Program for Climate, Ecosystem and Fire Applications

The Meteorological and Climatological Fire Extremes of California 2008

Report for US Forest Service – Region 5

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EXECUTIVE SUMMARY

On June 20 and 21, 2008, an anomalous lightning event started over one thousand wildfires in northern California during the two-day period. The shear number of fire starts overwhelmed fire suppression resources. Numerous fires could not be acted upon sufficiently during the initial attack phase, and subsequently burned for several weeks. By the time the last fire was contained, there had been 17 fire related fatalities, over 2,300 structures burned, and over one billion dollars spent on suppression costs. The spatial extent of burning generated continuous and extensive amounts of smoke across northern and north-central California into western Nevada. The presence of dense widespread smoke layer interacted with the atmosphere to help create conditions inhibiting the smoke dispersion and transport. A positive feedback process that exacerbated the inhibition of smoke mixing occurred between the atmospheric temperature profile and smoke across the area. Large amounts of smoke aerosols acted to reflect and absorb shortwave radiation, thereby decreasing temperatures below the smoke layer and increasing temperatures within the smoke layer. Collectively, these processes reduced the mixing height, inhibited atmospheric mixing and allowed the smoke to remain localized across the region for several weeks. The combination of four extreme events – drought, anomalous widespread lightning, a large number of fire starts and an unusual number of below average mixing height days synergistically created a significant wildfire event with associated increased public health risk from smoke.

1. Introduction

On June 20 and 21, 2008, an anomalous lightning event started over one thousand wildfires in northern California during the two-day period. The shear number of fire starts overwhelmed fire suppression resources. Numerous fires could not be acted upon sufficiently during the initial attack phase, and subsequently burned for several weeks. By the time the last fire was contained, there had been 17 fire related fatalities, over 2,300 structures burned, and over one billion dollars spent on suppression costs. The spatial extent of burning generated continuous and extensive amounts of smoke across northern and north-central California into western Nevada (Figure 1). The presence of dense widespread smoke layer interacted with the atmosphere to help create conditions inhibiting the smoke dispersion and transport. A positive feedback process that exacerbated the inhibition of smoke mixing occurred between the atmospheric temperature profile and smoke across the area. Large amounts of smoke aerosols acted to reflect and absorb shortwave radiation, thereby decreasing temperatures below the smoke layer and increasing temperatures within the smoke layer. Collectively, these processes reduced the mixing height, inhibited atmospheric mixing and allowed the smoke to remain localized across the region for several weeks. The combination of four extreme events – drought, anomalous widespread lightning, a large number of fire starts and an unusual number of below average mixing height days synergistically created a significant wildfire event with associated increased public health risk from smoke.

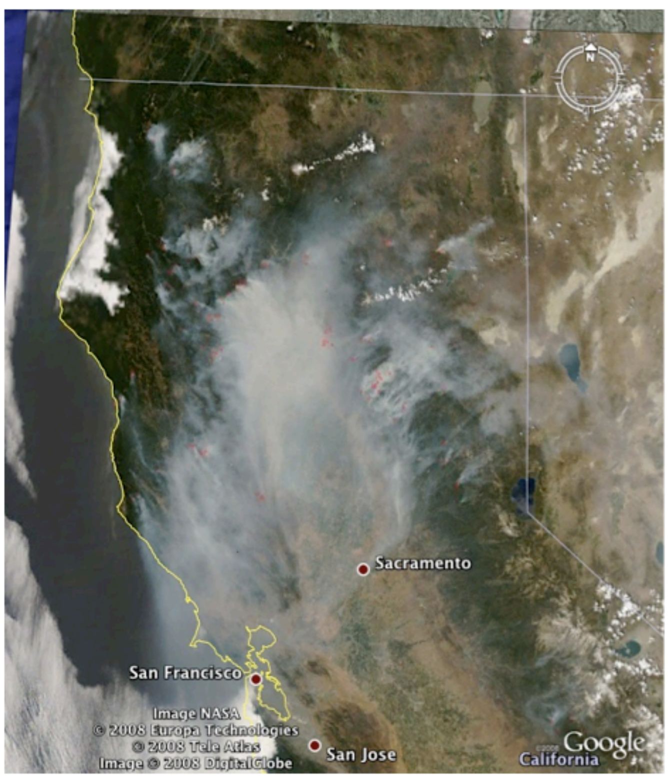


Figure 1. NASA MODIS image of the smoke distribution across northern California and western Nevada on 11 July 2008. Fire hot spots are shown as light red areas.

2. Meteorological and Climatological Extremes

2a. Drought

Preceding the fire starts was a drought. Figure 2 shows Palmer Drought Severity Index (PDSI) percentiles for June 2008 based on PRISM data. Note that much of central and northern California is around 10% or less as denoted by the red shading. Much of northern and central California experienced their driest spring over the period of record, with some locations not observing a significant wetting precipitation event (>2.5mm) for nearly 100 days by late June 2008. In fact, San Francisco had its driest spring on record as an example for a single station. The dryness was not just a recent event; Figure 3 shows the Standardized Precipitation Index (SPI) integrated over the 24-months ending in June 2008. The yellow and orange shaded climate divisions indicate that the entire state had been moderate to very dry overall during the past two years leading up to and including June. The spring and early summer drought pattern was reflected in 1000-hour time lag fuel moisture plots for Predictive Service Areas (PSA) in California (Figure 4). For example, except for the Northeastern area in early June, most of the season was below average (dotted line compared to solid grey line), and some days (especially in the mid-coast PSA) became the driest 1000-hour on record (red line).

