands Peak and Whale Point is about 2000 feet, with the latter being lower. Highlands Peak exhibited significantly warmer temperatures during the peak of the heat wave event, reaching 100°F on July 22, while Whale Point reached only 84°F around the same time. A visual comparison of these two temperature time series indicates how coastal stratus and fog affected the lower elevation Whale Point with sharp declines and then sharp increases in the air temperature from July 22 to July 24. Highlands Peak was not affected by the coastal stratus and fog during these same times. Using relative humidity as a proxy for determining coastal stratus and fog around a station shows the daily cycles of high and low humidity at Whale Point that is not exhibited at Highlands Peak (Fig. 25). These two stations are evidence of the uniqueness of coastal climate and weather, as well as how different relatively close locations can be in areas of complex terrain.

A further analysis of the July 2006 temperature data by the National Oceanic and Atmospheric Administration (NOAA) put the extreme temperatures into perspective. Data was organized and ranked for an area as large as the lower 48 United States down to smaller regions within each state. Data was available for the past 112 years and used in this analysis. The lower 48 United States experienced its second warmest July (ranked number 111 of 112). A closer look at California revealed that the state saw its third warmest July on record (ranked number 110 of 112). When further dividing California into the National Climate Data Center’s climate regimes, the south coast division of California experienced its warmest July over the past 112 years. Other regions across the state saw either above normal or much above normal temperatures (Fig. 26).

Impacts:

The electricity demand was extremely high and the situation so unique that it prompted the California Energy Commission (CEC) to hold a special workshop regarding the heat wave of July 2006. The recorded maximum electricity demand on July 24, 2006 was 50,270 Megawatts (MW). The net internal demand, which recorded demand plus estimated outages, was 51,525 MW. Representatives from major power producers at the CEC workshop compared this heat wave to those of 1971 and 1955, labeling the 2006 heat wave as a 1 in 25 to 1 in 50 year event.

The record-setting peak electricity demand occurred on a weekday, which traditionally has higher demand than on weekends, at the end of a 3-day warm period. The peak demand was over forecast, but left the electricity suppliers prepared for the necessary deliveries. No rolling blackouts occurred during July 2006. This was a challenge to achieve because of the widespread nature of this heat wave. Under normal circumstances, these types of episodes will not affect all suppliers, so those who experience less of an impact are able to deliver electricity to users in other regions.

Recent mortality statistics due to heat are difficult to obtain, primarily due to the fact that there is a delay between reporting by health care centers and publishing these statistics by the state Department of Health. The Centers for Disease Control (2002) have estimated that 8,015 Americans died from excessive heat exposure during the period from 1979 to 1999. Other organizations' estimates of death from historic heat waves during this period suggest that this figure grossly underestimates the true number. For example, the National Climatic Data Center (2003) estimates that about 10,000 deaths were associated with oppressive heat during the summers in the 1980s. Media reports estimated somewhere between 131 and 164 deaths attributed to the extremely warm temperatures during the prolonged heat episode of July 2006. This is significant compared to recent statistics of heat-related deaths. For the period 1989-2004, 357 deaths have been heat-related. As of this writing, we are unsure of the demographics that comprised these deaths in 2006. However, statistics from the California Department of Health reveal that most of those who perished due to heat-related causes between the years 1999-2004 were in urban areas and in the age range of 35 to 44 years old. This information is counter to the thought that elderly people, who made up the second most common age group, are at higher risk of death due to high temperatures than others. Although record-keeping has improved in recent years, it must be noted that a universal definition of heat-related deaths and more accurate numbers are necessary to provide the best information.

Agricultural impacts resulted in a significant effect on the California economy. Large amounts of crop loss and livestock death were reported, especially across the southern Sacramento and much of the San Joaquin Valleys. Exact figures on the total damage were hard to tally. According to the California Farm Bureau Federation, the ultimate effect of the heat would take some time to realize. As is the case for walnuts, crop damage may be seen right away. However, crops such as tomatoes are harder to predict because they are not harvested until later in the season. The dairy industry predicted losses near $1 billion, since cows do not produce enough milk, or worse, perish from the heat.

Conclusions:

The July 2006 record-breaking heat wave developed as the result of an amplified flow pattern across the northern hemisphere and its effects on the typical summertime synoptic regime over the western United States and eastern Pacific Ocean. An upper level high pressure ridge centered over southern Utah was the primary feature present, which contributes to the development of most heat wave events. However, other factors contributed to making the July 2006 heat episode extremely noteworthy. Extremely warm air aloft was able to reach the surface under strong subsidence. Temperatures at 850mb peaked near 30°C with anomalies over the 11-day period peaking near +7°C. At the surface, the development of a thermally induced trough of low pressure along the west coast of California resulted in the reversal of moderating onshore flow. Instead, weaker easterly offshore flow dominated during the heat wave episode. This change in the pressure pattern weakened seasonal northwesterly flow along the coastal waters of California. Consequently, the upwelling of cooler waters decreased, allowing sea surface temperatures to warm. Anomalies during their peak ranged from +0.5°C to +3.5°C, with the greatest departures from normal found in the coastal waters from Santa Barbara, CA to San Diego, CA. Also, with the typical flow aloft being adjusted from a dry southwest to west direction to an east to south direction, and given the coinciding time of year with the southwestern United States monsoon, the July 2006 heat wave saw an influx of moisture over California. Cloud cover associated with short wave troughs rotating around the periphery of the western United States upper level high pressure ridge contributed to record high overnight minimum temperatures throughout the event. Finally, the urban heat island effect played a role in exacerbating overnight minimum temperatures across developed locations. All of these combined features resulted in a heat wave that reached a record-breaking magnitude. When diagnosing the potential for a developing heat wave, these factors need to be considered when determining its magnitude and effects on the surrounding society and the economy.

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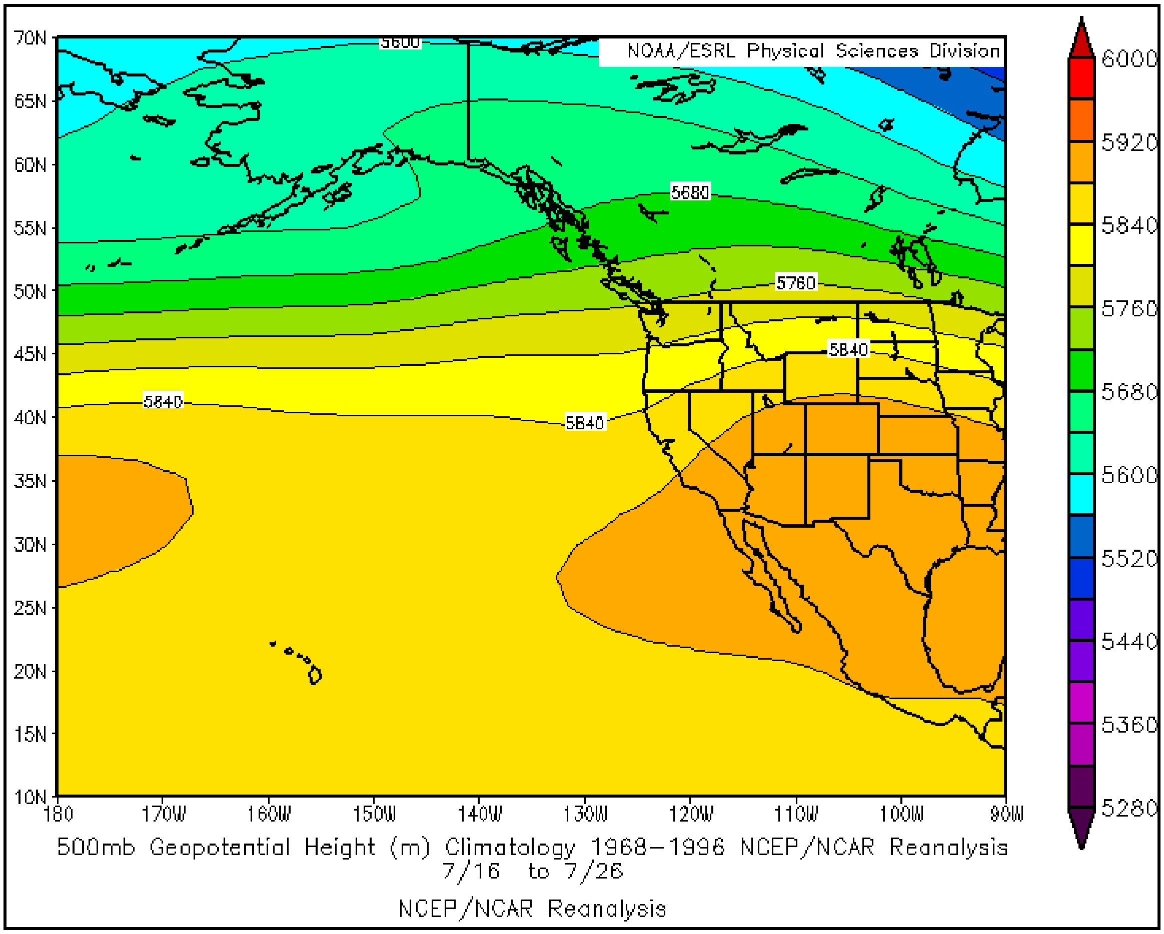

Figure 1: Indicates 500mb geopotential height (m) climatology (1968 – 1996) for the period of the 2006 heat wave (Sunday, July 16 through Wednesday, July 26, 2006). Weak upper level ridging is generally aligned along the crest of the Rocky Mountains with a center over the state of New Mexico. Dry west to southwest flow is situated along the west coast of the United States.

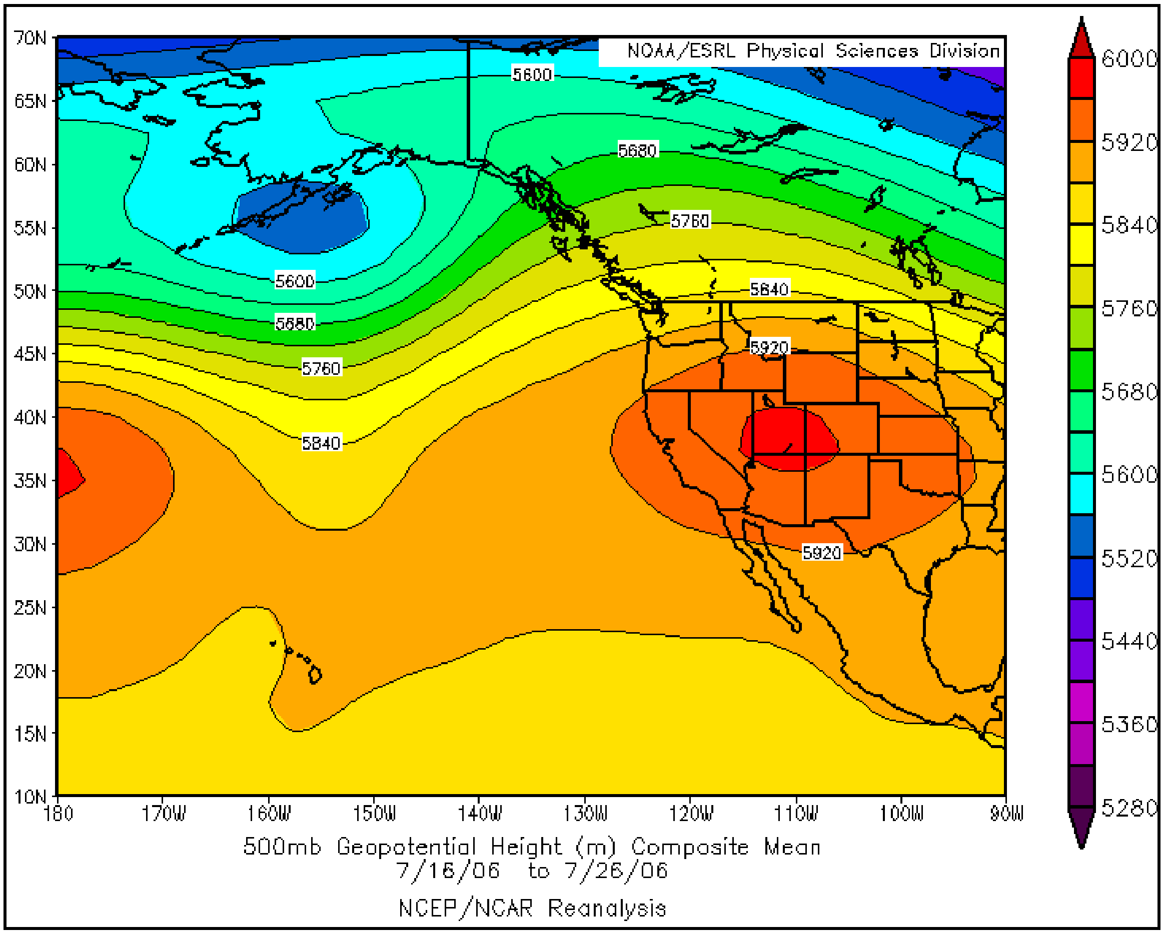

Figure 2: Displays the composite mean of the 500mb geopotential heights (m) through the duration of the July 2006 heat wave. The semi-permanent summertime upper high pressure ridge across the western United States strengthened and displaced westward with its core located over southern Utah. This pattern adjusted flow across much of California with easterly to southerly winds.

