5A.8 THE RECORD-BREAKING CENTRAL CALIFORNIA HEAT WAVE OF JULY 2006

Warren Blier *
NOAA/National Weather Service, Monterey, California

1. INTRODUCTION

A record-breaking heat wave affected much of the state of California during the period 16-26 July 2006. Although numerous daily maximum and minimum temperature records were set, other aspects of the event were perhaps even more remarkable. Of particular note were both the degree of elevation of the overnight minimum temperatures, and the number of consecutive days the hot weather persisted. Many inland valley locations set their all-time high minimum temperature records, in some cases exceeding the previous record by a wide margin; many new records for 3-, 5-, 7- and 10-day average temperatures were also established, here too often far exceeding previous records. Accompanying dew points were also unusually high, reflective of an influx of subtropical moisture aloft that occurred during the event, and which further increased the impact of the hot weather.

This prolonged extreme high temperature event had significant adverse impacts on California's economy and energy supply, as well as on the health of its population. The all-time state record for energy consumption was set on 24 July 2006 with 50,270 Megawatts used, while more than one million customers ultimately lost commercial electrical power. In excess of 140 deaths were directly attributable to this heat wave.

**Corresponding author address:* Warren Blier, NOAA/ National Weather Service, 21 Grace Hopper Ave, Stop 5, Monterey, CA 93942-5505; e-mail: warren.blier@noaa.gov.

2. METEOROLOGICAL OVERVIEW

This heat wave occurred in association with the development and subsequent persistence of an extraordinarily robust large-scale upper-level high, centered over the Great Basin and with a ridge axis extending westward through central California (Fig. 1a). Even in the depicted 11-day average, 500 hPa heights exceeded 594 dm over much of the southwestern United States. Mean 850 mb temperatures for this same 11-day period reached a maximum of about 30 C (Fig. 1b), with peak values situated a bit to the west of the center of the 500 mb anticyclone.

The corresponding NCEP/NCAR climatological mean 500 mb height and 850 mb temperature fields are shown in Figs. 1c and 1d, respectively. Interestingly, for both parameters, highest values for the period of the heat wave only modestly exceeded climatology: maximum 500 mb heights (850 mb temperatures) over the southwestern U.S. were approximately 40 m (4 C) greater than the climatological maxima for the same period. However, examination of the difference fields indicates significantly larger peak anomalies. The 500 mb height anomaly analysis (Fig. 1e) shows greatest values of a bit more than 90 m in the vicinity of Oregon, well to the northwest of the 500 mb heat-wave mean anticyclonic circulation center. Appreciable easterly 500 mb geostrophic wind anomalies thus existed over California during the heat wave, in contrast to the climatological weak upper level trough along the west coast evident in Fig. 1c, and associated southwesterly flow aloft. The 850

