The Strong, Dry Winds of Central and Northern California: Climatology and Synoptic Evolution

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ABSTRACT: Strong, dry downslope winds over Northern and central California have played a critical role in regional wildfires. These events, sometimes called Diablo or North winds, are more frequent over the Bay Area and nearby coastal terrain than along the western slopes of the Sierra Nevada, where the highest frequency occurs over the midslopes of the barrier. For the Bay Area, there is a frequency minimum during midsummer, a maximum in October, and a declining trend from November to June. The Sierra Nevada locations have their minimum frequency from February to August, and a maximum from October to January. There is little trend in event frequency during the past two decades over either region. For the Bay Area sites, there is a maximum frequency during the early morning hours and a large decline midday, while the Sierra Nevada locations have a maximum frequency approximately three hours earlier. Before the onset of these downslope wind events, there is substantial amplification of upper-level ridging over the eastern Pacific, with sea level pressure increasing first over the Pacific Northwest and then over the Intermountain West. The coincident development of a coastal sea level pressure trough leads to a large pressure gradient over the Sierra Nevada and Northern California. Diablo–North wind events are associated with below-normal temperatures east of the Sierra Nevada, with rapid warming of the air as it subsides into coastal California. The large horizontal variability in the frequency and magnitude of these events suggests the importance of exposure, elevation, and mountain-wave-related downslope acceleration.

KEYWORDS: Downslope winds; Synoptic climatology; Synoptic-scale processes; Wildfires; Mountain meteorology

1. Introduction

Central and Northern California frequently experience strong, dry downslope winds that are driven by the synoptic-scale flow and are modulated by interactions with the regional terrain (e.g., Nauslar et al. 2018; Smith et al. 2018; Bowers 2018; Mass and Ovens 2019). Such strong downslope winds can initiate and support wildfires in the region, causing significant damage and loss of life over the coastal mountains north and east of San Francisco and along the western slopes of the much higher Sierra Nevada (e.g., Pagni 1993; Coen et al. 2018). Historically, the downslope winds of central and Northern California were known by two names: the *North winds* that descend the high terrain near the Oregon–California border (the Siskiyou and Klamath Mountains) and northern Sierra Nevada, and the *Mono winds* that possess a more easterly component and descend the western slopes of the central Sierra Nevada (e.g., Schroeder and Buck 1970; Ruscha 1976; Whiteman 2000). Both are associated with the movement of high pressure into eastern Oregon and northwestern Nevada, with the Mono winds dominating when high pressure extends farther southeastward into the Great Basin of Nevada and the surrounding area.

More recently, the term *Diablo wind* has been introduced by the San Francisco National Weather Service office and local media (Jan Null 2018, personal communication; Diablo wind wiki page, https://en.wikipedia.org/wiki/Diablo_wind), with its initial usage limited to the region surrounding San Francisco Bay and the adjacent coastal terrain (Sonoma and Napa counties to the north, extending to Santa Clara and Santa Cruz counties to the south). The term Diablo wind was used because the apparent origin of strong northeasterly flow influencing the Bay area was in the direction of Mount Diablo. During the past five years, major media outlets (e.g., the *Los Angeles Times*,[1] *San Francisco Chronicle*[2]), California State government agencies, Pacific Gas and Electric, and other entities have often used the term Diablo winds to encompass strong, downslope winds over *both* the Bay Area/adjacent coastal mountain and the western slopes of the Sierra Nevada associated with northerly to easterly flow. This paper uses the term Diablo–North winds to encompass strong, dry, downslope flow over central and Northern California.

Diablo–North wind events have been associated with large and damaging wildfires over central and Northern California. On 8 November 2018, a strong downslope wind event initiated the Camp Fire, which destroyed the town of Paradise, California, located in the Sierra Nevada foothills east of Chico, California (Brewer and Clements 2020). The fire was initiated from wind damage to the power transmission infrastructure[3] northeast of Paradise, and driven by strong easterly winds, burned across 153 000 acres, destroying nearly 20 000 structures and killing 86 people.[4] Also recently (8–9 October 2017),

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[1] https://www.latimes.com/california/story/2019-10-25/two-destructive-fires-hundreds-of-miles-apart-one-culprit-winds.

[2] https://www.sfchronicle.com/environment/article/Are-infamous-Diablo-winds-responsible-for-recent-14570132.php.

[3] http://d18rn0p25nwr6d.cloudfront.net/CIK-0001004980/d92f453a-57c5-4fed-b5d6-33719dc73055.pdf.

[4] http://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=2277.

