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Brief Communication: Differences between Sundowner and Santa Ana wind regimes in the Santa Ynez Mountains, California

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Abstract. Strong afternoon downslope "Sundowner" winds in southern California's Santa Ynez Mountains favor wildfire growth. To determine whether Sundowners are different from Santa Ana winds (SAW), we use surface observations from 1979-2014 to develop a climatology of extreme Sundowner days. The climatology was compared against an existing SAW index from 1979-2012. Sundowner occurrence peaks in late spring whereas SAWs peak during winter. SAWs demonstrate amplified 500 hPa geopotential heights over western North America and strong anomalously positive inland mean sea level pressures. In contrast, Sundowner-only conditions occur during zonal 500 hPa flow and moderate negative inland sea level pressure anomalies.

1 Introduction

The combination of episodic low relative humidity and strong winds, complex terrain, and fuel conditions (e.g., load, moisture, and continuity) coupled with extensive wildland-urban interfaces (WUI) in southern California produces significant wildfire hazards with frequent large, severe, and costly fires (Westerling et al. 2004). In the semiarid steeplands of the Santa Ynez mountains and other Transverse ranges of Southern California (Figure 1a), fire represents a critical component of dominantly shrubland ecosystems (Moritz et al. 2003). The Mediterranean climate promotes accumulation of fine fuels during mild wet winters that cure during extended warm and dry summers. In this region, humans are the primary source of ignitions (Balch et al. 2017) with notable Santa Ynez fires (Figure 1a) resulting from accidental ignitions to arson.

Strong downslope wind events often contribute to fire weather conditions throughout mountainous regions and can lead to damaging fires when an ignition source is present (Sharples et al. 2010; Werth et al. 2016). In the Santa Ynez mountains, these winds are locally called "Sundowner" winds due to their characteristic onset during late afternoon or early evening (Blier 1998; Figure 1b-c). Wind gusts in the Santa Ynez foothills can exceed 25 m s^{-1} and low relative humidity result from adiabatic warming as air descends nearly 900 m from the crest of the Santa Ynez southward to the coastal plain (Figure 1b-c). During Sundowner conditions, wildfires ignited in the Santa Ynez Mountains rapidly grow downslope to threaten agriculture and densely populated urban communities along the mountain front and coastal plain regions. Although historical and paleofire regimes are dominated by large fires (Mensing et al. 1999), any fire near the WUI such as the Tea, Jesusita, or Painted Cave Fires (Figure 1a) can have devastating consequences. As climatic conditions increase water limitation (Williams and Abatzoglou 2016) and the WUI continues to expand, the risk to life and property from fires in dryland regions will grow. Understanding and quantifying the primary weather components that produce elevated local and regional fire weather will be valuable in anticipating and mitigating these risks.

Extensive study on extreme fire weather in southern California has focused on Santa Ana winds (hereafter SAW) that have contributed to many massive conflagrations (Raphael 2003; Hughes and Hall 2010; Moritz et al. 2010; Abatzoglou et al. 2013; Guzman-Morales et al. 2016). SAW conditions result from the development of a strong pressure gradient produced in response to a thermal gradient between the cold, inland deserts and warmer maritime airmass (Hughes and Hall 2010). This thermally-driven pressure gradient creates strong northeasterly winds and gravity wave-forced downward momentum transfer that yields regional downslope warming and low relative humidity. Despite the high impact of fires in the Santa Ynez Mountains on urban communities (i.e., WUI; Martinuzzi et al. 2015) and agricultural operations, little research has focused on the smaller-scale Sundowner winds and is limited to case studies (Blier 1998; Cannon et al. 2017). These studies indicate that different atmospheric processes are involved in Sundowner events compared to classic SAW events. However, these few case studies limit generalizing their results in a climatological sense and to our knowledge no studies have yet attempted to compare how Sundowner winds to SAWs.

