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The 2017 North Bay and Southern California Fires: A Case Study

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Abstract: Two extreme wind-driven wildfire events impacted northern and southern California in late 2017 leading to 46 fatalities and thousands of structures lost. This study describes the meteorological and climatological factors that drove and enabled these wildfire events and quantifies the rarity of such conditions over the observational record. Both extreme wildfire events featured fire-weather metrics that were unprecedented in the observational record in addition to a sequence of climatic conditions that preconditioned fuels. The North Bay fires that affected portions of northern California in early October occurred coincident with strong downslope winds. The vast majority of the fires' devastating effects and acres burned occurred overnight and within the first twelve hours of ignition. By contrast, the southern California fires of December were characterized by the longest Santa Ana wind event on record and included the largest wildfire in California's history. Both fire events occurred following an exceptionally wet winter that was preceded by the drought of record in California. Fuels were further preconditioned as the warmest summer and autumn on record occurred in northern and southern California, respectively. Accelerated curing of fuels coupled with the delayed onset of autumn precipitation allowed for critically low dead fuel moisture leading up to the foehn wind events. Fire weather conditions were well forecasted several days prior to the fire. However, the rarity of fire-weather conditions that occurred in the wildland urban interface, along with other societal factors were key contributors to wildfire impacts to communities.

Keywords: fire weather; fire climate; large wildfires; downslope windstorm; wildland urban interface; drought; foehn winds

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1. Introduction

California's storied fire history is littered with fast-moving, destructive wildfires adjacent to populated areas [1,2]. Many fires that occur in the coastal ranges of California burn across steep terrain with fuels shaped by a Mediterranean climate during periods of strong foehn winds that occur primarily in early autumn [3,4]. The coincidence of residential development in areas prone to topographically driven extreme fire weather (i.e., Santa Ana winds [5]) results in fire related hazards for a large number people [6]. Approximately one-third of Californians reside in the wildland-urban interface (WUI), which are susceptible to fire hazards, with overall population numbers expected to increase in the coming decades [7–9].

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Large wildfires are not new to California's landscape [10,11], but costs have escalated recently due to the increasing WUI, the legacy of fire exclusion associated with suppression activities, and more favorable climatic conditions for large fires. Previous research has shown that fire exclusion increases fuel loading and the potential for larger fires in forests that have historically had smaller and more frequent fire [2]. However, the impacts of fire exclusion in shrublands, such as chaparral in California, are more mixed and generally weaker [1,10]. Much of the western US has seen a noted increase in fire activity (burned area extent, number of large fires) over the past several decades [12] in part due to changes in climatic conditions that favor and facilitate fire in flammability-limited forests [13]. By contrast, trends in fire activity have been more subdued in Mediterranean California ecoregions and across broader southern California [12,14,15]. The reasons behind these diverging trends may be tied to a decrease in reported fire ignitions [15], which are nearly all human-caused [16], as well as anthropogenic activities including land-use, fire policies, and diligent fire suppression [17]. Nonetheless, interannual climate variability does exhibit significant relationships to burned area extent in these regions [3,15,18]. However, Mediterranean ecosystems are intermediate productivity biomes where fire is often neither fuel-limited or flammability-limited during the fire season [19], and often are co-located with sizeable human populations and anthropogenic land use [17], yielding less direct correlations to climate variability than in other areas.

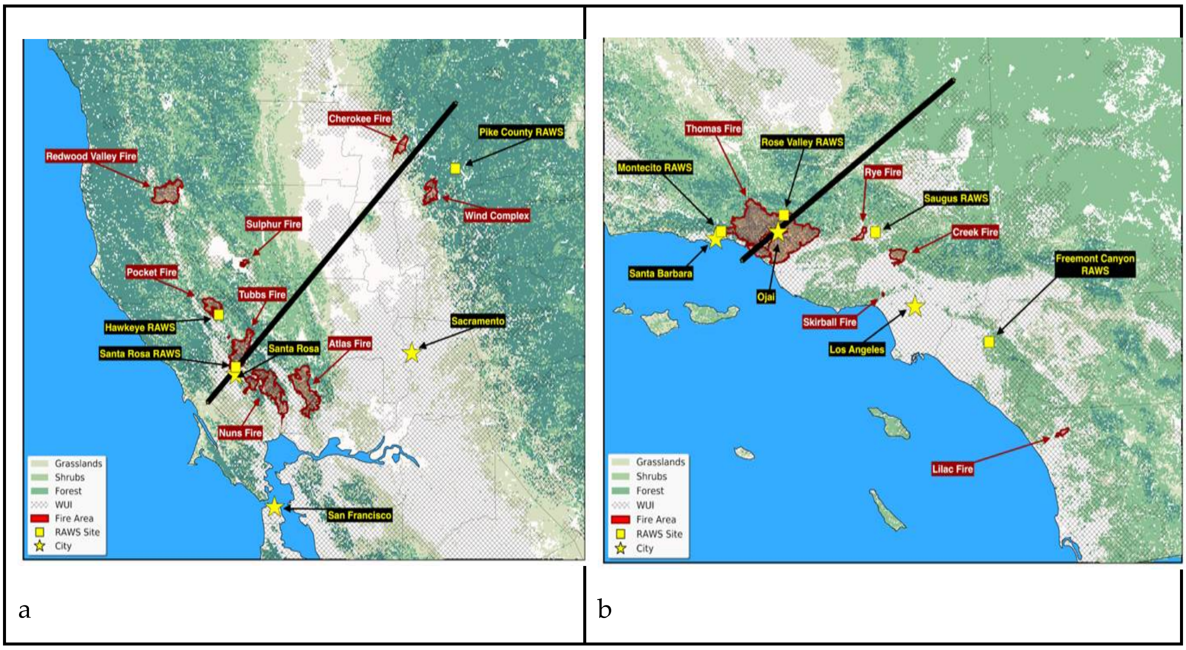

Fig. 1. a) Map of North Bay fires with select Remote Automated Weather Stations (RAWS). Forested areas shaded in green and Wildland Urban Interface (WUI) hatched in grey; b) Map of southern California fires with select RAWS. Black lines are the vertical cross-section transects for Figs. 2c, 4c.

In 2017, US federal wildland fire suppression costs exceeded $2.9 billion US dollars making it the costliest fire season on record, and more than 4 billion hectares (ha) burned, which is the second most area burned since 1984 [20]. The US wildfire season started across the southern Plains in early March but reached its peak in August and September. The national preparedness level, which is a measure of national fire activity and the number fire suppression resources committed and available, remained at its highest categorical level for 39 consecutive days (72 total days in 2017) when large

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conflagrations were found from northern California, into the Pacific Northwest and eastward into Montana coincident with one of the warmest and driest summers in the observational record for much of the region [21]. The 2017 fire season culminated with the wind-driven North Bay fires in October and southern California fires in December (Fig. 1), both extreme wildfire events [22]. The North Bay fires were reminiscent of the October 1991 Oakland Hills fire due to the rapid spread of wind-driven fires in densely populated areas around the Bay Area. The North Bay fires were the deadliest and most destructive wildfires in California's history with 44 fatalities and nearly 9,000 structures lost (Table 1). The southern California fires were led by the Thomas fire, which was the largest fire in California's history (Table 2).