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strong Diablo–North winds reaching 60–90 kt (1 kt ≈ 0.51 m s^{-1}) initiated and spread fires in the Wine Country region north of San Francisco, resulting in 44 deaths, 21 000 buildings damaged or destroyed, and an estimated 10 billion dollars in damage (Coen et al. 2018; Mass and Ovens 2019). Another major Diablo–North wind-driven fire (the Tunnel Fire) occurred in the Oakland and Berkeley Hills northeast of Oakland, California, during the weekend of 20–21 October 1991 (Sullivan 1997). Driven by easterly winds that gusted to 60 kt (31 m s^{-1}), this fire killed 25 people and destroyed 2843 homes and 437 apartments, with estimated damage of $1.5 billion 1991 dollars. The 1964 Hanley Fire, covering an area nearly identical to the highly destructive (5643 buildings destroyed, 22 deaths) 2017 Tubbs Fire, scorched 83 000 acres northeast of Santa Rosa, fueled by strong northeasterly winds in excess of 60 kt. Because that region was sparsely populated at that time, there was no loss of life, and damage involved only a handful of structures. As a final example, in 1923 the Berkeley Fire, also driven by strong easterly winds, destroyed 640 structures near the University of California Berkeley campus.

Considering the important role of strong, dry, downslope flow during recent and historical wildfires over central/Northern California, and the large attendant loss of life and property, this phenomenon is receiving increasing attention. Schroeder and Buck (1970) reviewed the general characteristics of North and Mono winds, while Ruscha (1976) described the Mono wind, including forecasting approaches. The synoptic and local wind patterns associated with strong regional downslope flow are described in Monteverdi (1973), Monteverdi and Wood (1973), and Pagni (1993), which noted the importance of high pressure over the Great Basin and the apparent similarity with the Santa Ana winds of Southern California (Sergius et al. 1962; Fosberg et al. 1966; Raphael 2003; Westerling et al. 2004; Miller and Schlegel 2006; Rolinski et al. 2019). Motivated by recent catastrophic wind-related wildfires over California, Nauslar et al. (2018) examined the general synoptic and antecedent climatic conditions associated with the 2018 Wine Country and Thomas Fires, noting the importance of strong downslope winds, human-related ignition sources, and dry conditions in the days and months preceding the events. Smith et al. (2018) described the climatological conditions associated with ''Diablo-like'' wind events using an approximately 18-yr observational record from USDA Forest Service Remote Atmospheric Weather Station (RAWS) sites over Northern California. Defining such events as 3-h periods in which northwesterly to southeasterly (315°–135°) surface winds of greater than 11.17 m s^{-1} (21.7 kt) were coincident with a humidity of less than 30%, they found such conditions most frequent from autumn to spring, are favored during the overnight period, and are not associated with warmer than normal conditions or unusual gust factors. Bowers (2018), examined the climatology of Diablo events and the fidelity of corresponding numerical simulations. Mass and Ovens (2019) completed a comprehensive observational and modeling study of the 8–9 October 2017 Wine Country wildfire, documenting strong winds (reaching 70–90 kt) at and downwind of the terrain crests and noting the realism of high-resolution Weather Research and Forecasting (WRF) Model simulations. They found that the strongest winds were associated with high-amplitude mountain waves, driven by strong incoming flow and a stable/critical level near crest level of the upstream terrain. Consistent with previous studies, the strong downslope winds of the October 2017 event were associated with above-normal sea level pressure to the east and north, upper-level ridging offshore, and a midtropospheric mobile trough moving southeastward over the Great Basin. Finally, Keeley and Syphard (2019) described both fuel-dominated and wind-dominated wildfires over California, noting that the wind-driven fires are usually associated with human ignition and that fuel availability rarely limits their initiation and spread.

Diablo–North winds are closely related to the Santa Ana winds of Southern California. Santa Ana winds are also dry, downslope winds associated with high pressure over the Great Basin and lower pressure over coastal California (e.g., Sergius et al. 1962; Fosberg et al. 1966; Raphael 2003; Westerling et al. 2004; Miller and Schlegel 2006; Rolinski et al. 2019). Similar to Diablo–North winds, Santa Ana winds are preferentially autumn and winter events, associated with cool air over the high desert areas of Nevada, northern Arizona, and eastern California that warms and accelerates as it descends to lower elevations over coastal California. Many Santa Anas display characteristics of downslope windstorms and appear to be well simulated by high-resolution mesoscale models (e.g., Cao and Fovell 2016, 2018), a characteristic also noted during the 2017 Wine Country Diablo wind event (Mass and Ovens 2019). Santa Ana winds are often strongest within and downstream of canyons and valleys of the coastal terrain of Southern California, although some Santa Ana events have their strongest winds on the upper western slopes of the regional terrain (Cao and Fovell 2016). Diablo–North wind events appear to precede Santa Ana occurrences (e.g., Bowers 2018), as cool air and attendant high pressure move southward east of the Sierra Nevada, a situation illustrated by the Diablo–North wind/Santa Ana event of 9–11 October 2019.