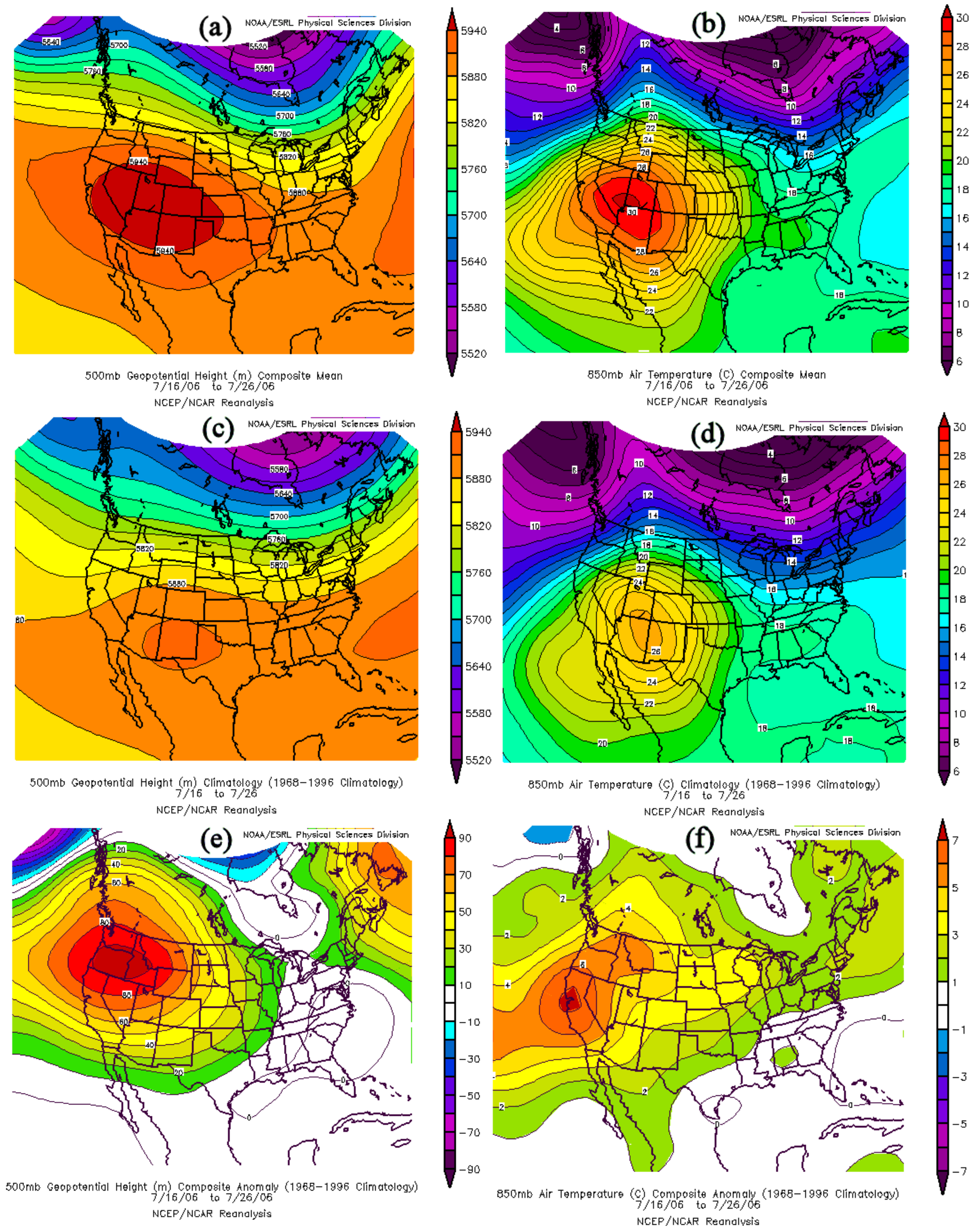

Fig. 1. (a) Composite mean 500 mb geopotential heights (m) for the period 16-26 July 2006. (b) Same as (a) but for 850 mb temperatures (C). (d) Climatological mean 500 mb heights (m) for the years 1968-1996. (e) Same as (d), but for 850 mb temperatures (C). (e) 500 mb height anomalies (m) for the period 16-26 July 2006. (f) Same as (e), but for 850 mb temperatures (C). Plots generated from the NOAA/ESRL/PSD interactive plotting and analysis web pages (http://www.cdc.noaa.gov/cgi-bin/PublicData/getpage.pl).

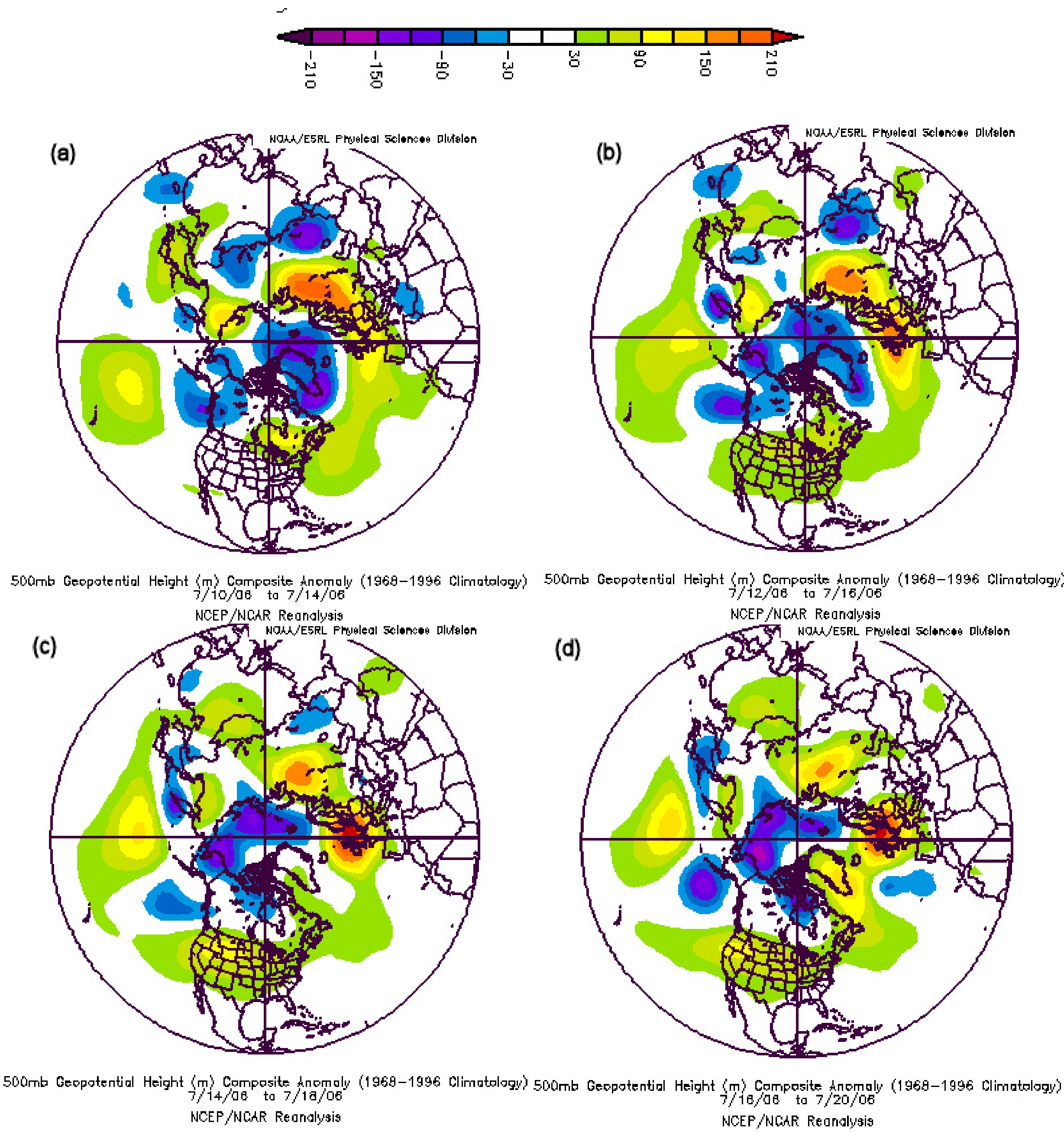

Fig. 2. Mean 500 mb geopotential height anomalies (m) for the 4-day periods (a) 10-14 July 2006, (b) 12-16 July 2006, (c) 14-18 July 2006, (d) 16-20 July 2006, (e) 18-22 July 2006, 20-24 July 2006, (f) 20-24 July 2006, (g) 22-26 July 2006 and (h) 24-28 July 2006. Plots generated from the NOAA/ESRL/PSD interactive plotting and analysis web pages (http://www.cdc.noaa.gov/cgi-bin/PublicData/getpage.pl).

mb temperature anomaly analysis (Fig. 1f) also shows a significant westward shift from the location of the thermal maximum, with largest values slightly in excess of 8 C centered over the north-central California coast.

