

Short Note

A Surface Observation Based Climatology of Diablo-Like Winds in California's Wine Country and Western Sierra Nevada

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Abstract: Diablo winds are dry and gusty north-northeasterly downslope windstorms that affect the San Francisco Bay Area in Northern California. On the evening of 8 October 2017, Diablo winds contributed to the ignitions and rapid spread of the “Northern California firestorm”, including the Tubbs Fire, which burned 2800 homes in Santa Rosa, resulting in 22 fatalities and \$1.2 B USD in damages. We analyzed 18 years of data from a network of surface meteorological stations and showed that Diablo winds tend to occur overnight through early morning in fall, winter and spring. In addition to the area north of the San Francisco Bay Area, conditions similar to Diablo winds commonly occur in the western Sierra Nevada. Both of these areas are characterized by high wind speeds and low relative humidity, but they neither tend to be warmer than climatology nor 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 total, these fires caused over \$9 billion in damages, left 350,000 people without power, destroyed 8900 buildings and resulted in 44 fatalities. Downslope winds, locally known as “Diablo winds,” promoted the rapid spread of many wildfires on the evening of 8 October and the morning of 9 October. At the Hawkeye remote automated weather station (RAWS), wind speeds of 22 ms^{-1} (50 mph) coincided with relative humidity below 15% around midnight. The Tubbs fire, which burned over 2800 homes and ultimately became the most destructive wildfire in California history, was ignited on the evening of 8 October, and the fire front travelled rapidly, covering over 12 miles (19 km) in its first three hours. It burned over 25,000 acres (10,111 ha) in its first day and ultimately burned over 5600 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 firestorm of 1991, very little is known quantitatively about them, especially relative to the Southern California downslope winds that favor wildfires, such as Santa Ana [1–10] and Sundowner [11–15] winds. A prescient preliminary analysis of ‘Santa Ana-like’ winds in the Oakland Hills was performed in 1973 [16], some 18 years prior to the Oakland Hills fire of 1991, and analyses [17–19] subsequent to that fire confirmed their localization at the eastern San Francisco Bay Area. Some time thereafter, colloquial usage of the term “Diablo winds”

by the National Weather Service expanded to include the Bay area in general (Jan Null, personal communication), in agreement with news stories on the October 2017 Northern California firestorm. These analyses found that Diablo winds originate from the high deserts of Nevada [20] and the Great Basin, and that they are dry and warm due to adiabatic compression through descent over the western slopes of the Sierra Nevada [16] and “blow through the mountain passes and spill over the coastal hills toward the Pacific Ocean” [21]. Taken together, the historical literature on Diablo winds in the eastern San Francisco Bay Area suggests a possible meso- to synoptic-scale linkage to similar conditions along the western slopes of the Sierra Nevada. Notwithstanding semantics around colloquial usage, there does not exist any peer-reviewed literature that objectively supports or refutes that linkage, circumscribes the occurrence of Diablo winds to one area of the San Francisco Bay Area versus another or the occurrence or absence of Diablo-like wind conditions along the western slope of the Sierra Nevada mountains.

Here, we provide an analysis of the RAWS station network in Northern California, which did not exist prior to the Oakland Hills fire of 1991, and in previous publications on Diablo winds in order to better understand, and provide some basic information about, Diablo winds. We evaluate where and when they tend to occur and how warm, dry and windy they tend to be. We also explore whether conditions similar to Diablo winds also occur along the western slopes of the Sierra Nevada.

2. Materials and Methods

We used available surface meteorological data from the RAWS network, which was acquired from MesoWest for the period spanning 1 January 1999 through 1 January 2018. We divided our area of interest into two sections of interest: One centered on the area north of the San Francisco Bay Area (NoBA), including the Northern Coast Range and another centered on the western Sierra Nevada (SN; Figure 1). We included stations in those areas with a period of record greater than 15 years, with the exception of the following stations, which exhibited very low Diablo-like wind condition occurrence: NoBA RAWS stations of Santa Rosa, Hopland and Highglade, SN RAWS stations of Mount Elizabeth, Bald Mountain, and Banner Road, and all of the Automated Surface Observing System (ASOS) network. Jarbo Gap was excluded due to channeling of flow down the Feather River canyon. The stations considered in our analysis are shown in Figure 1 and detailed in Table 1.