In this paper we provide a description of these two extreme fire events, with a particular focus on the roles of weather and climate in enabling and driving these fires. Through a case-study approach, we examined similarities and differences in synoptic to meso-scale weather factors that resulted in exceptional surface fire weather conditions that led to rapid fire growth for both fire events. Using a set of key fire weather indicators, we also assess the rarity of such conditions over the observational record. Finally, we discuss how well each of the events were forecasted from local and national perspectives.

Names of Wildfires and Complexes	Area Burned (ha)	Structures Destroyed/Damaged	Start Date and Time (UTC)
Tubbs	14,895	5,636 / 317	10/9/17 0545
Nuns	22,877	1,355 / 172	10/9/17 0800
Atlas	20,892	120 / 783	10/9/17 0552
Pocket	7,024	6 / 2	10/9/17 1130
Redwood Valley (Mendocino Lake Complex)	14,780	546 / 44	10/9/17 0736
Sulphur (Mendocino Lake Complex)	893	162 / 8	10/9/17 0759
Cascade (Wind Complex)	4,042	264 / 10	10/9/17 0703
LaPorte (Wind Complex)	2,489	74 / 2	10/9/17 0857
Cherokee	3,406	6 / 1	10/9/17 0545

Table 1. List of wildfires including wildfire complexes, their final size, the number of structures they destroyed and damaged, and their ignition time during the northern California wildfire event in October 2017. Sources available: http://cdfdata.fire.ca.gov/incidents/; http://calfire.ca.gov/communications/downloads/fact_sheets/Top20_Deadliest.pdf; http://www.fire.ca.gov/communications/downloads/fact_sheets/Top20_Destruction.pdf)

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Wildfire Names	Area Burned (ha)	Structures Destroyed/Damaged	Start Date and Time (UTC)
Thomas	114,078	1,063 / 280	12/4/17 1435
Creek	6,321	123 / 81	12/5/17 1144
Rye	2,448	6 / 3	12/5/17 1931
Lilac	1,659	157 / 64	12/6/17 1431

Table 2. List of wildfires, their final size, the number of structures they destroyed and damaged, and their ignition time during the southern California wildfire event in December 2017. Sources available: http://cdfdata.fire.ca.gov/incidents/; http://calfire.ca.gov/communications/downloads/fact_sheets/Top20_Deadliest.pdf; http://www.fire.ca.gov/communications/downloads/fact_sheets/Top20_Destruction.pdf)

2. Overview of fire impacts and progression

The North Bay and southern California fires would have been notable in isolation given their size and rapid rate of spread near densely populated areas. However, both events occurred in the same state at the end of a very active US fire season and pushed the bounds of conventional fire wisdom with the extreme rates of spread, size, and timing of the fires. The North Bay fires burned nearly 100,000 ha with the majority of these devastating consequences occurring within 12 hours of ignition on 9 October 2017 (Table 1), including four of the top 20 deadliest and most destructive wildfires in the state's history. Suppression costs exceeded $400 million, $10 billion in insurance claims were filed, and overall economic impacts including evacuation and displacement of local residents are estimated to exceed $85 billion [23,24]. More than 200,000 people were evacuated during the multi-week fire event in southern California during December 2017. The total costs of the southern California wildfires are still being calculated with current suppression expenditures for the Thomas Fire totaling $382 million (federal: $207 million; state: $175 million) [23], and an estimated $2.5 billion in insurance claims. The causes for all of the North Bay and southern California fires remain under investigation, but lightning has been ruled out.

2.1. North Bay Fires

The North Bay Fires were an outbreak of wildfires that occurred across the Northern Coast Ranges and foothills of the northern Sierra in northern California (Fig. 1a). These areas are characterized by a Mediterranean climate, fine and flashy fuels, such as shrubs and annual grasses, with some trees, and steep terrain [25]. Most of the wildfires, including all of the large fires (Tubbs Fire, Nuns Fire, Atlas Fire, Pocket Fire, Mendocino-Lake Complex, Wind Complex, and Cherokee Fire), ignited during a six-hour period (05:45 – 11:30 UTC 9 October) and spread rapidly overnight, mostly to the southwest, coincident with the onset and peak of a downslope easterly wind event, which is known as Diablo Winds near the San Francisco Bay Area and Northeast Foehn Winds along the western slopes of the Sierra Nevada (Fig. 1.; Table 1). The rapid spread of these wildfires combined with nighttime ignition and proximity and progression toward populated areas created an exceptional wildfire hazard.

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The Tubbs Fire was not the largest wildfire during this event but was the most destructive as it moved downslope into the city of Santa Rosa, California and surrounding communities (Fig. 1a; Table 1). Embers lofted by strong winds ahead of the flaming front ignited spot fires, including embers that directly landed on or inside homes within suburban communities further complicating suppression and evacuation efforts [26]. By the time the Tubbs fire was contained, it was the most destructive (5,636 structures) and second deadliest (22 deaths) wildfire in California's history. The Nuns Fire burned in eastern Sonoma County affecting communities Sonoma, Glen Ellen, and Kernwood while burning 22,877 ha and destroying 1,355 structures (Fig. 1a; Table 1). The Atlas Fire burned 20,892 ha and destroyed 783 structures east and north of Napa, CA (Fig. 1a; Table 1). Further to the north, the Mendocino-Lake Complex burned more than 15,000 ha and destroyed more than 700 structures while on the western slopes of the Sierra, the Wind Complex and Cherokee Fires burned nearly 10,000 ha and destroyed nearly 350 structures (Fig. 1a; Table 1).

2.2. Southern California Fires

An extended period of Santa Ana Winds in December 2017 drove several large wildfires westward and southward across the slopes of the Transverse Ranges of southern California (Fig. 1b). Similar to the North Bay Fires, the combination of strong downslope winds, fine and flashy fuels, steep terrain, and the proximity of the wildfires to densely populated areas created a dangerous situation. The Thomas Fire burned 114,078 ha in southwestern California becoming the largest wildfire in the state's modern history as it burned from 4 December 2017 - 12 January 2018 (Table 2). The Thomas Fire started 14:35 UTC 4 December 2017 in Ventura County between southeast of Ojai and burned more than 40,000 ha within 48 hours of ignition spreading generally to the west (Fig. 1b). The Thomas Fire grew more than 25,000 ha on two separate days (4-5 December and 9-10 December) and 4,000 ha on eight separate days including two days (13-14 December and 15-16 December) that were more than a week after its ignition. The Thomas fire destroyed 1,063 structures and directly resulted in two fatalities. While other recent Santa Ana Wind driven fire events, such as those that occurred in October 2003 and 2007, directly caused more deaths and destruction, the flooding and mudslides associated with the Thomas Fire burn scar that occurred in Montecito and Santa Barbara claimed at least another 17 lives and destroyed more than 100 homes [27].