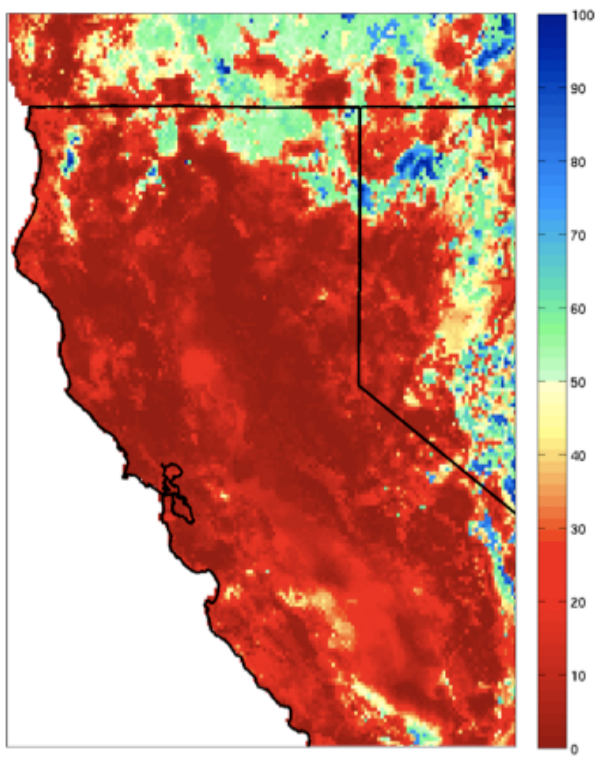


Figure 2. Percentiles of Palmer Drought Severity Index for California for June 2008.

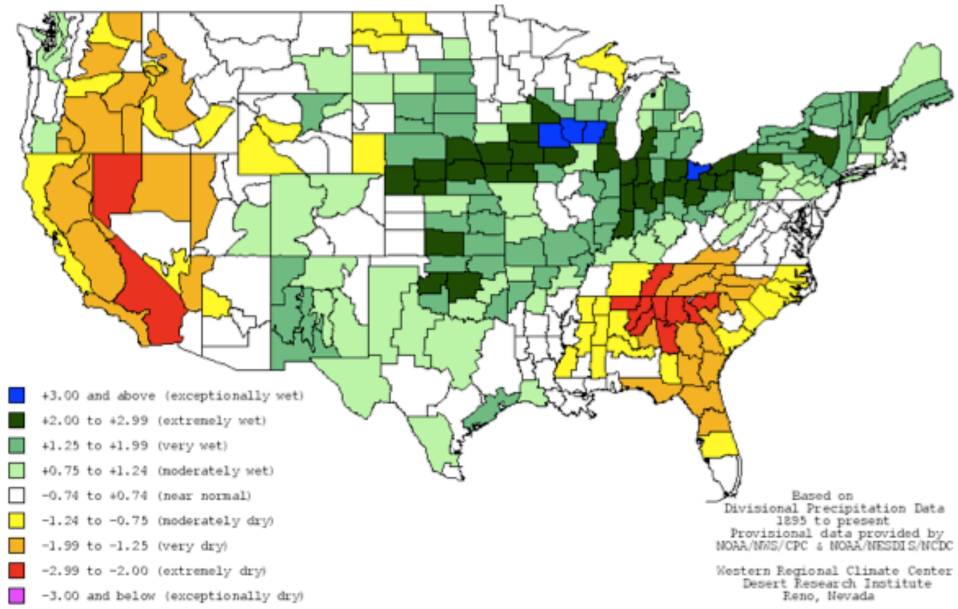


Figure 3. Integrated 24-month Standardized Precipitation Index through June 2008.

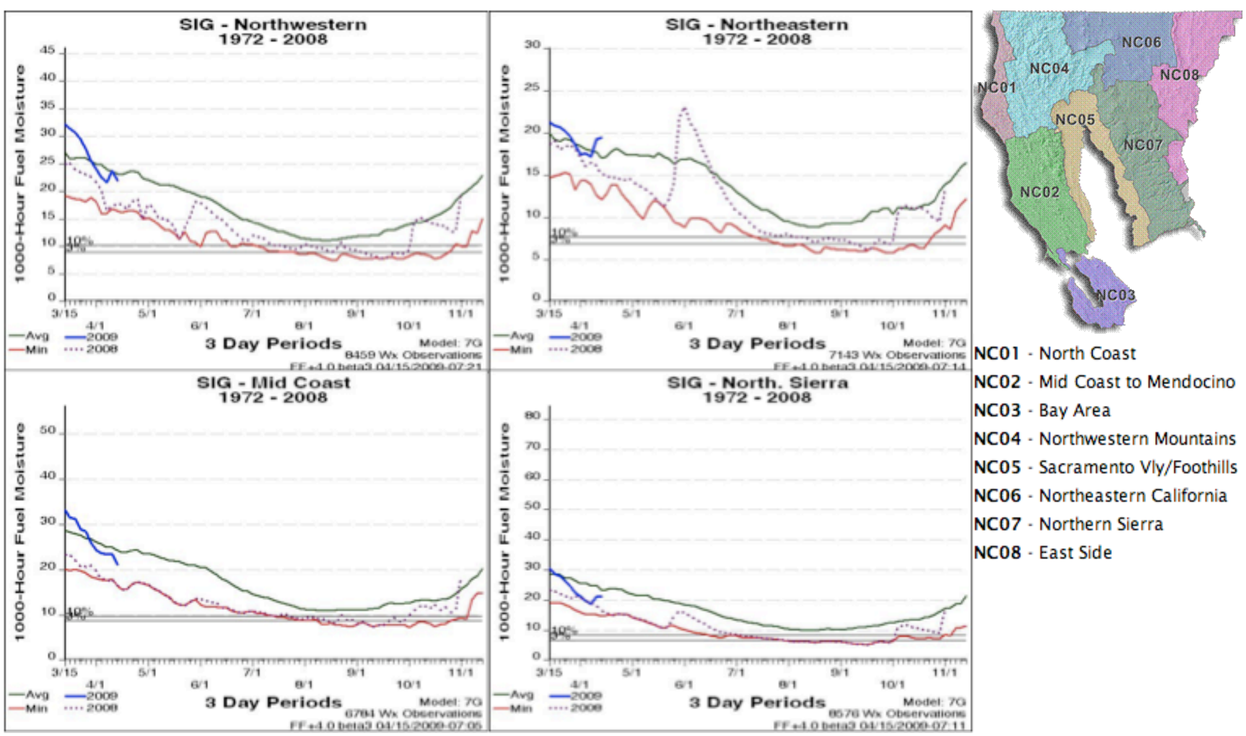


Figure 4. Time lag (1000-hour) fuel moistures for four northern California Predictive Service Areas. The solid grey line depicts the long-term average values, the dotted line 2008 values and the red line the climatological minimums (extreme driest). Geographic reference to the area names is given on the right.