The evolution of the 500 mb height anomaly associated with this heat wave is shown in Fig. 2. For the period 10-14 July 2006, just prior to the onset of the event, Fig. 2a shows a broad positive anomaly extending westward across the midlatitude Atlantic Ocean and into

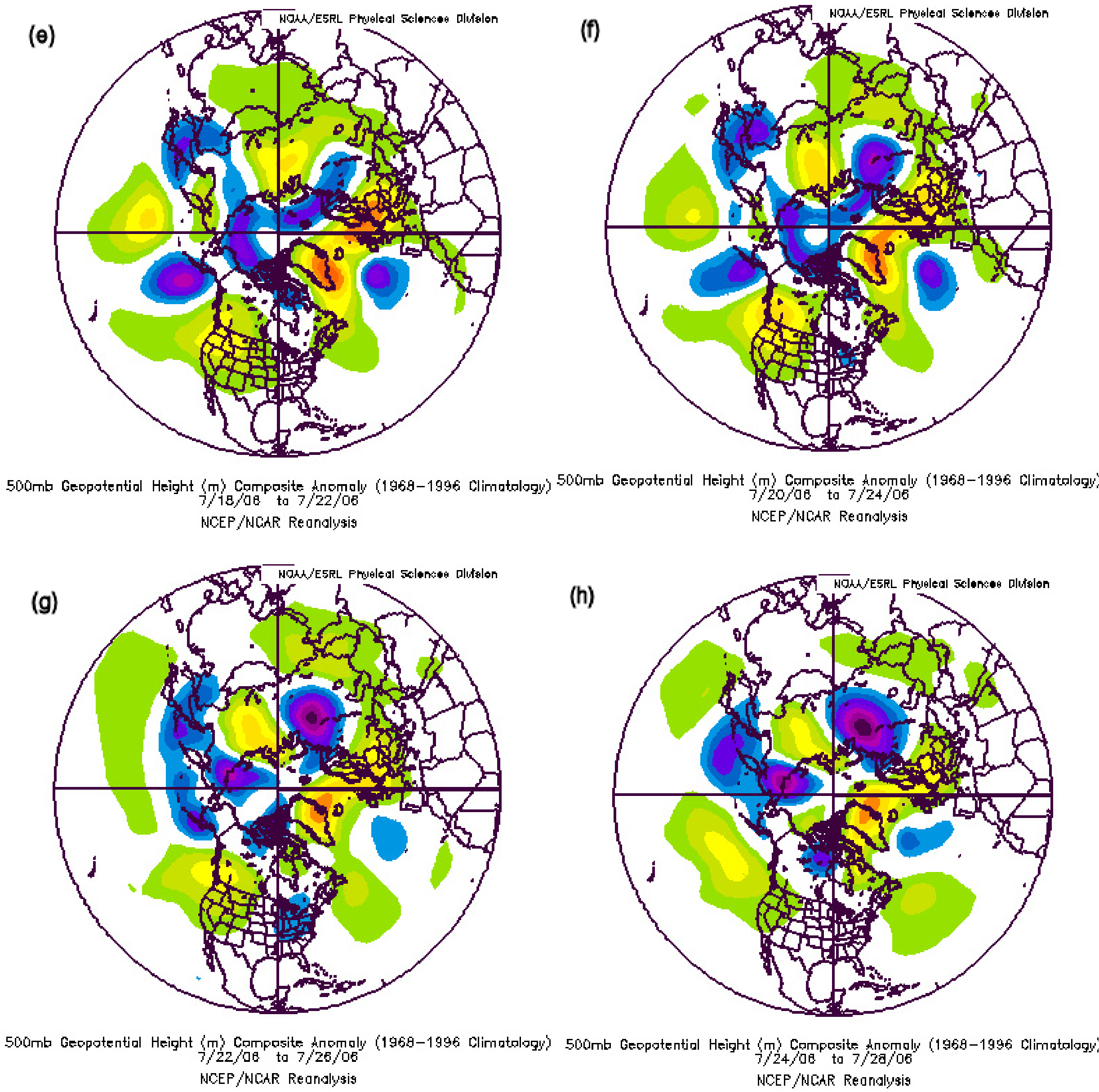

Fig. 2.(cont)

southeastern Canada and the northeastern United States. At the same time, a negative anomaly is centered near the British Columbia coast and a positive anomaly north of Hawaii. This anomaly pattern appears at least somewhat suggestive of the positive phase of the PNA pattern, and in fact the PNA index was positive for the first half of July 2006 (Fig. 3). Over the ensuing days into the beginning of the heat wave, the anomaly pattern appears to retrograde, with the positive 500 mb height anomaly initially centered over southeastern Canada shifting westward to the northwestern U.S. It reaches its maximum amplitude during the 20-24 July period (Fig. 2f), when the heat wave itself was beginning to crest. It then continues to shift westward into the Pacific Ocean, ultimately bringing the heat wave to an end as a weak upper level trough develops along the

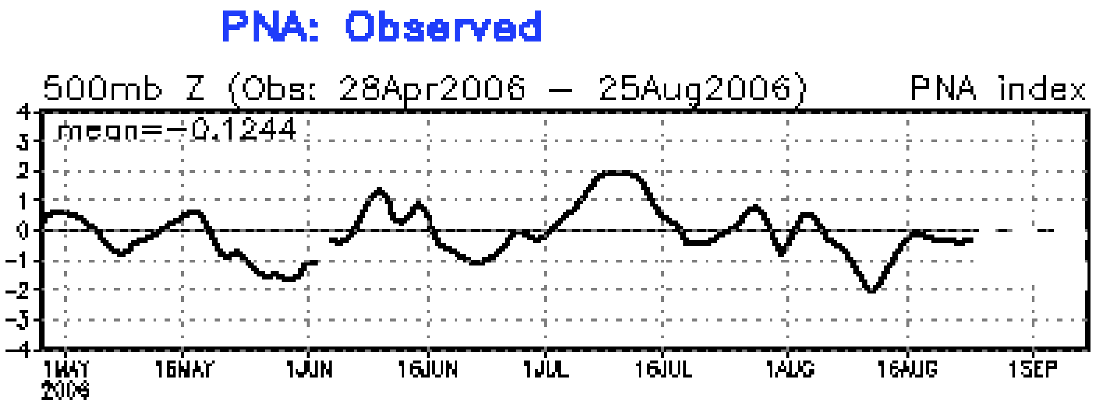

Fig. 3. NOAA/CPC observed PNA500 mb Height Index for 28 April to 25 August 2006.