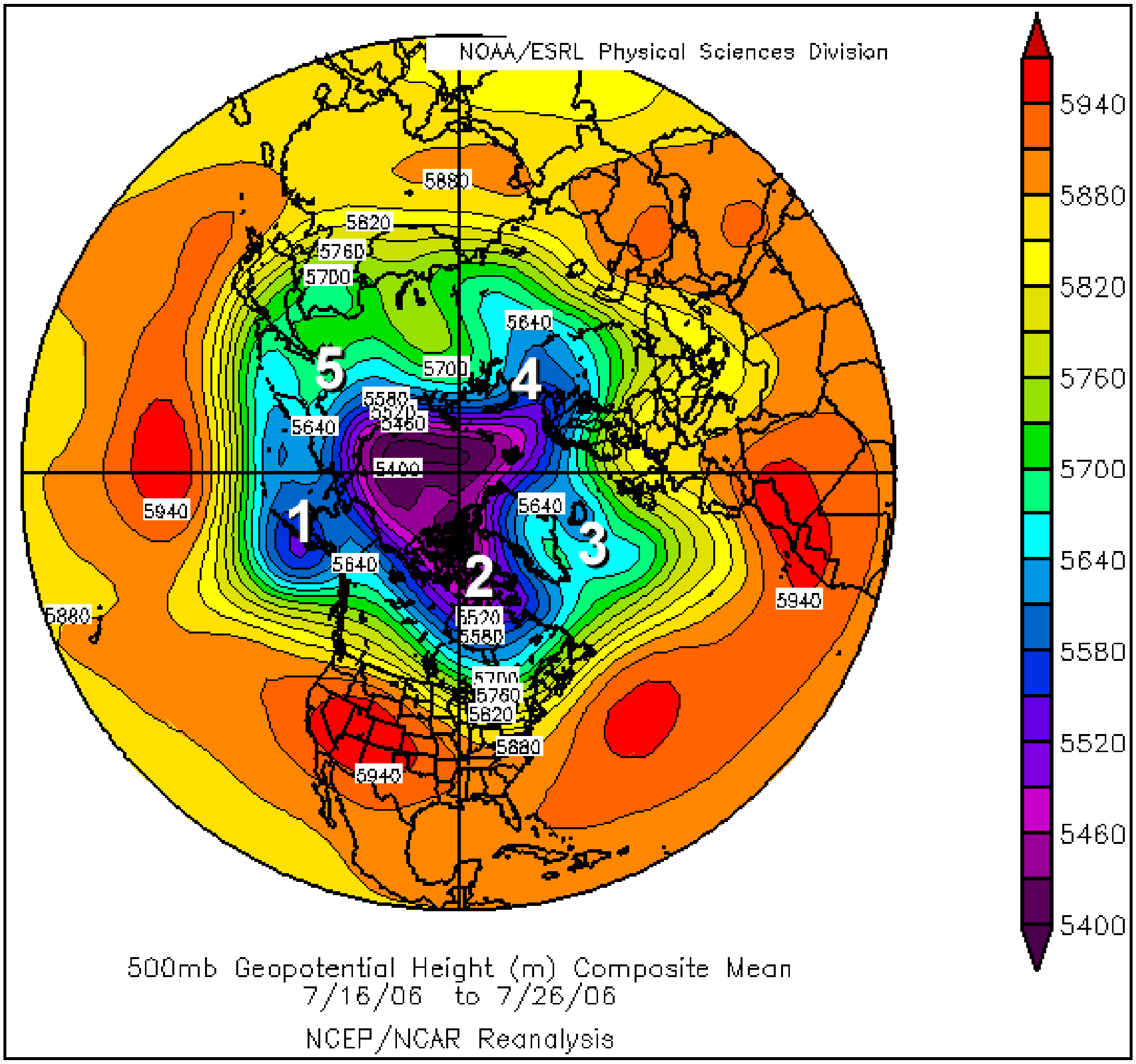

Figure 3: Shows the northern hemispheric 500mb geopotential height (m) composite mean throughout the heat wave episode. The building upper high pressure ridge responsible for the state of California heat wave centered over southern Utah was part of an overall amplification of the flow across the entire northern hemisphere, which resembled a wavenumber 5 pattern (albeit weak given the summer season). Please note the annotated numbers in large white numbers (1 through 5) indicating the waves.

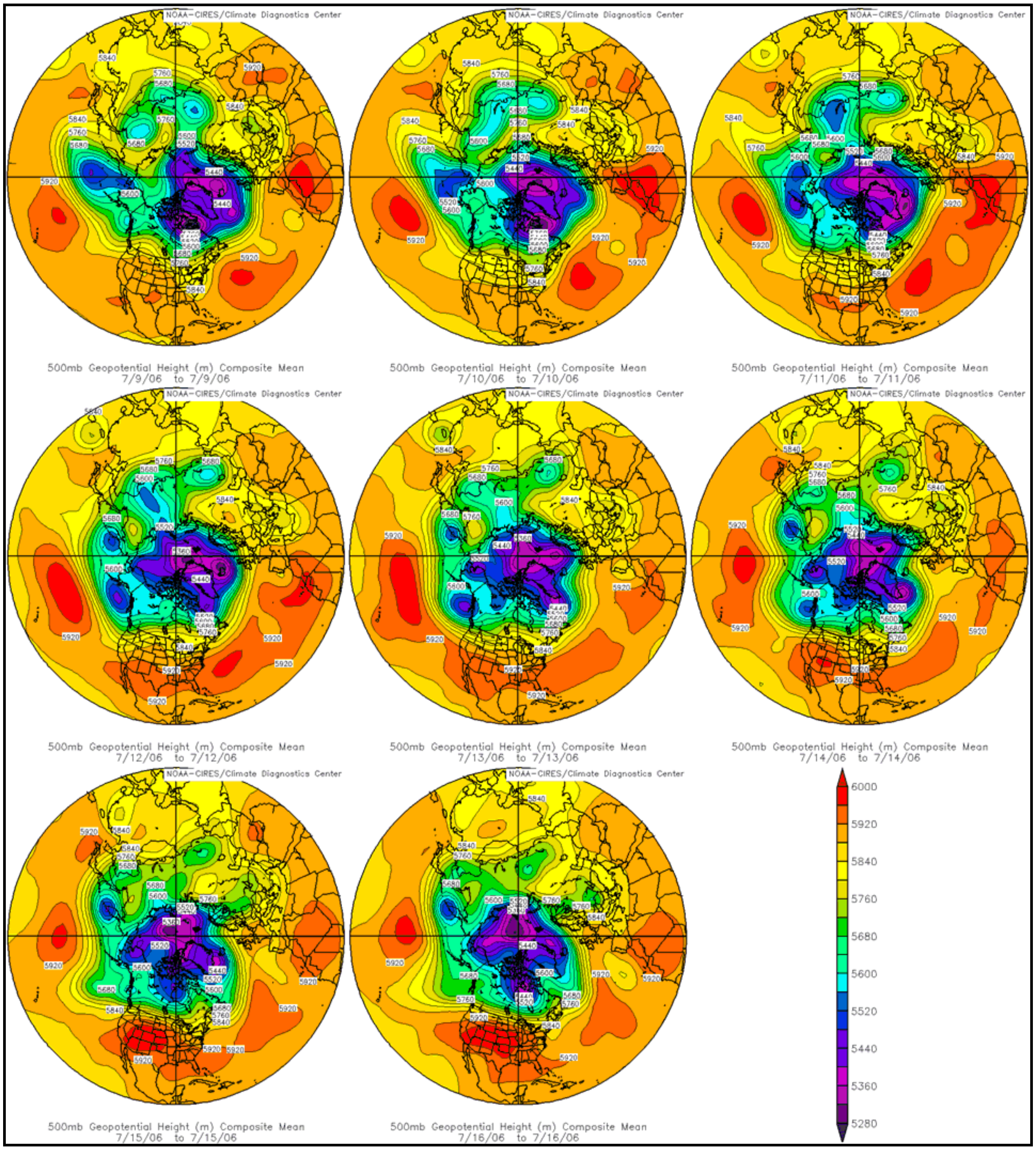

Figure 4: Displays daily averaged 500mb geopotential heights (m) from July 9 through July 16, 2006 (representing the week leading up to the heat wave episode). The feature of note is the upper level trough of low pressure off the eastern Russia coast over the western Pacific. This disturbance propagates across the northern Pacific before splitting near the Alaska Peninsula. A portion of the energy associated with this system dissipates inland over British Columbia, while a secondary piece of energy digs southward and develops an upper level trough of low pressure along 150°W. This not only resulted in the retrogression of the subtropical upper level high pressure, but also generated a downstream adjustment of the westerly flow and the strengthening of the upper level high pressure across the western United States.

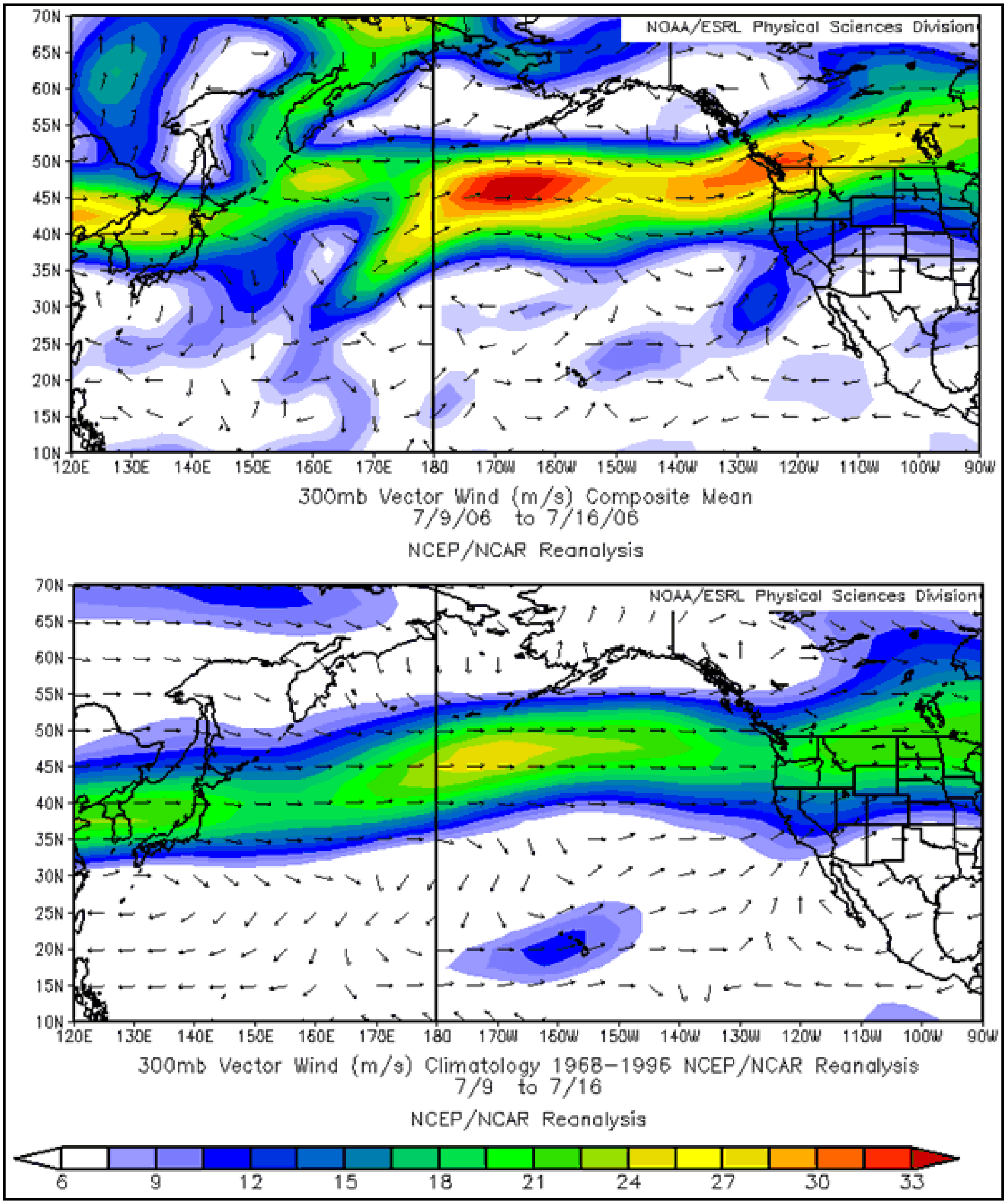

Figure 5: Specifies the 300mb wind speed and vector for the period representing the week prior to the July 2006 heat wave episode (upper graphic), and the climatological mean (1968 – 1996) for the similar time period (lower graphic). Note the enhanced jet stream between 40°N and 50°N due to the increased temperature gradient between the strengthening subtropical high and the cooler troughs traversing the northern Pacific. Also, on the July 9 through July 16, 2006 image, the jet stream indicates a split as it crosses 150°W with vector divergence apparent.

