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Research Note

Characteristics of Diablo-like Wind conditions in Northern California Based on a Climatology from Surface Observations

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Abstract: Diablo winds are dry and gusty north-northeasterly downslope windstorms that affect the Northern California. On the evening of October 8, 2017, Diablo winds contributed to the ignitions and rapid spread of the "Northern California Firestorm", including the Tubbs Fire, which burned 2,800 homes in Santa Rosa, resulted in 22 fatalities and $1.2B USD in damages. We analyzed 18 years of data from a network of surface meteorological stations and show that Diablo winds tend to occur overnight through early morning in Fall, Winter and Spring. Conditions similar to Diablo winds occur commonly in the Sierra Nevada Mountains in addition to the area North of the San Francisco Bay Area including the Northern Coastal Ranges. Diablo winds are characterized by high wind speeds and low relative humidity, but they tend to neither be warmer than climatology nor do they have a higher gust factor, or ratio of wind gusts to mean wind speeds, than climatology.

Keywords: Diablo winds; downslope windstorms; Northern California, wildfire meteorology

1. Introduction

The Northern California Firestorm of October 2017 consisted of over 250 separate wildfires that burned over 245,000 acres (99,000 ha) in Napa, Lake, Sonoma, Mendocino, Butte and Solano counties during dry and windy conditions that followed an anomalously hot and dry summer. In Napa and Sonoma county, the Tubbs Fire alone grew to become the most destructive wildfire in California history. In total, these fires caused over $9 billion in damages, left 350,000 people without power, destroyed 8,900 buildings and resulted in 44 fatalities. Downslope winds locally known as "Diablo winds" promoted rapid spread of many wildfires on the evening of October 8 and morning of October 9. At the Hawkeye remote automated weather station (RAWS), wind speeds of 22 ms^{-1} (50 mph) coincided with relative humidity below 15% near midnight. The Tubbs fire was ignited on the evening of October 8 and the fire front moved over 12 miles in its first three hours. It burned over 25,000 acres in its first day and ultimately burned over 2,800 structures in the city of Santa Rosa, California.

Despite the massive destruction wrought by the Diablo winds associated with the Northern California Firestorm of October 2017 and the Oakland Hills Fire of 1991, very little is known quantitatively about Diablo winds, especially relative to Southern California downslope winds that favor wildfires such as Santa Anas ([1-10]) and Sundowners ([11-15]). Some analysis on Diablo winds was presciently performed prior to (16) and subsequent to (17, 18, and 19) the Oakland Hills Fire of 1991. By 1993, the definition of Diablo winds that existed in the peer reviewed literature (18) was attributed to personal communication with a National Weather Service forecaster by the name of John Quadros. At this time and going forward, colloquial usage by National Weather Service is that Diablo winds generally refer to Bay area in general (Jan Null, personal communication), however, no peer reviewed literature has shown that Diablo winds (or conditions similar) do or do not exist outside of the area affected by Oakland Hills Fire of 1991. After the Northern California firestorm of October 2017, it's commonly accepted that Diablo winds affect the area North of the Bay

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Area as well, so there is a precedent for redefining the phenomena based on observations, and virtually no RAWS stations existed in the Bay Area or Sierra Nevada prior to the late 1990's. The first clear reference to Diablo winds labeled them as 'Santa Ana weather types' and noted that they are dry and warm due to their origination from the Great Basin and adiabatic compression through descent over the western slopes of the Sierra Nevada (16). The origination of Diablo winds from the high deserts of Nevada was further confirmed by Null and Mogil (20), and reinforced by a US Fire Administration technical note on the Oakland Hills Fire which stated that Diablo winds are a "strong wind of exceptionally dry air, blowing through the mountain passes and spilling over the coastal hills toward the Pacific Ocean." Taken together, the historical literature on Diablo winds (or conditions similar) strongly suggests their simultaneous occurrence in East Bay Area, North of the Bay Area, and the Sierra Nevada mountains, and notwithstanding semantics around colloquial usage, does not suggest nor support any rigorous and quantitative criteria to circumscribe their occurrence to any one of those locations and not the others.