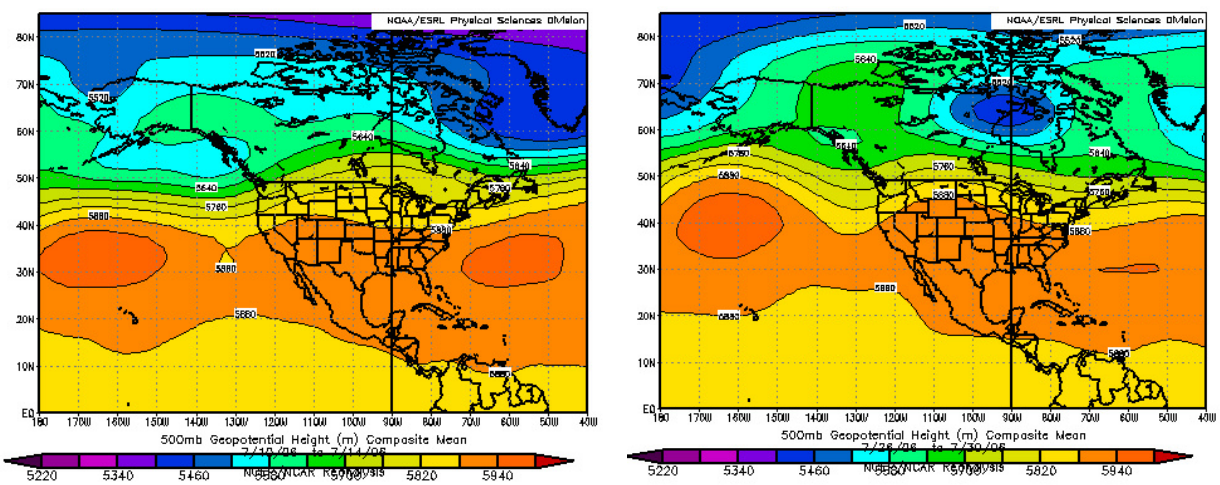

Fig. 4. (a) Composite mean 500 mb geopotential heights (m) for the period 10-14 July 2006. (b) Same as (a) but for period 26-30 July 2006. Plots generated from the NOAA/ESRL/PSD interactive plotting and analysis web pages (http://www.cdc.noaa.gov/cgi-bin/PublicData/getpage.pl).

west coast (Fig. 4b) – very similar to that which existed prior to the heat wave onset (Fig. 4a).

The peak of this central California heat wave occurred during the period 22-26 July 2006. The ECMWF 500 mb height analysis for 00Z 22 July (Fig. 5) includes an analyzed 600 dm contour in the vicinity of southeastern Idaho – consistent with depicted radiosonde-derived 600 dm 500 mb geopotential heights at both Boise, Idaho and Salt Lake City Utah. Observed 500 mb temperatures at these locations were a remarkably warm -4 C and -3 C, respectively. The superimposed ECMWF 1000/500 mb thickness analysis contains maximum values of approximately 590 dm in the vicinity of the California/Arizona border. Consistent with the height analysis, 500 mb radiosonde winds show flow out of the east-southeast into California, while generally limited dew point depressions indicate significant upper level moisture over the southwestern United States.