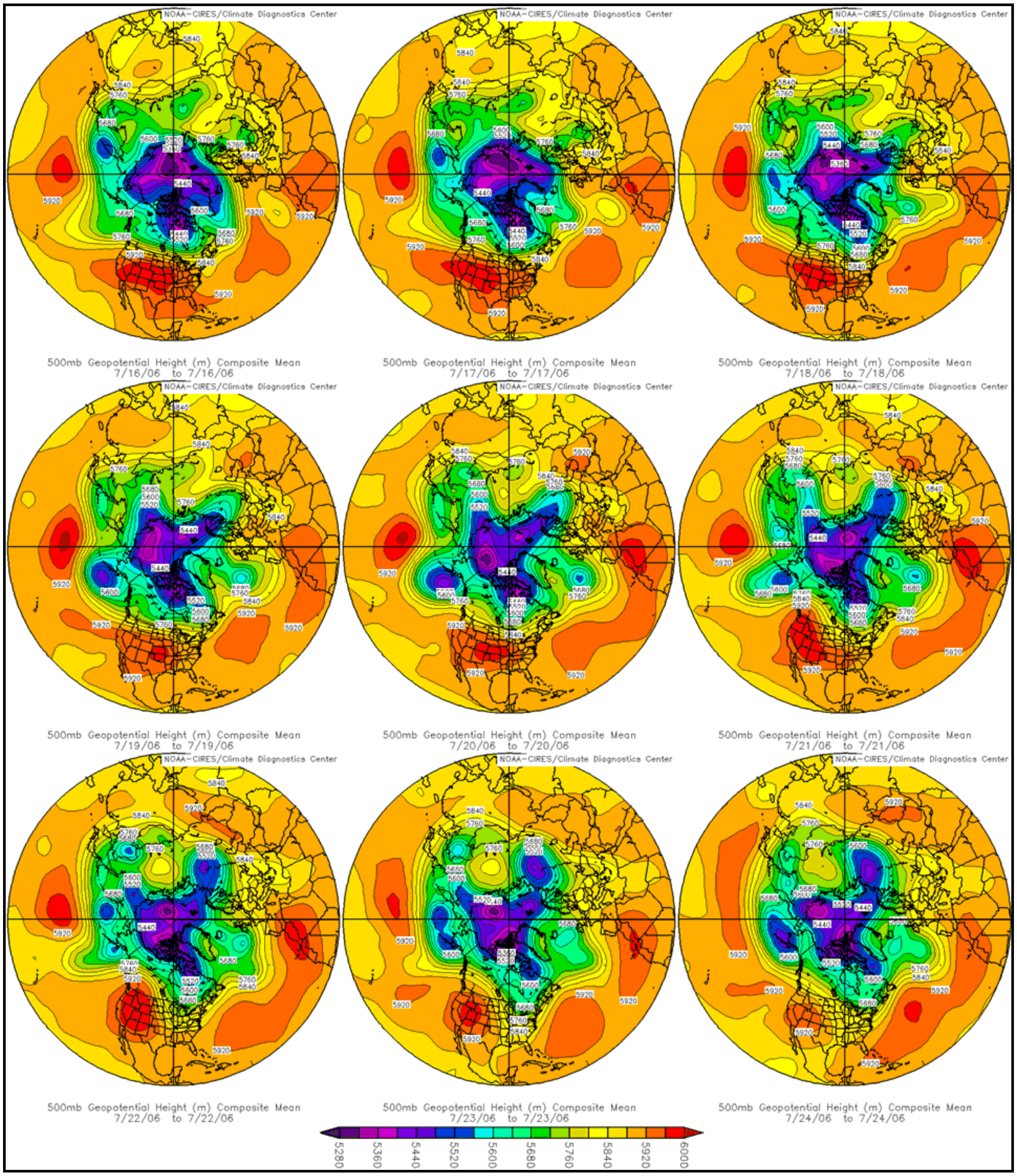

Figure 6: Displays daily averaged 500mb geopotential heights (m) from July 16 through July 24, 2006. This represents the majority of the heat wave, including the peak of this event occurring between Friday, July 21 and Monday, July 24, 2006. The feature of note is another upper level short wave trough of low pressure over the Kamchatka Peninsula of eastern Russia on July 16. This system propagated eastward over the northern Pacific Ocean over the next 3 to 4 days before deepening between 150°W and 160°W. This strengthening upper level trough of low pressure over the east-central Pacific Ocean resulted in prolonging the heat wave episode, and reinforcing the already anomalous western United States upper level ridge of high pressure ridge.

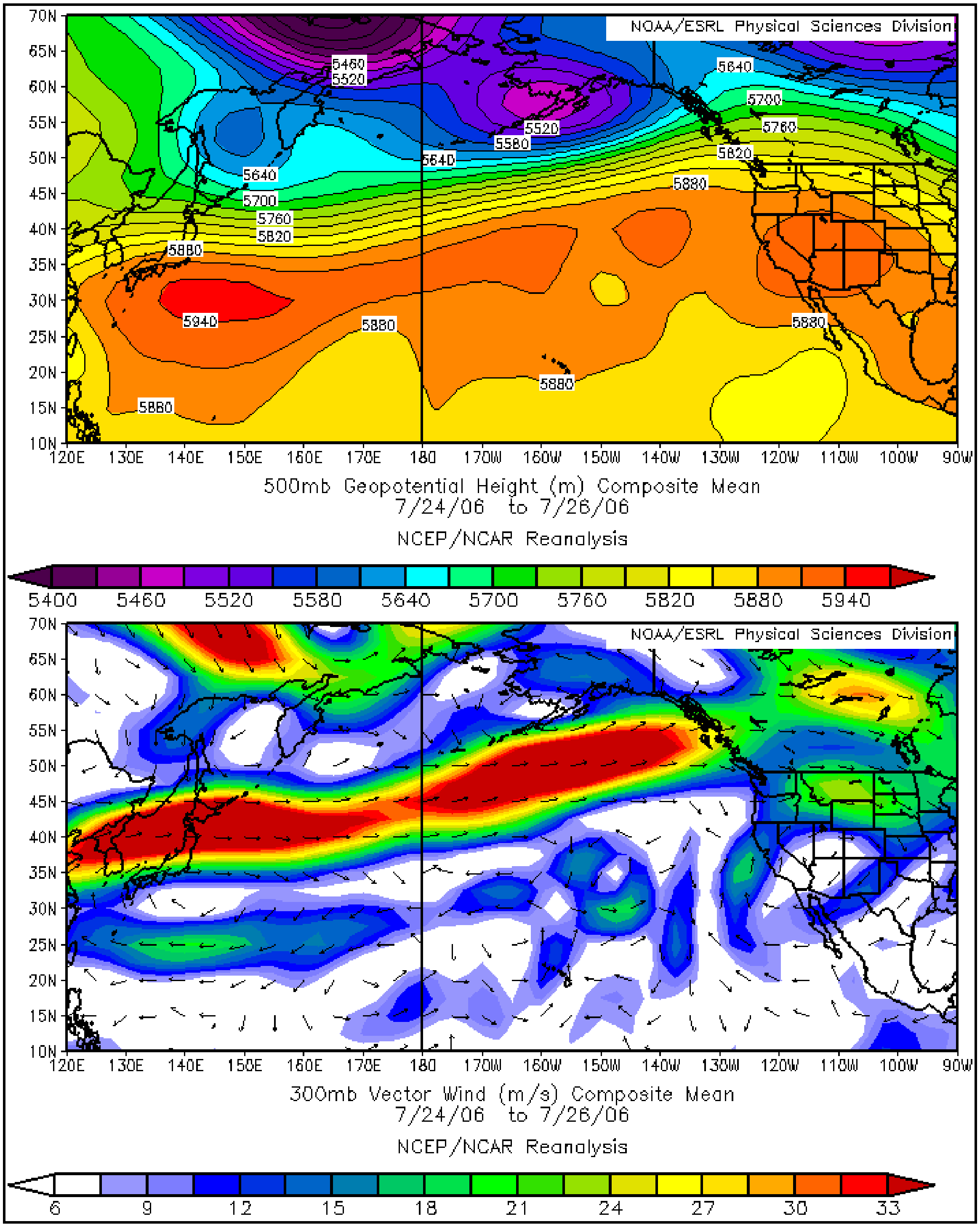

Figure 7: Indicates the 500mb geopotential heights (m) and 300mb vector wind (m/s) from July 24 through July 26, 2006. This shows the increasing heights across the east-central Pacific, as well as the strengthening zonal jet stream crossing the Pacific. This zonal jet stream reduced the amplified flow, including the western United States upper level high pressure ridge responsible for the July 2006 heat wave.

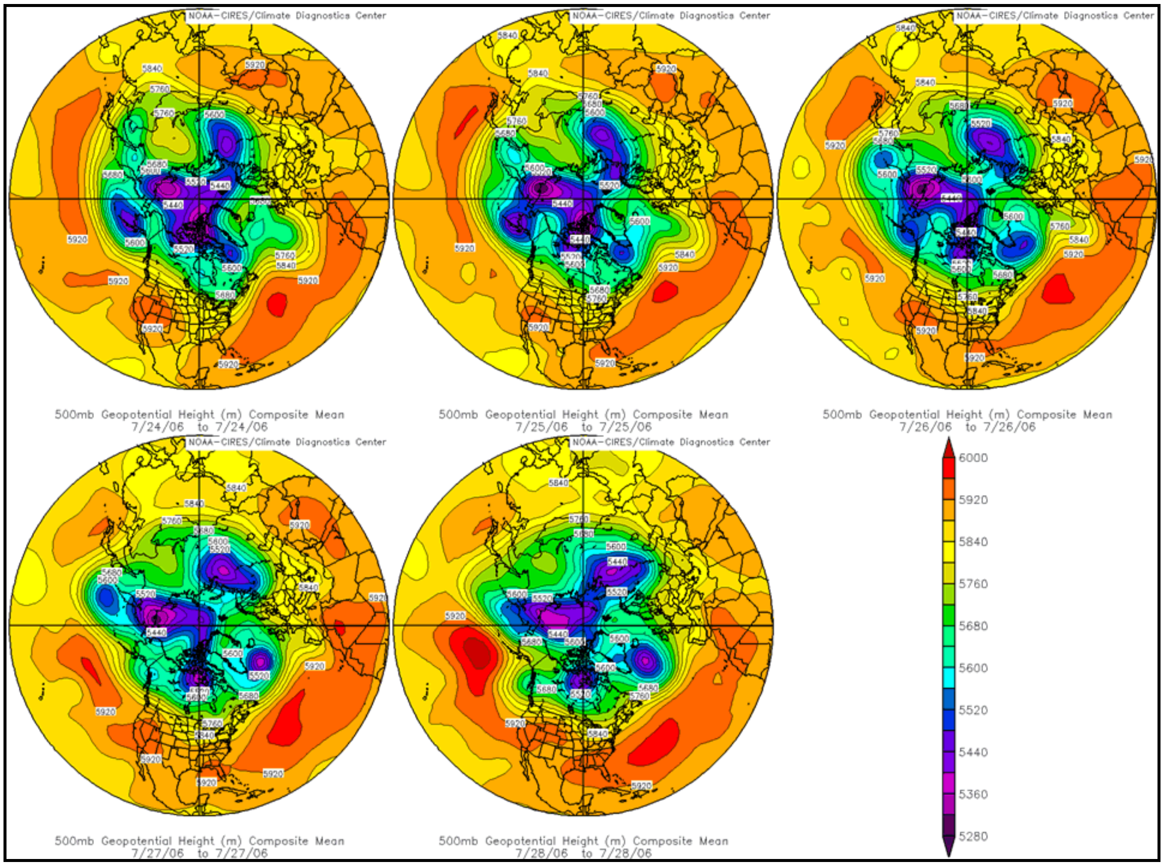

Figure 8: Displays daily averaged 500mb geopotential heights (m) from July 24 through July 28, 2006. This represents the dissipating phase of the heat wave event where flow transitioned from an easterly to southerly regime to a more climatologically dry west to southwest flow. Note the weakening of both the subtropical upper level high pressure ridge centered near the International Data Line and western United States upper level high pressure ridge. In the last couple frames, a deep upper level low pressure trough developed over the western Pacific, resulting in the expansion of the subtropical upper level high pressure ridge north of Hawaii. Given this pattern shift, a system over the Gulf of Alaska dropped southeast, turning flow over the west coast of the United States to a climatologically dry west to southwest.