2b. Lightning

Figure 5 shows the distribution of lightning strikes during the June 20-21 period as denoted by the "+" symbols. A total of 5,504 strikes are shown on this map for the two-day period. This event ranks as 9th for the number of strikes for any two-day period starting with 1990, and 3rd for a June two-day period. It is not particularly unusual to have a large number of strikes in June; in the past 19 years there have been thirty two-day June events that have exceeded 1000 (an arbitrary reference number) strikes. Table 1 shows the distribution of northern California lightning strikes for large (>1000 strikes) two-day June events.

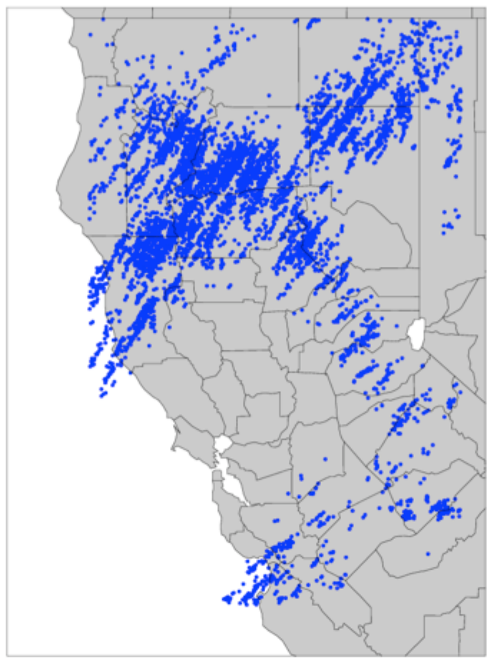


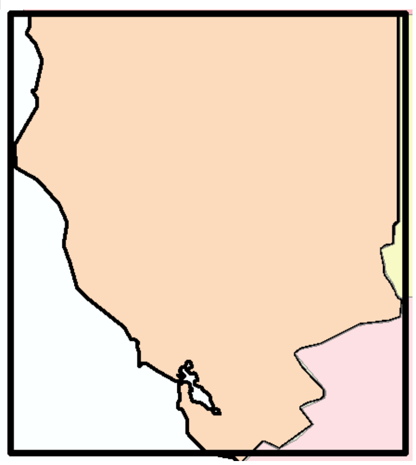
Figure 5. Distribution of lightning strikes (blue "+" symbols) for north-central California on 20-21 June 2008.

2c. Fire starts

The drought, low fuel moistures and available fuels leading up to this event allowed for very efficient lightning ignitions of nearly one start for every five strikes as a little over 1,000 fire starts began on these two days. Figure 6 shows the spatial distribution of starts over the northern California GACC.

Table 1. Distribution (sorted by strike count) of northern California lightning strikes for large (>1000 strikes) with date as the 2nd day of the event. The corresponding map shows location for strike counts with the shaded area indicating the outline of the northern California Geographic Area Coordination Center (GACC).

Date	Number of strikes
28-Jun-06	6367
24-Jun-92	5689
21-Jun-08	5179
10-Jun-97	4484
29-Jun-04	4469
27-Jun-06	4303
11-Jun-97	4047
29-Jun-06	3968
28-Jun-04	3796
23-Jun-92	3495
07-Jun-98	3314
12-Jun-98	2975
09-Jun-97	2888
25-Jun-92	2590
06-Jun-98	2589
18-Jun-92	2104
13-Jun-98	2041
26-Jun-06	1978
02-Jun-98	1968
12-Jun-97	1881
30-Jun-95	1599
13-Jun-06	1468
01-Jun-02	1458
11-Jun-98	1410
08-Jun-98	1409
02-Jun-95	1338
03-Jun-98	1325
01-Jun-07	1271
19-Jun-92	1229
27-Jun-04	1213



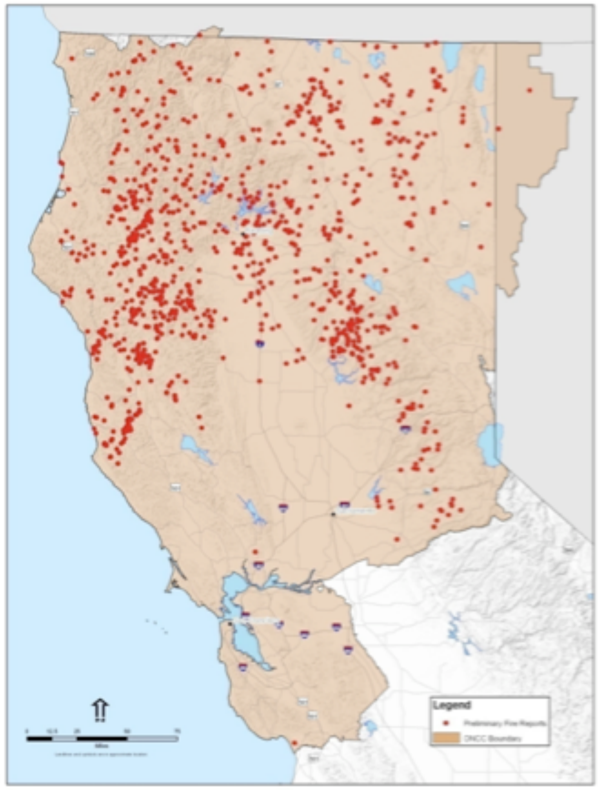


Figure 6. Location (red dots) of lightning caused fire starts on 20-21 June 2008. Graphic from northern California Predictive Services.

2d. Mixing heights

The lack of a radiosonde located near the fire complex precludes a direct calculation of mixing heights over the smoke impact area. An alternative approach that enables a complete spatial view of atmospheric stability across the smoke impact area is obtained using the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR). NARR provides model “observations” for relevant surface variables at high temporal (3-hourly) and spatial (32-km) resolution (Mesinger *et al.* 2006). Twenty-nine years (1980-2008) of gridded meteorological output were used to contextualize the post-ignition atmospheric stability over the northern California fires.