Several questions remain regarding Diablo–North wind events. What is the climatology of such winds, both on an annual and diurnal basis, and how does this climatology vary spatially? Is there a long-term trend in Diablo–North winds based on the observational record? Do both Bay Area and Sierra Nevada downslope winds occur under the same synoptic evolution and thus should be considered one phenomenon? This paper will build on previous work to help answer these questions.

The paper is organized as follows. Section 2 describes the Diablo–North wind definition used, with section 3 reviewing the resulting climatology. Section 4 reviews synoptic composites and describes the large-scale evolution associated with Diablo–North wind events. Finally, section 5 presents discussion and conclusions.

2. Diablo–North wind definition

In this paper, the term Diablo–North winds refers to strong dry, downslope winds associated with the terrain of central and Northern California, including the mountains north and east of San Francisco, the Siskiyou/Klamath Mountains near the Oregon–California border, and the central/northern Sierra Nevada. As noted earlier, our usage of the term Diablo–North winds subsumes the previous definitions of Diablo winds, North winds, and Mono winds that were previously applied to specific areas. As described later, the common origin and nature of these downslope wind occurrences suggests the use of a common term for all.

Both NOAA/NWS/FAA ASOS and USDA Forest Service/Bureau of Land Management RAWS surface observations are used to evaluate the occurrence of Diablo–North winds, with the RAWS observations providing more observations in regions of complex terrain and ASOS contributing more data over the adjacent lowlands. The RAWS observations used in this analysis were provided by the Western Region Climate Center's (WRCC) Desert Research Institute (DRI) and the ASOS observations were obtained from the NOAA/NWS National Center for Environmental Information (NCEI). The RAWS wind data were quality controlled (QC'd) by removing observations in which the maximum gust was greater than 15 times the hourly averaged wind speed. ASOS wind speed, maximum wind speed, or relative humidity observations were removed if flagged as suspect by NCEI. Both datasets were generally available for the 20-yr period from 0000 UTC 1 January 1998 to 0000 UTC 1 January 2018, and this work used observations from both the San Francisco Bay Area, the coastal mountains immediately to its north, and the western slopes of the Sierra Nevada (Fig. 3). Two observation locations used in the analysis, Jarbo Gap and Atlas Peak, did not encompass the entire 20-yr period (starting in 2003 and 2005, respectively). Metadata for the observation locations are provided in Tables 1 and 2.

As noted above, Diablo and North winds have been used to describe the strong, dry, downslope winds of central and Northern California. To help develop criteria for such winds, maximum hourly surface winds are plotted (Fig. 1) as a function of direction for 1998–2018 using the observation locations noted in Tables 1 and 2 for the two regions of interest (the Bay Area/adjacent coastal mountains[5] and the western slopes of the Sierra Nevada). The relative humidity at the time of each maximum hourly wind observation is noted. For the Bay Area stations, there is a primary broad peak of strong winds and low relativity humidity that encompasses northwesterly to easterly flow (roughly 330° and 90°). In contrast, for the sites on the western slopes of the Sierra Nevada, the periods of strong winds and low relative humidity are dominated by a northeasterly wind peak (roughly 30° to 90°). There is a lesser secondary peak of moderate to strong winds and low relative humidity for the Sierra Nevada western slopes from roughly 200° to 240°. This peak is associated with downslope flow on the coastal mountains during onshore southwesterly flow. The frequency of the strongest winds [e.g., greater than 20 m s^{-1} (39 kt)] is less for the Sierra Nevada sites than for the Bay Area locations. Smith et al. (2018), which made a similar plot for two observing sites based on USDA RAWS data, also found two peaks for both areas, centered around northeasterly and southwesterly flow, but with substantially different structures. Figure 1 also indicates that periods of strong winds accompanied by high relative humidity are observed for southeasterly to southwesterly flow, particularly for the Bay Area sites. Such periods are associated with the approach of strong synoptic systems during the cool season or strong marine air intrusions during the summer.

