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Supplementary Material

Autumn precipitation: the competition with Santa Ana winds in determining fire outcomes in southern California

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Supplemental Material: Parts I-IV.

Supplemental Material Part I. Number of fires and area burned, 1948-2018, South Coast (NOAA climate region 6) and other California NOAA climate regions (1, 2, 4 and 5) that have experienced substantial fire activity.

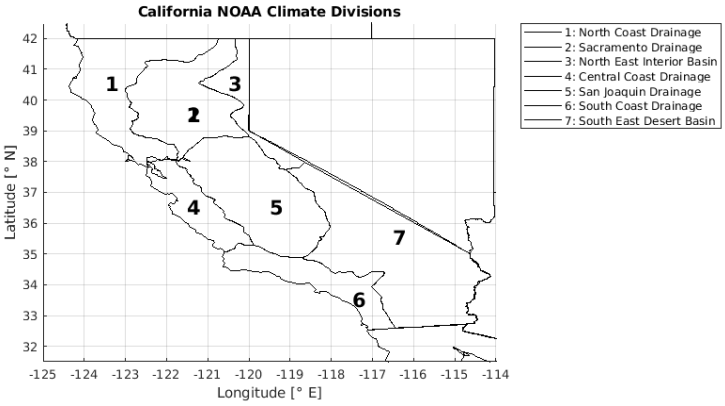


Figure SI.1. NOAA Climate Divisions in California. Region 6, the South Coast division is the focus of this study.

To evaluate the area mean Livneh gridded precipitation as a measure of autumn precipitation onset, we derived Livneh 8.5mm onset over San Diego County, the largest county in NOAA region 6, and compared that time series with results obtained from daily precipitation time series from 6 individual weather stations, Cuyamaca, Larke Henshaw, North Island, Oceanside, Palomar, and San Diego. The results, shown in **Table SI.1**, indicate that, for these particular stations, an onset threshold of 17 to 22 mm produces a mean onset time that is relatively close to that of from Livneh 8.5 mm onset and has close temporal correspondence (correlations exceeding 0.7 and number of agreements exceeding 75%) over the 1948-2018 record.

Table SI.1 Comparison, Livneh 8.5 mm onset time series, San Diego County vs onsets for a range of thresholds obtained from daily precipitation time series from 6 individual weather stations: Cuyamaca, Larke Henshaw, North Island, Oceanside, Palomar, and San Diego.

	Livneh 8.5mm	**Station 5.1mm**	**Station 10.2mm**	**Station 15.2.mm**	**Station 20.3”**	**Station 21.6mm**	**Station 22.9mm**	**Station 24.1mm**	**Station 25.4mm**
Correlation	1	0.25	0.44	0.63	0.74	0.68	0.66	0.68	0.68
Matching days	100%	42%	58%	73%	80%	78%	77%	77%	74%
Mean day of onset	Nov 5	Oct 4	Oct 16	Oct 25	Oct 31	Nov 4	Nov 7	Nov 7	Nov 8

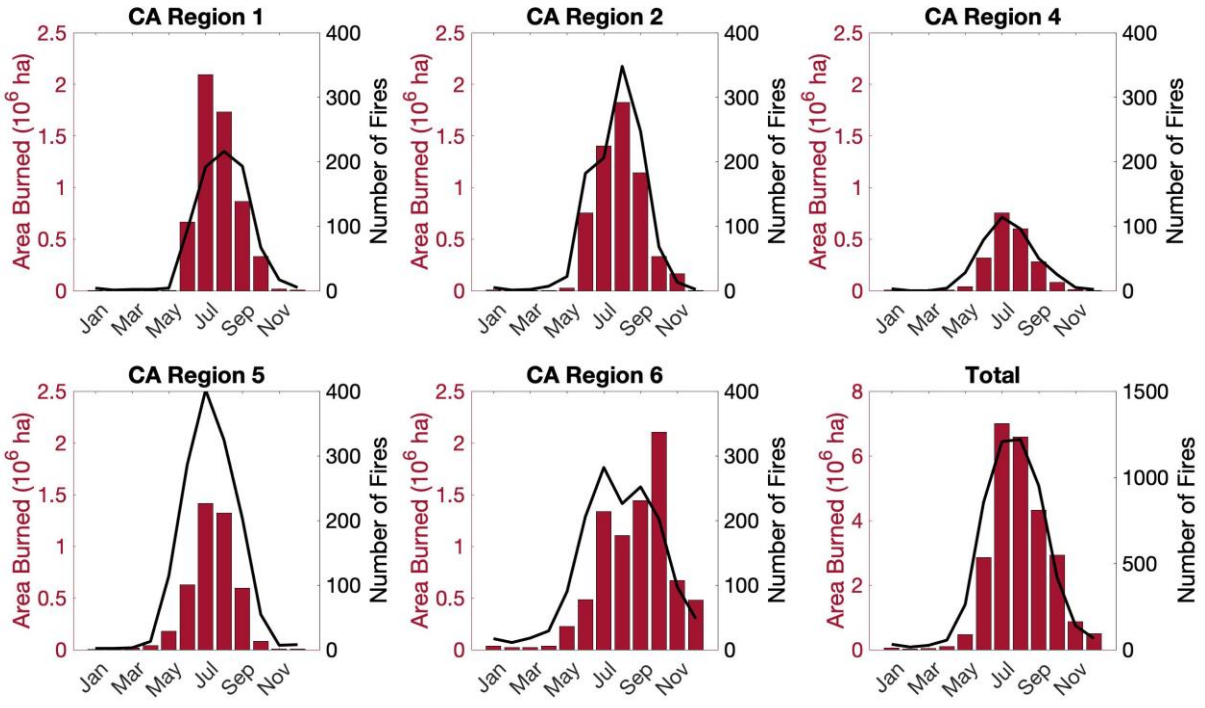


Figure SI.2 Number of fires and area burned, 1948-2018. NOAA climate division regions 1, 2, 4, 5, 6. Fires and area burned from FRAP dataset, ≥100ha fires.