A handful of other large wildfires occurred during the prolonged offshore wind event across southern California in December. The Creek and Rye Fires began the morning of 5 December in northwestern Los Angeles County and burned 6,321 and 2,448 ha, respectively (Fig. 1b; Table 2). The Lilac Fire began at 19:15 UTC 7 December in northern San Diego County burning 1,659 ha and destroying 157 structures. Outside of the Thomas Fire, wildfires burned more than 10,500 ha, destroyed more than 300 structures, and damaged more than 160 structures.

3. Meteorological conditions

3.1. North Bay Fire Weather

The synoptic conditions leading to the North Bay fires featured a rapidly southeastward moving shortwave trough embedded in a broader scale trough that moved through the inland Pacific Northwest and Intermountain West during 8-9 October 2017 (Fig. 2). Behind this positively tilted

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shortwave upper tropospheric trough, heights raised aloft the West Coast and strong northeasterly flow developed across the Sierra and Northern Coastal Ranges of California (Fig. 2a-b). An unusually dry air mass prevailed across most of northern California in the days before the passage of the upper tropospheric trough with day time high temperatures 25-30°C and minimum relative humidities below 20% (not shown). The dry air mass was reinforced by the developing northeasterly flow, which began to increase winds during the afternoon of 8 October (Fig. 2a-b). Aloft, multiple inversions and critical layers existed below 2000 m (not shown) and with strong cross-mountain flow, it created a conducive environment for downslope windstorms [28,29].

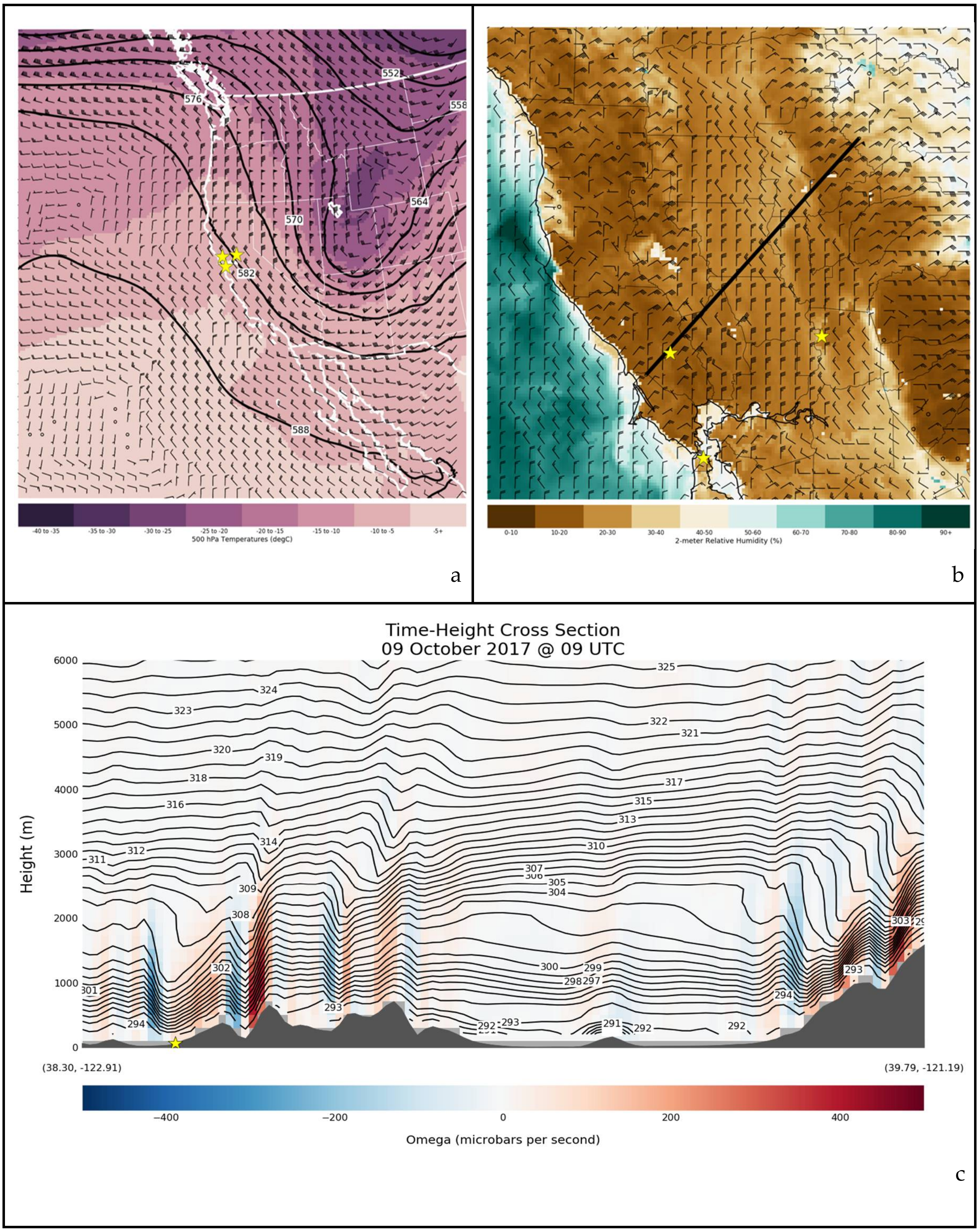

Fig. 2. California and Nevada Smoke and Air Committee (CANSAC [30]) 2-km Weather Research and Forecasting Model (WRF) output valid at 0900 UTC 9 October 2017 a) 500 hPa heights (dm) contoured, winds (barbs; MPH), temperature (color filled), and yellow stars representing three cities on Fig. 1a and Fig. 2b (San Francisco, Santa Rosa, Sacramento); b) surface relative humidity (color filled; %), winds (barbs; MPH), cross-section transect (same as Fig. 1a), and yellow stars representing three cities on Fig. 1a and Fig. 2a (San Francisco, Santa Rosa, Sacramento); c) vertical cross section with potential temperature (contoured, K); omega (color filled; μbars s^{-1}; positive values (red) represent downward motion), terrain (dark grey), model terrain (light grey), yellow star denoting Santa Rosa, CA, and latitude and longitude in decimal degrees in parentheses of starting and ending points of the cross-section transect.