Convective mixing heights were approximated using the Holzworth method. Direct use of daily maximum temperatures from NARR is problematic given large biases and the inability of the model to assimilate surface temperatures. Furthermore, while the vertical resolution of NARR in the lower-troposphere is 25hPa, this resolution is inadequate for assessing mixing heights in regions of complex terrain. As an alternative approach, strictly the free air temperatures on pressure surfaces were examined. To estimate the convective mixing height, 2.5°C was added to the isobaric surface directly above the topography. The value 2.5 represents a compromise between estimation of convective mixing heights from daily minimum temperatures (where 5°C is added) and daily maximum temperatures.

To put context on the analysis, the summer (June-July-August) daily mean afternoon mixing height computed from NARR shows spatial patterns across Northern California conforming to geographic features (Figure 7). Mixing heights are relatively low along the coast associated with the summertime marine inversion layer. Relatively low mixing heights occur inland through the Sacramento-Delta region, and gradually rise as they diverge away from the marine influence towards the San Joaquin valley to the south and northern Sacramento valley to the north. Mixing heights are substantially higher over the heated interior, generally 1000-2000 m above ground level.

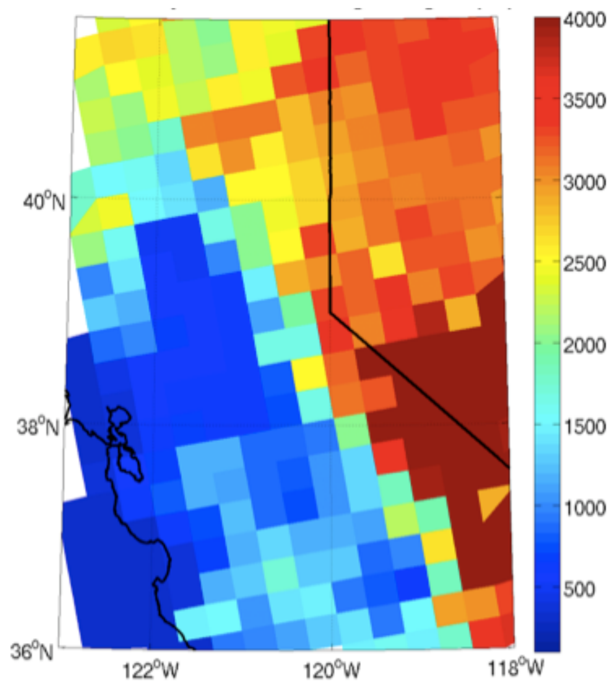


Figure 7. Climatological afternoon mixing height (m) for the summer season (June-August) calculated from the 32-km NARR dataset.

The seasonal cycle of mixing heights varies substantially across the domain, but in general, mixing heights are lower during the winter and higher in summer across the interior (Figure 8). Across the north-central portion of the state (39.5-42°N, 120.5-123°W), mixing heights at lower elevations (<800 m) climatologically peak in June, with a secondary maximum in late summer-early fall. However, mixing heights at higher elevations (>1600 m) tend to peak in late summer. Note in the graph above average mixing heights just prior to the lightning event, followed by nearly two months of below average mixing height.

Figure 8 also shows what took place during 2008. Following the June 20th lightning bust across the smoke impact area, a long period of inhibited mixing occurred, where mixing levels were substantially below average. From June 23rd to July 3rd mixing heights were particularly suppressed, with mixing heights being in the bottom quartile of the distribution for a one-week period.

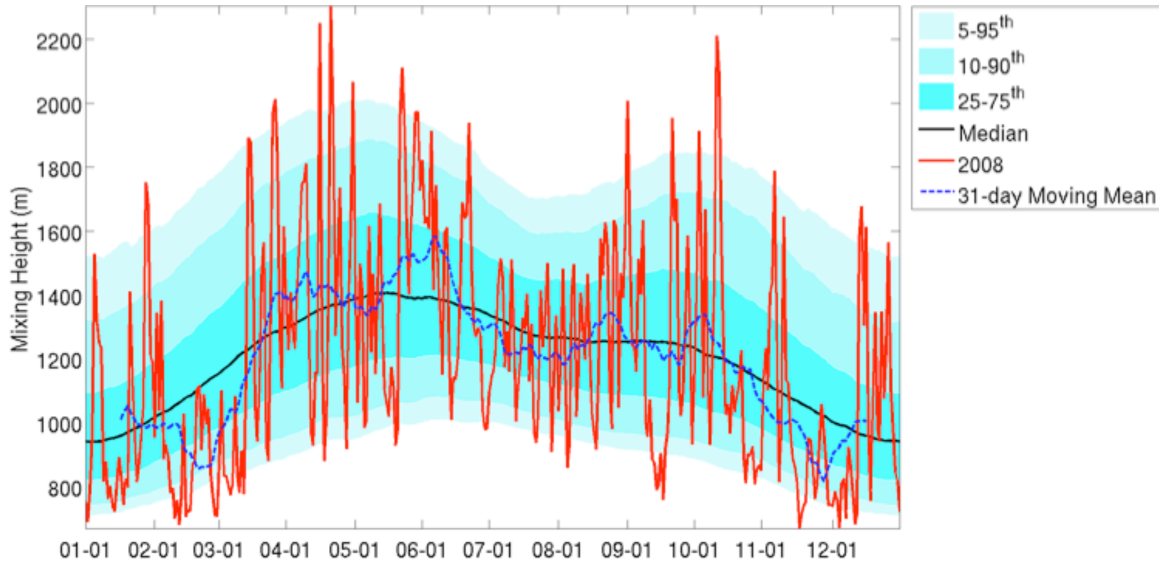


Figure 8. Mixing heights averaged over north-central California (39.5-42°N, 120.5-123°W) for NARR grid cells located below 800 m. Daily mixing heights from 2008 are shown in red, with the blue dashed line showing the 31-day moving average. Climatological median and percentile values are also shown.

Spatially, mixing heights were below average across most of northern California and northwestern Nevada with anomalies locally exceeding 600 m averaged over this same period (Figure 9). The only exception was the eastern slopes of the Sierras, where mixing heights at higher elevations were actually above normal. This alludes to the stability profile of the atmosphere as a relatively warm lower-troposphere near 800-850 hPa that would both increase stability at lower elevations and decrease stability at higher elevations. Averaged over this 11-day period, much of the region experienced mixing heights that were in the bottom 10th percentile for this period.