Supplemental Material Part II. Temporal and spatial distribution of precipitation before and during autumn 8.5mm precipitation onset.

Time series (**Figure SII.1**), and the spatial distribution (**Figure SII.2)** of precipitation before, during and before plus during 8.5mm autumn precipitation onsets illustrate the considerable variability from year to year and across the South Coast region.

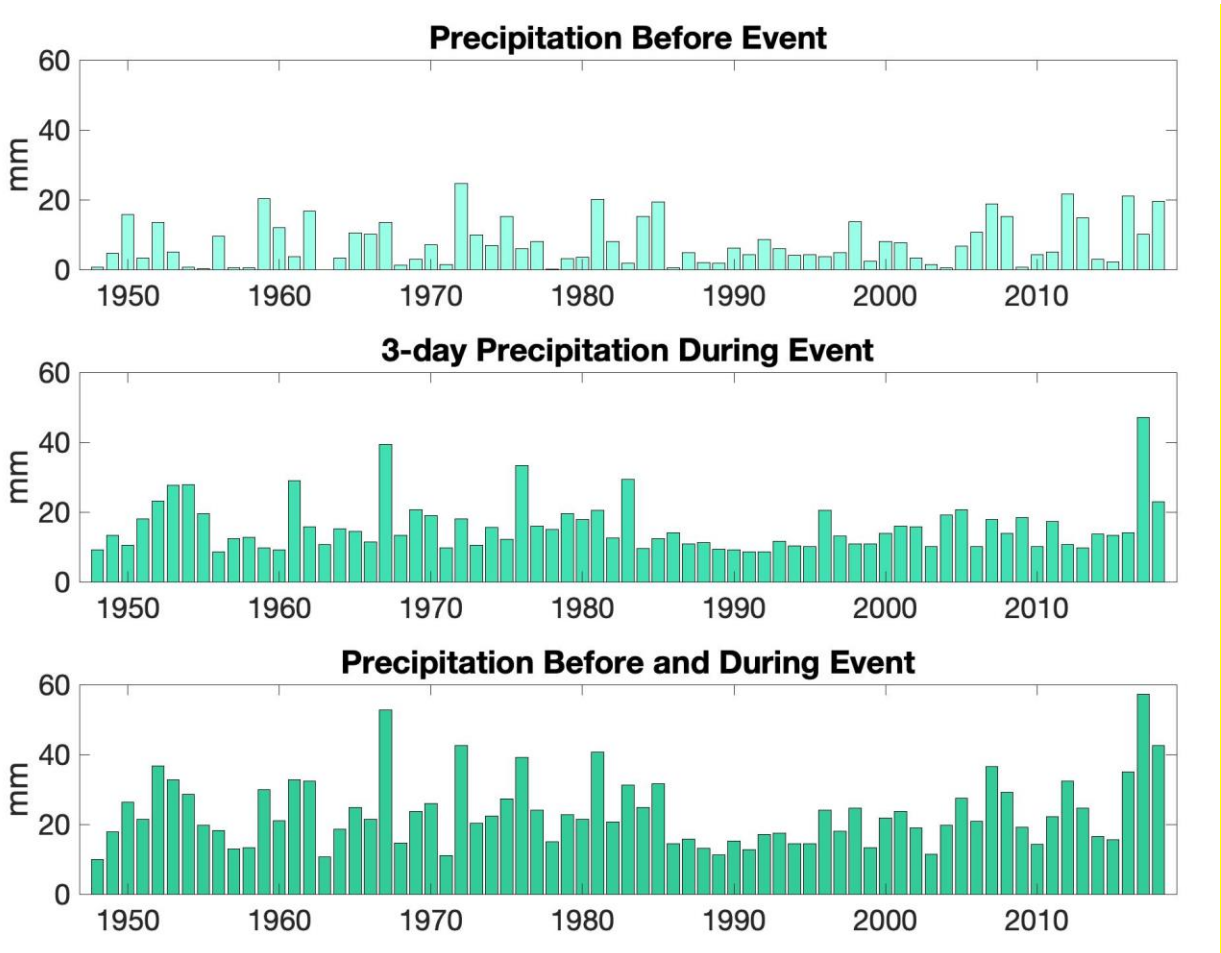


Figure SII.1. (upper) Cumulative precipitation (mm), September 1 through the day before autumn 8.5mm precipitation onset for each year, 1948-2018. (middle) Precipitation total (mm) during 3-day autumn 8.5mm precipitation onset events of each year. (lower) Cumulative

precipitation (mm), September 1 through the last day (day 3) of the 3-day precipitation onset of each year.