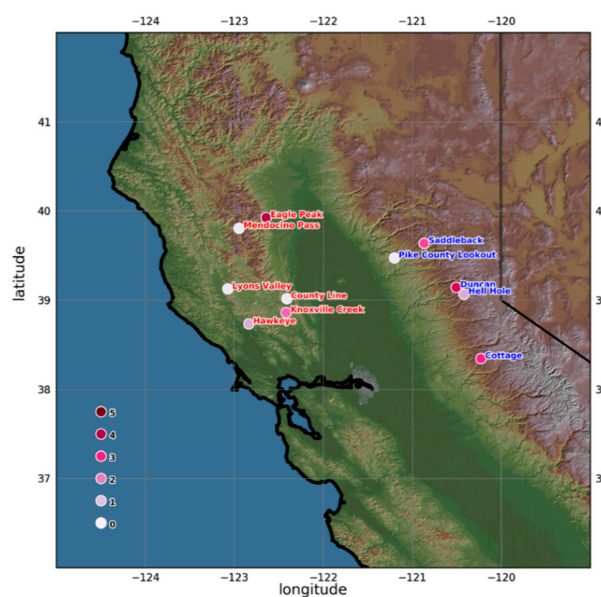


Figure 1. Study area map, including the stations considered. Stations are colored according to their frequency of Diablo-like event days per year. Station name colors correspond to the northern San Francisco Bay Area (NoBA) (red) and Sierra Nevada (blue) area.

Table 1. Station metadata, including name, period of record (POR), longitude, latitude, elevation and corresponding area.

Station Name	POR (Years)	Longitude (°W)	Latitude (°N)	Elevation (Meters)	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

RAWS stations report variables, such as wind speed, as 10 min averages at hourly intervals near their specified Geostationary Operational Environmental Satellite (GOES) transmission time and report wind speed gust as the maximum wind speed identified in the previous hour, such that the wind speed gust may be drawn from a sequence of observations that are not included in the reported wind speed values. Most RAWS station observation samples are taken at 5 s intervals (Greg McCurdy, personal communication). The observations for each station were mapped to their nearest hour, such that our results have a temporal fidelity of not less than 29 min 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 hour across all stations for each area of interest (NoBA and SN). The example time series of the station average wind speeds and relative humidity of two representative Diablo events are shown for the 22 November 2013 event and the 9 October 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 wind speeds during the day and increases in wind speeds overnight. The 22 November 2013 event exhibited a massive multi-day secular decrease in relative humidity. This pattern was seen in multiple events, sometimes superimposed on moderate relative humidity recoveries, according to a typical diurnal pattern. Both of these events show a relatively uniform degree of wind speed and relative humidity characteristics that help justify our usage of an area-wide average of stations. However, in other events, a significant amount of inter-station variability is present. Therefore, we do not attempt to address this in our analysis; instead, we focus on the variability between the North of the Bay and the Sierra Nevada areas.

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

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

Conditions meeting the above criteria at any station were considered Diablo-like events on an hourly per station basis. Diablo-like events on an hourly per area basis were defined as any single station in an area that meets the criteria. Diablo-like days on a per station basis were defined as any Diablo-like event on an hourly per station basis at any hour of a given day. Diablo-like days on a per area basis were defined as any single station in an area that meets the criteria at any hour of a given day.