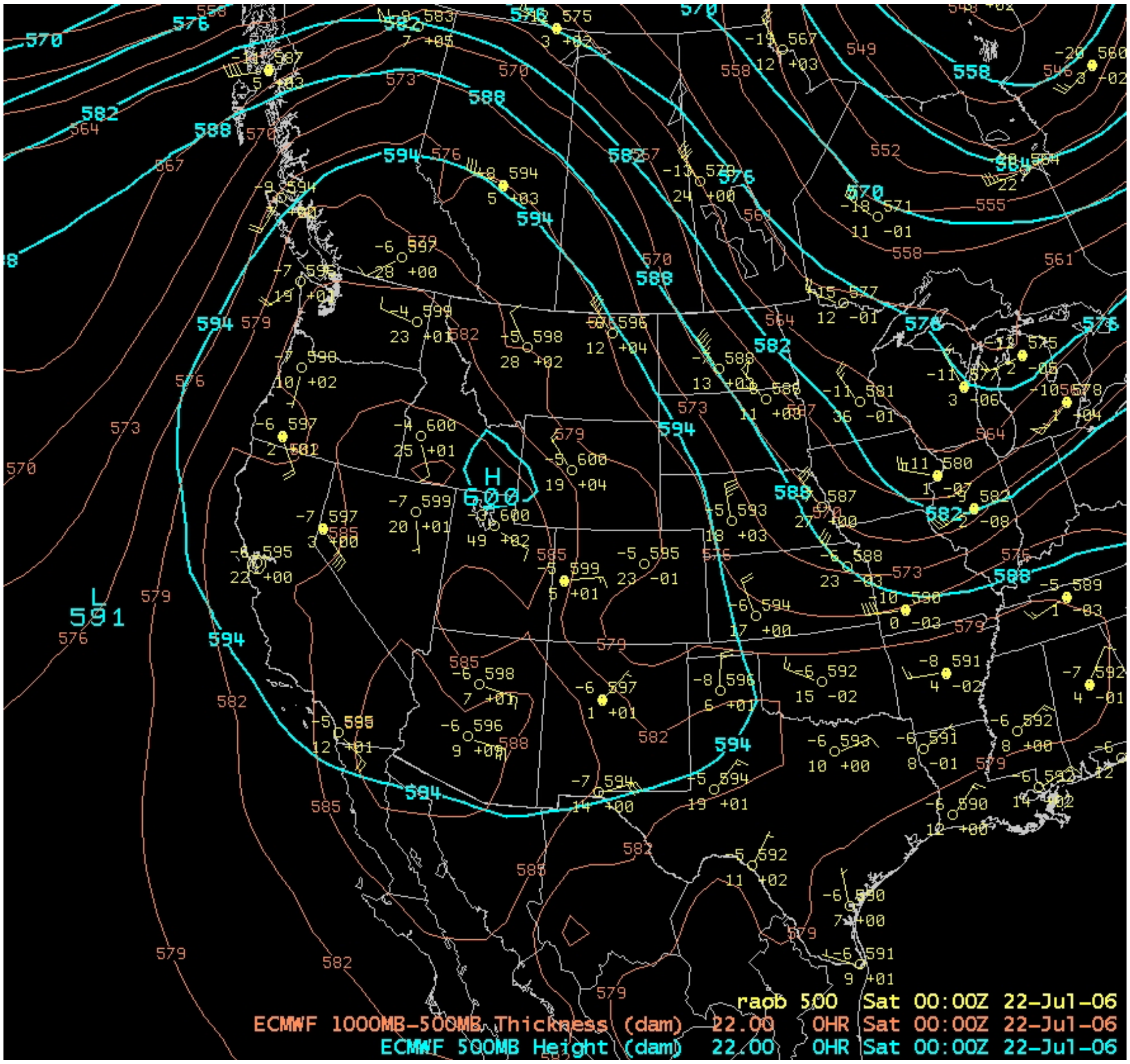

Fig. 5. ECMWF 500 mb geopoential height and 1000/500 thickness analyses (m) for 00Z 22 July 2006, with radiosonde observations superimposed.

3. HISTORICAL CONTEXT

Record and near-record temperatures were widespread across lower-elevation non-coastal central California, especially during the peak of the event between 22 and 26 July. An emblematic example is provided by the observations from Fresno International Airport (KFAT) in the middle of the San Joaquin Valley (location indicated by point E in Fig. 6). Maximum, minimum and average temperatures for each day of July 2006 are provided in Table 1, along with the departures from the corresponding daily climatological mean values. The previous all-time record high temperature for this site of 112 ^{o}F was tied on 22 July 2006 (and subsequently repeated on 26 July), and then exceeded by the 113 ^{o}F temperature observed the following day. This record 113 ^{o}F temperature was then repeated on both 24 and 25 July. Prior to this heat wave, the record

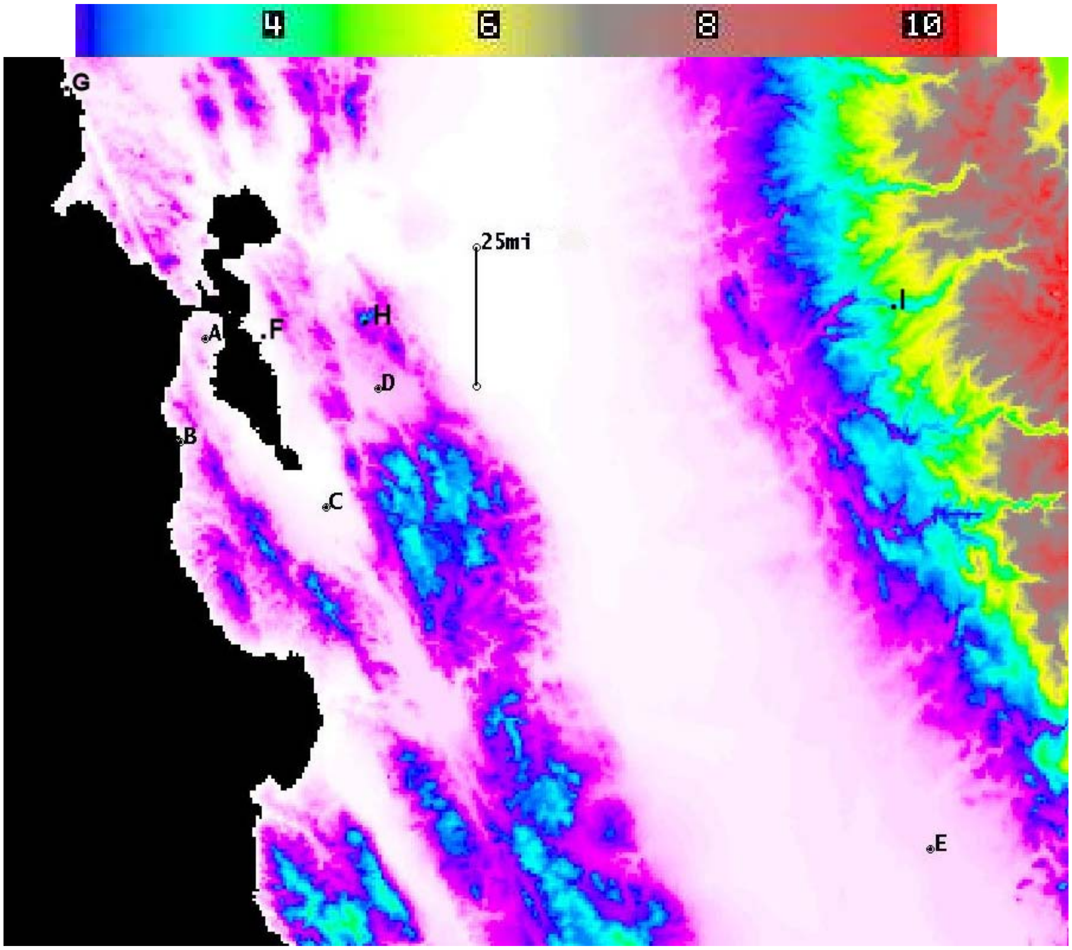

Fig. 6. Topographic map of north-central California. Surface elevation scale (kft) indicated at top. Location A = downtown San Francisco, B = Half Moon Bay, C = downtown San Jose, D = Livermore, E = Fresno International Airport, F = Oakland Airport upper air site, G = Bodega Bay NOAA wind profiler, H = Mt Diablo Junction and I = Calaveras Big Trees. A 25-mi (40-km) distance scale is indicated. Surface elevation of all specified locations is less than 400 ft (121 m), except Mt Diablo Junction [elevation = 2168 ft (661 m)] and Calaveras Big Trees [elevation = 4700 ft (1433 m)].

maximum temperature of 112 ^{o}F had first been reached on 5 July 1991 and then repeated on 13 August 1996. Thus, over the entire 58-year length of record for this site, 5 of the 7 hottest-ever days occurred during this single July 2006 heat wave.