South Coast area average autumn precipitation amounts preceding onset (**Figure SII.1, upper, Figure SII.2 upper right**) exhibited a median value of 5mm with most years having less than 20mm. As described in the main body narrative and shown in Figure 6, the median pre-onset period occupied 67 days (median onset date was November 7), but varied considerably across the 1948-2018 study period. Within the 3-day onset period, the distribution of precipitation amounts, which by definition met or exceeded 8.5mm, had a median value of 14mm with amounts ranging from 8.5mm to 41mm (**Figure SII.1, middle**). Under the onset definition that is employed, most of the precipitation occurred during days two and three of the onset event (**Figure SII.3**). All of the onset events experienced precipitation within the South Coast region on the third day of the 3-day onset event (**Figures SII.2** and **SII.3**), with median precipitation amounts on the third day being about 10mm (**Figure SII.3**). **Figure SII.3** also shows that for many onset episodes, an extension of significant rainfall amounts occurred beyond the 3-day onset period through day 4, and in some years day 5 or day 6.

The third measure in **Figures SII.1** and **SII.2** is a combination of the first two, being the precipitation that accumulated from September 1 through the end of 8.5mm onset. This accumulated amount was always greater than the 8.5mm onset threshold (**Figure SII.1, lower**), reflecting contributions of pre-onset precipitation and onset event amounts that often exceeded 8.5mm. The median value of these accumulated amounts September 1 through last day of onset

was 21.4mm, with minimum of 9.9mm and maximum of 57.3mm. Thus, an alternative to using 3-day onset events as a metric for autumn precipitation start could have been to employ a threshold cumulative precipitation amount beginning September 1, e.g. a threshold of 21.4mm. The record shows that in most years, the day upon which an accumulated amount reaches or exceeds 21.4mm (0.85 in) is within two days of autumn precipitation onset of 8.5mm.

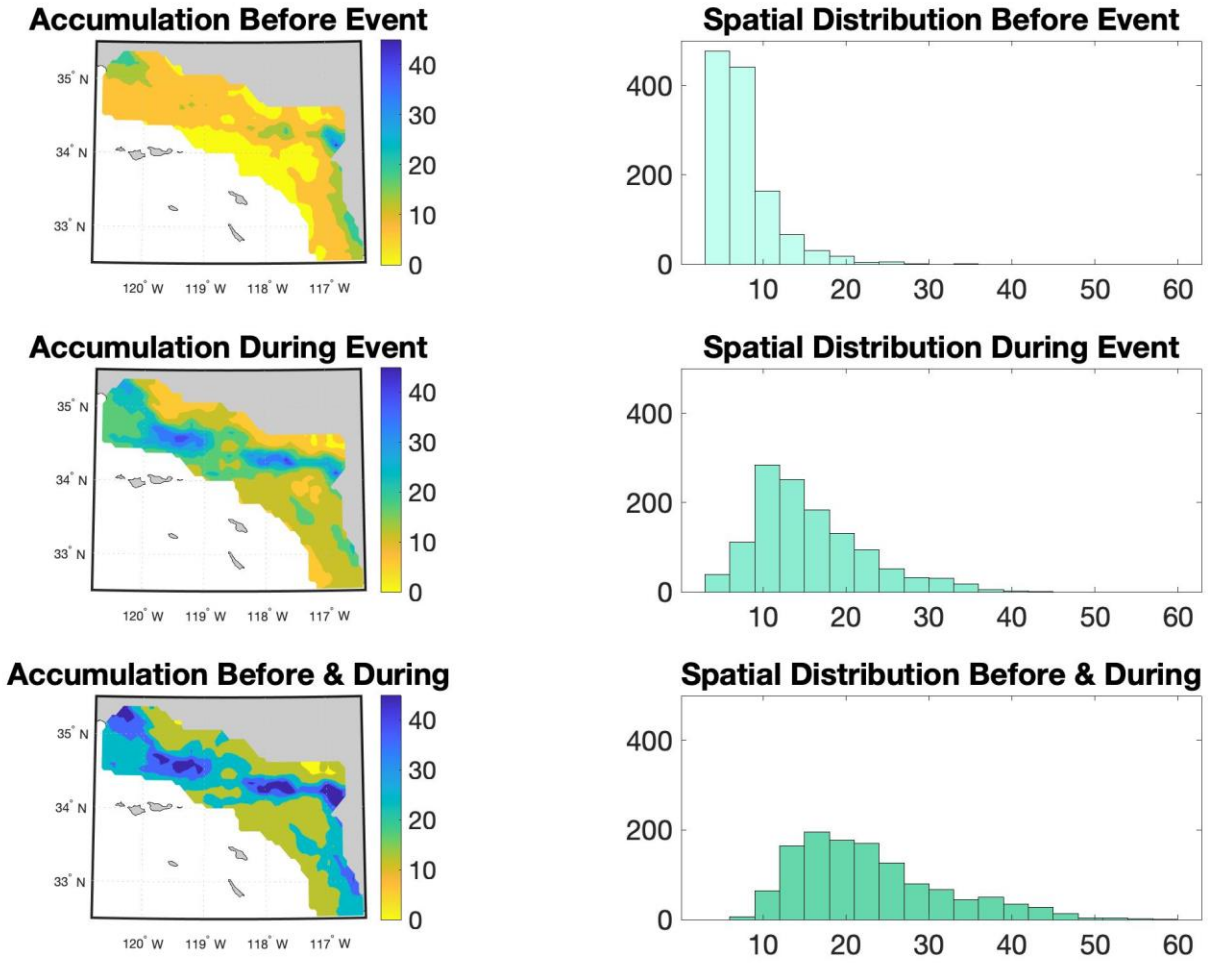


Figure SII.2. *Left*: Precipitation (mm) averaged over 1948-2018 (upper) accumulated from September 1 until the day before autumn precipitation onset, domain average 5.7mm; (middle)

during each year's 3-day autumn precipitation onset equal or greater than 8.5mm, domain average 23mm; (lower) accumulated from September 1 until day 3 of autumn precipitation onset, domain average 28.8mm. *Right*: distributions of grid values across the South Coast region of average precipitation shown on left.