Northeasterly surface winds accelerated during the afternoon to early morning on 8-9 October across much of the region, coincident with a decline in relative humidity (RH) (Fig. 2b). Consistent with downslope windstorms, the strongest winds and downward motion (Fig 2c; positive values; color-shaded red) were observed near ridge tops and on or near lee slopes with a standing wave feature resolved in potential temperature fields from high-resolution mesoscale modeling forecasts (Fig. 2b-c). Across northern California, widespread wind gusts of 15-20 ms^{-1} with RH below 15% were observed from the afternoon of 8 October to morning of 9 October. Three RAWS were chosen based on their proximity to the fires (Fig. 1a) and their period of record (>20 years). The Santa Rosa RAWS at 1100 UTC 9 October reported a temperature of 32.8°C, RH of 7%, E-NE wind gust of 27.3 ms^{-1}, Fosberg Fire Weather Index (FFWI) of 78, and 10-hour dead fuel moisture (FM10) of 12.8% (Table 3). Similar observations of low humidity and FM10 accompanying high winds and FFWI were found at other stations (Table 3). These values of wind gusts, RH, FM10, or FFWI were typically in the bottom or top 1st percentiles for station hourly observations for the 20+ year observational record (Table 3). When these four near surface meteorological variables were considered jointly during the North Bay Fires, we found unprecedented conditions for at least four consecutive hours (between 0400 – 12000 UTC 9 October) during which Santa Rosa and Hawkeye RAWS had >99th percentile wind speed/gusts and FFWI, as well as <2nd percentile RH. Such conditions were also seen at Pike County Lookout RAWS but were not unprecedented as seen during two prior occasions.

	Santa Rosa RAWS	Hawkeye RAWS	Pike County Lookout RAWS
Fosberg Fire Weather Index / Percentile	78 / 99th	128 / (MAX)	77 / 99th
Surface Relative Humidity / Percentile	7% / 1st	12% / 2nd	17% / 2nd
Surface Wind Gust / Percentile	27.3 ms^{-1} / 99th	35.3 ms^{-1} / 99th	21.9 ms^{-1} / 99th
Surface Wind / Percentile	11.6 ms^{-1} / 99th	21.5 ms^{-1} / 99th	13.9 ms^{-1} / 99th

10-Hour Fuel Moisture / Percentile	12.8% / 5th	3.8% / 5th	5.4% / 9th
Observation Time (UTC)	1100 9 October	0700 9 October	1200 9 October
Period of Record (Month/Year)	01/92 – 10/17	01/94 – 10/17	01/92 – 10/17

Table 3. Select nearby RAWS hourly observations (Fig. 1a) during the peak of critical fire weather conditions during the North Bay fires. Fosberg Fire Weather Index, surface relative humidity, surface wind gust, surface wind speed, and 10-hour fuel moisture values, percentiles, and any records shown.

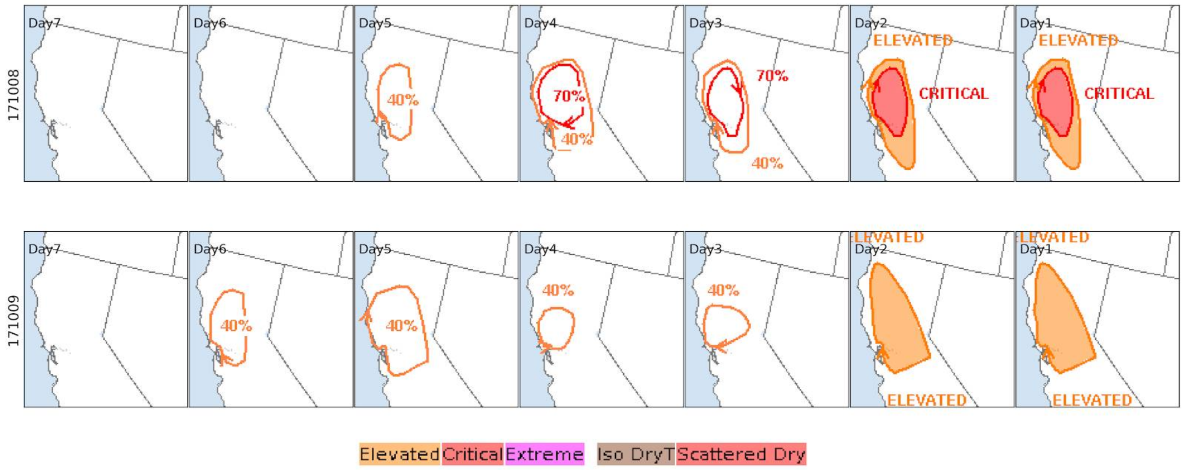

Fig. 3. Storm Prediction Center fire weather outlook progression for forecasts valid 8-9 October 2017 across northern California. Each first row denotes the daily fire weather outlook progression beginning six days in advance (Day 7) and continuing until the valid date (Day 1). Valid date listed at beginning of each row. The 40% and 70% contours represent the probability of critical fire weather conditions until Days 1-2 when elevated and critical fire weather conditions are forecasted. Source: http://www.spc.noaa.gov/products/fire_wx/overview.html

Fire weather conditions were well forecasted by the National Weather Service (NWS) up to a week prior to the event (Fig. 3). The NWS San Francisco/Monterey Bay forecast office first mentioned the possibility of offshore flow with low RH for the weekend (8-9 October 2017) in its fire weather forecast on 2 October 2017, and Storm Prediction Center (SPC) first mentioned the possibility of critical fire weather conditions due to offshore flow and low RH for northern California on 3 October 2017 (Fig. 3). The NWS San Francisco/Monterey Bay WFO issued a Fire Weather Watch on 5 October valid Sunday morning through Monday morning (8-9 October). That was later upgraded to a Red Flag Warning on 6 October valid from 1800 UTC 8 October to 1200 UTC 10 October for much of the San Francisco Bay area highlighting low RH, strong winds, and that any wildfire ignition would spread rapidly while SPC forecasted elevated to critical fire weather conditions for the same areas.

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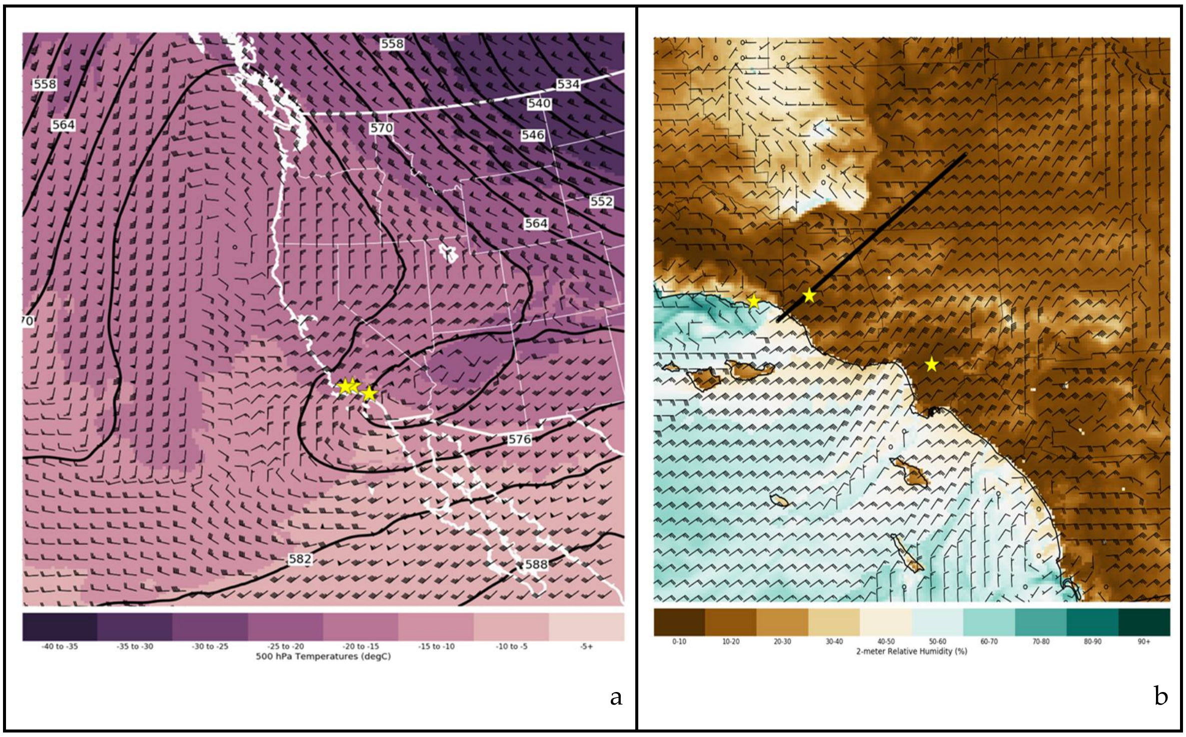
3.2. Southern California Fire Weather