The next step was to establish quantitative criteria for Diablo–North wind events for the Bay Area and Sierra Nevada locations. A Diablo–North wind threshold of the maximum hourly wind equaling or exceeding 12.9 m s^{-1} (25 kt) was selected, a reasonable choice since this wind speed is often associated with large tree movement, with the potential for the loss of branches and contact with power lines.[6] This wind speed is indicated on Fig. 1 by a black line. For a relative humidity criterion, we required that relative humidity be below 20%, a threshold consistent with California Red Flag criterion[7] and suggested by experienced fire weather and wildfire researchers (e.g., Dr. Brian Potter, USDA Forest Service and Professor Brian Harvey, University of Washington, 2019, personal communication). The 20% relative humidity threshold used in this study was also used by Rolinski et al. (2016) for Santa Ana–related wildfire events. We note that this criterion is less than the 30% threshold used in Smith et al. (2018), which also used a lesser wind threshold [11.18 m s^{-1} (21.7 kt)].

To establish a wind direction criterion for Diablo–North winds in an objective way, the smallest directional range that encompassed 80% of strong wind/low-relative humidity 3-h periods was determined, resulting in 660 events for the Bay Area and 362 for the Sierra Nevada sites over the entire period of record (this is the sum of the number of events for all stations in each area). Figure 2 presents the maximum hourly wind speeds (top panels) and frequencies (bottom panel) for the identified events as a function of wind direction for 3-h periods. The 80% directional ranges for the Bay Area and Sierra Nevada (shown by the vertical black lines) are somewhat different for the two regions, with the Bay Area events extending from approximately 320° to 70°, and the Sierra Nevada cases encompassing 10°–100°. This difference is not surprising considering the differences in the orientations of the major terrain features. As evident in the figure, the 80% criterion correctly isolates the well-defined primary frequency modes for each region. Making use of this analysis, we define a Diablo–North wind event at a station as 3-h periods in which

[5] For the remainder of the paper, the term "Bay Area" will denote the region encompassing the San Francisco Bay area and extending along the coastal mountains through Ukiah in the north.

[6] https://botanicgardens.uw.edu/wp-content/uploads/sites/7/2018/12/Trees-and-Storms-pub08-24.pdf or reference to the Beaufort scale: https://en.wikipedia.org/wiki/Beaufort_scale.

[7] https://gacc.nifc.gov/oscc/predictive/weather/myfiles/Watches_and_Warnings_for_California.htm. This watch and warning criterion presents a complex table with relative humidity requirements based on time of today, wind speeds, and antecedent precipitation; 20% represents an average condition over a variety of diurnal conditions.

TABLE 1. Bay Area surface observation sites and the number of events over the entire period (1998–2018).

Name	Lat (°N)	Lon (°W)	Elevation (ft MSL)	Weak events	Events	Strong events
Alder Spring	37.934	122.118	1450	1	0	0
Atlas Peak	38.475	122.265	1934	50	5	0
Barnaby	38.028	122.702	935	2	1	0
Ben Lemond	37.132	122.17	2630	26	2	0
Briones	37.934	122.118	1450	0	0	0
Brooks	38.738	122.145	354	157	14	0
Calaveras Road	37.553	121.844	1230	126	49	3
Eagle Creek	39.926	122.642	3713	302	101	21
Hawkeye	38.735	122.837	2024	191	94	16
High Glade	39.208	122.808	4840	119	30	4
Knoxville	38.862	122.417	2200	431	189	31
Konocti	38.914	122.709	2149	23	0	0
La Honda	38.305	122.808	872	9	0	0
Livermore	37.693	121.814	397	35	7	0
Los Gatos	37.203	121.943	2000	21	1	0
Lyons Valley	39.126	123.074	3200	117	21	2
Mallory Ridge	37.817	121.779	1948	0	0	0
Mendocino	39.808	122.945	5420	53	17	1
Napa	38.213	122.281	11	33	8	0
Oakland	37.718	122.233	3	16	1	0
Oakland North	37.865	122.221	1403	66	29	10
Oakland South	37.786	122.145	1095	101	26	3
Rose Peak	37.502	121.736	3060	148	55	7
Santa Rosa	38.479	122.712	599	41	5	1
Soda Creek	39.425	122.977	1773	1	0	0
Sonoma	38.500	122.817	125	30	2	0
Stonyford	39.367	122.575	1200	122	3	0

1) the maximum hourly wind speeds for each hour of a 3-h period at the station exceeds 25 kt (12.9 m s^{-1})
2) the corresponding relative humidity at that station for each component hour is less than 20%
3) the surface wind direction is 320°–70° for the Bay Area stations and 10°–100° for the Sierra Nevada locations.