The South Coast region has complex terrain which receives varied amounts of precipitation, with generally higher amounts on higher elevations of windward slopes. Mean amounts that occurred during the 3-day onset, and cumulative period from Sept 1 through the day before and on the last day of 8.5mm onset events are mapped in **Figure SII.1,** left: upper, middle and lower. The spatial distribution of the average amounts of precipitation constructed from the Livneh gridded observations is shown in **Figures SII.1**, right: upper, middle and lower. Mean autumn precipitation preceding onset events is modest (**Figure III.1**, upper, left), with small amounts (<10mm) across coastal lowlands and peak values mostly <25mm in highest elevations. The mean over 3-day onset events (**Figure SII.1** middle, left), precipitation on coastal lowlands typically amounts to 10mm with greatest amounts along windward uplands, where amounts reached or exceeded 25mm. Precipitation before (September through the day before onset) and during each 3-day autumn 8.5mm precipitation onset is plotted in the upper and lower frames of Figure S**II.2**. Onset precipitation events, which by definition had a region average which equaled or exceeded 8.5mm (**Figure SSII.1** middle) contributes to a cumulative area average beginning September 1 whose precipitation reached amounts that in many locations and many years reached more than double the 8.5mm threshold (**Figure SII.1** lower, right).

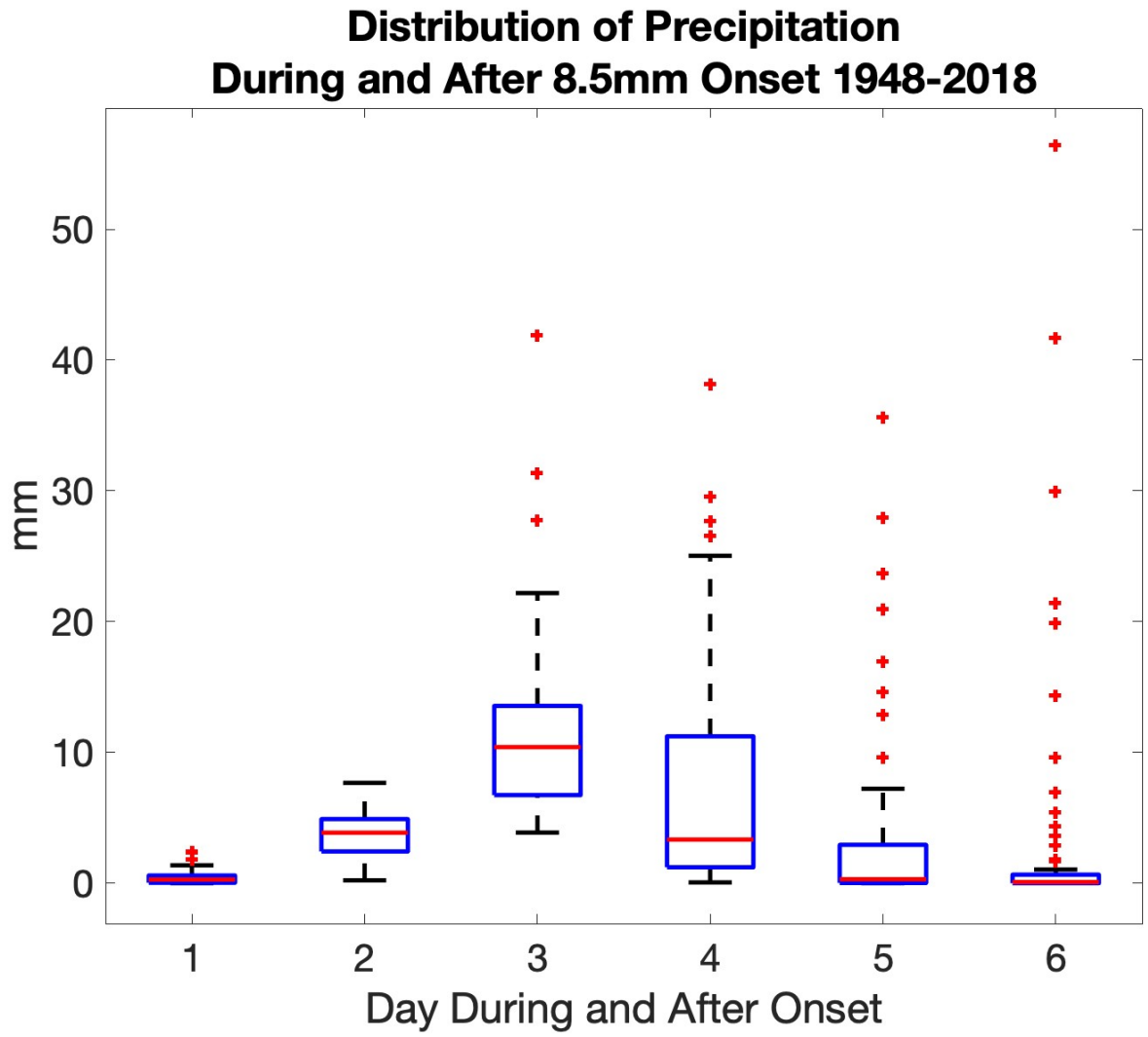
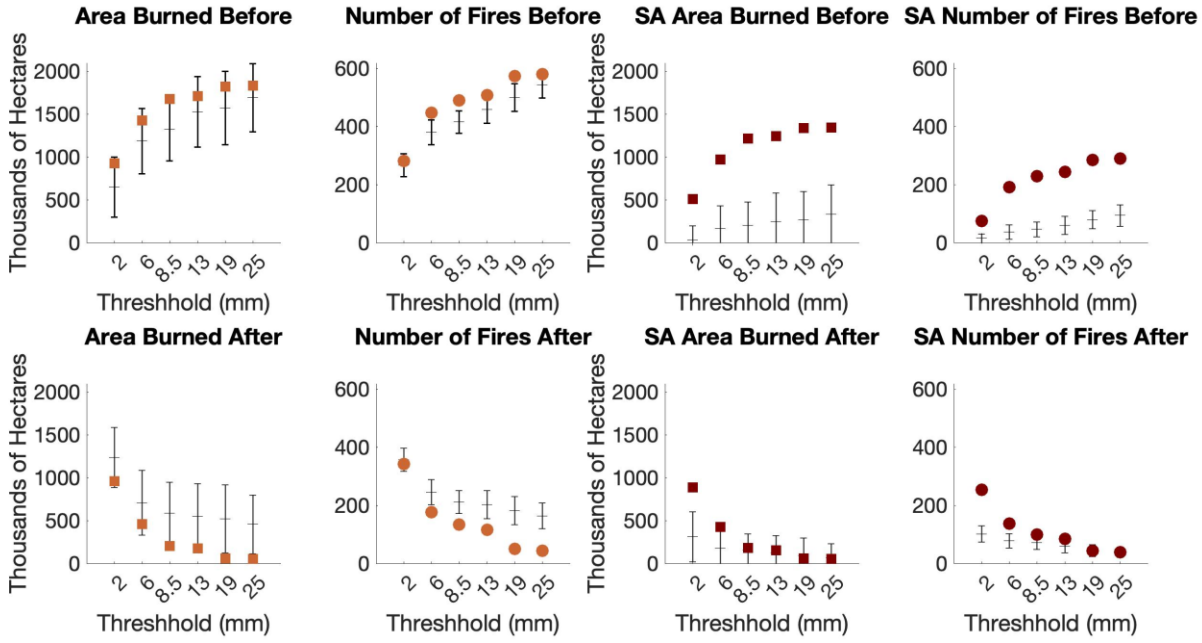