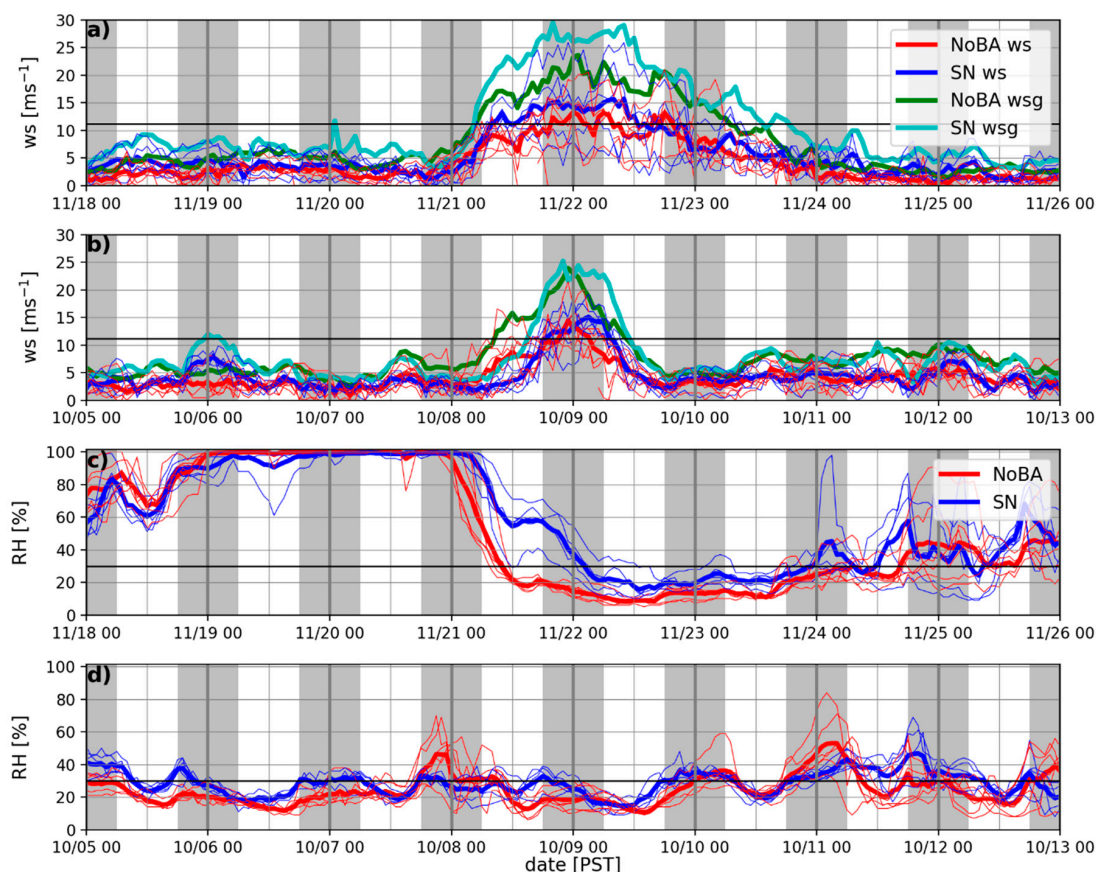


Figure 2. Station-wide average (thick lines) and individual stations (thin lines): Wind speed and wind speed gust (a,b) and relative humidity (c,d) for the north of Bay (NoBA) and western Sierra Nevada (SN) areas during the 22 November 2013 (a,c) and 9 October 2017 (b,d) Diablo-like wind events. The horizontal dark gray lines correspond to the minimum wind speed (a,b) and maximum relative humidity (c,d) criteria for Diablo-like events.

Several select Diablo-like events, ranked by wind speed and wind speed gust magnitude, at Duncan and Knoxville Creek are presented in Table 2. We verified that our findings are robust with respect to different values of minimum wind speed, relative humidity, consecutive hours and number of stations, simultaneously meeting the criteria. Example plots, showing all available hourly wind speed and wind direction observations for the Duncan and Knoxville Creek RAWs, along with our wind speed and wind direction criteria, are shown in Figure 3. We computed the mean gust factor (gf), defined as wind speed gust divided by wind speed, as a function of wind speed, for all observations. In order to characterize how hot, dry, and windy Diablo-like days are compared to climatology, we also computed anomalies for each Diablo-like day. In this calculation, the minimum and maximum daily wind speed, temperature, and relative humidity for each Diablo-like event day was compared to a climatology calculated from the corresponding Julian day long-term average minimum and maximum values on a per station basis.

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

Date	Duncan ws_{\max}/wsg_{\max} (ms^{-1})	Knoxville Creek ws_{\max}/wsg_{\max} (ms^{-1})
2002-02-28	9.8/15.6	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