This prolonged offshore wind event began as an area of lower heights and temperature moved southwest from Idaho to central California as the large upper tropospheric trough thinned and two separate temperature and height minima split west and east across the Intermountain West on 3-4 December (not shown). The western temperature and height minima continued moving south and became cut-off from the larger flow regime over Arizona/southern California producing northeast flow aloft and at the surface over southern California (Fig. 4a-b). A positively tilted upper tropospheric ridge slowly moved onshore, centered over the U.S. Pacific coast, with this general pattern persisting until 20-22 December, keeping offshore flow across southern California (not shown). Both Santa Ana and Sundowner winds develop under this synoptic configuration [5,31,32].



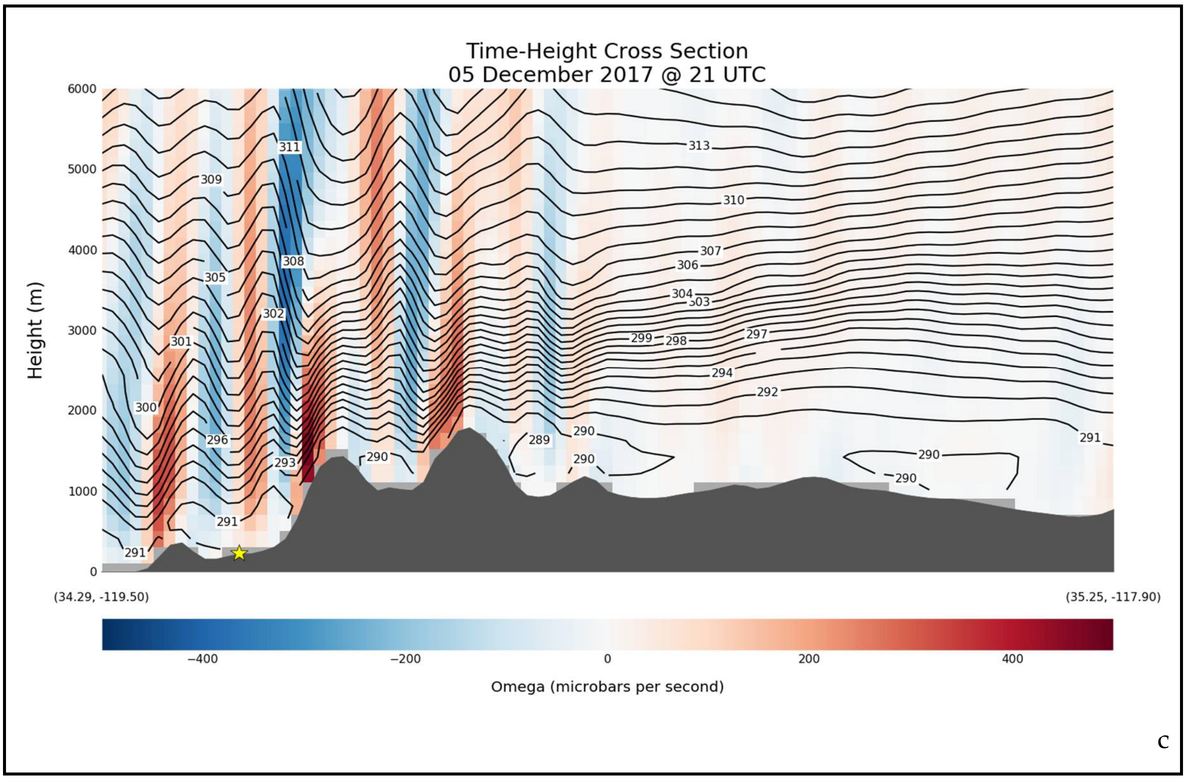


Fig. 4. California and Nevada Smoke and Air Committee (CANSAC [30]) 2-km Weather Research and Forecasting Model (WRF) output valid at 2100 UTC 5 December 2017 a) 500 hPa heights (dm) contoured, winds (barbs; MPH), temperature (color filled), and yellow stars representing three cities on Fig. 1b and Fig. 4b (Santa Barbara, Ojai, Los Angeles); b) surface relative humidity (color filled; %), winds (barbs; MPH), cross-section transect, and yellow stars representing three cities on Fig. 1b and Fig. 4a (Santa Barbara, Ojai, Los Angeles) c): vertical cross section with potential temperature (contoured, K); omega (color filled; μbars s^{-1}; positive values (red) represent downward motion), terrain (dark grey), model terrain (light grey), yellow star denoting Ojai, CA, and latitude and longitude in decimal degrees in parentheses of starting and ending points of the cross-section transect.

Widespread strong east-northeast surface winds and RH below 15% developed by 0000 UTC 5 December and expanded in coverage and intensity by 2100 UTC 5 December (Fig. 4b). The depth and magnitude of the dry air was apparent from local atmospheric soundings including the 1200 UTC 7 December San Diego atmospheric sounding setting a daily record for lowest precipitable water at that location (2.54 mm) (since 2 January 1948) (not shown). By 2100 UTC 5 December, the northerly-easterly winds increased, and RH dipped as strong downward motion developed on the lee slopes across southern California indicating a downslope windstorm (Santa Ana Winds) event (Fig. 4b-c).