Here, we provide an analysis of existing surface observations in order to better understand and provide some basic information about Diablo winds: where and when Diablo winds tend to occur and how warm, dry and windy they tend to be.

2. Materials and Methods

We used publicly available surface meteorological station RAWS data downloaded from MesoWest for the period spanning January 1, 1999 through January 1, 2018. We divided our area of interest into one section centered on the area North of the San Francisco Bay Area (NoBA) including the Northern Coastal range and another centered on the Sierra Nevada (SN) to the East (Figure 1). We specifically excluded from our analysis multiple areas in which conditions similar or equivalent to Diablo winds may or do occur, including the East Bay Area and Southern Sierra Nevada. The stations we selected (Table 01) were based on a propensity for Diablo wind event occurrence, and we specifically excluded stations with very low event occurrence including all of the ASOS network and the North of Bay Area stations of Santa Rosa, Hopland and Highglade, and Sierra Nevada stations of Mount Elizabeth, Bald Mountain, and Banner Road. Jarbo Gap was excluded due to funneling of flow along the Feather River flow. We excluded RAWS stations with period of record less than 15 years. All other RAWS stations were included in this analysis.

RAWS stations report variables as 10 minute averages near their specified GOES transmission time, with wind speed gust defined as the highest 3 seconds average wind speeds during the previous hours, and these observations for each station were mapped to their nearest hour such that our results have a temporal fidelity of not less than 29 minutes in either direction. From this we computed hourly averages of wind speed (ws), wind speed gust (wsg), wind direction (wd), relative humidity (RH) and temperature (T) for each time across all stations for each area of interest and performed analysis on averages of those variables computed across all stations in each area (NoBA and SN). Our primary interest was in determining variability of Diablo winds between the area North of the Bay area versus the Sierra Nevada, and not in determining inter-station variability in each area.

Example time series of station average wind speed and relative humidity of two Diablo events are shown for the November 22, 2013 event and the October 9, 2017 event (Figure 2). While both of these events show a short period of large wind speeds with rapid onset and decay, many other events lasted multiple days, often with a decay in the magnitude of the wind speeds during the day and increases in wind speeds overnight. The November 22, 2013 event exhibited a massive multi-day secular decrease in the relative humidity. This pattern was seen in multiple events, sometime superimposed on moderate relative humidity recoveries according to a typical diurnal pattern.

Our criteria for finding Diablo wind events on an hourly basis per station consisted of the following:

- wind speeds greater than 11.17 ms^{-1} (25 mph)
- wind direction between 315^o and 135^o
- relative humidity below 30%
- the above conditions satisfied for three or more consecutive hours

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Conditions meeting the above criteria at any station in an area were considered a Diablo wind event for that area on an hourly basis (hourly hit per station). Diablo wind event days on a per station basis were defined as any hourly hit per station in any given hour of that day (daily hits per station). Hourly and daily hits on a per station basis were also aggregated to a per area basis, in which any single station experiencing a hit on an hourly basis was defined as an hourly hit for the area that that station is located in (hourly hits per area), and any single station experiencing a hit on a daily basis was defined as a hit for the area that that station is located in (daily hits per area).

Table 2 lists a few select events which were further ranked by wind speed and wind speed gust magnitude at Duncan and Knoxville Creek. We verified that our conclusions are robust to different values of minimum wind speed, relative humidity, consecutive hours and number of stations simultaneously meeting the criteria. Example plots showing hit criteria and all available hourly wind speed and wind direction observations for Duncan and Knoxville Creek RAWS are shown in Figure 3. This figure also shows wind direction and wind speed criteria for hit events, and observations which meet both of those criteria but are not shown as hits did not also meet the maximum relative humidity criteria, which is otherwise not shown in Figure 3.