Perhaps even more remarkable, though, are the new all-time records set at KFAT for minimum temperature and daily average temperature. Prior to July 2006, the all-time record high minimum temperature had been 83 ^{o}F, set on 13 July 1999 and then repeated on 30 July 2003. Not only was this exceeded on each of the 3 consecutive nights 22-24 July 2006, but the new record value of 90 ^{o}F on 23 July surpassed this previous record by 7 ^{o}F. Similarly, a new all-time record daily-average temperature of 101.5 ^{o}F was set on 23 July, 4.5 ^{o}F above the previous record of 96.0 ^{o}F on 28 July 1980.

The historical significance of the duration of this heat wave is next considered, through examination of the record 10-day daily average temperatures for Fresno, Livermore, downtown San Jose, and Mt Diablo Junction [at an elevation of 661 m (2168 ft)] (Table 2);

see Fig. 6 for locations.

The first three of these were selected to be representative of the more heavily populated lower-elevation inland areas where heat wave impacts were greatest, while the latter enables assessment of the relative historical magnitude of the event at a neighboring higher-elevation rural location.

Prior to this July 2006 heat wave, the record 10-day average temperature for Fresno was 92.5 ^{o}F (for the 10-day period ending 1 August 1980). This was exceeded by 9 new records: for the 10-day periods ending each of the days July 22-30. The maximum value of 95.7 ^{o}F was for the 10-day period ending 26 July 2006.

Qualitatively similar results were found for both Livermore (period of record 1903-2007) and downtown San Jose (period of record 1893-2007). At Livermore, a new all-time extreme 10-day average temperature of 88.8 ^{o}F was set – for the 10-day period ending 26 July 2006. This far exceeded the pre-July 2006 record of 82.8 ^{o}F (for the 10-day period ending 2 August 1980). As for Fresno, a total of nine new 10-day average temperature records were set during this heat wave – for the same eight 10-day periods as for Fresno, plus the 10-day period ending 22 July 2006. Almost identical results were found for San Jose, where new 10-day average temperature records were set for the same nine 10-day periods as at Livermore, with a peak value of 82.3 ^{o}F for the 10-day period ending 25 July 2006. The pre-July 2006 record was 78.1 ^{o}F for the 10-day period ending 8 September 1988. The comparative rankings of these July 2006 dates between the 3 sites do suggest, however, that the heat wave reached its peak a bit earlier nearer the coast than it did farther inland.

Fresno: July 2006

	Tmax	Δ	Tmin	Δ	Tavg	Δ
1	98	3	63	-1	80.5	0.5
2	101	6	68	3	78.0	2.0
3	101	6	66	1	83.5	3.5
4	99	3	68	3	83.5	3.5
5	96	0	66	1	81.0	2.0
6	93	-3	61	-5	77.0	3.0
7	96	0	62	-3	79.0	-2.0
8	103	7	69	3	86.0	5.0
9	107	11	74	8	90.5	9.5
10	107	10	72	6	89.5	8.5
11	101	4	69	3	85.0	4.0
12	95	-2	63	-3	79.0	-2.0
13	99	2	64	-2	81.5	0.5
14	103	6	69	3	86.0	4.0
15	104	7	69	3	86.5	4.5
16	107	10	73	7	90.0	8.0
17	109	12	76	10	92.5	10.5
18	105	8	79	12	92.0	10.0
19	107	10	79	12	93.0	11.0
20	109	12	77	10	93.0	11.0
21	109	12	82	15	95.5	13.5
22	112	15	84	17	98.0	16.0
23	**113**	16	**90**	23	**101.5**	19.5
24	**113**	16	85	18	99.0	17.0
25	**113**	16	82	15	97.5	15.5
26	112	15	78	11	95.0	13.0
27	106	9	73	6	89.5	7.5
28	99	2	72	5	85.5	3.5
29	97	0	73	7	85.0	3.0
30	94	-3	68	2	81.0	-1.0
31	96	-1	67	1	81.5	-0.5

Table 1. Daily observed maximum, minimum and daily average temperatures (^{O}F) at Fresno International Airport (KFAT) for July 2006, along with departures from corresponding climatological values. New all-time record values are indicated in **red**. Period of record for KFAT is 1949-2007. Data obtained from the Applied Climate Information System (ACIS); see http://www.rcc-acis.org/.

San Jose (1893-2007)		Livermore (1903-2007)		Fresno (1949-2007)		***Mt Diablo Junction (1949-2007)***	
82.3	7-25-06	88.8	7-26-06	95.7	7-26-06	87.9	7-25-60
82.1	7-26-06	88.5	7-25-06	95.4	7-27-06	87.4	8-10-78
81.2	7-27-06	88.0	7-27-06	95.2	7-25-06	87.3	7-26-60
81.2	7-24-06	87.0	7-28-99	94.8	7-28-06	87.3	8-21-67
80.2	7-28-06	87.0	7-24-99	94.1	7-24-06	87.2	8-22-67
79.8	7-23-06	85.7	7-29-06	94.0	7-29-06	87.1	8-11-78
79.4	7-29-06	85.5	7-23-06	92.8	7-23-06	86.9	7-26-06
78.8	7-22-06	84.5	7-30-06	92.8	7-30-06	86.8	8-23-67
78.5	7-30-06	83.8	7-22-06	92.5	8-01-80	86.8	8-20-67
78.1	9-08-98	82.8	8-02-80	92.4	8-02-80	86.8	7-24-60

Table 2. Record 10-day average average temperatures (^{o}F) for official NWS climate sites at San Jose, Livermore, Fresno and Mt Diablo Junction (locations C, D, E and H, respectively, in Fig. 1). End dates of 10-day periods are listed. Periods of record are provided. Data obtained from the Applied Climate Information System (ACIS), available through http://www.rcc-acis.org/.

In striking contrast to the preceding, the historical significance of the duration of this July 2006 heat wave appears less notable at the elevated, rural climate site of Mt Diablo Junction (location indicated by point H in Fig. 6). Here, only a single 10-day period from July 2006 appears in the top ten list shown in Table 2: a number 7 ranking for the 10-day period ending 26 July 2006. To ascertain that this isn't simply a chance artifact of the averaging period, rankings for this site were also similarly constructed for both 5-day and 3-day blocks (not shown). For the former, the highest ranking for July 2006 was a tie for #4 (5-day period ending on the 26th), while for the latter it was a #6 ranking (3-day period ending on the 24th).