Extreme fire weather conditions were observed consistently across southern California during this offshore wind event. To demonstrate the rarity and persistence of these conditions, percentiles were calculated using the entire period of record of hourly observations at each RAWS (Table 4). RAWS were chosen based on proximity to wildfires and/or ridgetops and period of record (>20 years) (Fig. 1b). The Saugus RAWS from 1700-2100 UTC 5 December observed >99th percentile values for FFWI, wind gust maximum, and wind speed with RH in the 4th percentile. At Fremont Canyon RAWS, >99th percentile values for FFWI, wind gust maximum, and wind speed with RH in the 2nd

percentile were observed from 1600-1800 UTC 7 December. Up the coast the Montecito RAWS recorded its lowest RH ever (1.0%) at 0900 UTC 12 December with 6.7 ms^{-1} northerly winds, and >99th percentile values for FFWI, wind gust maximum, and wind speed from 1100-1200 UTC 16 December. Shortly after these observations the Montecito RAWS was burned over by the Thomas Fire. The rare fire weather conditions were consistent and unrelenting with sizable portions of the hours >95th and 99th percentiles for FFWI, wind gusts, and speed and <5th and 1st percentiles for RH and FM10 (Table 4). Per the criteria established by [5] which uses reanalysis data, Santa Ana wind conditions occurred for 12 consecutive days, 4-15 December, the longest duration event in the observational record dating back to 1948. The previous longest SAW event was nine consecutive days (5-13 February 2006).

	Saugus RAWS	Fremont Canyon RAWS	Rose Valley RAWS	Montecito RAWS
Fosberg Fire Weather Index	22.2% (5.5%)	57.1% (13.0%	8.3% (3.0%)	3.4% (0%)
Surface Relative Humidity	66.8% (25.2%)	67.0% (12.5%)	39.6% (12.2%)	80.4% (62.1%)
Surface Wind Gust	12.7% (0%)	38.2% (0%)	10.5% (0.6%)	0.9% (0.6%)
Surface Wind Speed	15.2% (2.5%)	46.3% (9.7%)	4.2% (1.1%)	1.2% (0%)
10-Hour Fuel Moisture	0% (0%)	55.4% (22.2%)	46.0% (12.7%)	N/A
Period of Record (Month/Year)	01/95 – 12/17	01/92 – 12/17	01/94 – 12/17	01/97 – 12/17

Table 4. Percentage of total hours between 0800 UTC 3 December and 0800 UTC 19 December 2017 above the 95th (99th) percentile for Fosberg Fire Weather Index, surface wind gust, and surface wind speed and below the 5th (1st) for surface relative humidity and 10-hour fuel moisture for select RAWS.

The offshore wind event was well forecast by the NWS, up to a week prior to the onset of offshore winds. On 28 November, the NWS Oxnard/Los Angeles WFO mentioned the possibility of offshore winds for the following week, and on 30 November, SPC forecasted probabilities of critical fire weather conditions across southern California for the following week (Fig. 5). By the afternoon of 1 December, a Fire Weather Watch was issued for Santa Barbara, Ventura, and Los Angeles counties for a moderate-to-strong prolonged offshore wind event and was subsequently upgraded to a Red Flag Warning by the next afternoon (2 December). Through the event, at least one Red Flag Warning was valid per day in southern California from 2-21 December, and SPC forecasted critical fire weather conditions consistently through the event including the peak (4-9 December) (Fig. 5).

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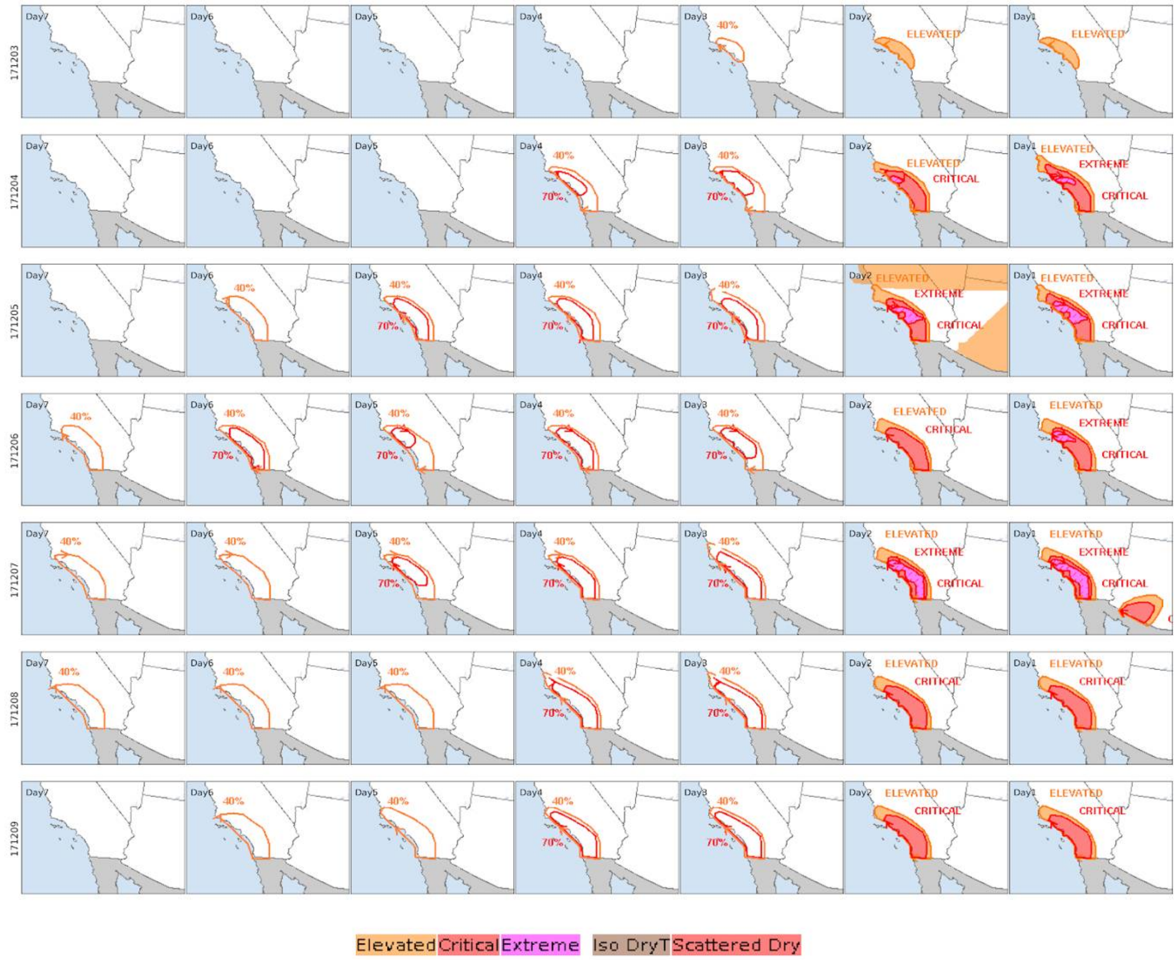

Fig. 5. Storm Prediction Center fire weather outlook progression for forecasts valid 3-9 December 2017 across southern California. Each first row denotes the daily fire weather outlook progression beginning six days in advance (Day 7) and continuing until the valid date (Day 1). Valid date listed at beginning of each row. The 40% and 70% contours represent the probability of critical fire weather conditions until Days 1-2 when elevated and critical fire weather conditions are forecasted. Day 2 in the 3rd row from the top (valid date: 5 December 2017) had an error in the fire weather outlook, which explains the odd coloring. Source: http://www.spc.noaa.gov/products/fire_wx/overview.html