Perhaps more remarkable is that following the lightning event in northern California, 57 consecutive days passed with the mixing height across lower elevation regions of the state below 1500 m (or approximately 5000 ft). The 1500 m level approximates the physical barrier for smoke dispersion north to eastward from the source region given the geophysical barriers of the Sierra and southern Cascades. While the median mixing height during summer for lower elevations of the study area is below 1500 m, on average one day out of five during summer has mixing heights above 1500 m, therein providing a good ventilation mechanism for the region. Spatially, much of the region experienced mixing height standard anomalies over this period less than -2 sigma (Figure 10), although the eastern Sierra again showed the converse.

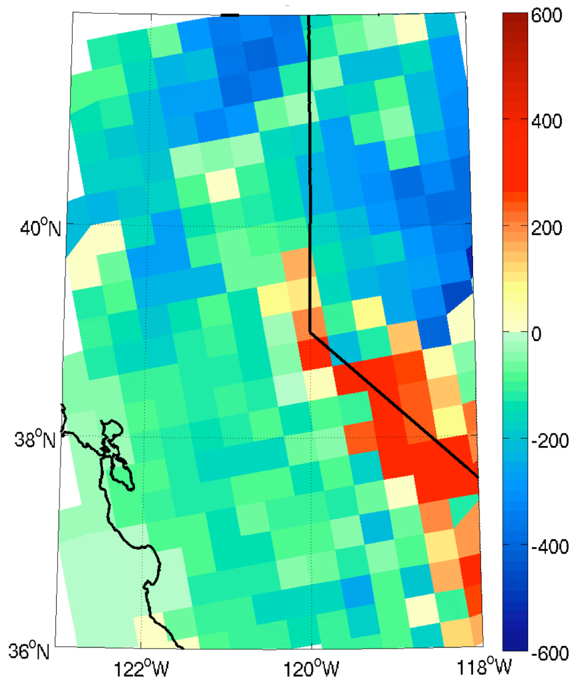


Figure 9. Mixing height anomalies (m) averaged over the period June 23-July 03, 2008.

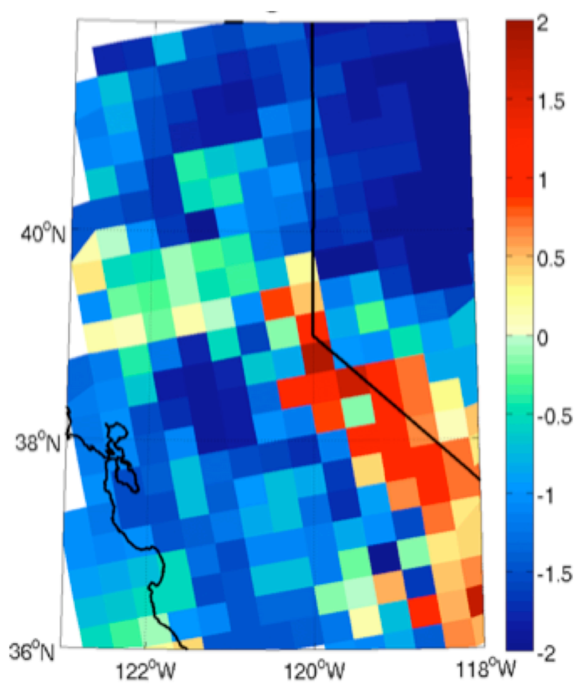


Figure 10. Mixing height standard anomalies for the period June 23-August 18, 2008.

Overall, the 57 days without mixing is remarkable for a mid-summer event, and the longest duration for the period of record. Figure 11 shows a climatological frequency histogram of extended duration events of 45 and 30 days, respectively for the same area as in Figure 8. The month reflects the start of the sequence, and 2008 data are included in the counts. Note that extended periods of non-mixing are fairly common in autumn and early winter. December in particular has a history of extended non-mixing days. June and July together show two periods of 45-days, with the 57-day period from June 23-August 18, 2008 being the longest sequence observed during summer.

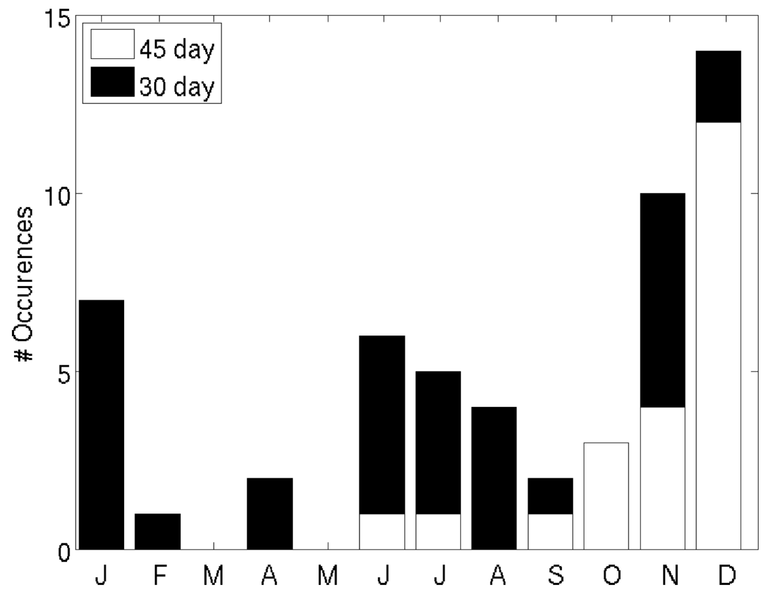


Figure 11. Frequency histogram of extended duration inhibited mixing events of 45 days (white) and 30 days (black). Month reflects starting month of sequence.