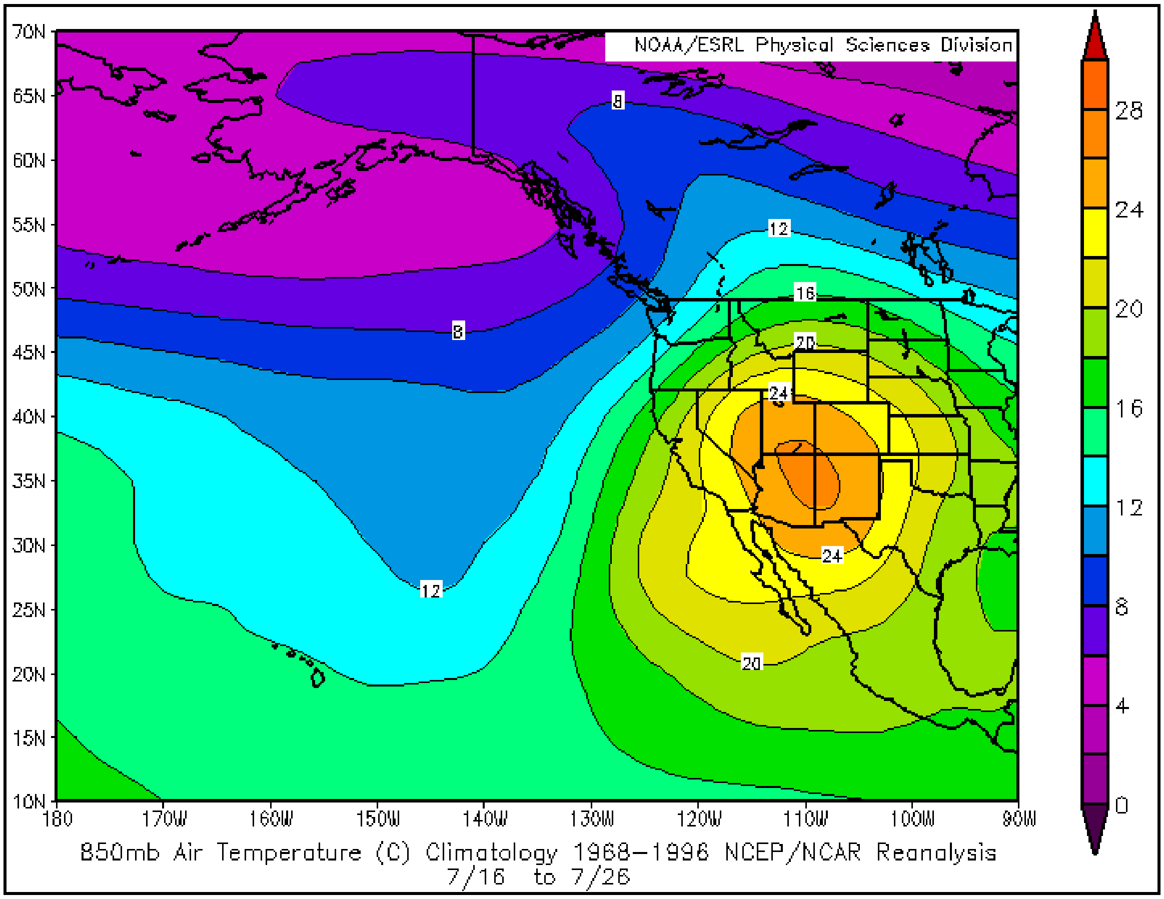

Figure 9: Indicates 850mb air temperature (°C) climatology (1968 – 1996) for the period of the 2006 heat wave (Sunday, July 16 through Wednesday, July 26, 2006). The core of the warm air mass associated with the western United States upper level high pressure ridge is located over the Four Corners region. Across California, typical values rise from near 16°C over northwest California to near 24°C over southeast California.

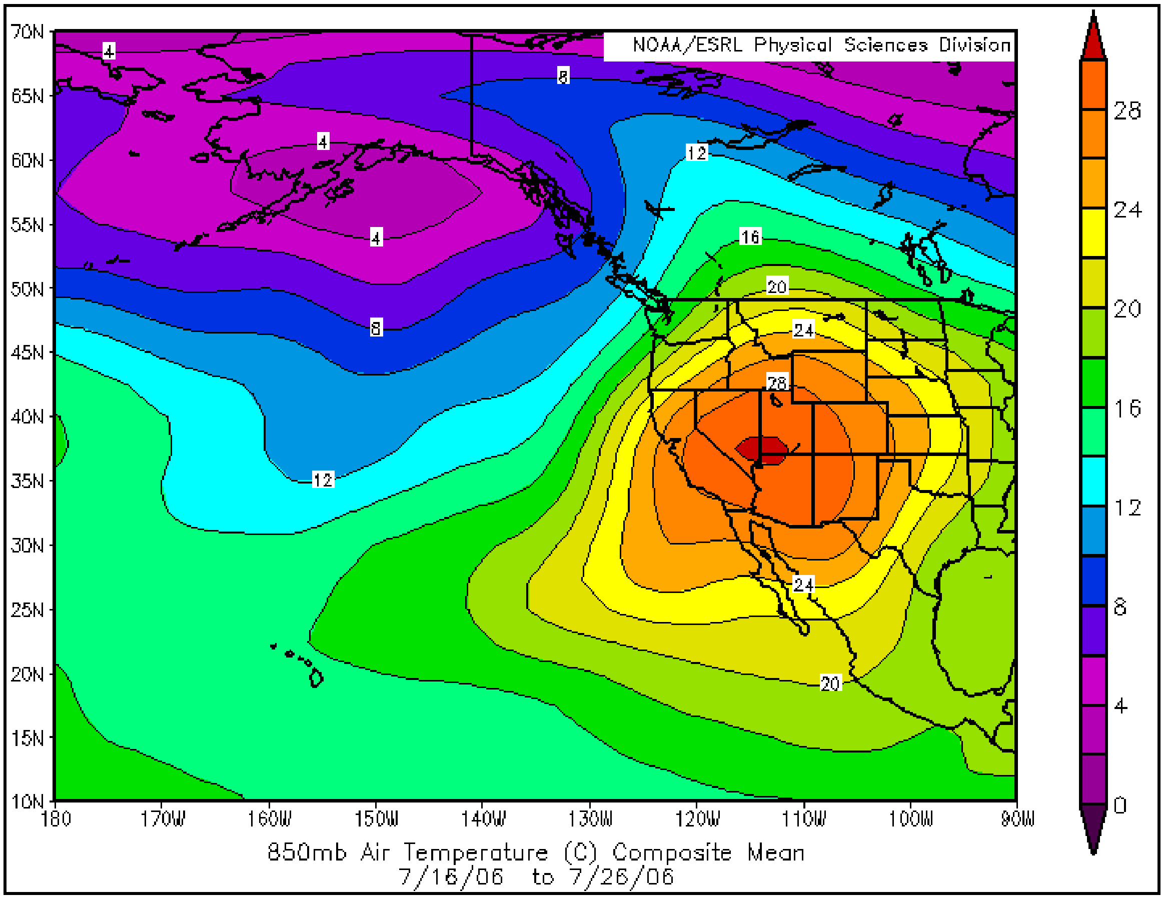

Figure 10: Displays the composite mean of 850mb air temperatures (°C) through the duration of the July 2006 heat wave. The core of the warmest air across the southwest United States shifted westward over southern Nevada and southwest Utah. The typical warm air mass over the southwest United States expanded and encompassed a bigger area.

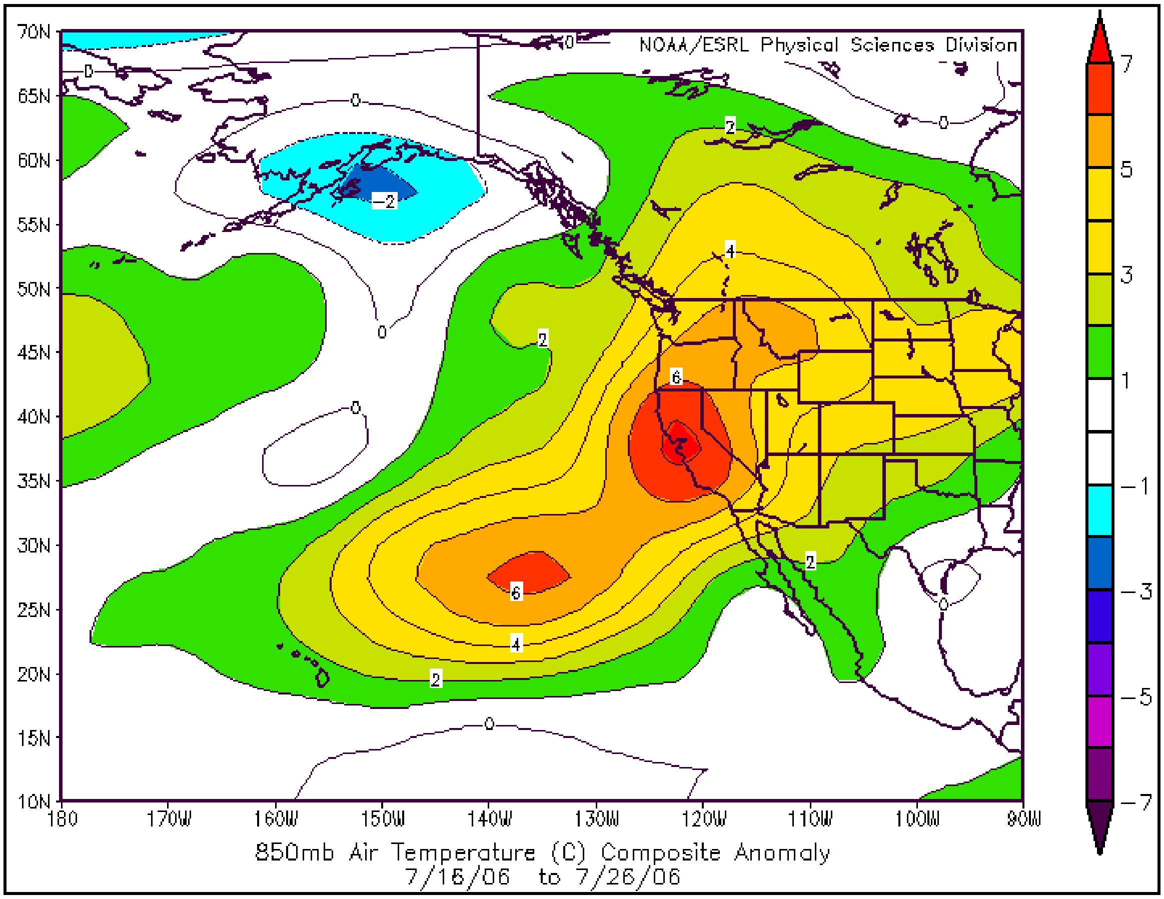

Figure 11: Shows 850mb air temperature (°C) anomalies during the period of the July 2006 heat wave. The strongest anomalies associated with the warm air mass across the southwest United States were located along the west coast. In particular, the peak departures from normal were located over the San Francisco Bay Area, the southern Sacramento Valley, and northern San Joaquin Valley.

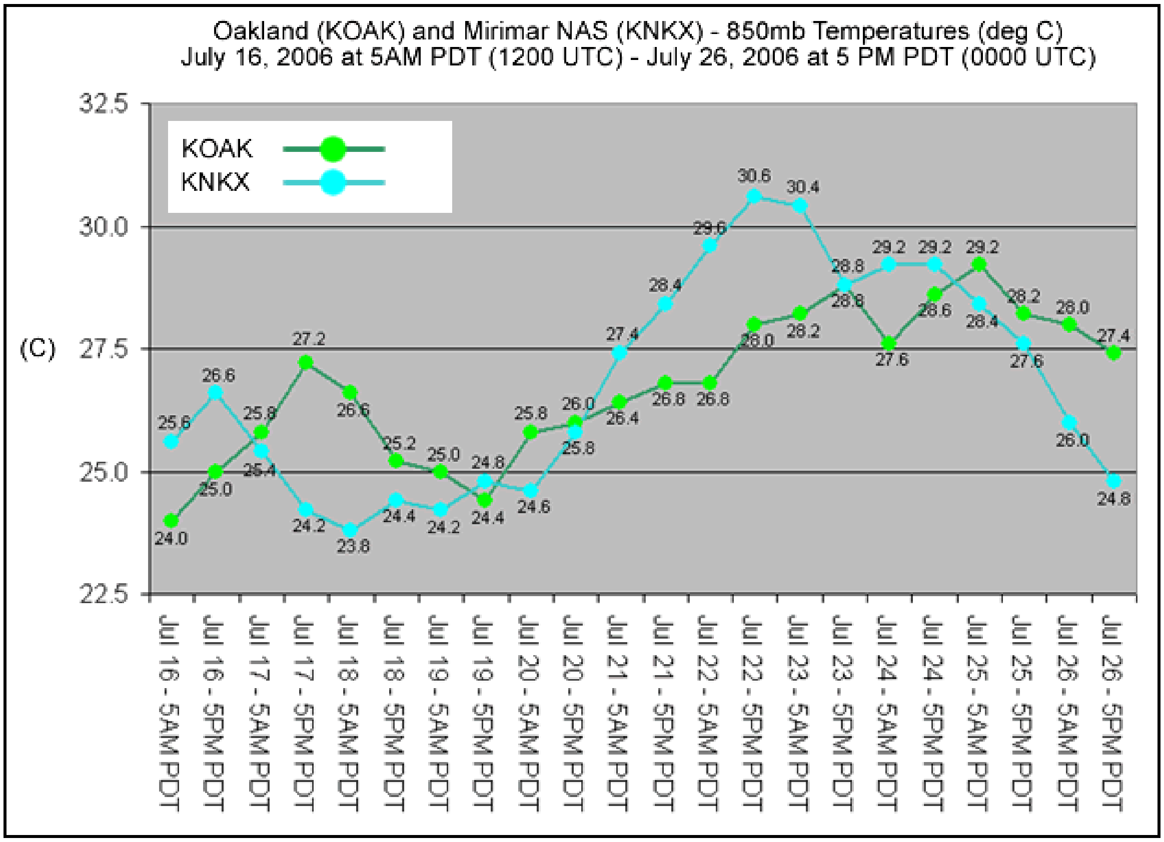

Figure 12: Indicates 850mb temperatures (°C) recorded at the Oakland (KOAK) and Miramar Naval Air Station (KNKX) sounding locations. Of note is the early peak of warm temperatures at both stations, followed by a slight decrease over the next couple days. Late on July 19 or early on July 20, 850mb temperatures rebounded and elevated to extremely warm levels. These temperatures cooled as the result of the weakening of the western United States upper level high pressure ridge and the return of dry west to southwest flow.