The 3-h periods are used to prevent events based on highly transient wind surges or intermittent sensor errors from degrading the statistics gathered for this study. It is important to note that the criterion described above is not based on the existence or actual initiation of wildfires, but rather identifies periods of strong, dry downslope flow.

TABLE 2. Sierra Nevada surface observation sites and the number of events over the entire period (1998–2018).

Name	Lat (°N)	Lon (°W)	Elevation (ft MSL)	Weak events	Events	Strong events
Bangor	39.398	121.386	803	4	0	0
Beale	39.133	121.433	113	0	0	0
Ben Bolt	38.591	120.934	905	10	0	0
Chico	39.780	121.850	239	1	0	0
Cohasset	39.872	121.769	1733	30	3	0
Duncan	39.144	120.509	7100	165	80	14
Foresthill	39.091	120.732	4355	19	0	0
Green Spring	37.833	120.500	1020	6	1	0
Jarbo Gap	39.735	121.489	2490	246	150	40
Lassen Lodge	40.341	121.714	4159	7	4	0
Lincoln	38.883	121.268	200	4	1	0
Oroville	39.514	121.556	194	5	0	0
Owens Camp	38.733	120.245	5240	1	0	0
Pike County	39.475	121.203	3714	214	49	5
Pilot Hill	38.833	121.009	1200	3	0	0
Quincy Road	39.973	120.942	3500	2	0	0
Reader Ranch	39.304	121.117	1968	7	0	20
Saddleback	39.638	120.865	6670	210	74	0
Secret Town	39.184	120.885	2826	1	0	0
Whitmore	40.619	121.899	2417	5	0	0

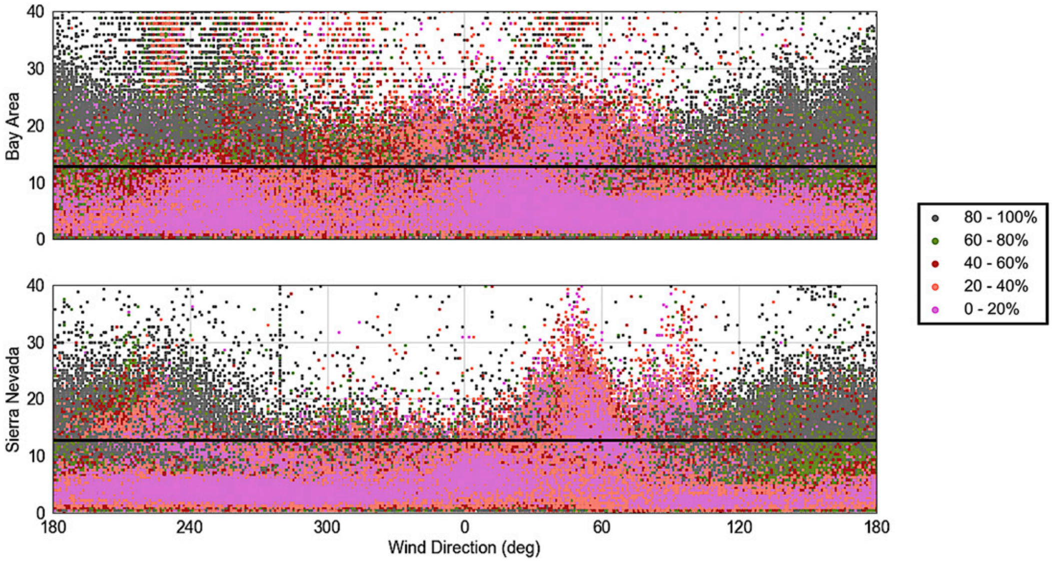

FIG. 1. Observed hourly maximum wind speed (m s^{-1}) and wind direction (°) for the (top) Bay Area and (bottom) western Sierra Nevada observing sites shown in Fig. 3. The black line indicates the wind speed threshold of 12.9 m s^{-1} (25 kt) used in this analysis. The observations are color coded by relative humidity.

Although virtually all of the major wildfires of the region occur during such periods, many dry/windy intervals exist without wildfires when a source of ignition is not present or when antecedent conditions have been wet. Using the definition noted above, the climatology of Diablo–North wind events is described in the next section, followed by a composite analysis of the associated synoptic evolution (section 4).