3. Mixing Heights and Smoke-Albedo Feedback

Several factors account for the longevity of the inhibited mixing event including dynamically induced subsidence, lack of frontal disturbances (and precipitation, which would curtail the fires/smoke) and the positive smoke-albedo feedback. Further, typical patterns of mountain-valley wind patterns did not occur during the smoke event (*private comm.*; John Snook, Predictive Services). Synoptic conditions that fostered the inhibited mixing included the northwestward migration of the upper-level ridge over the western US into the Pacific Northwest with the subtropical Pacific high to the west and thermal trough to the east. Figure 12 shows 200 hPa height anomalies for the week following the lightning event. Strong subsidence over northern California associated with the upper-level ridge allowed for compressional heating in the lower-troposphere (near 850hPa) and the general lack of winds across the area. Note the large area of above normal anomalies in the Pacific Northwest. This pattern is similar to September 1987, in which fires also created a smoke event with human health impacts.

Precipitation from mid-latitude frontal passages and convection was non-existent in July, with the north-central portion of the state recording no precipitation during the month (California Climate Tracker; http://www.wrcc.dri.edu/monitor/cal-mon). Several of the COOP stations reported light precipitation (generally < 2.5 mm) on June 20th, and not again until August 7th, with most stations again reporting less than 2.5 mm.

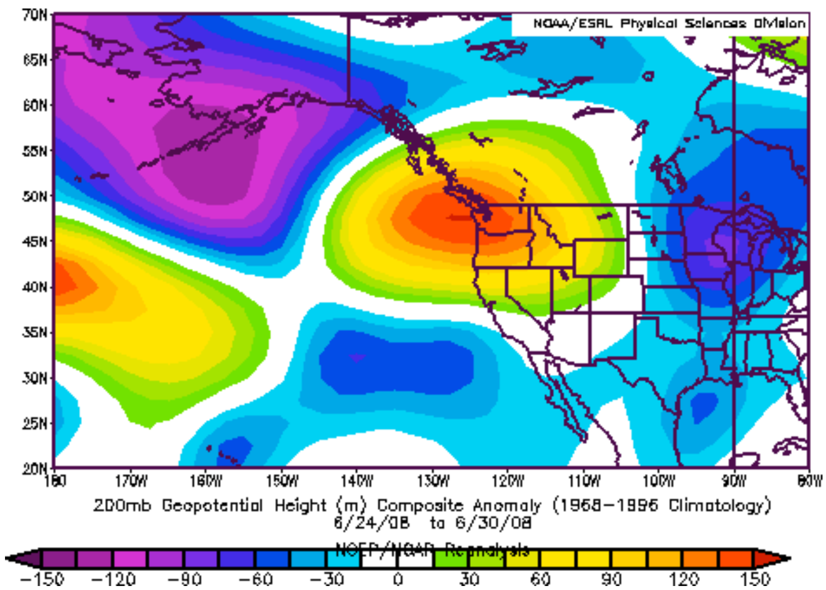


Figure 12. 200 hPa geopotential height anomalies for the period 24-30 June 2008. Source: NOAA/ESRL Physical Sciences Division.

The third factor represents a positive feedback process created by the smoke from the fires. As aerosols, smoke emissions reduce the amount of shortwave radiation that can reach and warm the surface, while at the same time increasing the absorption of shortwave radiation and warming the smoke layer itself. The decrease in surface temperature and increase in lower-atmospheric temperature in turn decrease the buoyancy of parcels at the surface air. As these parcels cannot rise as far, the mixing height lowers, subsequently increasing aerosol concentrations and begetting the positive feedback (Stone *et al.* 2008). Satellite imagery after the lightning bust and into August verified the generally high albedo of the emissions over northern California (see Figure 1 for example).

While observations alone preclude directly verifying this smoke-albedo feedback, observations of daily maximum temperatures for 17 COOP stations in the smoke impact area provide evidence to support this hypothesis. Daily maximum temperatures from the gridded NARR data set are paired to those from the stations at coexisting spatial locations. To account for the inherent bias in NARR, as mentioned previously, the dataset is bias corrected by adding the observed bias as calculated over the 29-year period. Daily differences between the paired observed minus bias corrected (equivalently, observed minus forecasted) NARR dataset represent differences unresolved by physical processes represented by NARR. Mesoscale features, their interaction with topography and radiation can all result in differences.

Immediately following the lightning bust when smoke emissions were at their greatest, observations ran significantly cooler (exceeding 2°C) across the southern portion of the domain (Figure 13). Light prevailing northerly flow and generally subsiding air forced smoke toward the southern end of the burning area. Locations to the north, which saw less smoke and are located generally at higher elevations, showed a more mixed signal. Over the 57-day period, difference fields support the argument that the surface daily maximum temperatures across the lower elevation regions were suppressed, as observations show coherent negative values locally exceeding 2°C, the largest negatives seen collectively over the 29-year period (Figure 14). For minimum temperatures, differences were rather mixed across the domain (Figure 15), suggesting that the dominating influence is in the shortwave spectrum. As presence of aerosols from the fires is not assimilated into NARR, it is very likely that the proposed feedback process reduced mixing heights even further than is shown here with NARR analysis alone. However, it is possible that some of the warmer nighttime temperatures were due to heat trapping at the surface by the smoke.

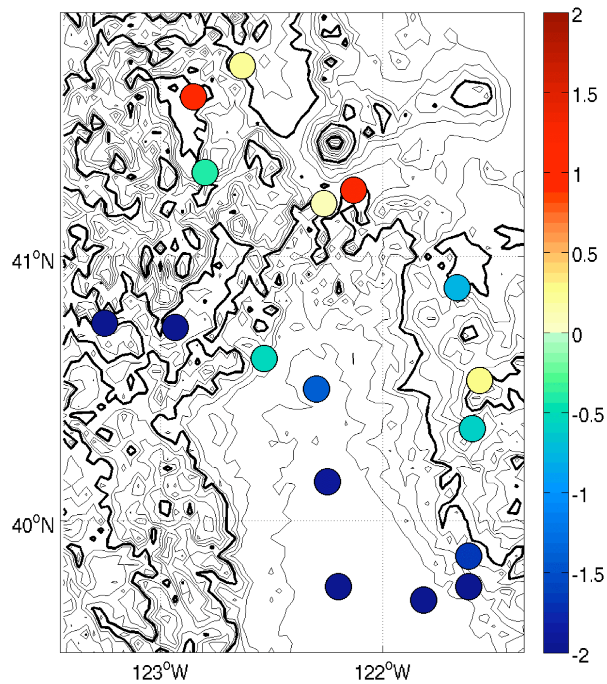


Figure 13. Observed minus bias-corrected maximum temperatures for 17 COOP stations averaged over the period June 23-July 03 2008. Contours show topographic relief every 200 m, with every 1000 m in bold.