Here we use observational data and atmospheric reanalysis products to produce a climatology of Sundowner winds in an effort to broaden the understanding of when and under what synoptic conditions Sundowner winds occur and to relate them to the well-studied SAWs. We hypothesize that Sundowner events are seasonally distinct from SAWs and have differing synoptic scale patterns associated with them. Identifying the nuances that differentiate Sundowners from SAWs may provide additional insight to fire weather forecasts and in understanding weather-fire-climate interactions (Mensing et al. 1999; Moritz et al. 2010; Williams and Abatzoglou 2016) in California's Transverse Ranges.

2 Data and Methods

To develop a climatology of Sundowner winds, we acquired quality-controlled hourly air temperatures, wind speed and direction, and dewpoint temperature at the Santa Barbara airport (KSBA; Figure 1d) from the National Center for Environmental Information (https://www.ncdc.noaa.gov/data-access/land-based-station-data) from 1 January 1979 to 31 December 2014. Downslope adiabatic warming of air parcels produces an abrupt increase in temperature in the coastal plain region, so we use hourly temperature ramps (increases) observed outside of the normal diurnal temperature cycle at KSBA as a proxy for Sundowner wind events (Figure 1e-g). Monthly mean diurnal heating cycles were calculated using KSBA data over the period of record. Days where temperature was observed to rise during the period where cooling normally occurred

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(typically 4PM LST to 7AM LST) were classified as a temperature ramp event. From this definition, we selected only the strong events, or those in the top 0.5% of the identified dates to be included as potential Sundowner events (n = 286 days). The use of the top 0.5% of events allowed us to focus on the atmospheric dynamics characterizing the strongest events. These events had a temperature ramp of at least 3.9 °C; this value provided confidence that observed heating was due to downslope warming and not merely due to advection of the marine boundary layer away from KSBA (Cayan and Iacobellis 2013).

The hourly SAW index used for comparison against our Sundowner climatology was developed for southern California by Guzman-Morales et al. (2016) using output from a dynamically downscaled regional climate model. To identify SAW-only days from the Guzman-Morales et al. (2016) SAW index, we selected dates satisfying the top 2% of SAW events (based on the median hourly SAW index for each day in the SAW index dataset; n = 248 days) that did not coincide with dates identified as potential Sundowners. For coinciding Sundowner and SAW days (hereafter Sundowner+SAW), we selected dates within the top 0.5% of Sundowner events and also required six hours of SAW index greater than zero (n = 215 days).

Output from the North American Regional Reanalysis (NARR; Mesinger et al. 2006) was used for composite analysis. Three-hourly, 32 km horizontal resolution mean sea level pressure (MSLP) and 500 hPa geopotential heights during each of the three regimes were averaged by peak seasons of identified Sundowner (April-May) and Santa Ana (December-January) regimes in order to separate out seasonal variability in geopotential heights and MSLP. Anomalies of MSLP and 500 hPa heights were calculated as differences from the 1981-2010 long-term means. To increase confidence that our temperature ramp identification technique selected favorable fire conditions (i.e., stronger wind and lower relative humidity compared to average conditions), we compared cumulative distributions of wind speed and relative humidity for all hours during peak Sundowner and Santa Ana months against the distribution of identified events for each five-hour period beginning with the temperature ramp hour. The August-Roche-Magnus approximation was used to calculate relative humidity at KSBA from observed temperature and dewpoint. In this evaluation, we also included an assessment of hourly wind speed and relative humidity values from 1 October 1997 to 31 December 2014 from the Montecito Remote Automated Weather Station (RAWS) located in the Santa Ynez foothills to the northeast of KSBA. Montecito RAWS data was acquired from the Western Regional Climate Center (http://www.wrcc.dri.edu/raws).

3 Results and Discussion

We find that Sundowner-only conditions peaked during spring and early summer with less frequent occurrences during fall and early winter (Figure 1h). Sundowner+SAW events primarily occur during the cool season (October-February) with a secondary April peak (Figure 1i). SAW-only frequency maximizes during the late fall and winter season (Figure 1j; Raphael 2003; Abatzoglou et al. 2013; Guzman-Morales et al. 2016) with SAWs being notably less frequent during spring and nearly