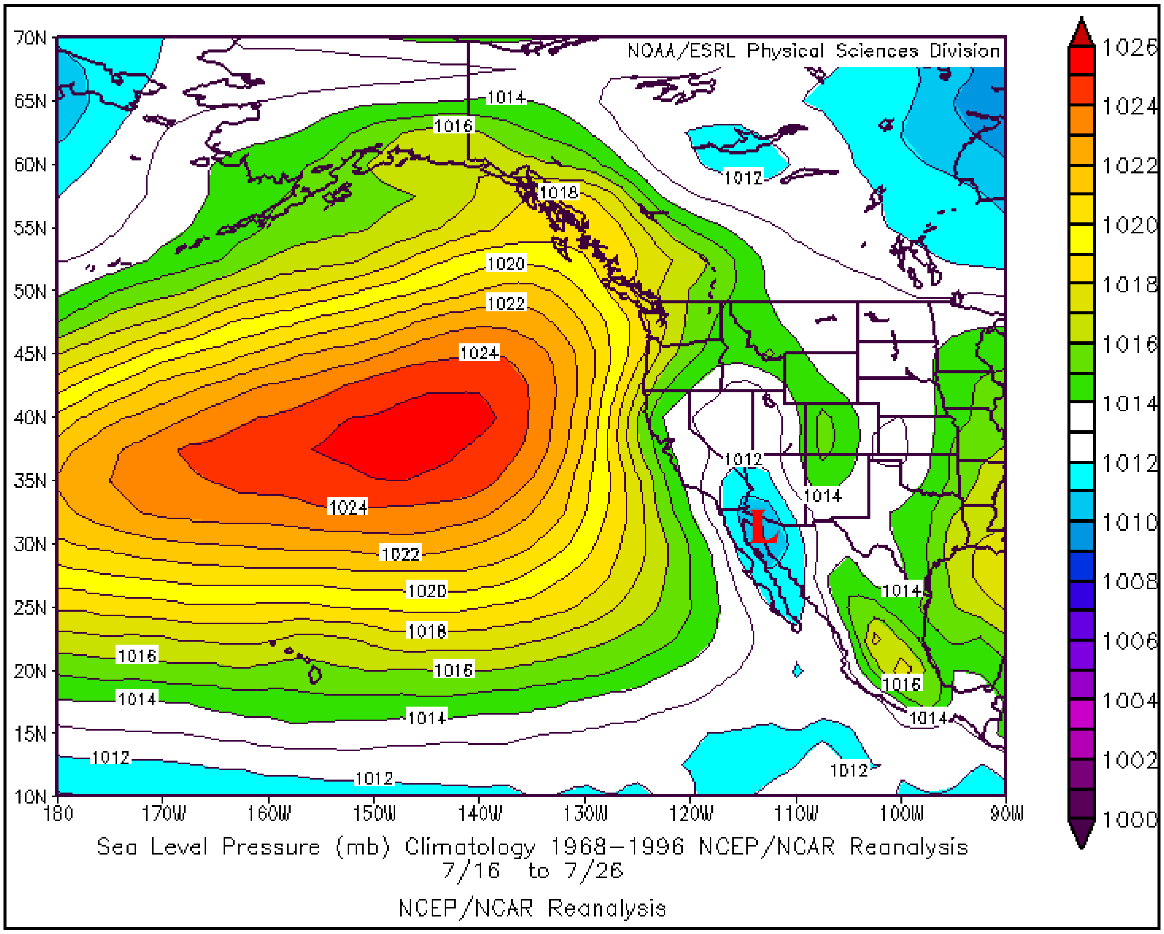

Figure 13: Climatology (1968 – 1996) indicates a thermally induced surface low pressure center located south of Yuma, Arizona over northwest Mexico. A thermal trough extends northward from this surface low, and is generally aligned along the Nevada and Utah border. Also, note a broad area of surface high pressure centered over the eastern Pacific Ocean. This generates northwesterly surface flow over coastal waters of the western United States, as well as upwelling of cooler waters in the same region.

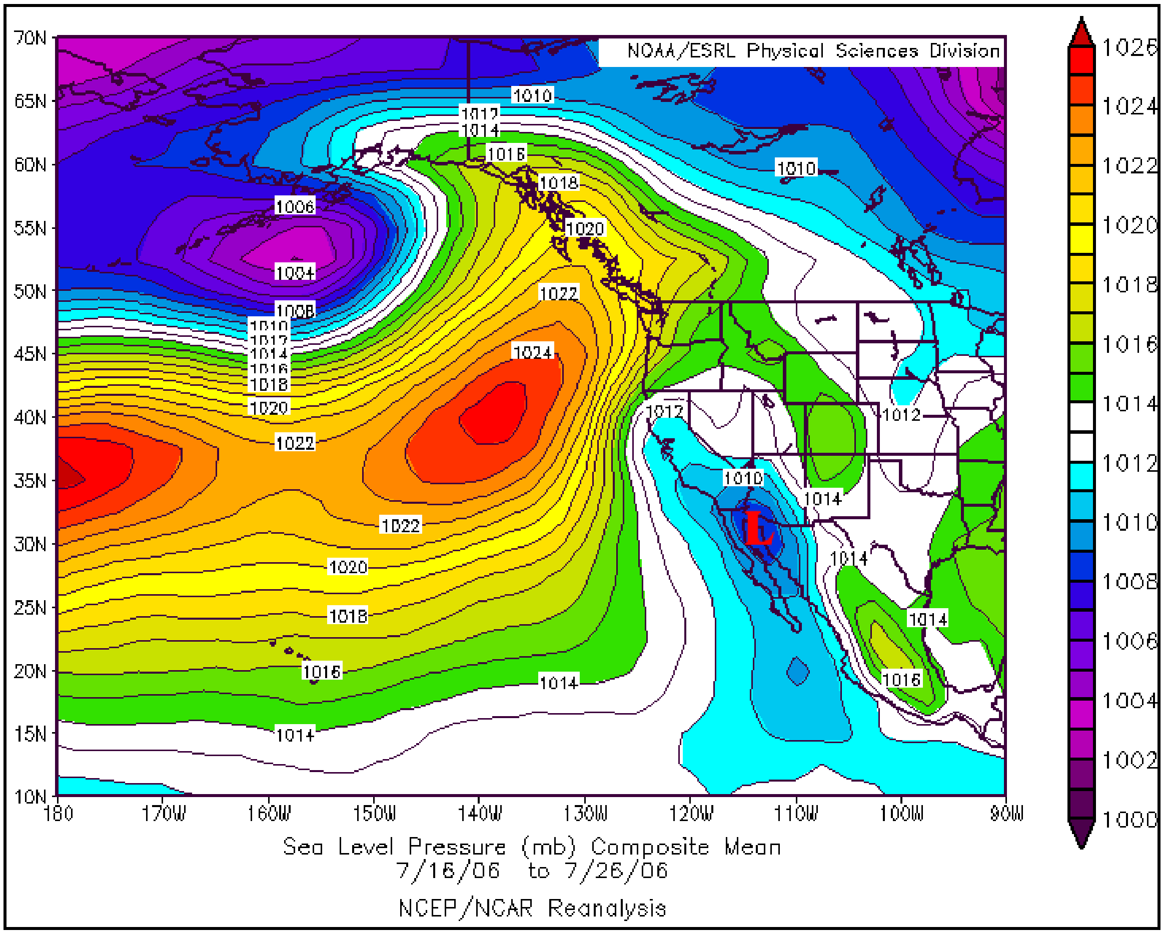

Figure 14: Displays sea level pressure (mb) during the July 2006 heat wave episode. The position of the thermally induced surface low and the alignment of the weak thermal surface low along the Nevada and Utah border are similar to climatology. However, a deeper thermal surface trough developed along the west coast of California. This thermally induced surface trough allowed for onshore westerly winds to shift to an easterly direction with lowered magnitudes. The marine layer along the coast, which typically penetrates inland during the overnight hours, was kept along the immediate coast. Also, the typical northwesterly pressure gradient along the coast of California was much weaker, resulting in calmer winds at buoys and a reduction of the upwelling of cooler ocean waters.

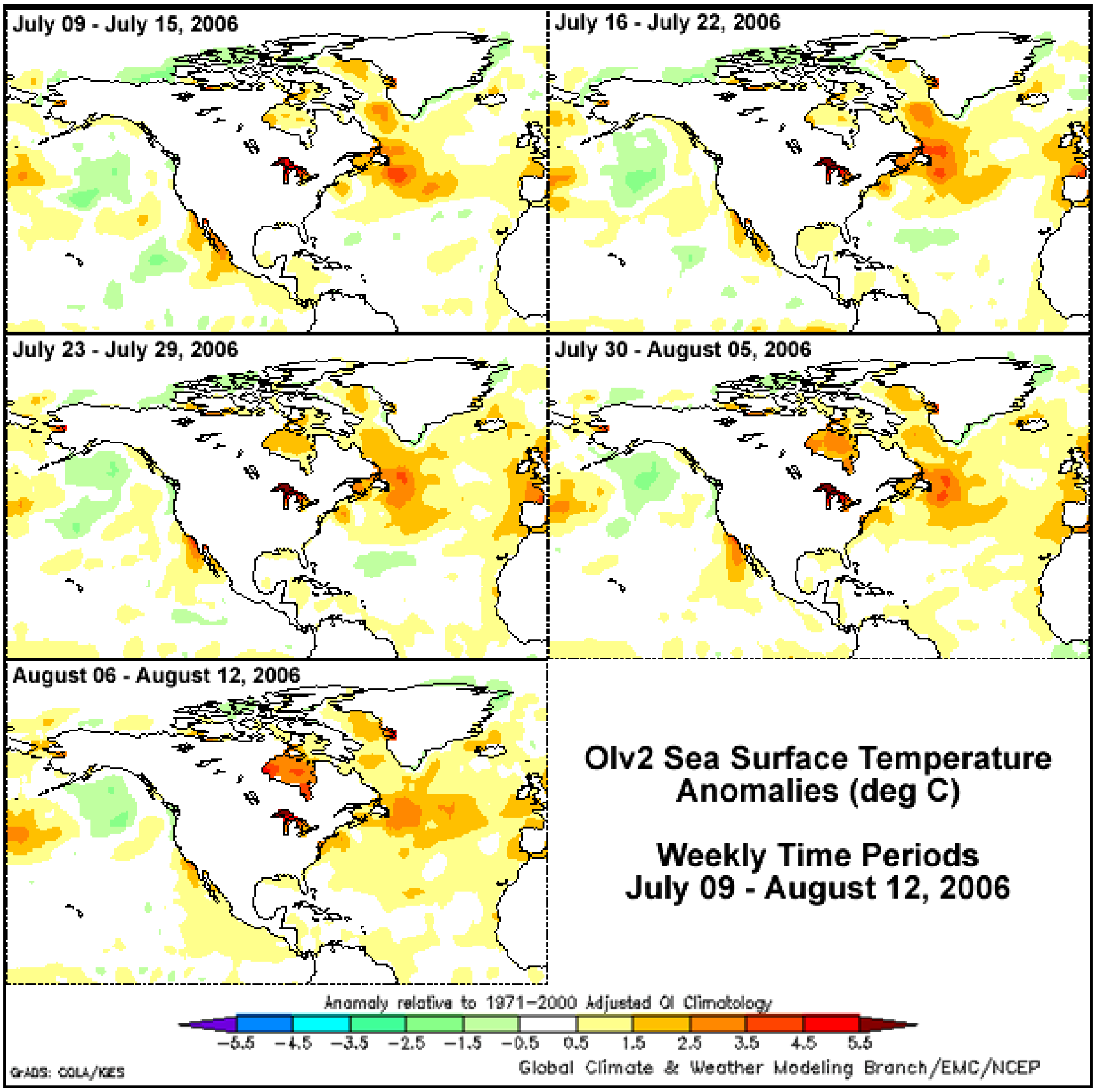

Figure 15: Represents weekly sea surface temperature anomalies for the period of July 9 through August 12, 2006. Note the increase in positive anomalies along the California coast from San Francisco to the United States and Mexico border during the heat wave event, peaking between July 23 and August 5, 2006. This increase in sea surface temperatures was the direct result of the weakening northwesterly gradient along the California coast, which resulting in a reduction of upwelling of cooler ocean waters. Finally, as the northwesterly gradient returned in August 2006, a lessening of the anomalies is noted in the week of August 6 through August 12.