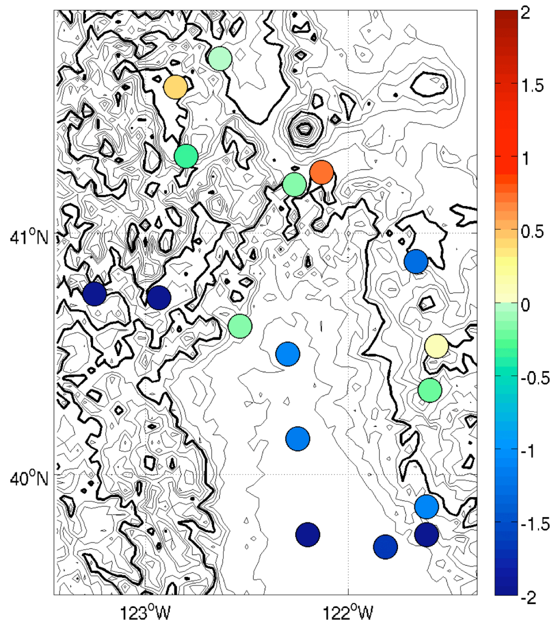


Figure 14. Observed minus bias-corrected maximum temperatures for 17 COOP stations averaged over the period June 23-Aug 17 2008. Contours show topographic relief every 200 m, with every 1000 m in bold.

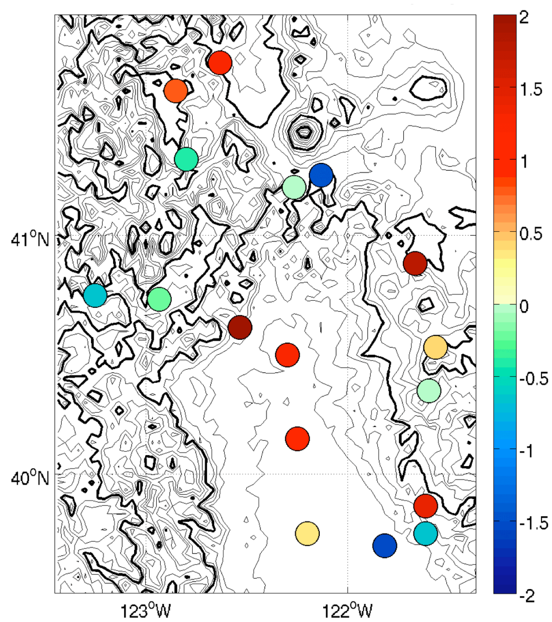


Figure 15. Observed minus bias-corrected minimum temperatures for 17 COOP stations averaged over the period June 23-Aug 17 2008. Contours show topographic relief every 200 m, with every 1000 m in bold.

Figure 16 shows the 21Z vertical temperature difference between 975 hPa and 925 hPa for free air conditions averaged over the time period 23 June – 3 July 2008 for NARR grid points with elevations below 500 m. The red shaded areas indicate temperature differences of 4-6°C over 50 hPa, suggesting on average a strong inversion. Across the northern Sacramento valley, temperatures differences were around 3°C, which is significantly lower than climatology for late June-early July. Examining the temperature difference with respect to climatology can better assess the inversion strength. Figure 17 shows the climatological percentile of 23 June – 3 July 2008 average 975-925 hPa temperature difference in comparison to the 29 years of 975-925 hPa temperature difference climatology for the same dates. For much of the smoke impact area, these differences were in the lower 10th percentile rankings, further indicating the anomalous strength of the daily inversions.

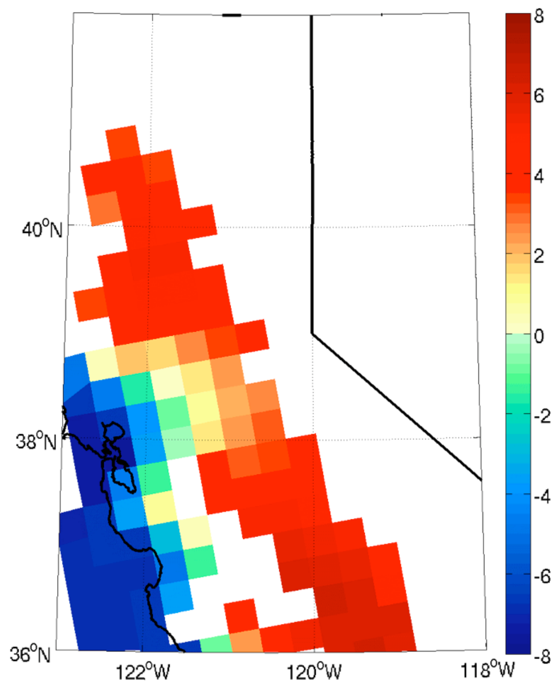


Figure 16. Vertical temperature difference (°C) between 975 hPa and 925 hPa averaged over the time period 23 June-3 July 2008. Positive values indicate temperatures at 975hPa exceed those at 925hPa. Values are shown only for NARR grid points with elevations below 500 m.

Figure 18 shows an example of a recalculation of mixing height by implementing a 1.5°C reduction in surface temperatures. This value is based on a rough average of the temperature differences between observations and NARR presented in Figure 13. The blue curve shows the daily mean temperature profile (observed from NARR), the black line the adiabatic trajectory of a parcel from the surface with maximum temperature from NARR, and the red line the adiabatic trajectory after the 1.5°C cooling has been applied to maximum temperatures. Note that the NARR and reduced temperature lines intersect at around 1100 m, indicating a 900 m reduction in mixing height given a cooler temperature of 1.5°C (which was observed). Figure 19 shows computation of modifications in mixing heights over the domain given that a 1.5°C cooling of surface temperatures is applied uniformly over the spatial domain. Note in all NARR grid cells positive values indicating a reduction in mixing heights, with reductions between 500 m-1000 m across much of the area affected by widespread smoke during the lifecycle of the event.