Figure SII.3. Distribution of precipitation (area average over South Coast from Livneh dataset) on days during and after 8.5 autumn precipitation onset. The boxes are the interquartile (line is median). The whiskers are "the extreme data points not considered outliers".["An outlier is a value that is more than 1.5 times the interquartile range away from the bottom or top of the box."]

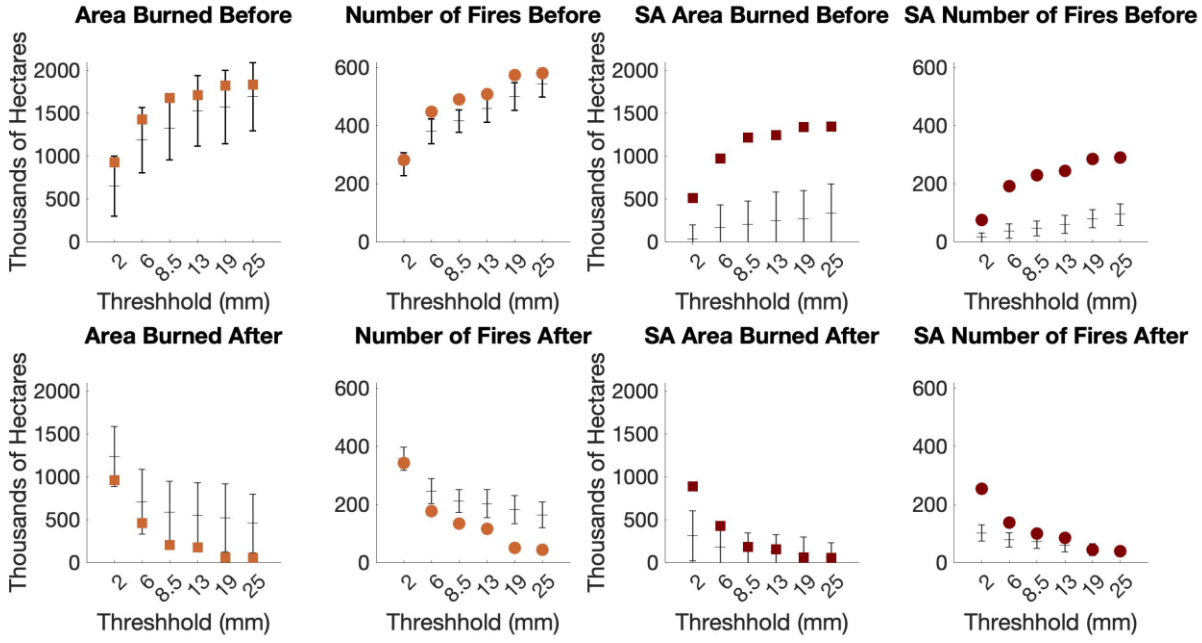
Supplemental Material Part III. Random Shuffle significance tests of wildfire occurrence, autumn precipitation onset, and Santa Ana wind associations.