We computed mean gust factor (*gf*), defined as wind speed gust divided by wind speed, as a function of wind speed for Diablo hit days and non-hit days. Also, in order to understand how hot, dry and windy Diablo events are, we also computed anomalies to climatology (i.e., observations minus the long-term average) for each Diablo event on a per station basis. In this calculation, on a per station basis and for each daily hit per station, the minimum and maximum daily wind speed, temperature was compared to a climatology calculated from the long term average minimum and maximum values for that station and each Julian day corresponding to a hit.

Table 1. Station name, period of record, longitude, latitude and elevation.

Station name	POR (yrs)	Longitude	Latitude	Elevation [m]	Area
Duncan	16.5	-120.509	39.144	2164	SN
Cottage	15.3	-120.230	38.346	1848	SN
Mendocino Pass	16.8	-122.945	39.807	1640	NoBA
Saddleback	16.8	-120.865	39.638	2033	SN
Knoxville Creek	18.4	-122.417	38.862	671	NoBA
Hell Hole	18.4	-120.420	39.070	1597	SN
Hawkeye	18.4	-122.837	38.735	617	NoBA
Lyons Valley	18.4	-123.073	39.126	1023	NoBA
County Line	18.4	-122.412	39.019	636	NoBA
Eagle Peak	17.1	-122.642	39.927	1132	NoBA
Pike County Lookout	18.4	-121.202	39.475	1128	SN

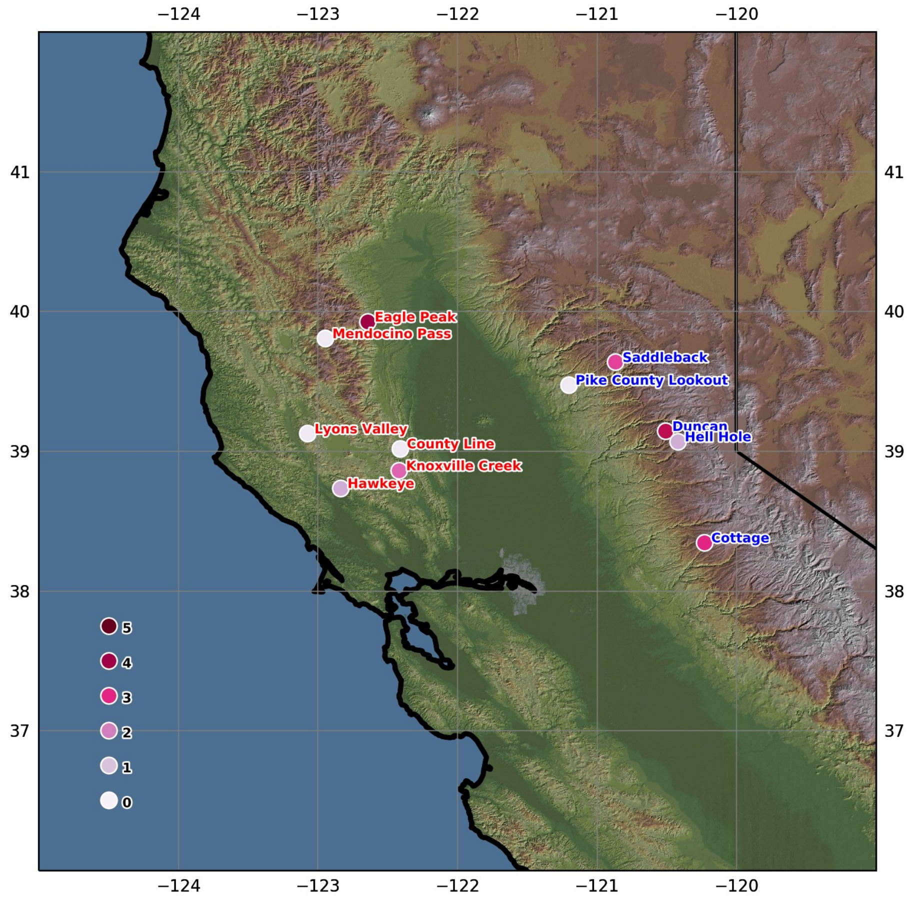

Figure 1. Study area map including stations considered. Stations are colored according to their frequency of Diablo wind event days per year as per the legend. Station name colors correspond to the area North of the Bay Area (NoBA) including the Northern Coastal Range (red) area and Sierra Nevada (SN) area (blue).