4. Climatic basis

Extreme fire weather conditions contributed significantly to the North Bay and southern California fires, but without certain antecedent climate conditions, the events might have unfolded quite differently. The climate of the months and even years preceding these events created a situation that allowed extreme fire weather to realize the environment's explosive potential. California hydroclimate is highly variable due to its location along the southernmost extent of the North Pacific jet stream and propensity to receive much of its annual precipitation in a few heavy events [33]. Prior to water year 2016-2017, California had endured the drought of record from 2012-2016, and likely the most extreme drought in 1200 years [34], due to chronic below normal precipitation and exceptionally high rates of potential evapotranspiration associated with the warmest years in the observational record [35]. This chronic drought resulted in large scale loss of tree canopy water [36] and tree mortality across much of the Sierra Nevada and water curtailments across much of the state. By

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contrast, water year 2016-17 delivered well above normal to record precipitation across much of the state, with much of the central to northern Sierra Nevada, and scattered locations near the San Francisco Bay Area receiving the most Oct-Apr precipitation since 1895 (Fig. 6a). While above normal to above-normal Oct-Apr precipitation was also seen across the southern part of the state, the region saw below normal May-Apr precipitation.

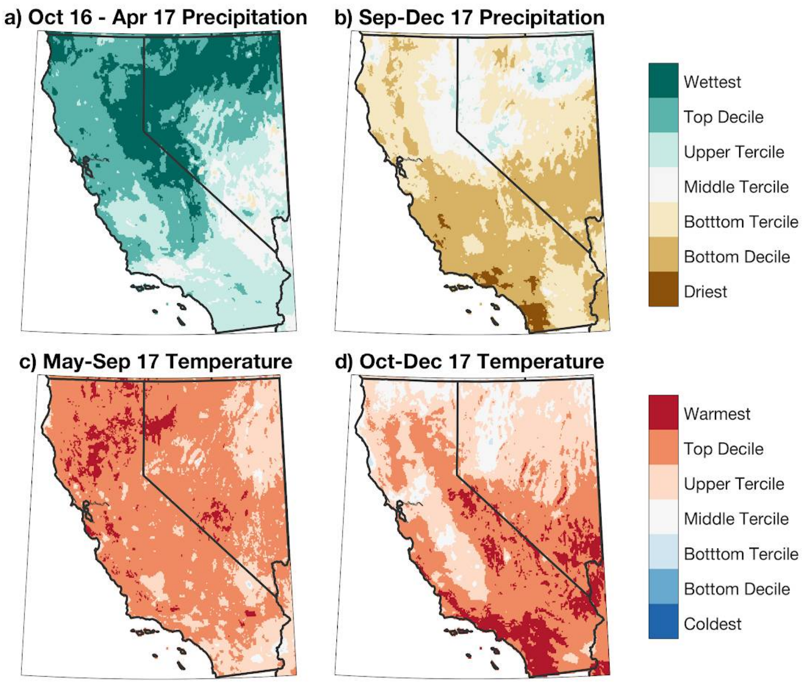

Fig. 6**.** Classified ranking of a) October 2016-April 2017 cumulative precipitation; b) September-December 2017 cumulative precipitation; c) May-September 2017 mean temperature; and d) October-December 2017 relative to conditions from 1895-2017. Data from the Parameterized Regression on Independent Slopes Model [37].

The above normal moisture across California during the winter of 2016-17 resulted in an anomalously productive landscape by spring 2017. Increased moisture content and biomass productivity in semi-arid regions often help promote fire in fuel-limited fire regimes through the accumulation of fine fuels that facilitate fire spread [38]. Previous climate-fire relationships have shown a weak positive correlation between early winter precipitation and burned area during the subsequent fire season in non-forested areas of southern California [18], and cumulative precipitation in several recent winters [3].

Little precipitation fell across California from May 2017 through the remainder of the calendar year. Dry summers are typical in California. However, the arrival of autumn precipitation was substantially delayed across the region. September-December precipitation was exceptionally low across the state, and the lowest in over 120 years across portions of south coastal California (Fig. 6b). Complementary to subpar precipitation, the region experienced exceptionally warm temperatures with much of northern and central California had their warmest May-September since

1895 (Fig. 6c), while much of south coastal California had their warmest October-December since 1895 (Fig. 6d). Despite, the wet start to the 2016-2017 water year, March-December precipitation across portions of southwestern California was the lowest since 1895. The delayed arrival of wetting precipitation (>2.5mm) was particularly notable across southern California near the Thomas Fire. The second longest dry spell on record (>240 days) was seen for two long-term (>60 years) weather stations near the Thomas Fire, Camarillo Airport and Ojai, with precipitation occurring in early January 2018 associated with the mudslides in Montecito.

Relationships between interannual variability in temperature and burned area in non-forested coastal Mediterranean ecosystems in California are generally weak [15] as they are often not flammability-limited, but yet do show a slight positive correlation with late summer to early fall temperature [18]. The nominal precipitation that occurs during the fire season in California is uncorrelated with historical burned area, although precipitation during the month of fire activity is negatively correlated with the sizes of Santa Ana driven fires [3].

The delayed arrival of autumn precipitation and continued warm temperatures leading up to the fire events allowed for fuel moistures to remain at levels more commonly found in mid-to-late summer. While climate variables like temperature and precipitation often help inform the ways in which climate variability enables fire, metrics calculated from climate and weather variables that are directly designed to represent biophysical processes such as vegetation desiccation (e.g., fuel moistures) and plant water use (e.g., actual evapotranspiration) often are superior correlates of burned area [18,39]. We provide two snapshots of 100-hour dead fuel moisture percentiles (calculated using the US National Fire Danger Rating System) coincident with the North Bay fires on 9 October 2017, and the southern California fires on 8 December 2017. In both cases, a large swath of exceptionally dry 100-hour fuels was co-located with the region of peak fire activity. On 9 October, much of the Bay Area, and southern Sacramento valley experienced fuel moistures below the historical 1% values (pooled over all calendar days of the year) (Fig. 7a). A companion time series of 100-hour fuels near the Atlas fire shows that fuel moistures were below the 3rd percentile for much of the early half of October (Fig. 7c). Similarly, much of south coastal California experienced 100-hour fuel moistures in the bottom 1-3% in early December 2017 (Fig. 7b), with exceptionally low fuel moistures during the period of peak fire activity including reaching the lowest values in the observational record (Fig. 7d).