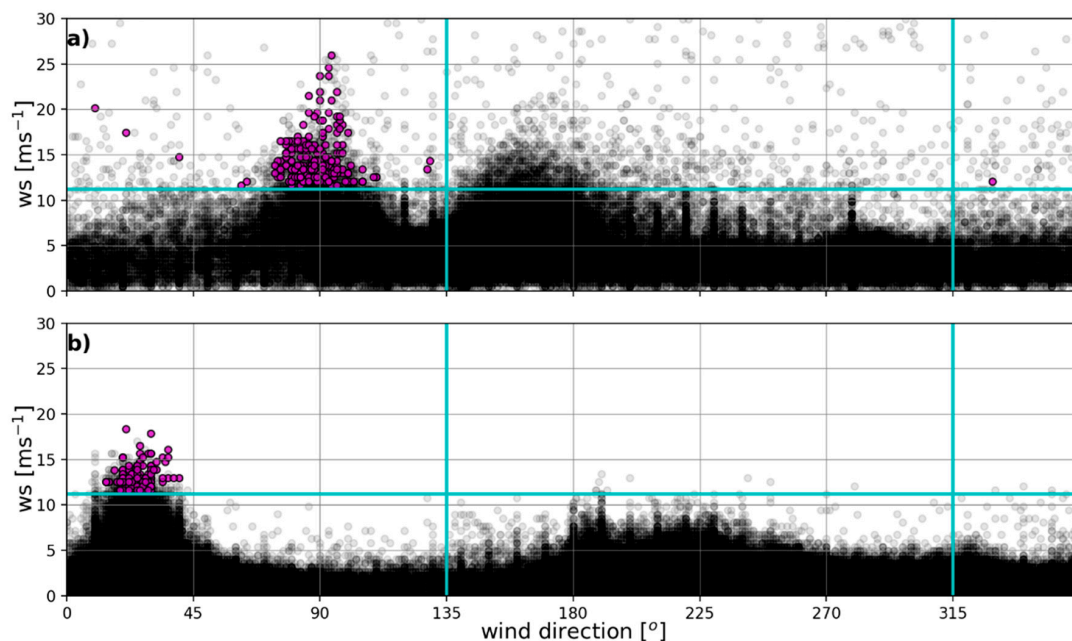


Figure 3. Scatter plot of wind speed versus wind direction for all available hourly observations at Duncan Canyon (a) and Knoxville Creek (b). Conditions satisfying the Diablo-like criteria of wind speed, wind direction and relative humidity are shown in magenta. Cyan lines correspond to the wind direction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

3. Results and Discussion

The average number of daily Diablo-like events per station per year that meet the criteria is shown, as a function of station elevation, in Figure 4a, and as colored dots, in Figure 1. The relationships shown indicate that interstation variability and micro-siting is likely an important component of observed Diablo-like wind conditions in the RAWS network. 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. 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 Diablo-like events per area, averaged as a function of the hour of day, is shown in Figure 4b. Daily Diablo-like events per area, averaged as a function of the month of the year, is shown in Figure 4c. Diablo-like wind events tend to occur overnight, through early morning most frequently (more than once per month) during late fall and early spring (October–March). Mid-to-late spring (April–June) and early fall (September) events are less frequent, occurring at a frequency of approximately one event per two months. They are quite uncommon during summer (July–August).

These results are consistent with a previous analysis [16]. The results indicate a very similar diurnal pattern for the SN stations to the NoBA stations (Figure 4b). Monthly frequencies are also similar, although NoBA stations appear to have slightly more frequent events during December and January (Figure 4c). The SN stations indicate a modest relationship between Diablo-like events and station elevation, while the NoBA stations do not (Figure 4a).

The departures from the Julian day climatology, on a per station basis, show that Diablo-like events tend to be very dry (Figure 5a) relative to climatology, with depressed daily minimum and maximum relative humidity on the order of 30%. This is consistent with the Southern California downslope wind regimes [1,13]. However, minimum and maximum daily temperatures are not elevated relative to climatology (Figure 5b), indicating that Diablo-like 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), which is in agreement with previous work on Santa Ana winds ([3], cf. Figure 13a).

The gust factor analysis (Figure 4d), in which the mean gust factor is computed per wind speed bin for Diablo-like event days on a per area basis, and compared to all observations, shows that the gust factor during Diablo-like event days is not elevated relative to non- Diablo-like event days. The wind speeds and wind speed gusts are both elevated during Diablo-like events, although the gust factor is not, indicating no support for Diablo-like winds being gustier than other high wind events that affect these stations under other atmospheric conditions. The identified relationship of gust factor versus sustained wind speed appears to be similar to that of Santa Ana's ([3], cf. their Figure 11c).