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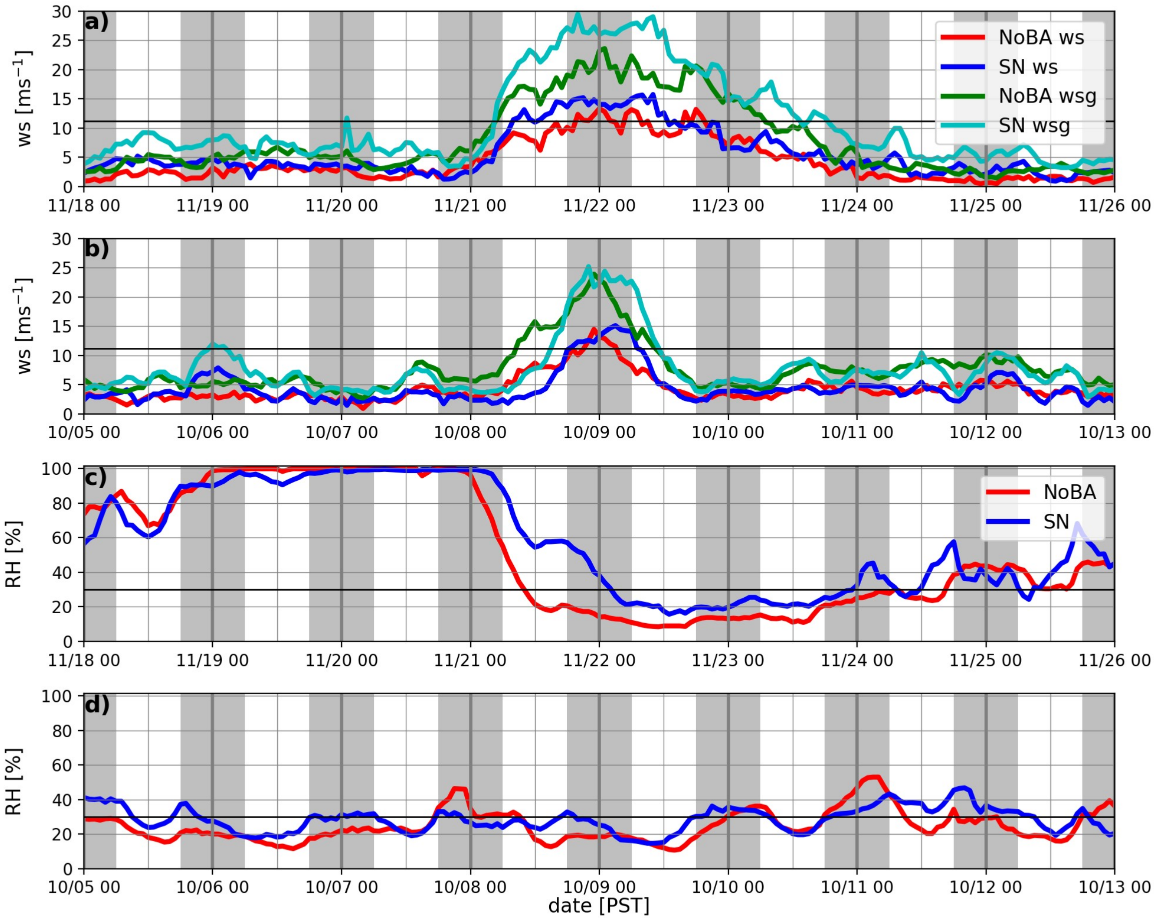

Figure 2. Station-wide average wind speed and wind speed gust (a) and (b) and relative humidity (c) and (d) for North of Bay area (NoBA) and Sierra Nevada (SN) areas during the 11/22/2013 (a) and (c) and 10/09/2017 (b) and (d) Diablo wind event.