Because associations between autumn rainfall onset, Santa Ana (SA) occurrence and fire are built from strongly seasonal processes, we conducted a random shuffle exercise to determine the extent to which these associations might arise from seasonal processes rather than causal linkages. Thereupon, the day and month of the series of autumn precipitation onset events were retained, but the year of each event was shuffled randomly and the 71 year sequence of shuffles was repeated to obtain 1000 random shuffle trials. Independently, the year of the train of SA days in a given year was shuffled randomly and the 71-year sequence of was also repeated to obtain 1000 random shuffle trials. For each of the 1000 random shuffle trials, the fire record (fires $\geq$100ha) for each of the 71 years was retained as it actually occurred. From the 1000 random shuffle trials, a distribution of associations between autumn precipitation onset, SA occurrence and fire start occurrence was determined, from which the observed number of fires and acres burned and the coincidence of fires with SA days was gaged for statistical significance. This evaluation was repeated for a series of autumn precipitation onset thresholds, from 2.5mm (0.1 inch) to 25.4mm (1 inch).

1948-2018 CA Region 6



1948-2018 CA Region 6



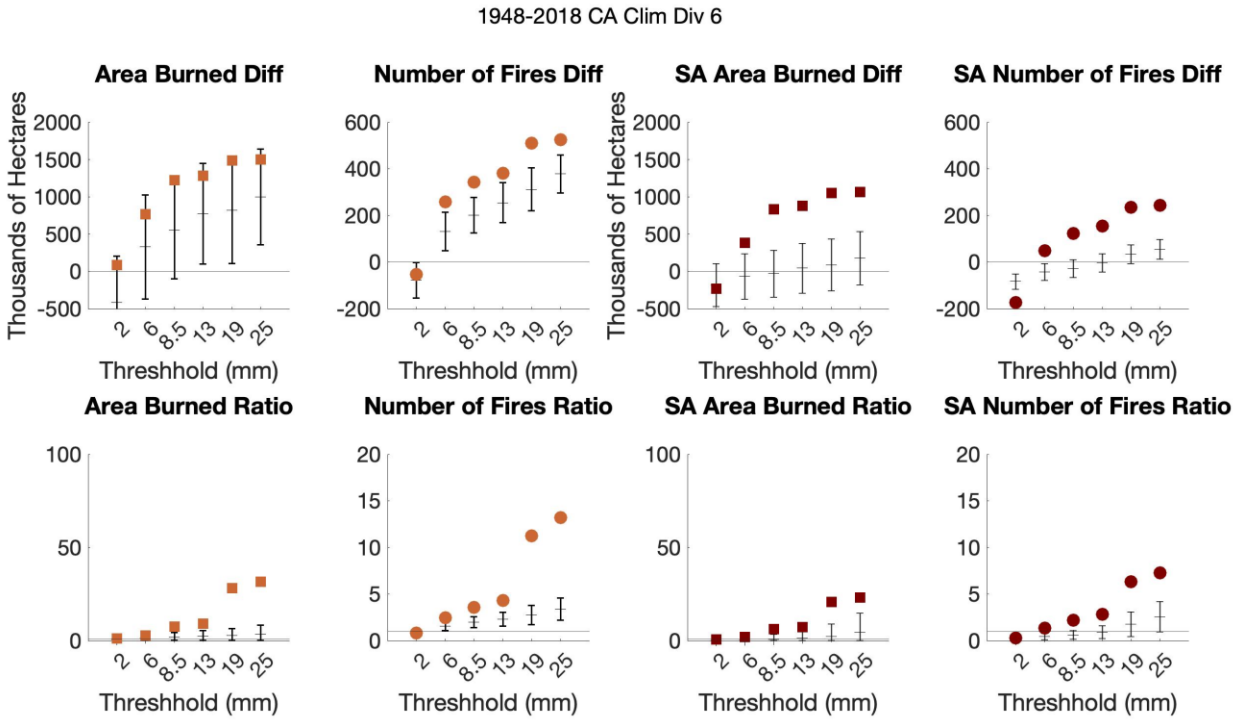


Figure SIII.1. Top two rows: 1000 member random shuffle distribution of a) Area burned (left) and number of fires (right) before autumn precipitation onset (above) and after autumn precipitation onset (below) for a range of onset amounts; b) same as a) but showing area burned by ≥100ha fires whose starts coincided with SA days and number of fire starts occurring during SA days. Bars delineate -2 to +2 standard deviations from the random shuffle distribution. Red dots show result from actual acres burned and number of fires. Bottom two rows: 1000 member random shuffle distribution of difference (above) and ratio (below) of a) Area burned (left) and number of fires (right) before autumn precipitation onset vs. after autumn precipitation onset for a range of onset amounts; b) same as a) but showing difference and ratio of area burned and number of fires whose starts coincided with SA days. Bars delineate -2 to +2 standard deviations from the random shuffle distribution. Red dots show differences and ratios from actual area burned and number of fires.