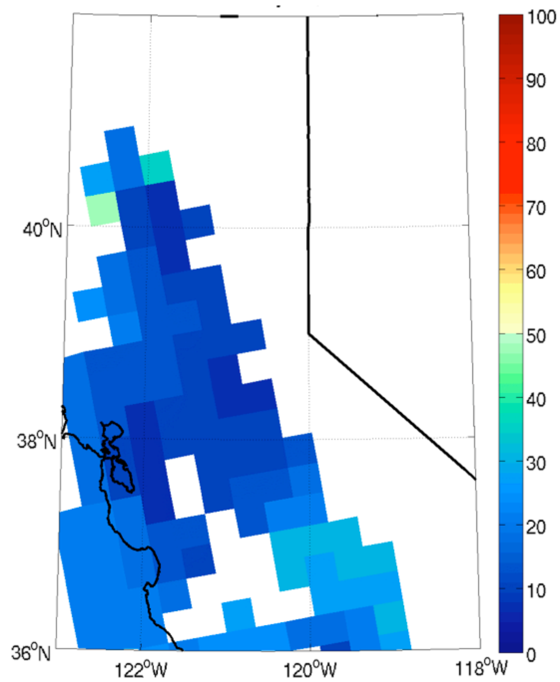


Figure 17. Percentiles of vertical temperature difference (°C) between 975 hPa and 925 hPa averaged over the time period 23 June-3 July 2008 ranked for the 1980-2008 climatology for the same dates. Values are shown only for NARR grid points with elevations below 500 m.

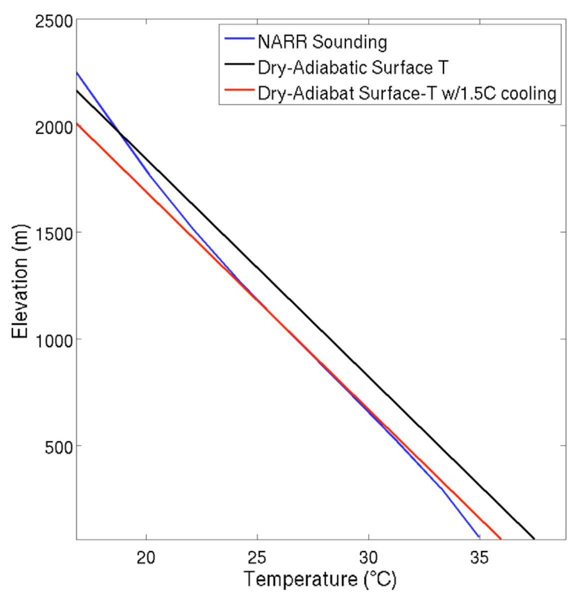


Figure 18. An example recalculation of mixing height by implementing a 1.5°C cooling in surface temperatures. The blue curve shows the NARR daily mean temperature profile, the black line the adiabatic trajectory of a parcel from the surface with maximum temperatures records and the red line the adiabatic trajectory after the 1.5°C cooling has been applied.

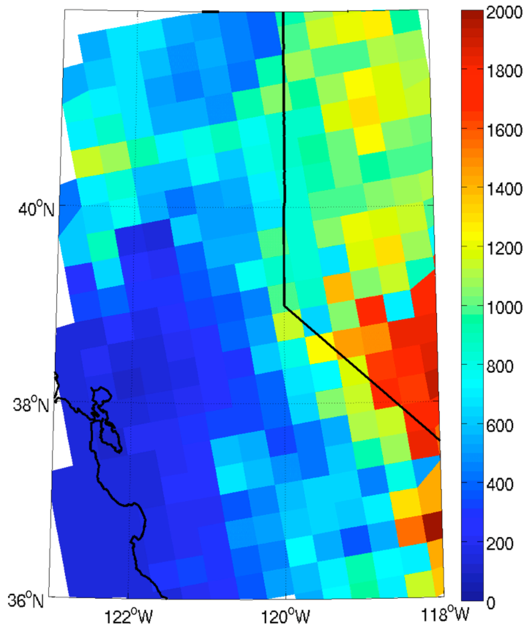


Figure 19. Mixing height perturbations given a 1.5°C cooling in surface temperatures averaged over the period 23 June-3 July 2008. Positive values indicate a reduction in mixing heights (meters).

4. Summary

Four extreme meteorological/climatological events merged synergistically to create the extensive fire and smoke event in northern California during summer 2008. First, widespread drought preceded the fire event for at least two years, including the driest spring on record across much of the area. Secondly, though not particularly unusual in terms of seasonal timing, the convective event did produce an anomalous number of strikes. Thirdly, these strikes were very efficient at ignition (nearly one of every five strikes) given antecedent conditions including ongoing drought, vegetative dryness and fuels availability. Finally, once a sufficient amount of smoke was in the lower atmosphere, the smoke generated a smoke-albedo positive feedback process that reduced parcel rise and atmospheric mixing, and lowered the mixing height to anomalous levels. This inhibited the transport and dispersion of the smoke out of the region, thereby potentially impacting millions of residents along with the more than 25,000 firefighters at the peak of suppression efforts. Unhealthy to hazardous Air Quality Index levels for both ozone and PM2.5 were observed on numerous days. The smoke event was exacerbated by dynamically induced subsidence, lack of frontal disturbances (and precipitation, which would curtail the fires/smoke), the positive smoke-albedo feedback and a reduction in seasonally typical topographic wind flow patterns. The event was extraordinary in that immediately following the fire ignitions, the primary smoke impact area experienced 57 consecutive days of below average mixing height, a record not observed before in the past 29 years.

The occurrence of these various extremes, distinct in individual ways, but not completely unrelated, is of interest from a societal impacts perspective. The smoke substantially increased human health risk. One documented case of a previous event in northern California was September 1987, where widespread smoke generated health issues (Duclos *et al.* 1990). An increase in extreme events is an expectation under a warmer temperature scenario (IPCC 2007). A warming trend has been taking place across the western US since the 1950s, and global climate models project this trend to increase and continue well into the 21st century. A question then is: will the frequency for large magnitude smoke events increase, thus causing even more societal impacts than what has been experienced thus far? The answer, to be determined, is clearly of relevance to fire and air quality managers, and the public at large.

Acknowledgements

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