Table 2. Select list of strongest events by wind speed and wind speed gust magnitudes at Duncan and Knoxville Creek matching the Diablo event criteria.

Date	Duncan ws_{max}/wsg_{max} [ms^{-1}]	Knoxville Creek ws_{max}/wsg_{max}[ms^{-1}]
2002-02-28	09.8 / 15.6	17.9 / 27.3
2002-03-01	13.4 / 25.0	14.3 / 29.5
2004-10-11	20.1 / 26.8	13.4 / 22.8
2006-12-28	15.2 / 19.7	17.0 / 26.4
2009-01-09	- / -	18.3 / 27.7
2011-12-01	18.8 / 36.7	12.5 / 20.1
2011-12-16	24.6 / 35.3	12.5 / 20.1
2013-11-22	25.9 / 40.7	15.6 / 26.4
2017-10-09	18.8 / 27.3	16.1 / 28.2

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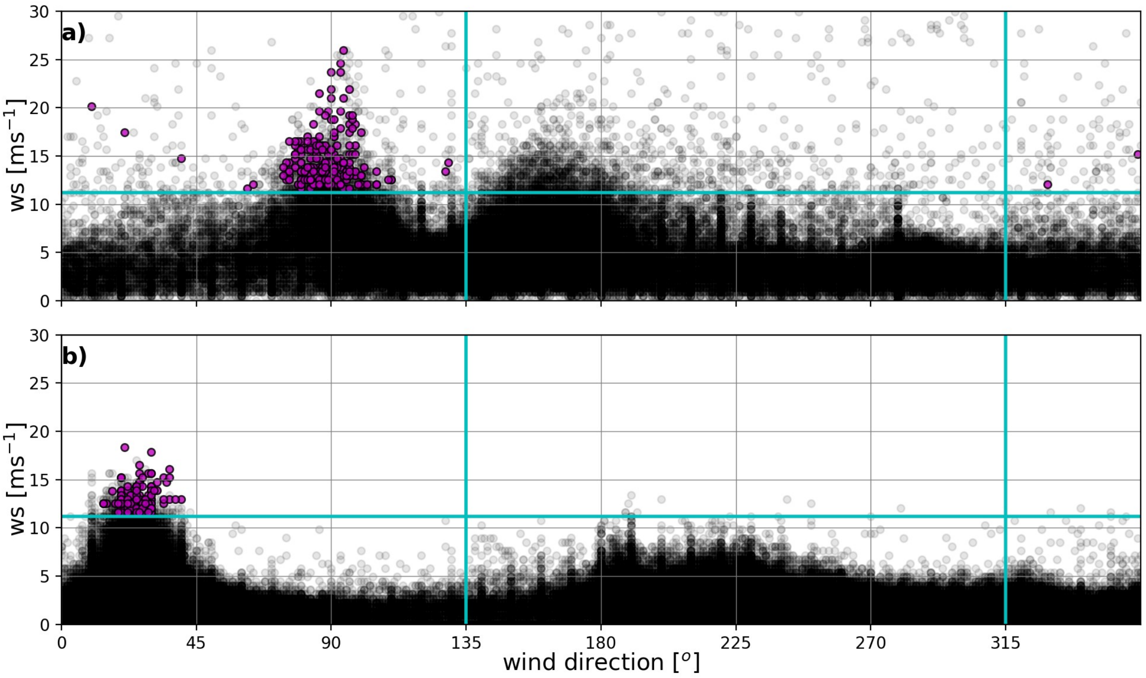

Figure 3. Scatter plot of wind speed versus wind direction for all available hourly observations at Duncan Canyon (a) and Knoxville Creek (b). Conditions satisfying the Diablo wind criteria of wind speed, wind direction and relative humidity are shown in magenta. Cyan lines correspond to wind direction and wind speed criteria for Diablo event.