3. Diablo–North wind climatology

The number of Diablo–North wind events, defined as periods of 3 h or more that fulfill the criterion noted in section 2,

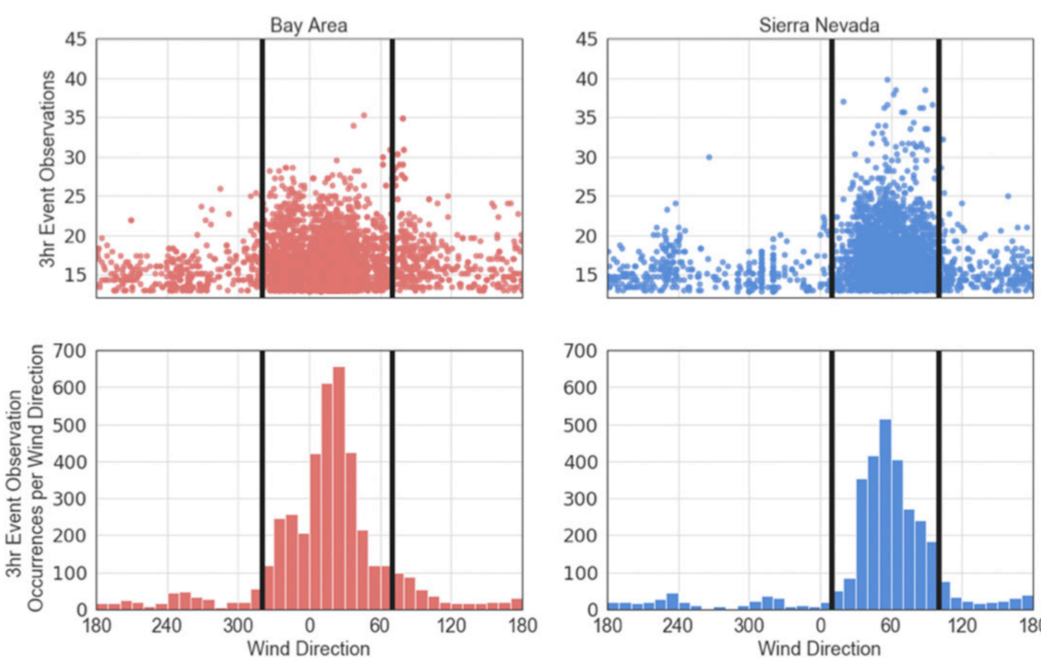

FIG. 2. (top) Scatter diagrams of the number of 3-h periods with maximum hourly winds greater than 25 kt and hourly relative humidity less than 20% for the (left) Bay Area and (right) Sierra Nevada locations. (bottom) The histograms, binned by 10° intervals, of the frequency of Diablo–North wind events as a function of wind direction. Vertical black lines indicate the wind directions that define Diablo–North winds in this study for each region.

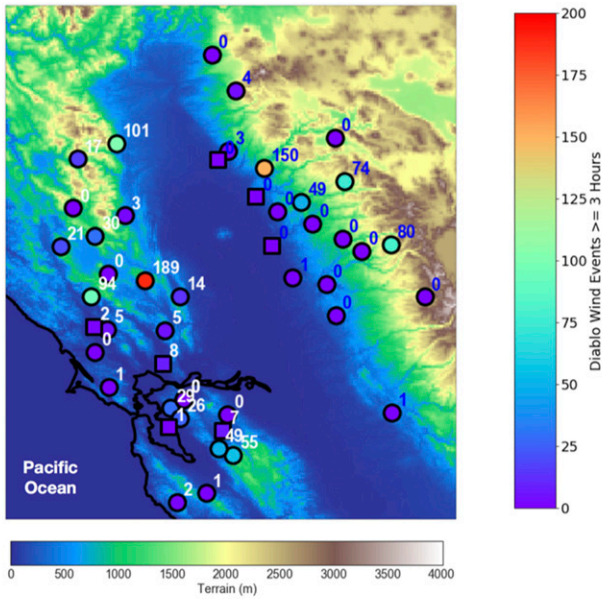

FIG. 3. Surface stations used in this study as well as terrain elevation. The total number of Diablo–North wind events for the ASOS (squares) and RAWS (circles) locations for the Bay Area and Sierra Nevada regions for 1 Jan 1998–1 Jan 2018 are shown using color shading.