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absent in summer (Figure 1j). The spring and early summer peaks in Sundowner-only occurrence (Figure 1h) are consistent with many notable fires that have occurred in Santa Barbara (Figure 1d; Cannon et al. 2017). Not all notable fires, including the Jesusita fire (Figure 1c), occurred during strong Sundowner or SAW events as we have defined them. The climate and fuel loading of the Santa Ynez creates an environment where damaging fires can occur under weaker Sundowner wind regimes should ignition occur. During both the Sundowner and Santa Ana peak seasons, the relative humidity during potential Sundowner events is lower by 20-40% at KSBA (Figure 2a) with winds that are between 2 and 4 m s^{-1} stronger (Figure 3b) than non-Sundowner days. Results from the Montecito RAWS station (Figure 2c-d) are consistent with the KSBA results with Sundowner days indicating reduced relative humidity and increased wind speed compared to all days for a given season. At both stations, springtime Sundowners demonstrated lower relative humidity and stronger winds compared to winter. One might expect the broad increases in spring and early summer fire hazard associated with these conditions to be magnified during years characterized by drier late winters that allow anomalously early fuel curing.

Composite analysis of NARR output during Sundowner-only days, SAW+Sundowner days, SAW-only days for the months during the respective peaks of each wind regime (November-February (winter) for SAW and March-June (spring) for Sundowner) indicates that regardless of peak season, Sundowner-only events are unique from either SAW and SAW+Sundowner events at the synoptic scale. During both winter and spring Sundowner-only events, the 500 hPa ridge axis is more zonally elongated (Figure 3a,d) compared to the other regimes (Figures 3b,c,e,f). During SAW or Sundowner+SAW cases, the 500 hPa geopotential heights become meridionally amplified and positively tilted from the southwest to the northeast over western North America with substantial positive anomalies centered near 40°N, 130°W (Figures 3b,c,e). This pattern is very similar to the 700 hPa anomalies shown by Hughes and Hall (2010) and promotes cold air advection from the interior western U.S. towards California (Abatzoglou et al. 2013) during strong SAW regimes (Figures 3c,f). The deeper troughs in the Gulf of Alaska and over Manitoba during SAW conditions indicates amplified flow regimes compared to the Sundowner-only regime. The Sundowner+SAW composites, while similar to the SAW pattern, are less amplified and less positively tilted compared to the SAW-only composites. The similarity in 500 hPa geopotential height patterns between the two SAW regimes supports the hypothesis that coinciding SAW and Sundowner events are dynamically linked. This linkage likely results from the large-scale thermal gradient and momentum fluxes resulting from the amplified ridging that produces broad offshore flow and downslope warming throughout southern California (Hughes and Hall 2010). The lack of highly amplified flow during Sundowner-only events suggests that these events are synoptically distinct from the conditions characterizing SAWs.

Mean sea level pressure (MSLP) fields and their anomalies are consistent with the differences between Sundowner and SAW wind regimes. During Sundowner-only events, the maximum MSLP region (> 1020 hPa) is offshore (Figures 3g,h) with small (>3 hPa) positive offshore anomalies and moderate negative onshore anomalies, especially in winter (Figure 3g). The Sundowner+SAW composites show an expansion of the eastern edge of the 1020 hPa area towards the northeast with a

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corresponding enhancement in positive offshore MSLP anomalies extending into the Pacific Northwest (Figures 3b,e). During SAW-only events, the 1020 hPa region extends into and across western North America with a 1030 hPa maximum over the northern intermountain west region (Figures 3i,l). Although offshore positive MSLP anomalies exist, the maximum anomalies exceeding 10 hPa shift to the northern Great Basin and Intermountain West regions (Figures 3i,l). A tighter east-west MSLP gradients exists west of the Santa Barbara region during Sundowner and SAW+Sundowner events compared to SAW only events. This MSLP gradient likely contributes to the northerly winds that blow perpendicular and downslope across the east-west trending Santa Ynez and other Transverse Ranges (Figure 1d) and lead to localized increases in fire weather conditions via decreased relative humidity and increased wind (Figures 1e,f and 2). As the regimes evolve from the Sundowner-only to SAW-only, a progression in amplification and positive tilt of the 700 hPa heights is observed with an extension of 1020 hPa MSLP contours extending further inland and a deepening trough in the Gulf of Alaska. While our composite analysis clearly indicates differences between Sundowner and SAW regimes, the weak MSLP anomalies and more zonal 500 hPa flow during Sundowners does not provide a compelling mechanism for their origin. This is consistent with the findings of Cannon et al. (2017) and suggests the important role of mesoscale forcing between low level wind and terrain. The 32 km horizontal resolution of NARR precludes a finer-scale analysis of how coastal winds and topography interact to produce Sundowners and is the subject of continuing research using a 10 year, 2 km horizontal resolution downscaled climatology produced with a numerical weather prediction model.