A similar analysis was done for the elevated, rural climate site of Calaveras Big Trees on the western slope of the Sierra Nevada Mountains (location indicated by point I in Fig. 6). Here the top three ranked 10-day periods for average temperature were from the heat wave of August 1978 (ending on the 11th, 10th and 12th, respectively), followed in ranks four through six by three from this July 2006 heat wave (ending on the 27th, 26th and 28th, respectively).

Here too, qualitatively similar results are found as the duration period considered is reduced, including down to a single day.

Although more extensive analysis is clearly warranted, these initial analyses suggest that this July 2006 heat wave manifested as a rarer/historically more extreme meteorological event in the low elevation valleys than at higher altitudes in the hills and mountains.

In addition to both the duration of the event and the individual record warm maximum and minimum temperatures, dew points were significantly higher than normal, especially during the hottest portion of the heat wave. At Fresno, for example, the climatological average dew point for the month of July is 55 ^{o}F (based on 1950-2002 data), while during the 3-day period 21-23 July, it averaged 61 ^{o}F. And, as indicated in Fig. 7, early afternoon inland dew points as high as the lower 70s (^{o}F) are evident during one of the peak days of the heat wave.

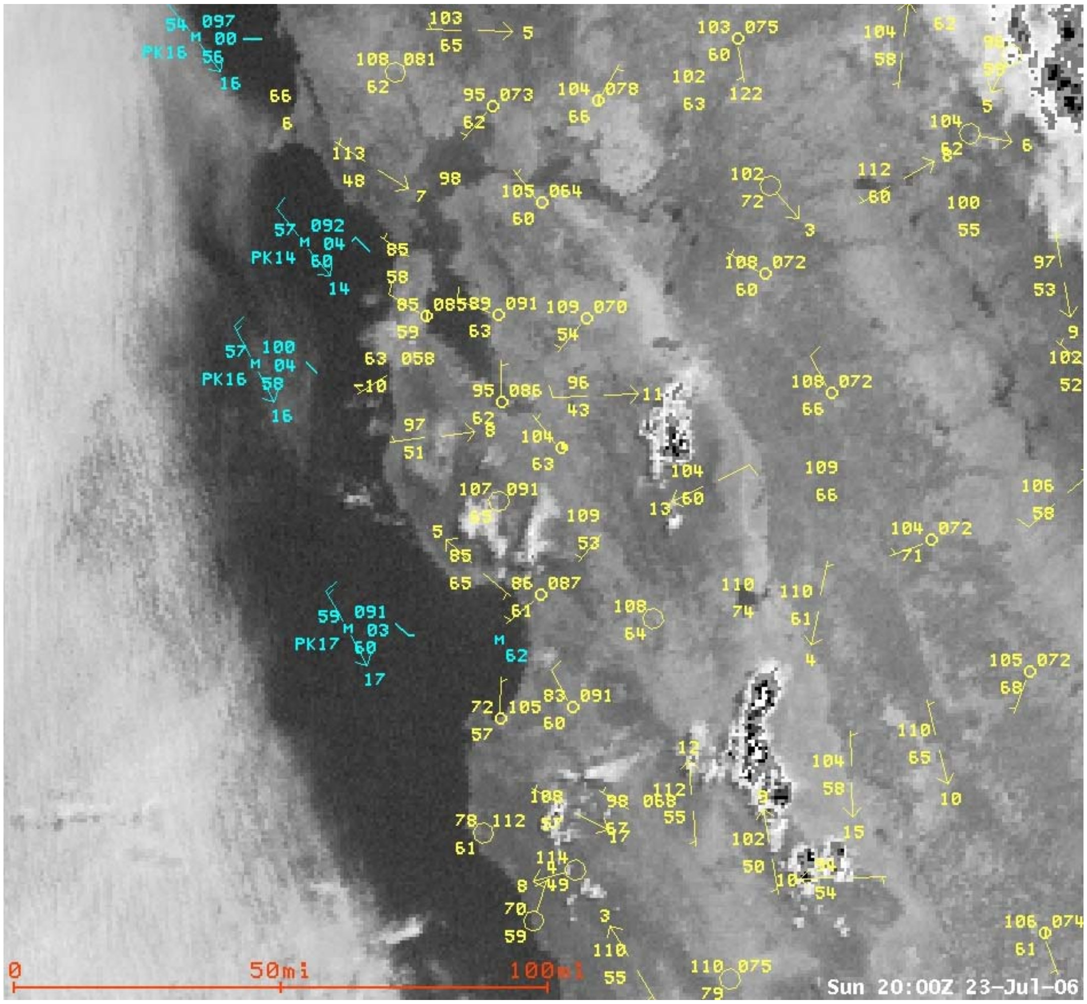

Fig. 7. VIS satellite image of the central California coast at 2015 UTC 23 July 2006 with selected 2000 UTC surface (yellow) and NDBC buoy (blue) observations. A 100-mi (161 km) distance scale is indicated.

4. MESOSCALE COASTAL VARIABILITY

In striking contrast to the extreme and prolonged inland heat wave, temperatures at the coast remained unremarkable. At the coastal site of Half Moon Bay (location B in Fig. 6), for example, the highest temperature reached during the entire month of July 2006 was only 73 ^{o}F (19 July), and the warmest minimum temperature was a still chilly 57 ^{o}F (24 July). These values are far below the all-time record high maximum temperature for this site of 94 ^{o}F (multiple occasions, most recently 27 October 2006) and record high minimum temperature of 68 ^{o}F (20 September 1999).

The striking contrast between coastal temperatures and those at locations just a short distance inland is illustrated by the 2000 UTC (1300 PDT) 23 July 2006 observations plotted in Fig. 7. Note that air temperatures at the near-shore buoys are only in the 50s (^{o}F) (and sea surface temperatures 56-60 (^{o}F), with temperatures in the 60s and 70s (^{o}F) prevailing at coastal land-based observation sites. In contrast, simultaneous observations from nearby stations in the coastal hills and valleys are locally as high as 110 ^{o}F to 114 ^{o}F.