are shown in Fig. 3 for locations in both regions based on observations during 1998–2018, with Tables 1 and 2 providing additional information. There is substantial spatial variability in the number of events for both regions. For the Bay Area region, the highest frequencies are found at Hawkeye RAWS (94 events, 610-m elevation), Knoxville RAWS (189 events, 671 m), and Eagle Creek (101 events, 1132 m). For the Sierra Nevada, there are few events over the lower western slopes and the adjacent Central Valley, but greater numbers on the western midslopes, with 50–90 events at some locations. The highest frequency on the Sierra Nevada western slopes is at Jarbo Gap (150), which has good exposure to northeasterly flow accelerating down the Feather River Valley. Importantly, strong easterly winds in the Feather River Valley led to the Camp Fire of November 2018. Smith et al. (2018), examining event frequency for a smaller collection of stations (11), found somewhat different results, such as a lower event frequency at the Hawkeye RAWS, north of San Francisco; that paper lacked sufficient observations to explore Diablo–North event variability along the western slopes of the Sierra Nevada.

The substantial spatial variability of the frequency of Diablo–North wind events reflects the complex meteorology of the region, with issues such as exposure, terrain gaps, and varying mountain-wave structure under different synoptic conditions. Such spatial variability is evident in each of the events examined during this study. Furthermore, it is clear that even the relatively dense observation network shown in Fig. 3 is inadequate for sampling the full Diablo–North wind event spatial variability over the region. To illustrate the complex spatial variability during a Diablo–North wind event, the maximum wind gusts from midnight to noon PDT during the event of 10 October 2019 is shown in Fig. 4, which takes advantage of the recent large increase in the number of observing sites installed by Pacific Gas and Electric (PG&E). Specifically, gusts

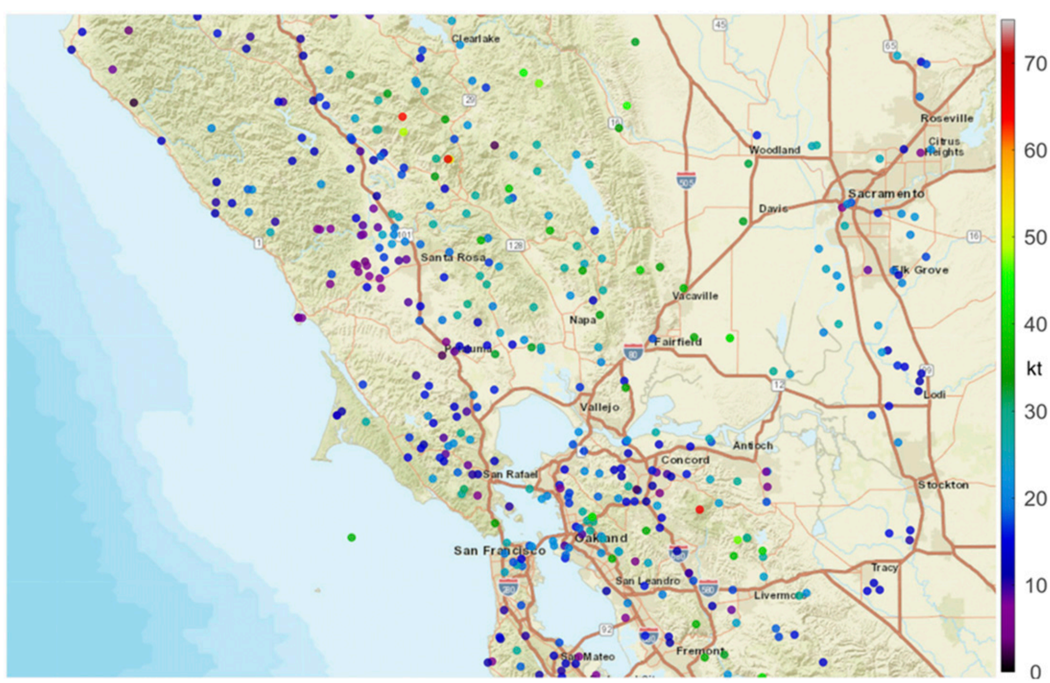

FIG. 4. Maximum wind gusts (kt) over the central coastal California for the period from 0000 to 1200 PDT 10 Oct 2019. Image produced by Conor McNicholas.