Our findings demonstrate different synoptic regimes associated with Sundowner and SAW-like conditions and suggest that uncritically attributing all large fires to SAWs (e.g., Mensing et al. 1999), especially in the absence of meteorological data, might be an oversimplification. Similarly, lumping southern California fires that occur outside of the peak SAW season as onshore flow events (Jin et al. 2014) may miss the localized importance of offshore flow in the Santa Ynez that produces downslope growth of fires. Ongoing work seeks to evaluate meteorological conditions associated with historical large fire and warm season fire occurrence in the Santa Ynez to identify the frequencies of specific wind regimes associated with these fires. Further investigation using mechanistic fire models driven by fine scale (>5 km) weather inputs (e.g., Peterson et al. 2011) will help clarify historical relationships and constrain the range of possible future shifts in fire frequencies under varying scenarios of future land use change such as population growth, shifts in ecosystems in response to disturbance and climate, and climate itself. We postulate that for the Santa Ynez region, similar findings would occur for Sundowner events as Peterson et al. (2011) found for SAW events, i.e., Sundowner intensity should also explain variance in modeled fire size and likely fire growth rate given broad similarity in fuels, terrain, and climate.

4 Summary

We defined Sundowner events as observed Santa Barbara airport temperature ramps that occurred outside of the normal diurnal cycle under the assumption that these ramps were driven by adiabatic descent of air parcels over the Santa Ynez Mountains. During the most extreme (top 0.5%) of identified temperature ramps, reduced relative humidity and increased winds were observed in the foothills and at the coastal plain, thus supporting the validity of this assumption. These identified days were compared against an existing index of Santa Ana wind (SAW) regimes to evaluate potential differences between these two wind regimes. We found that Sundowners occur most frequently during late spring and have a secondary maximum during winter that is often associated with SAWs. During either season, SAW regimes have distinctly different large scale conditions compared to Sundowner-only conditions, with Sundowner-only conditions being absent of the amplified geopotential heights and enhanced inland anomalous MSLP found during SAW regimes. Our results indicate that Sundowner winds, particularly during spring, are a unique mesoscale phenomenon to the Santa Barbara region as previously suggested by Blier (1998) and Cannon et al. (2017). Continuing work seeks to understand more precisely how Sundowner winds are produced and to provide more detailed information regarding their local variability across the Santa Ynez Mountains. Such information could improve spot weather forecasts (Nauslar et al. 2016), evaluating future fire-weather-climate interactions, and aid mitigating fire hazard in the Transverse Ranges.

5 Code Availability

The MATLAB code used in this study will be made available upon request to the corresponding author BH.

6 Data Availability

All data has been properly cited in the text and is publically available.

7 Author Contributions

CS designed the temperature ramp identification technique, BH wrote all code, performed the analysis, and prepared the manuscript with contributions from all co-authors.

8 Competing Interests

The authors declare that they have no conflict of interest.