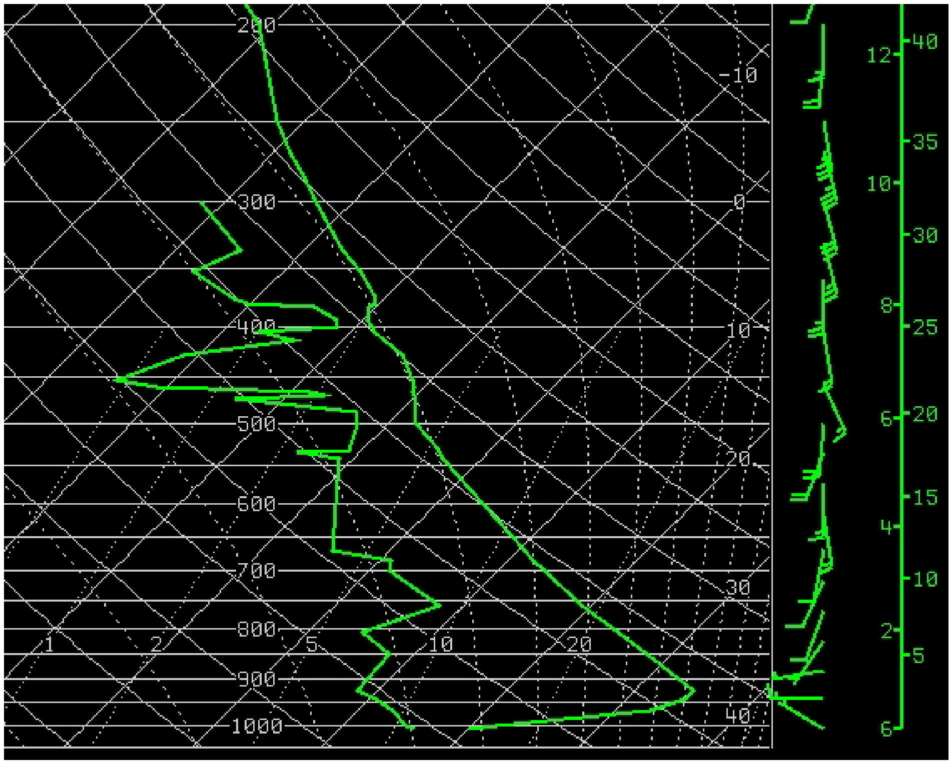

Fig. 8. 12Z 23 July 2006 Oakland Airport sounding (location indicated by letter F in Fig. 3).

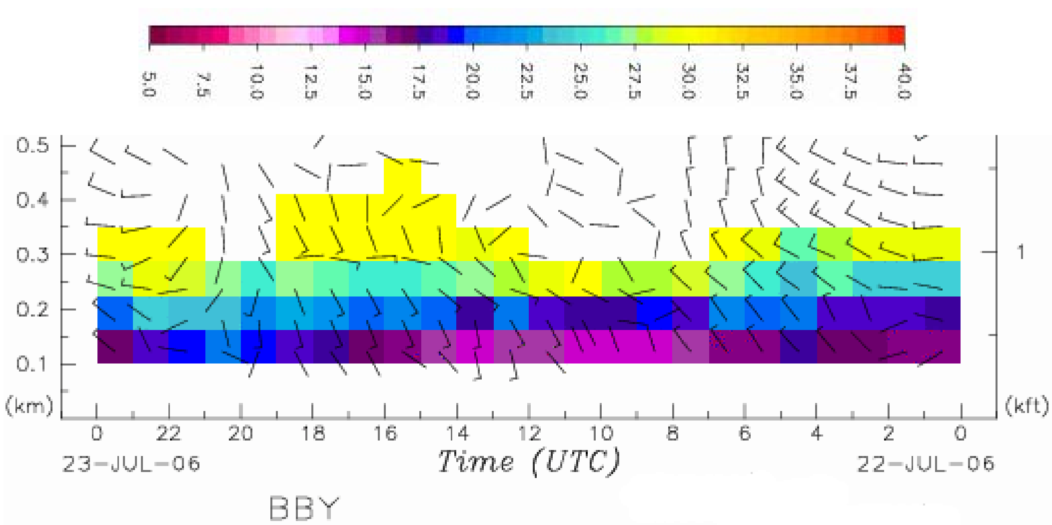

Fig. 9. NOAA Bodega Bay integrated 915-MHz wind profiler winds and Radio Acoustic Sounding System (RASS) virtual temperatures (C) from 00Z 22 July to 00Z 23 July 2006 (location indicated by letter G in Fig. 3).

These dramatic small spatial scale variations reflect the presence of a very shallow coastal marine layer. Some reflection of this can be seen in the 12Z 23 July Oakland Airport (location indicated by point F in Fig. 6) sounding (Fig. 8), which shows a surface (sea level) temperature of 68 ^{o}F (20 C) while at an altitude of 617 m (2023 ft), the temperature has increased to 34 C (94 ^{o}F). The striking but shallow marine layer is also evident in the Bodega Bay (location indicated by point G in Fig. 6) profiler data

(Fig. 9), which shows 23Z (4 pm PDT) July 22 temperatures increasing from approximately 17 C (63 ^{o}F) at 0.1 km to 30 C (86 ^{o}F) at 0.3 km.

5. SUMMARY

A record-setting heat wave occurred in central California during the latter half of July 2006. Onset of the event was associated with retrogression of the 500 mb height anomaly field and subsequent development of a robust large-scale upper-level high centered over the Great Basin -- with a ridge axis extending westward through central California. Very warm temperatures existed aloft, with 500 mb heights reaching as high as 600 dm over the Great Basin, and a maximum in 11-day average 850 mb temperature anomalies of 8 C centered over coastal central California.

Although numerous daily maximum temperature records were set, this heat wave was perhaps even more remarkable for the degree of elevation of the overnight minimum temperatures, and the duration of the event. Negative human impacts were further exacerbated by the concurrent anomalously high dew points. Interestingly, a preliminary analysis suggests the climatological magnitude of the event was appreciably greater at inland valley locations than at neighboring elevated sites. Also, a dramatic contrast in prevailing temperatures existed close to the coast, where a shallow but significant marine air influence persisted.