The number and area burned of wildfire before onset were consistently high, relative to the random shuffle distribution, and those *after* onset were unusually low. This result was obtained for observations in the entire 71 years (**Figure SIII.1**) and also for both the first (1948-1983) and second (1984-2018) halves of the record **Figures SIII.2 and SIII.**3, and summarized in **Table SIII.1**. The observed association of fire starts with Santa Ana before onset was unusually strong, exhibited across the range of fire sizes on the righthand side of **Figures SIII.1 and SIII.**2,

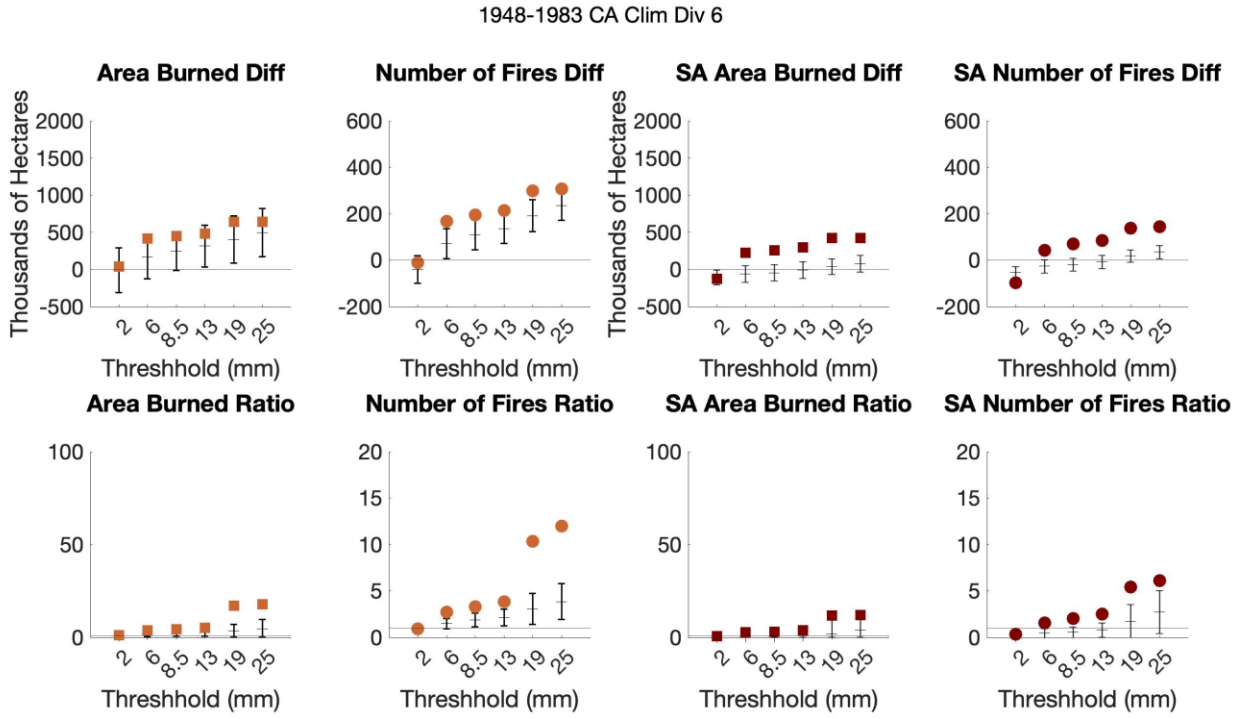


Figure SIII.2. As in **Figure SIII.1**, but from first half (1948-1983) of record.

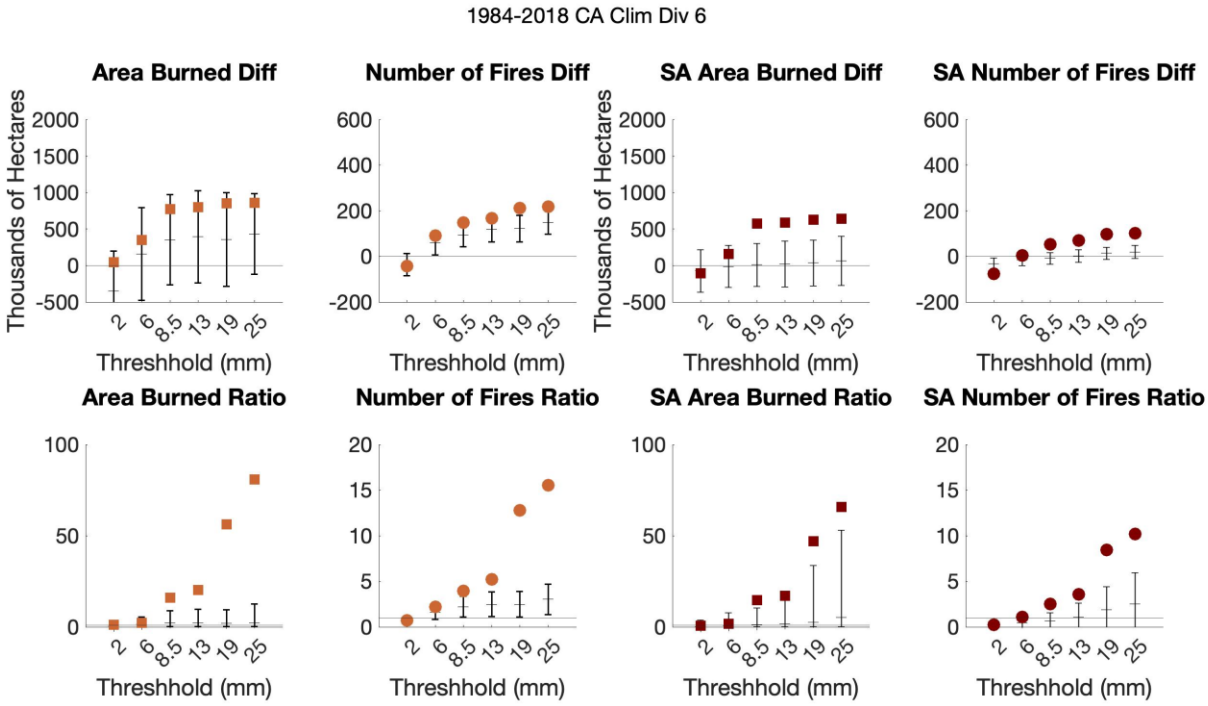


Figure SIII.3. As in **Figure SII1.2**, but from second half (1984-2018) of the record.