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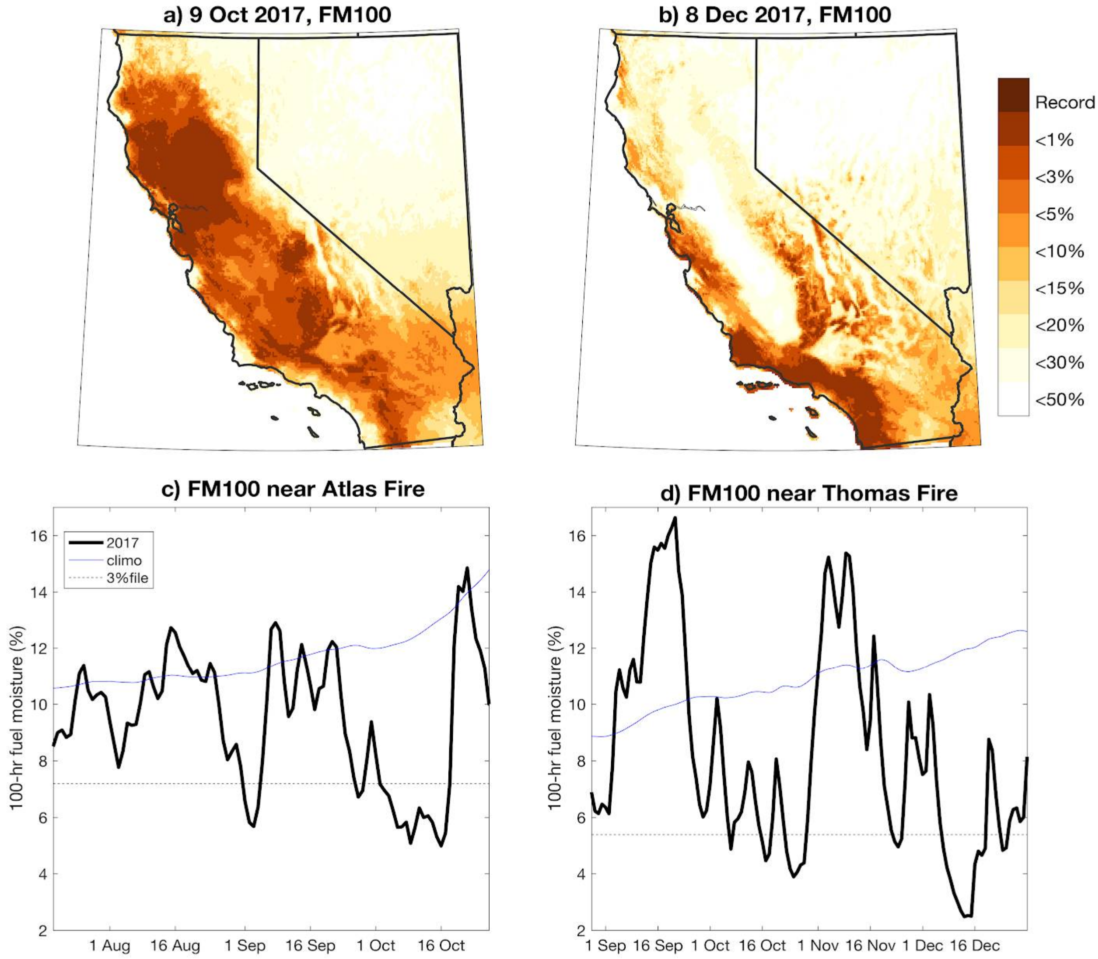

Fig. 7. Maps of 100-hour dead fuel moisture percentiles for a) 9 October 2017; and b) 8 December 2017. Percentiles are calculated relative to data pooled over the calendar year from 1979-2015. Time series of 100-hour fuel moisture near the c) Atlas fire; and d) Thomas fire prior to and throughout the duration of the fire. The light blue lines show 1981-2010 average fuel moisture levels, and the horizontal line denotes the 3rd percentile. Data from the gridded surface meteorological dataset [40].

5. Summary and Conclusions

The North Bay and southern California fires were wind-driven conflagrations that affected densely populated areas on the heels of an extended hot and dry period that followed an anomalous wet winter. The sequencing of climatological and meteorological conditions for these fire events mirrors other notable fires of record in California [2,41] and other portions of the world [42] reinforcing the important roles that both climate variability and meteorological factors have on extreme fires in terms of preconditioning fuel abundance, flammability, and driving fire spread. Rare conditions were seen across a spectrum of timescales coinciding with these two fire events. From a meteorological perspective, we found that stations near the North Bay Fires experienced their most acute fire weather conditions (as viewed through FFWI and combinations of wind speed, RH, FM10, and FFWI) in their observational record (hourly observations), which dates back more than two decades (Table 3). Southern California experienced its longest duration Santa Ana wind event on record, which led to chronic periods of fire danger (e.g., >95th percentile FFWI) accompanied by daily records for atmospheric dryness (Figs. 6-7; Table 4). The worst drought (2012-2016) in California for 1200 years preceded well above normal to record setting precipitation in the wet season prior to the fires with some areas recording their wettest October – April in 120 years. 100-hour dead fuel moistures were below the 3rd percentile during both fire events, including the lowest 100-hour dead fuel moisture in the observational record (1979-2017) with the Thomas Fire (Figs. 6-7). Such conditions were facilitated by exceptionally warm temperatures in the months preceding the fires, and the driest March – December since 1895 in southern California. We do not attempt to quantify the relative roles of these climatic extremes on the extent or rate of spread of these extreme wildfire events, although additional analyses may help elucidate the complementary role that fuel conditions played in these wind-driven conflagrations.

The nexus of climate, weather, fuels, and terrain drive large wildfire occurrence [43–45]. These factors all contributed to the North Bay and southern California fire events as detailed in this manuscript. The question remains as to whether the risk posed by foehn wind-driven fires is underestimated in such regions both in California and globally. We demonstrate that novel conditions in the observational record occurred for both fire events, but emergency management and city planners must prepare for these rare and unprecedented events given the dire consequences of rapidly spreading fires in populated areas.

Beyond limitations posed by the observational record, changes in the fire environment have and are continuing to occur that may further affect fire risk. For example, the continued expansion of WUI into geographic areas where fuels, terrain, and foehn wind events occur may very well incur additional risk for fire impacts. Changes in climate have and will continue to alter certain properties of the fire environment including increasing fuel aridity [13,46] and fewer days with precipitation [47] thereby increasing the frequency of certain ingredients for such fires. It is not currently well resolved how climate change will affect the occurrence or intensity of foehn wind events [48,49]. However, as these fires, like many others than occur with foehn winds in California, were anthropogenically-ignited, efforts to reduce ignitions coincident with forecasted wind events may limit exposure such as re-routing or cutting off power in areas of prone to high winds.

The NWS forecasts for these events were accurate and provided lead time to the public and emergency personnel, but the hazards still materialized leading to 46 deaths and thousands of homes destroyed with costs exceeding $10 billion. The NWS should continue improving its fire weather program and decision support services to better communicate the risks and impacts associated with its forecasts. Other preparative or reactionary measures could have helped reduce some of the impacts these fires had on losses including reverse evacuation calls [50], improved public communication [50,51], and better zoning and building codes to withstand spotting embers [52]. Given the recent catastrophic wildfires globally (e.g., Fort McMurray, Portugal, Gatlinburg, Chile), co-existing with wildfires and mitigating their effects are of paramount importance since these issues will not resolve themselves on their own or quickly.

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