9 Acknowledgements

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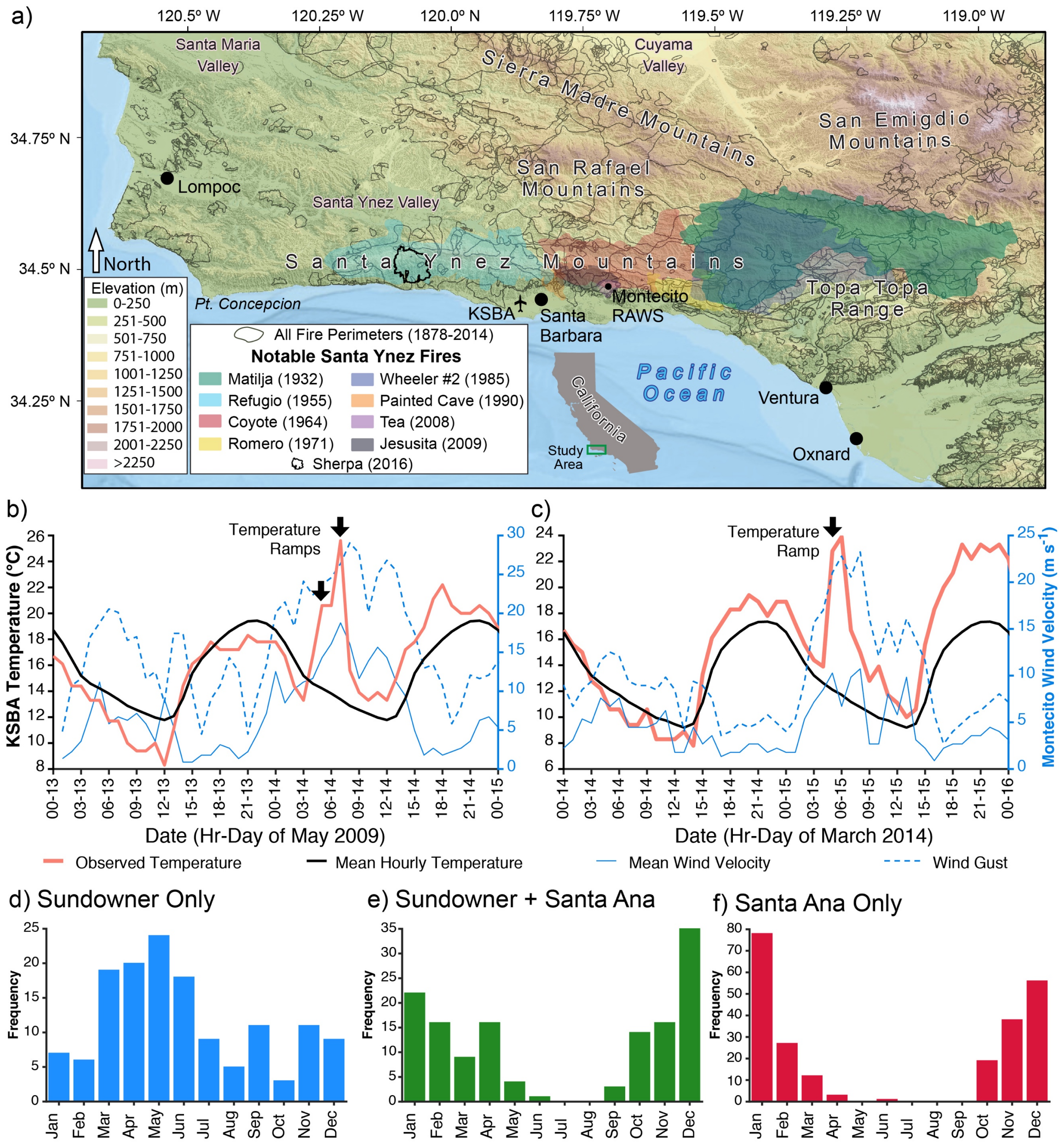

Figure 1: (a) Map of study area. Notable fire perimeters with impact to urban communities and agricultural operations are colored. The Santa Barbara Airport (KSBA) weather station was used to estimate temperature ramps produced by Sundowner wind events and the Montecito RAWs was used to evaluate winds during Sundowner conditions. (b-c) Examples of two characteristic temperature increases

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(‘temperature ramps’) that occur outside of the month-averaged diurnal heating cycle (black line). The right y-axis shows temperature at KSBA with the left y-axis Montecito RAWs wind speed and gust velocity. (d-f) Monthly frequencies of top 0.5% Sundowner-only events (h), top 0.5% of Sundowner events and any 6-hour period of Santa Ana winds (i) events (Sundowner+SAW in the text), and top 2% Santa Ana only (SAW in the text) events (j). Note differing y-axis scales.