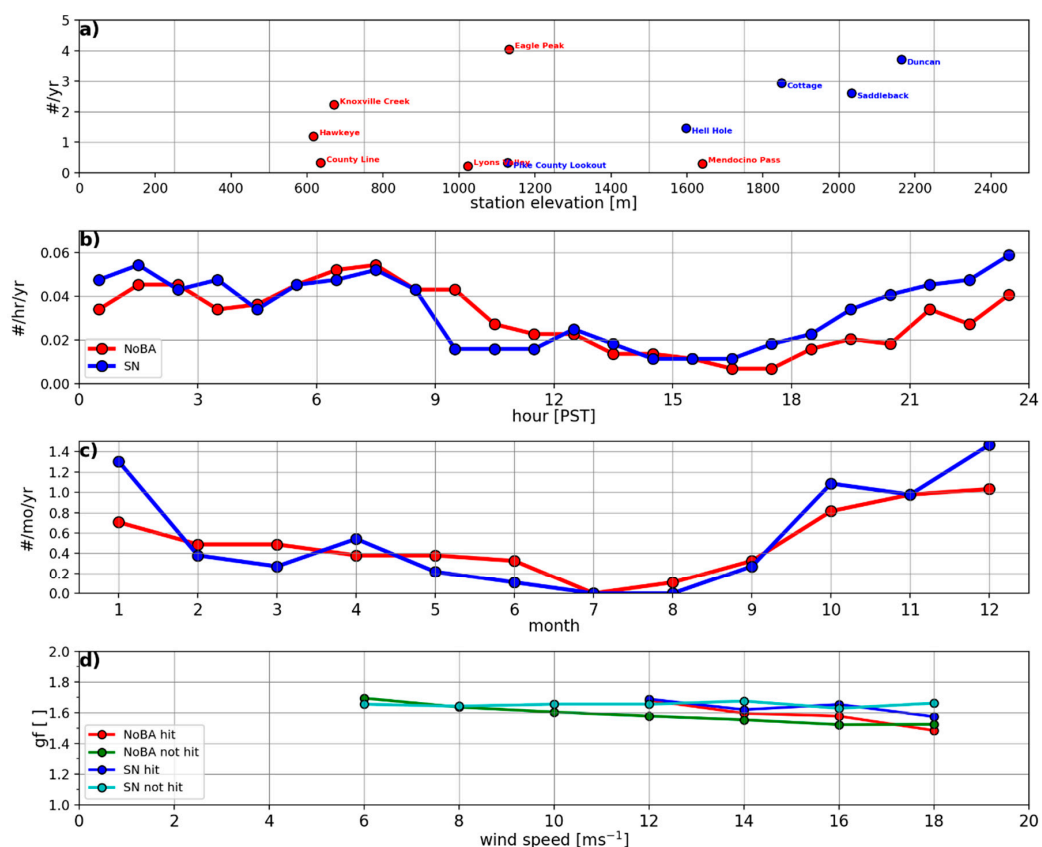


Figure 4. Average number of daily Diablo-like events per station per year versus station elevation (a), average hourly Diablo-like events per area, as function of the hour, (b), average daily Diablo-like events per area, as a function of the month of the year, (c) the area mean gust factor, as a function of the wind speed bin for Diablo-like days per area, and (d) all observations not meeting the criteria.