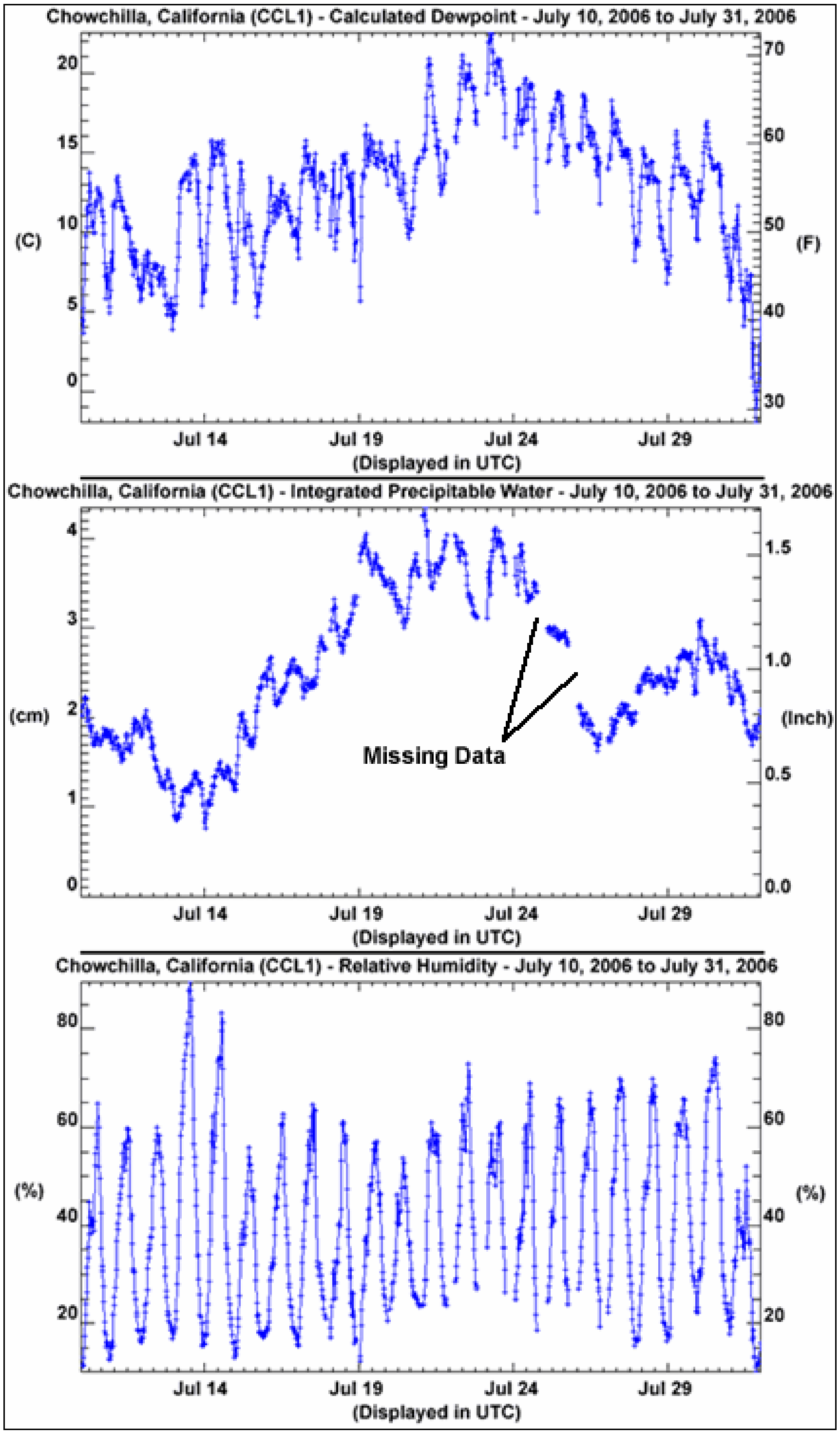

Figure 16: Depicts three unique moisture parameters, surface dew point temperature, integrated precipitable water, and relative humidity at Chowchilla, California (north-central San Joaquin Valley) from July 10 through July 31. Notice the increase of surface dew point temperature and integrated precipitable water values during the peak of the heat wave event. Also, notice the lack of change in relative humidity, except for typical diurnal fluctuations.

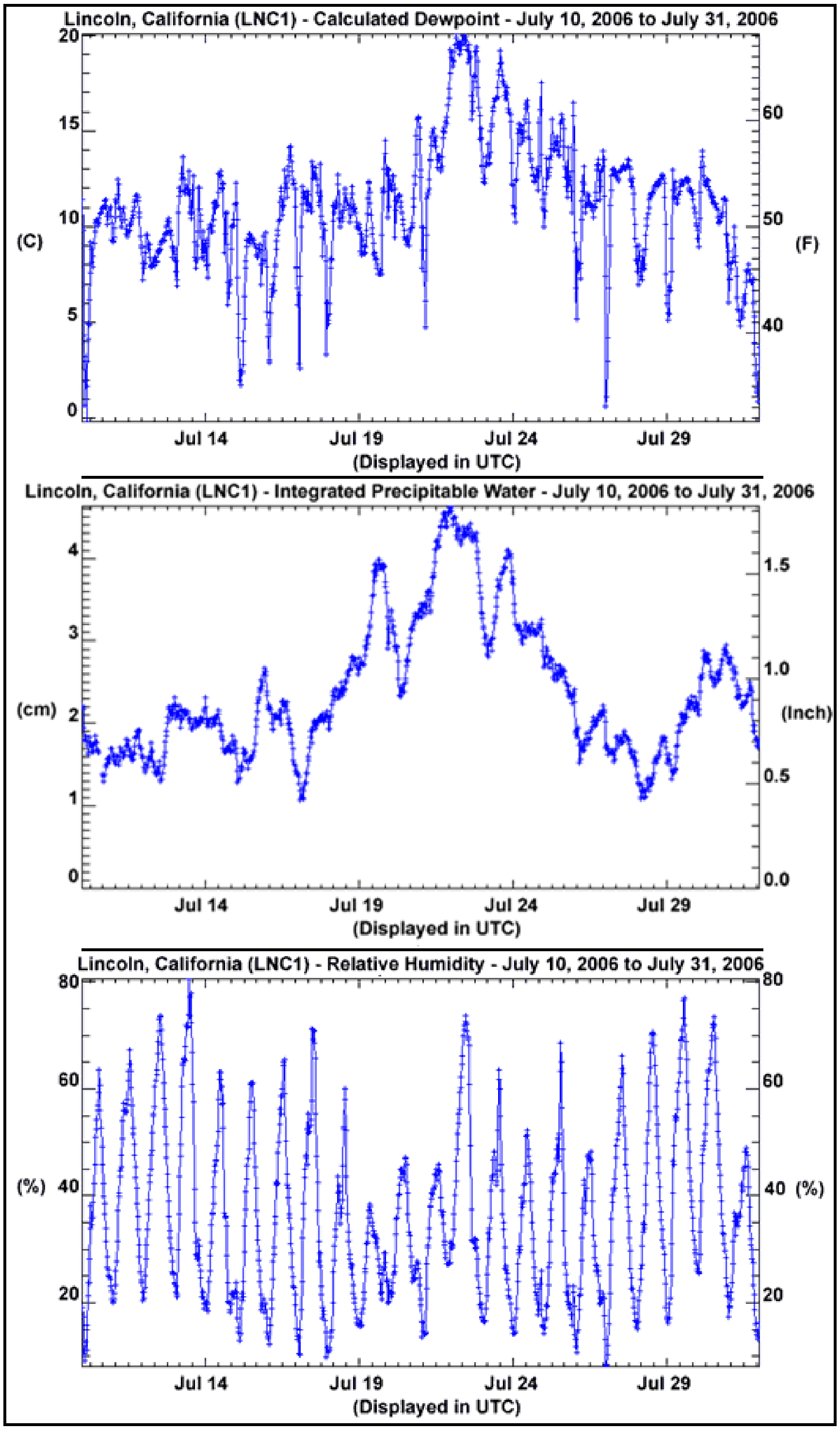

Figure 17: Depicts three unique moisture parameters, surface dew point temperature, integrated precipitable water, and relative humidity at Lincoln, California (southern Sacramento Valley) from July 10 through July 31. Notice the increase of surface dew point temperature and integrated precipitable water values during the peak of the heat wave event. Also, notice the lack of change in relative humidity, except for typical diurnal fluctuations.

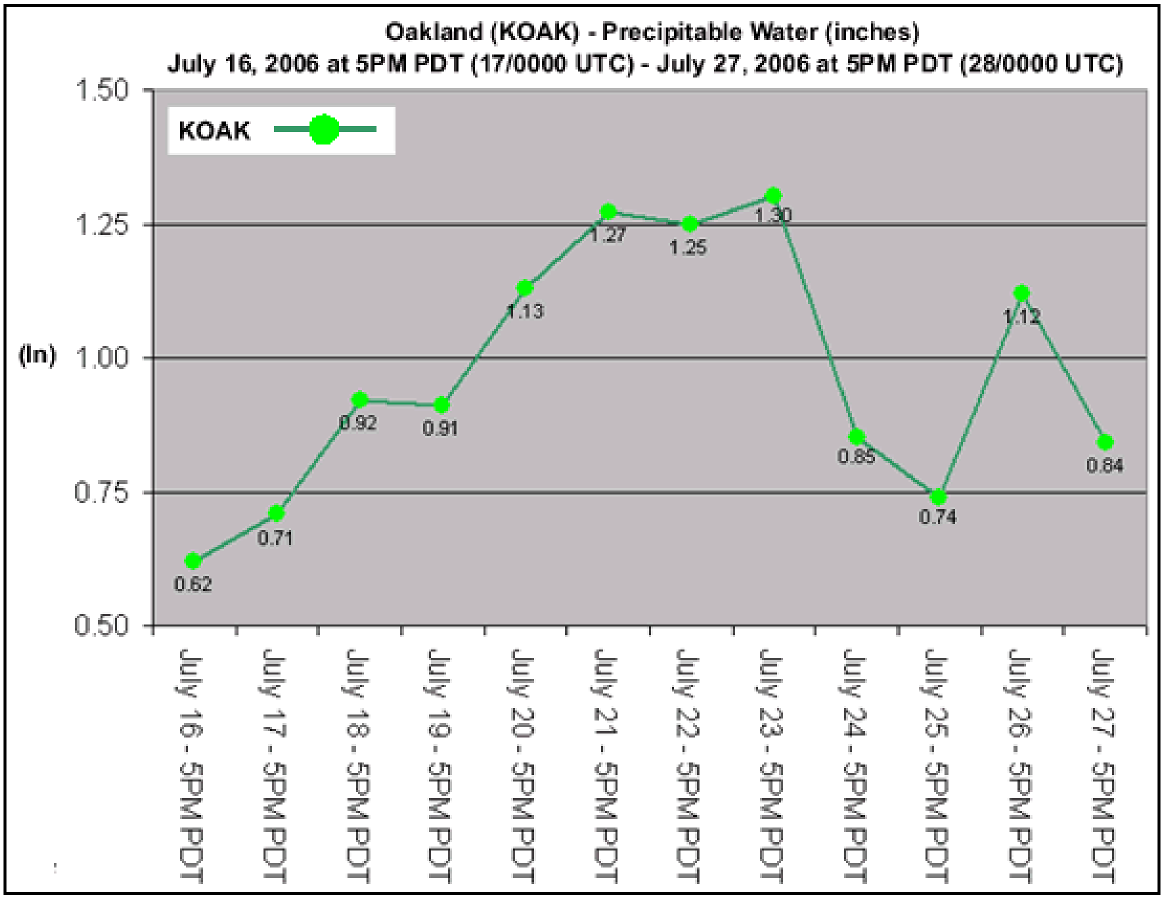

Figure 18: Depicts the precipitable water values (inch) recorded at the Oakland (KOAK) sounding site during the afternoon launches. Notice the increase in monsoonal moisture through the heat wave event, peaking between July 21 and July 23. This correlates well to the elevated overnight minimum temperatures, which peaked on July 23.

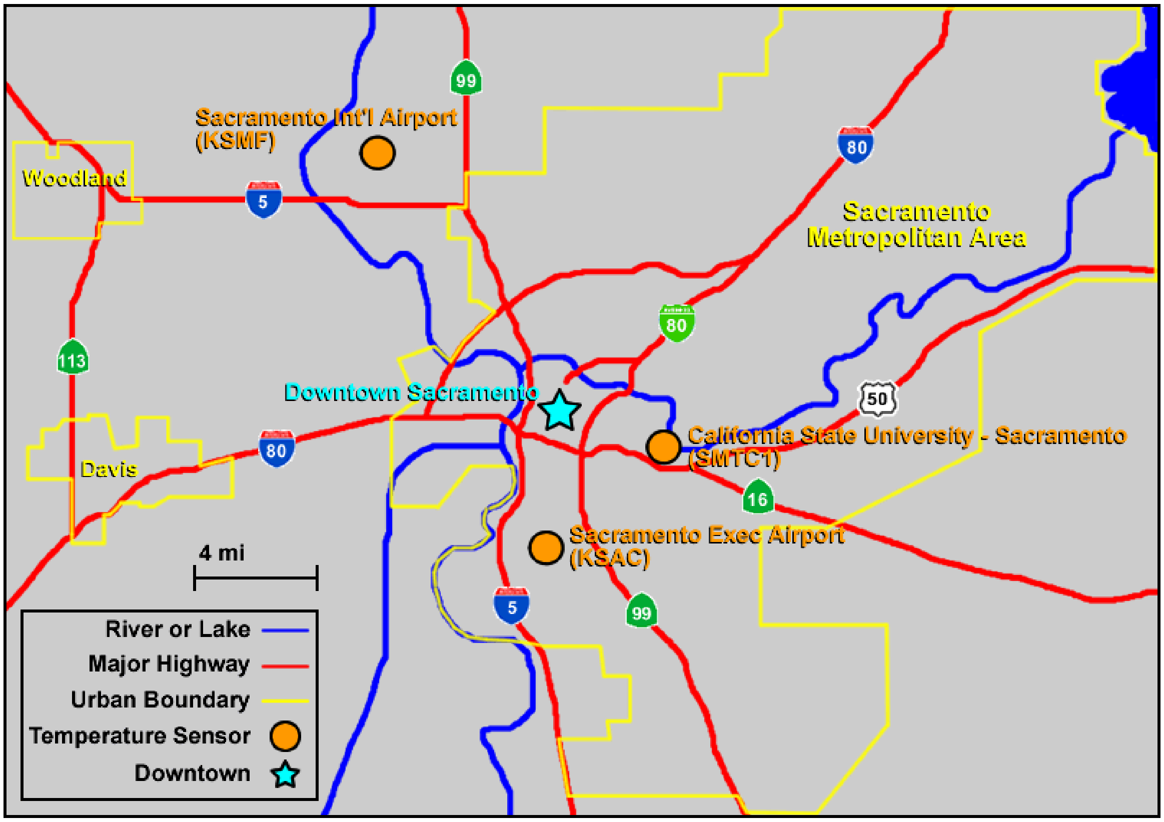

Figure 19: Displays the three observation stations located throughout the Sacramento region. Also, the general urban boundary is depicted. Sacramento International Airport is in a rural setting just outside the urban boundary to the northwest. Sacramento Executive Airport is located near the edge of the urban boundary on the southwest part of the area. California State University – Sacramento is located near the middle of the Sacramento urban area.