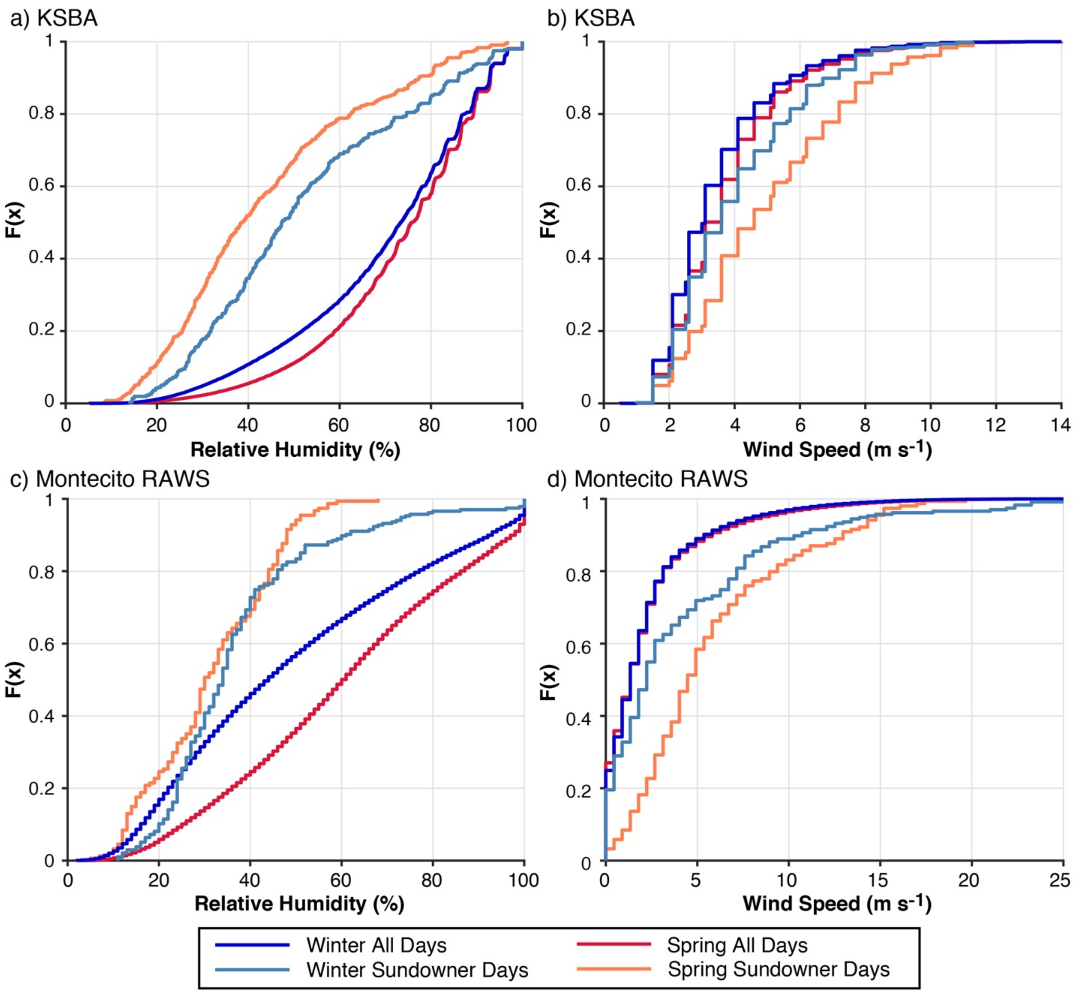

Figure 2: (a) Cumulative distributions of relative humidity at KSBA during the extended spring (March-June) Sundowner maxima and extended winter (November-February) Santa Ana maxima. (b) Cumulative distributions of wind speed at KSBA. (c-d) As in (a-b) but for the Montecito RAWS. (d) Distributions are created from either all hours or for the five hours following each identified possible top 0.5% Sundowner event during the respective peak seasons (see Figure 1d-f).