3. Results

The average number of daily hits per station per year meeting the Diablo wind criteria is shown as a function of station elevation in Figure 4a, and in the map in Figure 1. The large difference in event occurrence at the somewhat closely located stations Mendocino Pass and Eagle Peak suggests that station micro-siting issues cannot be fully excluded from our analysis, and since Eagle Peak experiences a high event count due to North-northeasterly events, we verified that our results are similar if we excluded Eagle Peak from the analysis. Hourly hits per area averaged as a function of hour of day is shown in Figure 4b and daily hits per area averaged as a function of month of year is shown in Figure 4c. Diablo wind events tend to occur overnight through early morning during Fall, Winter and Spring. During those months, they occur at a frequency roughly of one event per two months. They are very uncommon during summer. Our results are consistent with a previous analysis (16). The results show a very similar pattern for the Sierra Nevada stations as the North of Bay Area stations. The Sierra Nevada stations appear to suggest a relationship between Diablo events and station elevation while the North of Bay area stations do not.

The departures from the Julian day climatology on a per station basis shows that Diablo events tend to be very dry (Figure 5a) relative to climatology, with depressed daily minimum and maximum relative humidity. However, minimum and maximum daily temperatures are not elevated relative to climatology at all (Figure 5b), indicating that Diablo wind events are not anomalously warm. Daily maximum wind speeds and wind speed gusts are elevated relative to climatological averages (Figure 5c), and both the wind speed and wind speed gust are highly correlated to each other (Figure 5d).

The gust factor analysis (Figure 4d), in which mean gust factor is computed per wind speed bin for Diablo events and all non-Diablo events, shows that gust factor during Diablo wind events is not elevated relative to non-Diablo days. Although wind speed and wind speed gusts are both elevated during Diablo wind events, the gust factor is not, indicating no support for Diablo winds being gustier than other high wind events that affect these stations under other atmospheric conditions.

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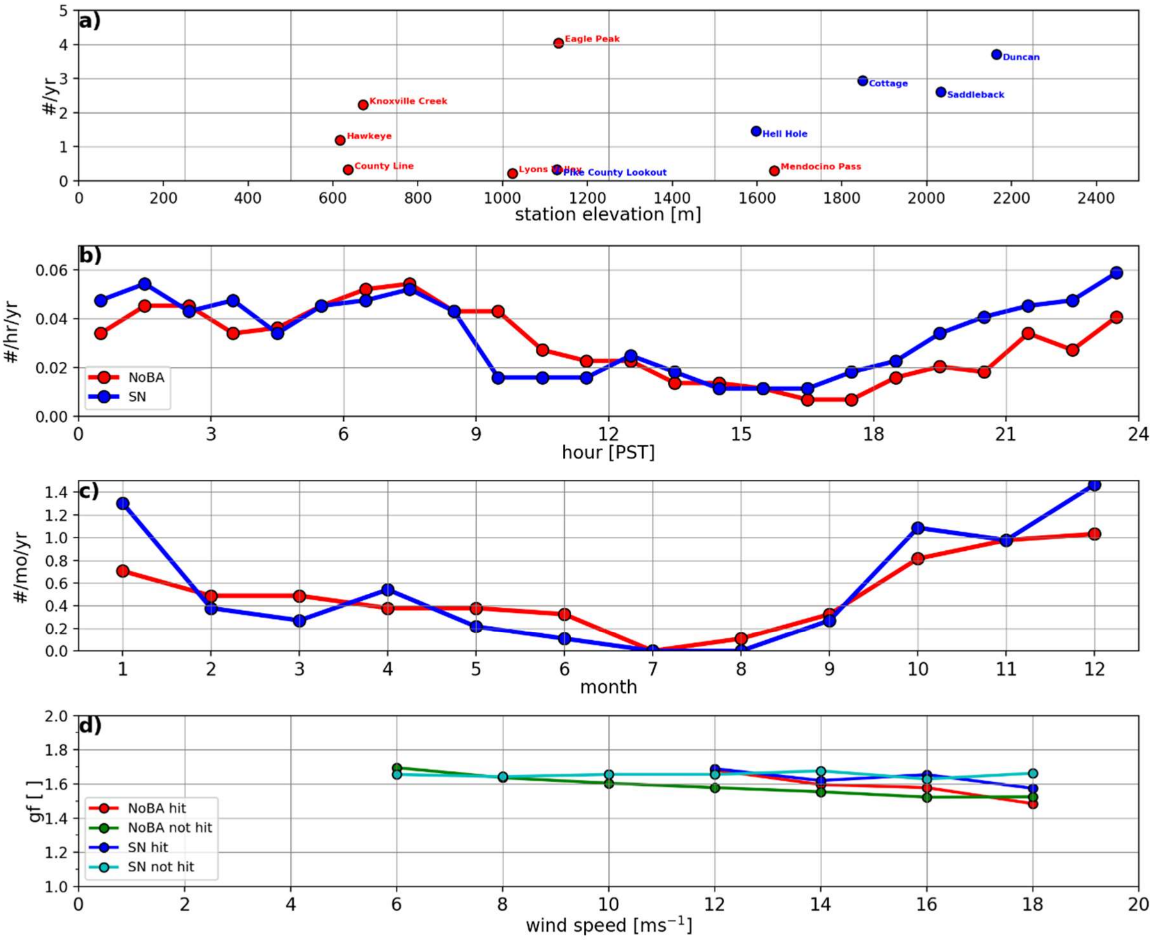