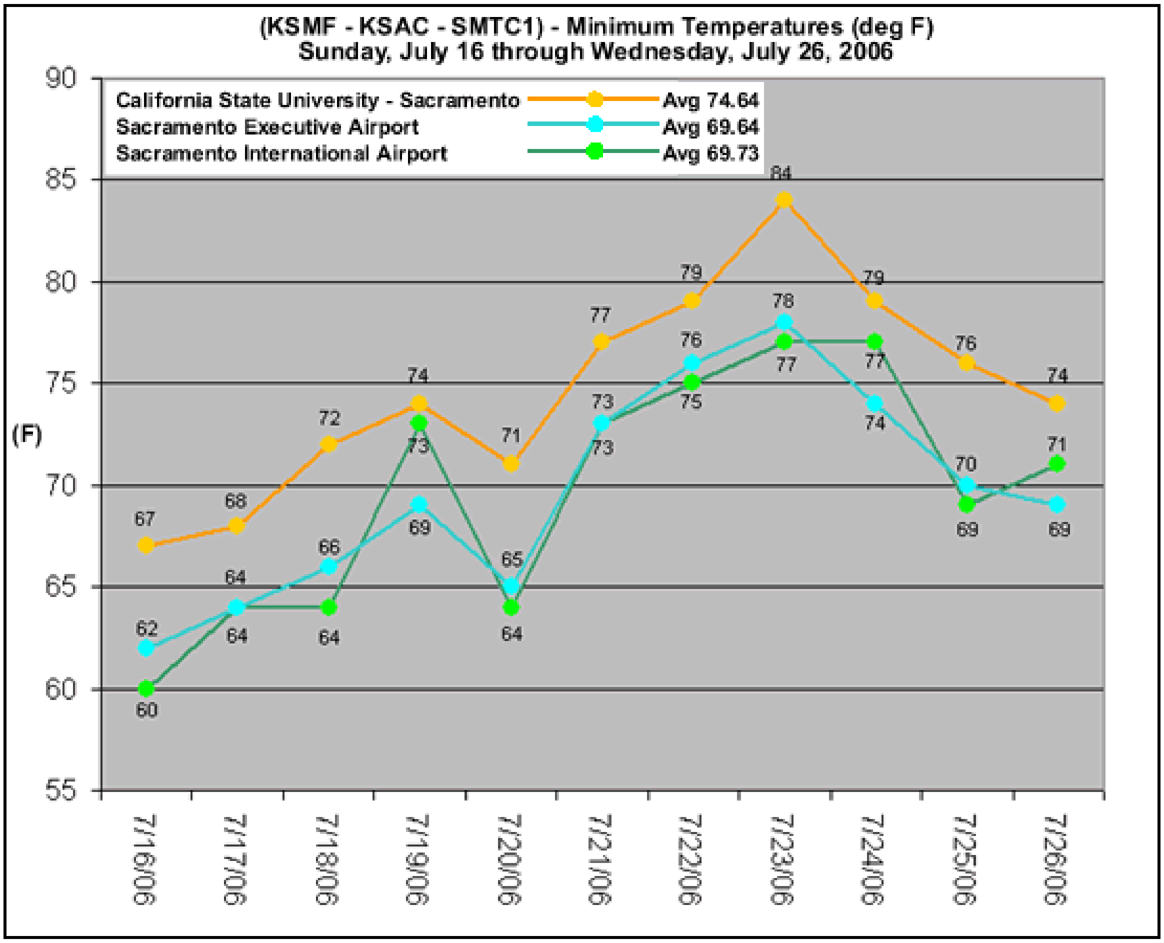

Figure 20: Depicts overnight minimum temperatures at three locations throughout the Sacramento region during the July 2006 heat wave event. All three locations recorded elevated minimum temperatures; however, the urban heat island effect was noted at the California State University – Sacramento observation station. The average temperature was approximately 5°F warmer than the Sacramento International and Executive Airports.

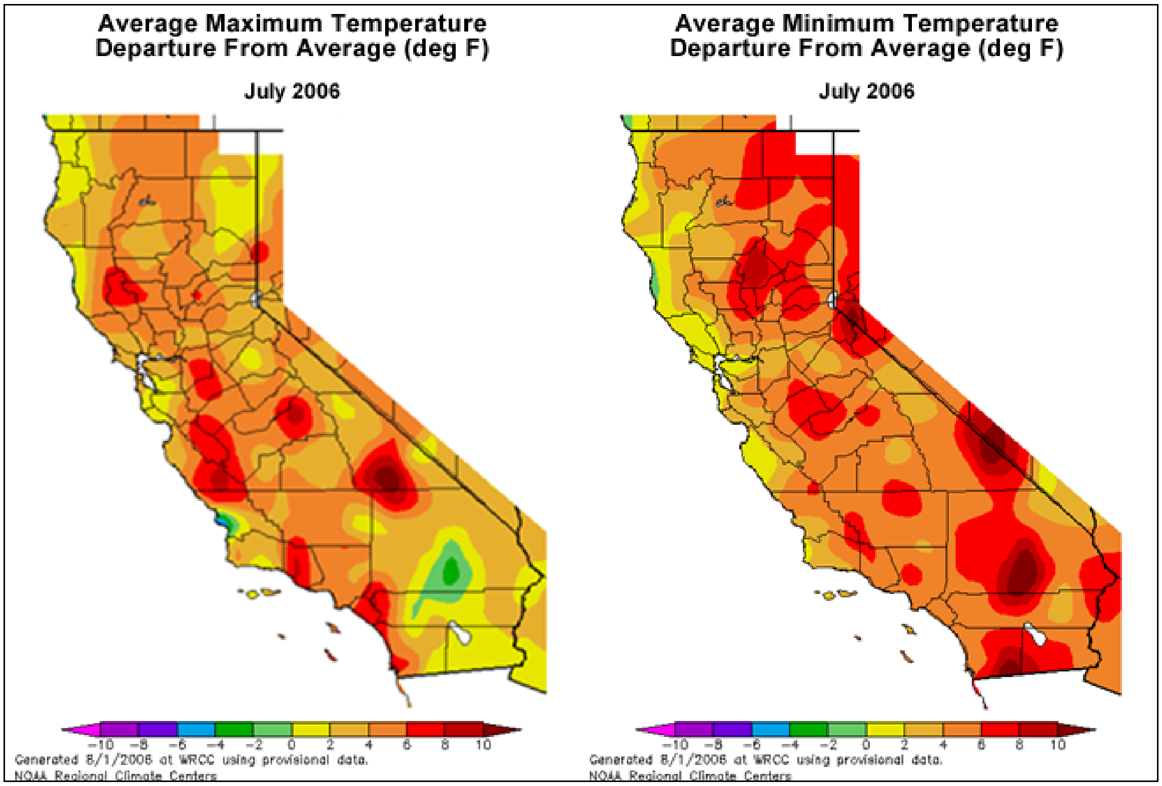

Figure 21: Depicts the departure from average for both the average maximum and average minimum temperature (°F) for July 2006. As one would expect, average maximum and average minimum temperature both exhibited above normal conditions across much of California. In fact, one of the aspects that made the July 2006 heat wave noteworthy was the elevated overnight minimum temperatures, which is reflected well in the right hand image.

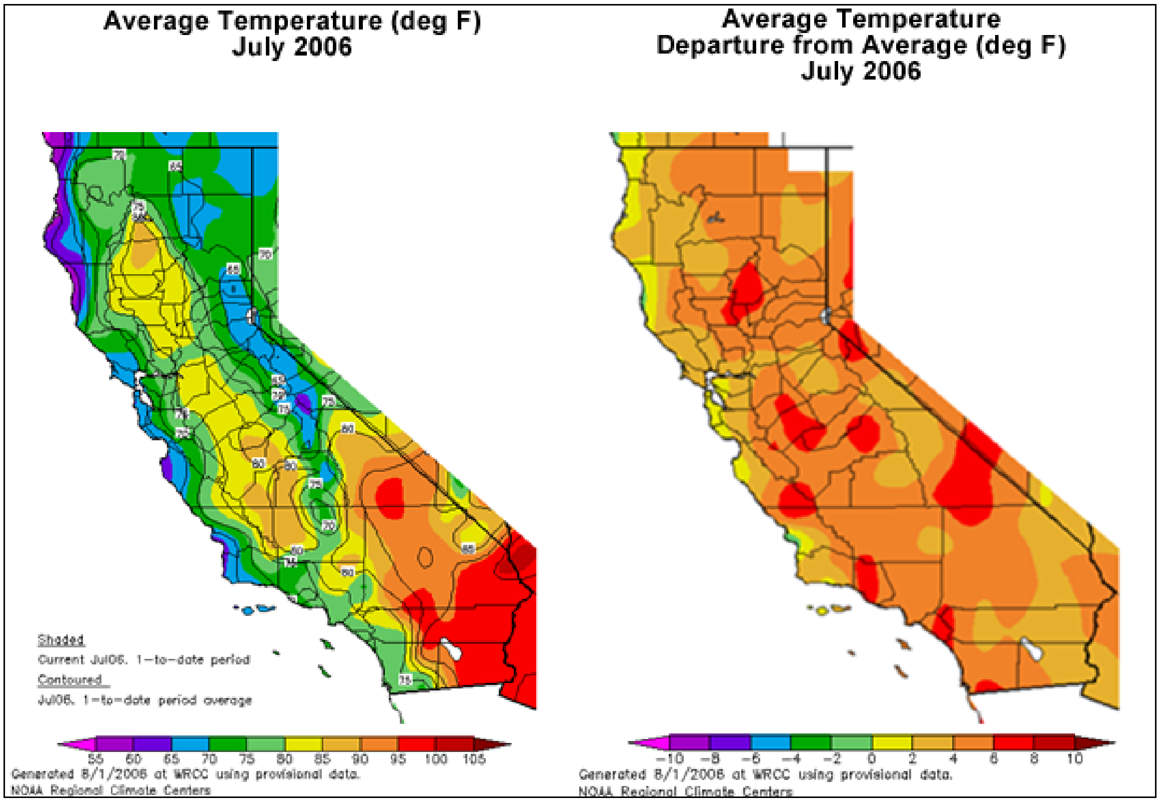

Figure 22: Displays the average temperature (°F) for July 2006, and the departure from normal. As expected, anomalies warmer than normal were recorded across much of the state of California. Peak readings ranged from 6°F to 8°F.

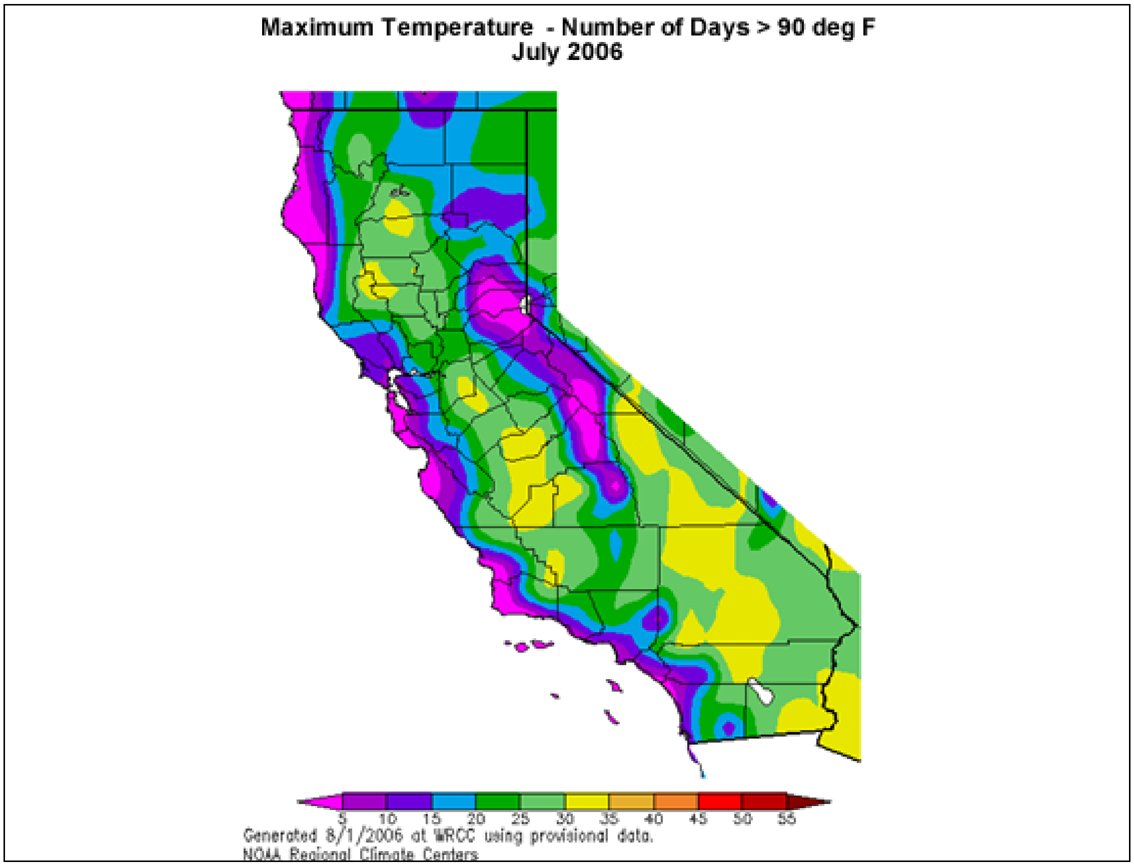

Figure 23: This graphic displays the number of days the maximum temperature was above 90°F. As expected, the greatest numbers were located across the Sacramento Valley and San Joaquin Valley, as well as the interior deserts of southeast California.