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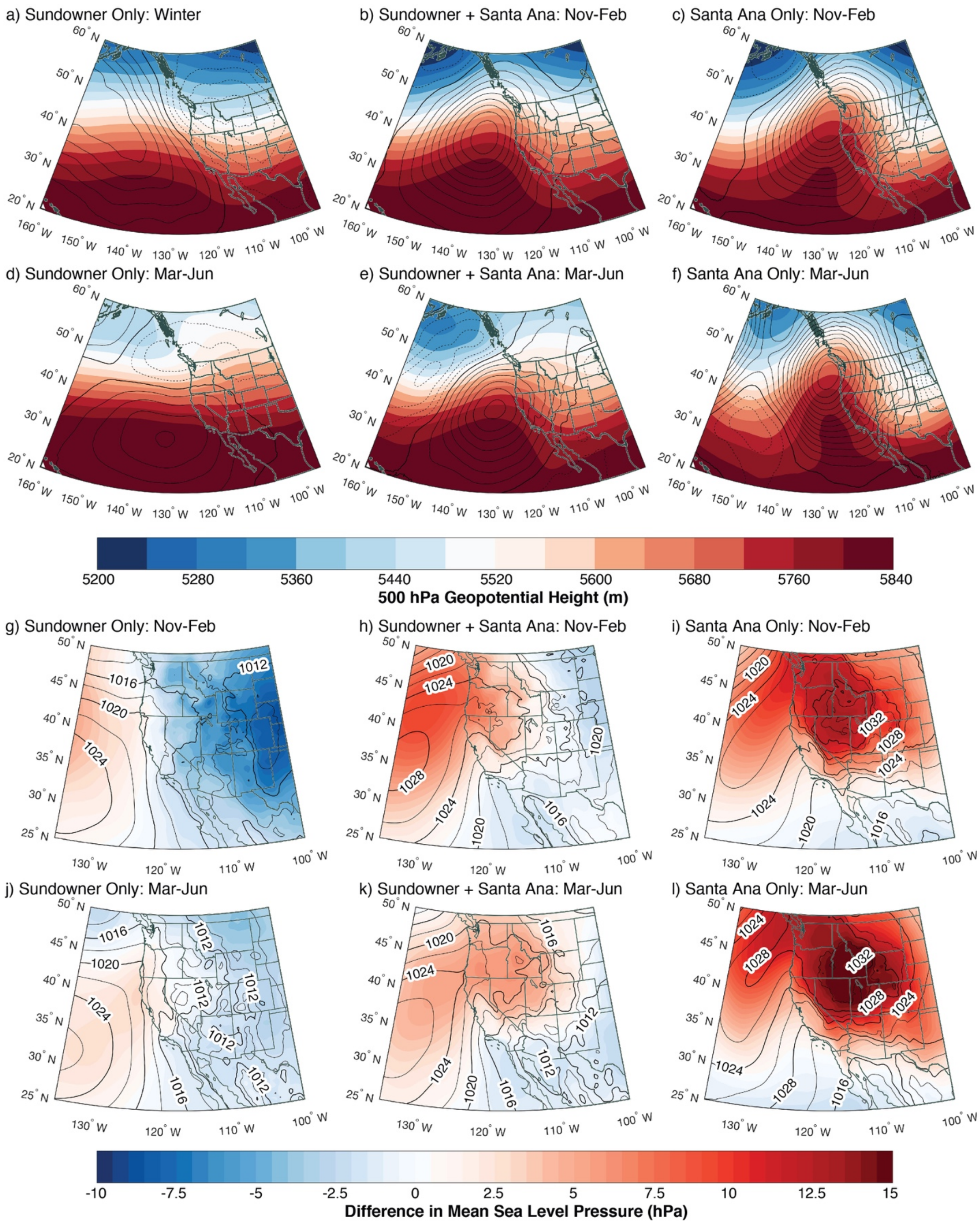

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Figure 3: (a-f) Composite North American Regional Reanalysis 500 hPa geopotential heights (filled contours) and geopotential height anomalies calculated as differences from the 1981-2010 long-term means (negative values are dashed; contour interval 10 m). (g-l) Mean sea level pressure anomalies calculated as differences from the 1981-2010 long-term means (filled contours). Contour lines show mean sea level pressure (contour interval 2 hPa; thick lines show 4 hPa).