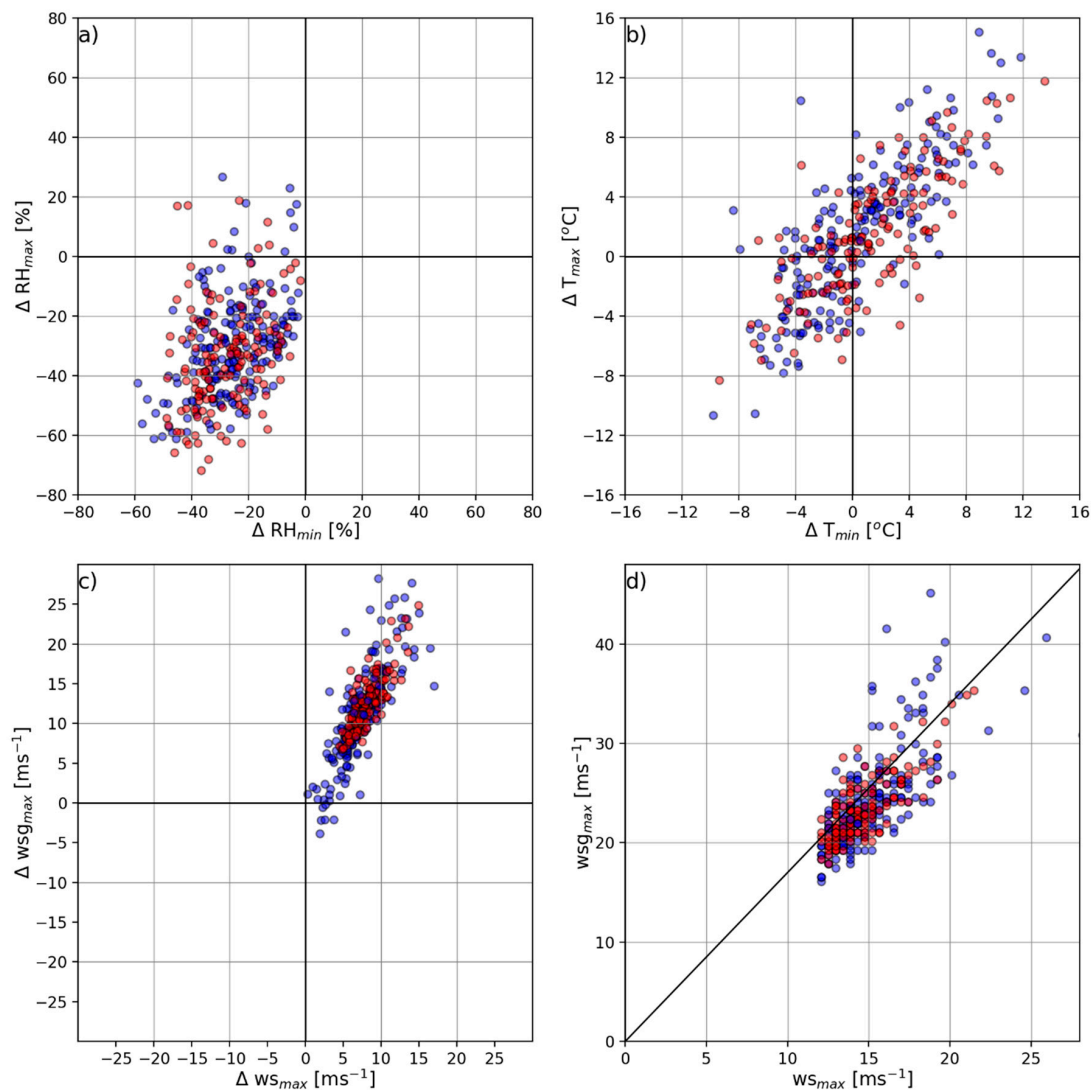


Figure 5. Daily Diablo-like event departures from Julian day climatology on a per station basis for the north of Bay Area (NoBA; red) and western Sierra Nevada (SN; blue) area observations of: Daily minimum and maximum relative humidity (a), daily minimum and maximum temperature (b), daily maximum wind speed and wind speed gust (c), and daily maximum wind speed versus daily maximum wind speed gust (d). The diagonal black line in (d) corresponds to a gust factor slope of 1.7.

4. Summary 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 conditions similar to Diablo winds tend to occur at night or in the early morning and are most common during the cool season (late fall through spring). However, our analysis is somewhat constrained by the binary nature of our criteria, and we did not consider the eastern San Francisco Bay Area nor the San Francisco Peninsula. Further research is required to address many issues posed by the sparse RAWS network used in this study, including the production and analysis of a long-term, high resolution downscaled numerical climatology.

Of the total number of Diablo-like wind conditions, identified on a daily basis per area, 35% occurred north of the San Francisco Bay area only, 41% occurred in the western Sierra Nevada only, and 23% occurred in both areas. Thus, conditions similar to Diablo winds appear to be 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 local phenomenon of the San Francisco Bay Area. This indicates that wildfire fighting resources may be required throughout Northern California, including the western Sierra Nevada, when conditions similar to Diablo winds are forecast. Since historical usage of the term Diablo winds was initially confined to the Oakland Hills, it might be more appropriate to refer to Diablo-like wind conditions in the Sierra Nevada as “Diablos del Sierra” or “Bruja” winds. Associated numerical weather simulations (not shown) strongly suggest the downstream linking of mountain wave breaking over the Sierra Nevada to Diablo wind conditions north of the San Francisco Bay Area. We hypothesize that this mechanism drives Diablo-like wind conditions in both areas and 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 the surface and control of the characteristics of Diablo winds in the San Francisco Bay Area.

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

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