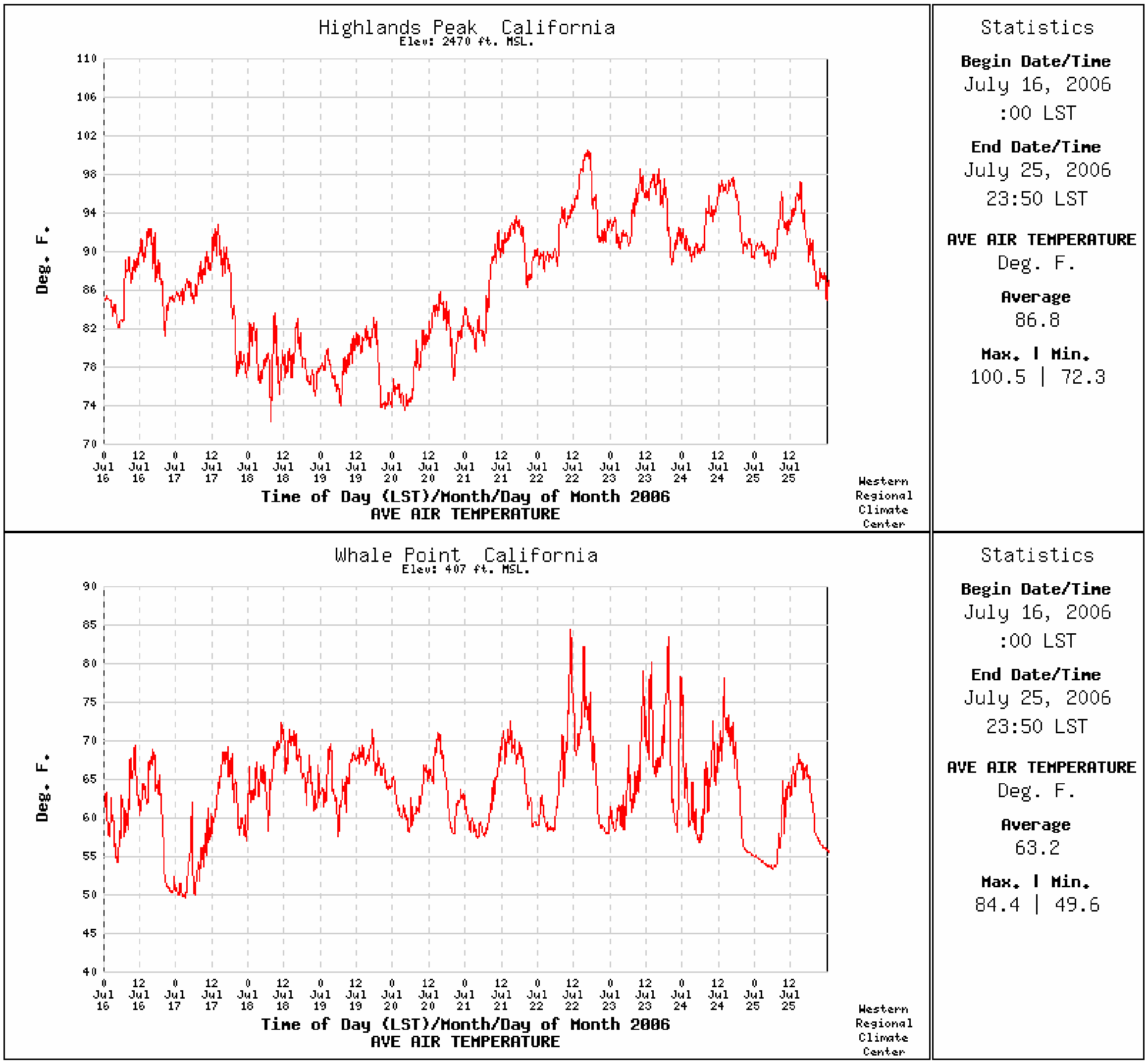

Figure 24: Temperature time series at Highlands Peak and Whale Point, California, for July 16-26, 2006. Although these two locations are approximately one mile apart, the affects of the marine layer on two stations at different elevations were evident. Notice the much cooler temperatures at Whale Point (elevation 407 feet) versus Highlands Peak (elevation 2470 feet).

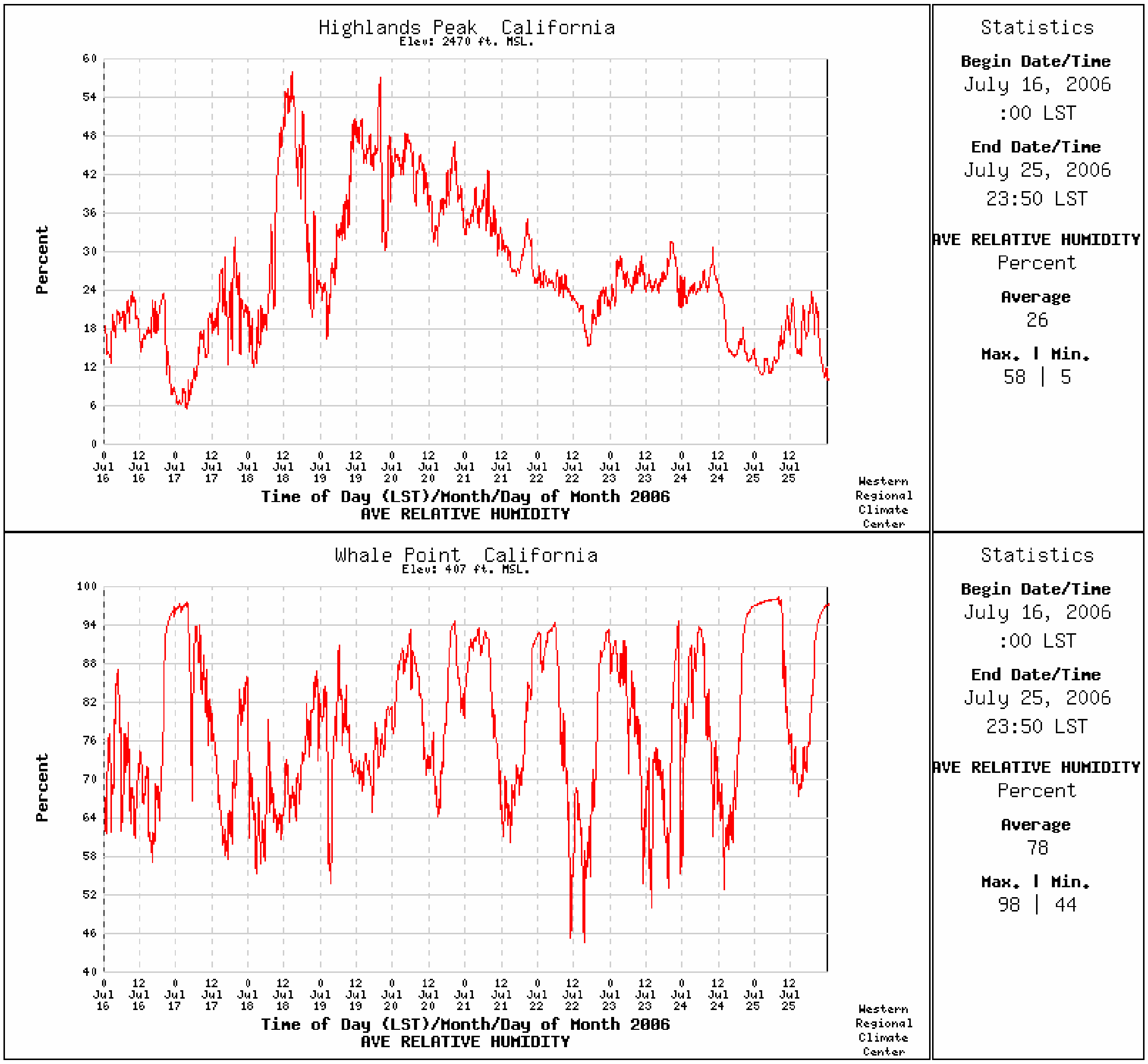

Figure 25: Relative humidity time series for Highlands Peak and Whale Point, California, for the dates July 16-26, 2006. Although these two locations are approximately one mile apart, the affects of the marine layer on two stations at different elevations were evident. Notice the higher relative humidity at Whale Point (elevation 407 feet) versus Highlands Peak (elevation 2470 feet), indicating where the marine layer affected certain locations.

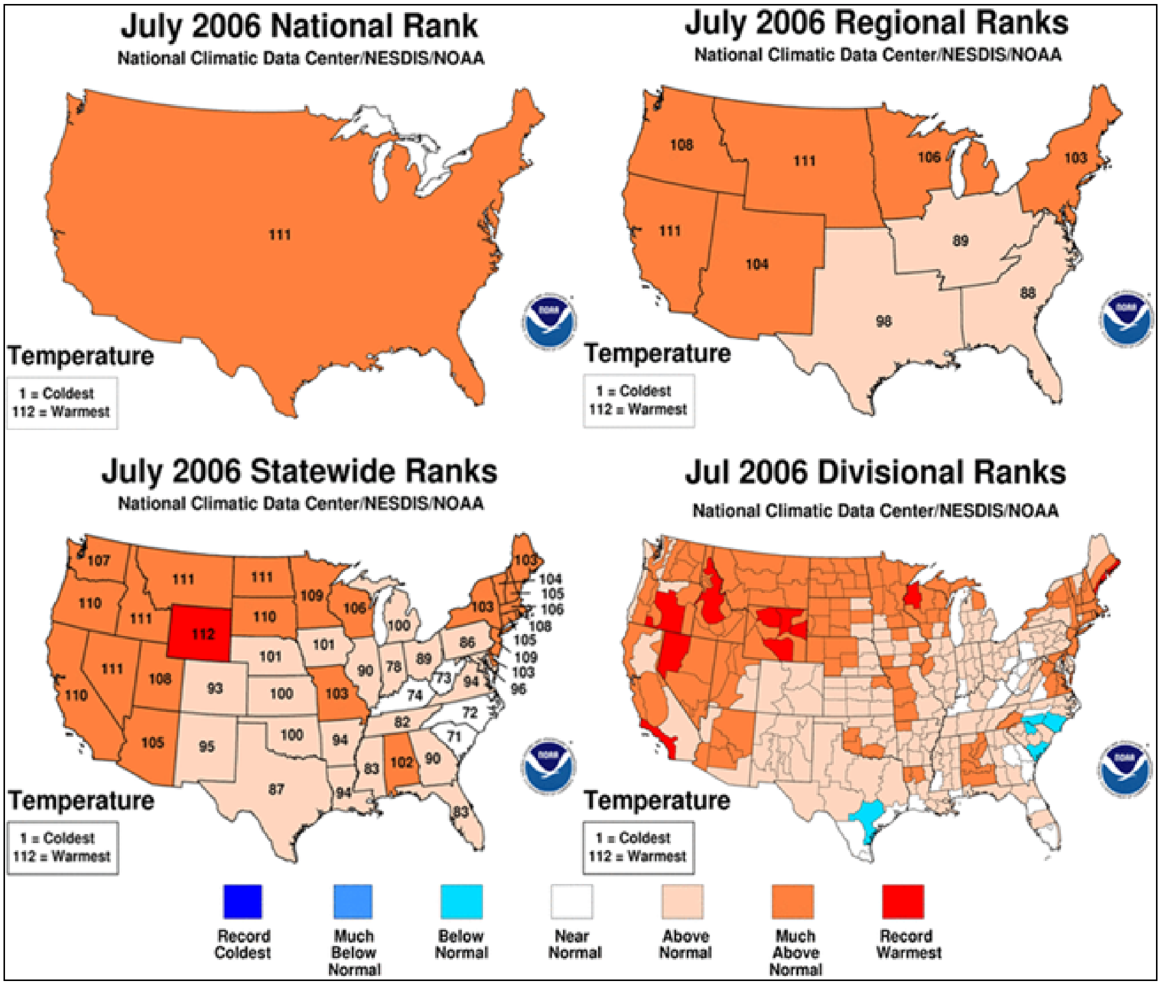

Figure 26: The above graphic shows a breakdown of the July 2006 temperatures, ranking each area based on the past 112 years of observed data. The data is ranked for areas as large as the lower 48 United States down to smaller divisions within each state. The lower 48 United States recorded its second warmest July on record. Looking at California, the state saw its third warmest July. When considering California by climate division, the south coast of California experienced its warmest July ever, while other areas of the state saw either above normal or much above normal conditions.

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