In **Figures SIII.1 and SIII.2**, similar to those exhibited by the whole record in **Figure I.2,** highly significant random shuffle results obtained from the first (1948-1983) and second (1984-2018) halves of the record for before vs. after autumn precipitation onset fires, area burned, and SA associations.

Table SIII.1. Before vs *after* 8.5mm precipitation onset difference and ratio of fire numbers and area burned for the first (1948-2018) and second (1984-2018) halves of the record, for fire starts whose area burned was ≥100ha. Shuffled results were generated from a random shuffle exercise performed separately for the first and second halves.

	1948-1983			1984-2018		
	Shuffled mean	**Shuffled mean + 2σ**	**Obs**	**Shuffled mean**	**Shuffled mean + 2σ**	**Obs**
Number fires, difference	110	173	195	99	151	160
Number fires, ratio	1.87	2.62	3.3	2.2	3.3	4.2
Area burned, difference (thousands of ha)	239	489	448	471	1085	900
Area burned, ratio	2.00	3.32	4.31	2.70	9.7	18.3

Supplemental Material Part IV. Largest (≥10,000 ha) Autumn and Early Winter Fires, South Coast region, 1948-2018.

Table SIV.1 Fires in South Coast region greater than 10,000 ha whose starts occurred September 1 – February 29. Fires whose start occurred after 8.5mm autumn precipitation onset are shaded in gray. Fires whose start was *not* within one day of a SA day are labeled "No"..

Name	**Area Burned (acres)**	**(ha)**	**Start Date**	**Autumn Precip Onset date**	**SA within 1 day**
Refugio	79,429	32,144	Sept 5, 1955	Nov 15, 1955	No
Outside Orig	46,602	18,860	Nov 23, 1956	Dec 7, 1956	
Sherwood/Zum	35,170	14,233	Dec 27, 1956	Dec 7, 1956	
Coyote	65,339	26,442	Sept 21, 1964	Oct 30, 1964	No
Clampitt Fir	115,537	46,757	Sep 24, 1970	Nov 27, 1970	

Wright Fire	28,202	11,413	Sep 24, 1970	Nov 27, 1970	
Laguna	174,162	70,482	Sep 25, 1970	Nov 27, 1970	
un-named San Bernardino Nation Forest	37,472	15,165	Sep 27, 1970	Nov 27, 1970	
Bear	51,665	20,909	Nov 10, 1970	Nov 27, 1970	No (Nov 12)
Mill Fire/Us	51,220	20,728	Nov 21, 1975	Nov 29, 1975	
Kanan Fire	25,589	10,356	Oct 22, 1978	Sep 6, 1978	
Sage Fire/Us	28,913	11,701	Sept 12, 1979	Oct 21, 1979	No
Creek Road	32,706	13,236	Sept 17, 1979	Oct 21, 1979	No
Turner	31,447	12,726	Nov 15, 1980	Dec 5, 1980	
Indian	28,940	11,712	Nov 23, 1980	Dec 5, 1980	
Dayton Canyon	43,097	17,441	Oct 8, 1982	Sep 27, 1982	
Ferndale	46,805	18,942	Oct 13, 1985	Nov 11, 1985	
Marre	43,822	17,735	Sept 24, 1993	Nov 12, 1993	No
Green Meadow	38,479	15,572	Oct 25, 1993	Nov 12, 1993	
Steckel	27,085	10,961	Oct 26, 1993	Nov 12, 1993	
Edna	28,136	11,386	Oct 4, 1998	Nov 9, 1998	
Williams	38,119	15,427	Sept 22, 2002	Nov 8, 2002	No
Grand Prix	50,618	20,485	Oct 21, 2003	Nov 2, 2003	No (Oct 23)
Piru	63,726	25,790	Oct 23, 2003	Nov 2, 2003	
Simi Fire	107,570	43,533	Oct 25, 2003	Nov 2, 2003	
Old	91,428	37,000	Oct 25, 2003	Nov 2, 2003	
Cedar	270,686	109,545	Oct 25, 2003	Nov 2, 2003	
Paradise	56,546	22,884	Oct 26, 2003	Nov 2, 2003	
Mine/Otay	44,734	18,104	Oct 26, 2003	Nov 2, 2003	
Day	161,816	65,486	Sept 4, 2006	Dec 11, 2006	No
Esperanza	40,177	16,259	Oct 26, 2006	Dec 11, 2006	
Ranch	58,410	26,638	Oct 20, 2007	Dec 1, 2007	
Witch	162,070	65,589	Oct 21, 2007	Dec 1, 2007	
Harris 2	90,728	36,717	Oct 21, 2007	Dec 1, 2007	
Santiago	28,430	11,505	Oct 21, 2007	Dec 1, 2007	
Buckweed	38,348	15,519	Oct 21, 2007	Dec 1, 2007	
Poomacha	49,411	19,996	Oct 23, 2007	Dec 1, 2007	
Freeway_Complex	30,305	12,264	Nov 15, 2008	Nov 26, 2008	
Thomas	281,791	114,039	Dec 4, 2017	Jan 10, 2018	
Woolsey	96,949	39,235	Nov 8, 2018	Nov 30, 2018	