Figure 4. Average number of daily hits per station per year versus station elevation (a), average hourly hits per area as function of hour (b), average daily hits per area as a function of month of year (c) and area mean gust factor as a function of wind speed bin for Diablo and non-Diablo events (d).

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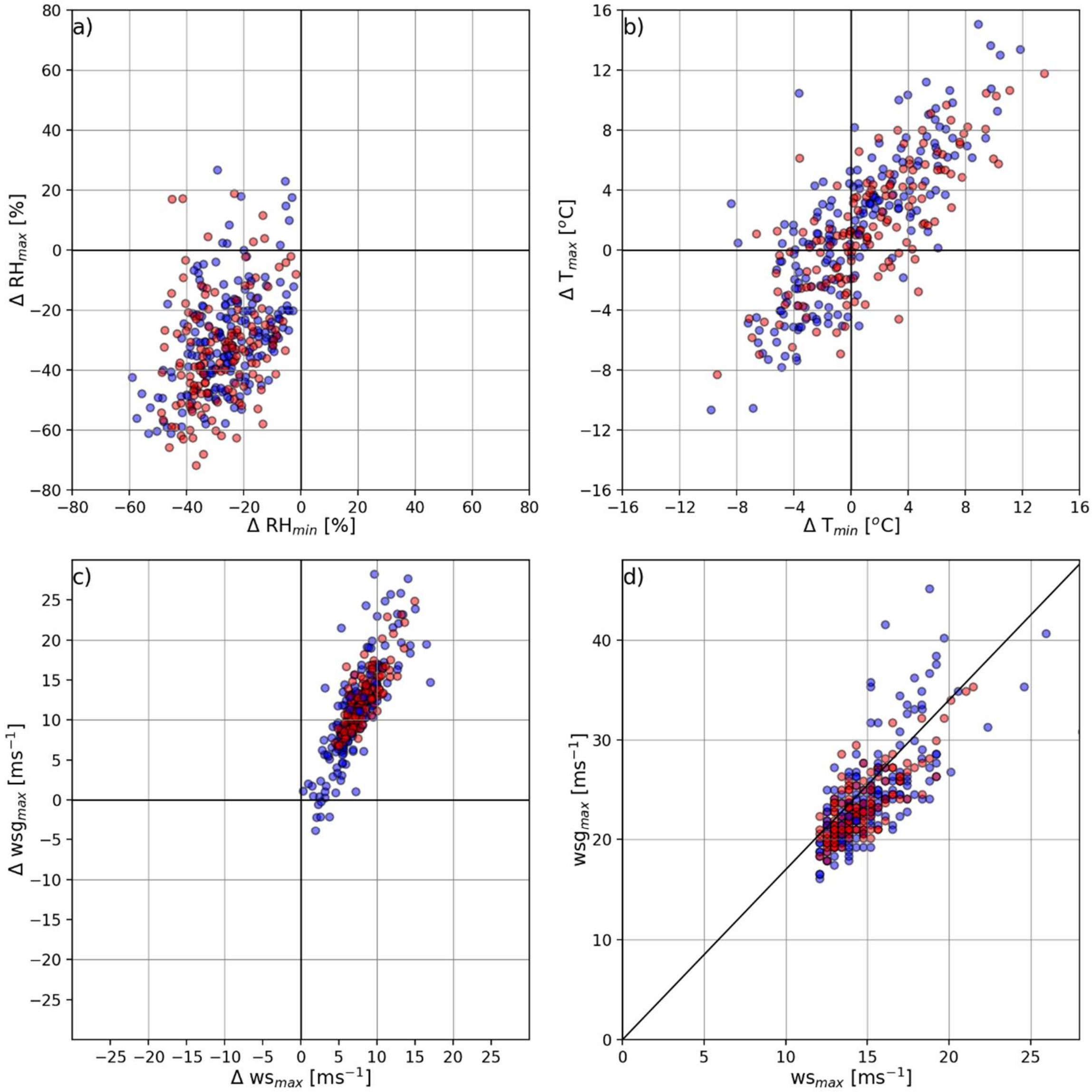

Figure 5. Diablo wind event departures from Julian day climatology on a per station basis for North of Bay Area (red) and Sierra Nevada (blue) area observations of daily minimum and maximum relative humidity (a), daily minimum and maximum temperature (b), daily maximum wind speed and wind speed gust (c). and daily maximum wind speed versus daily maximum wind speed gust (d) with a diagonal black line that corresponds to a gust factor slope of 1.7.

4. Discussion and conclusions

During the October 2017 Northern California Firestorm, Diablo winds were thrust to the forefront of the public consciousness and the broader wildfire meteorology community as a meteorological phenomenon about which little is known. Our analysis showed that Diablo winds tend to occur at night or in the early morning and are most common during the cool season (late fall through spring). This analysis indicates that during Diablo conditions, wildfire fighting resources may be required throughout Northern California including the Sierra Nevada Mountains when Diablo winds are forecast, though a limitation of our analysis is that we did not consider the Eastern Bay Area or the San Francisco Peninsula.

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Our analysis shows that conditions similar to Diablo winds are just as common in the Sierra Nevada as they are in the area North of the San Francisco Bay Area. This implies that they are a regional wind system of Northern California and not a Bay Area localized phenomenon. Associated numerical weather simulations (not shown) strongly suggest the linking of mountain wave breaking over the Sierra Nevada mountains to Diablo wind conditions North of the Bay Area, and we hypothesize that vertical profiles of wind speed and stability East of the Sierra Nevada play a primary role in determining the altitude at which the Sierra downslope jet is lofted off of the surface and hence the characteristics of Diablo winds North of the Bay Area.

Of the total number of Diablo wind conditions identified on a daily basis per area, 35% occurred North of the Bay area only, 41% occurred in the Sierra Nevada only, and 23% occurred in both areas. Based on this analysis, we neither claim support nor refute that Diablo wind conditions occur simultaneously in the Sierra Nevada and North of the Bay Area, nor that Diablo winds apply to the Bay Area only and not the Sierra Nevada. Clearly, further research is required and a long term downscaled numerical climatology could help address many issues posed by the sparse RAWS network used in this study.

Historical usage of the term Diablo winds was initially confined to the Oakland Hills, but has now grown to encompass the East Bay and area North of the Bay Area. Our analysis does not suggest that the term should also encompass the Sierra Nevada mountains since the term is partly defined through common usage and not just meteorological conditions. On the other hand, we also hesitate to suggest the alternative that conditions similar to Diablo winds in the Sierra Nevada should be called something else instead, such as 'Diablos del Sierra', or 'Bruja winds'.

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Conflicts of Interest: The authors declare no conflict of interest.

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