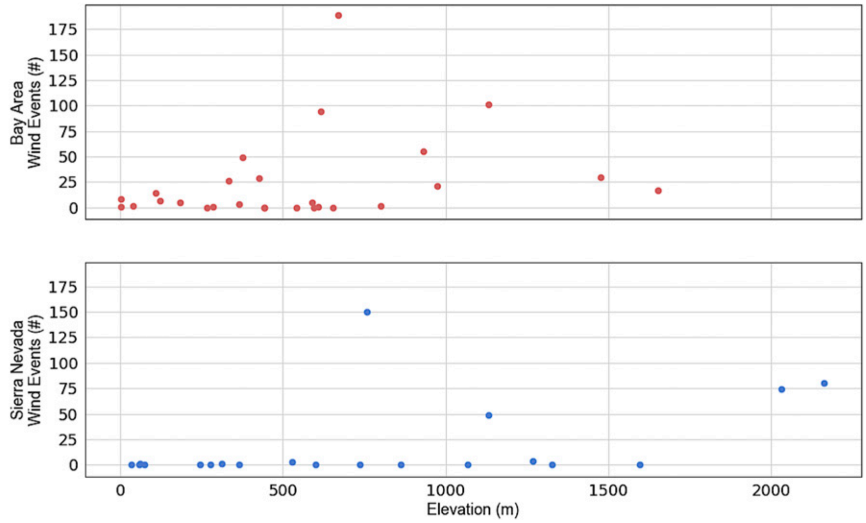

FIG. 5. The number of Diablo–North wind events by elevation (m) for the (top) Bay Area and (bottom) Sierra Nevada locations shown in Fig. 3.

range by factors up to 4 within kilometers, such as the nearly adjacent speeds of 67 kt (4 m s^{-1}) and 13.9 kt (7.15 m s^{-1}) in the terrain above Santa Rosa.

Tables 1 and 2 not only present the location and positions of the stations used in this study, but also the total number of 3-h Diablo–North wind events that equal or exceed 15 kt (weak events, 8 m s^{-1}), 25 kt (canonical events discussed in this paper, 13 m s^{-1}), and 35 kt (strong events, 18 m s^{-1}) for the entire period (1998–2018). There is a large variation in the frequency of events among the stations and a large decline in frequency for the higher threshold. For the Bay Area (Table 1), weak events occur at all stations but one (Briones), six locations never observe a 25-kt event, and less than half experience a strong event. The Hawkeye, Knoxville, and Eagle Creek locations, all at 610 m (2000 ft) or higher, experience the most Diablo–North wind events for the Bay Area group. For the Sierra Nevada stations (Table 2), less than half of the stations experience a 25-kt canonical event, and only 4 report strong events. Jarbo Gap, downstream of the Feather River Gap, has the most Diablo–North wind periods of any Sierra Nevada location.

The variation of Diablo–North wind events with elevation over the entire period using the stations shown in Fig. 3 is presented in Fig. 5. There are far more events for the Bay Area observing sites (top panel) than over the western slopes of the Sierra Nevada (bottom panel). For the Bay Area, there is large variability in the number of events as a function of elevation, with the largest number between 300 and 1200 m. The number of Bay Area events below 300 m is smaller, but generally nonzero. The substantial variability in the number of events, even at similar elevations, suggests the importance of exposure and topographic configuration in producing Diablo–North winds. For example, small changes in incoming flow can result in significant changes in mountain-wave structure, amplitude and position that can substantially alter the winds at particular locations (e.g., Guarino et al. 2018). For the stations on the western slopes of the Sierra Nevada, there are few Diablo–North wind events below 700 m, with a maximum number at Jarbo Gap (760 m), and fewer, but substantial numbers at three sites at higher elevations. As with the Bay Area, there is variability in the number events for stations of similar elevation. Smith et al. (2018) plotted the number of events per year with elevation for fewer (11) stations, finding substantial variability over the north Bay region and a tendency for increasing frequency with height in the Sierra Nevada.

To what degree do Diablo–North wind events occur over both Bay Area and Sierra Nevada regions simultaneously? This is an important question since it provides insights into whether Diablo–North winds are produced by the same synoptic conditions for both areas, and a practical one, since the occurrence of downslope wind events in both areas simultaneously might tax the resources of fire management agencies. Table 3 shows the number of days with Diablo–North wind events in each region for the 1998–2018 period, with an event-day defined as one in which at least two stations in a region experience a Diablo–North wind event, as defined above. The days in which both regions experience such conditions are also noted. There are considerably more Diablo–North wind days over the Bay Area (159) than on the western slopes of the Sierra Nevada (91), with events occurring simultaneously in both regions for 47 days. In total, 52% of the Sierra Nevada events are accompanied by a Diablo–North wind occurrence in the Bay Area, but only 30% of the Bay Area events are

TABLE 3. Number of Diablo–North wind days for 1998–2018 for the Bay Area and Sierra Nevada regions, as well as the number of simultaneous occurrences.

Region	Diablo–North wind days
Bay Area	159
Sierra Nevada	91
Bay and Sierra	47

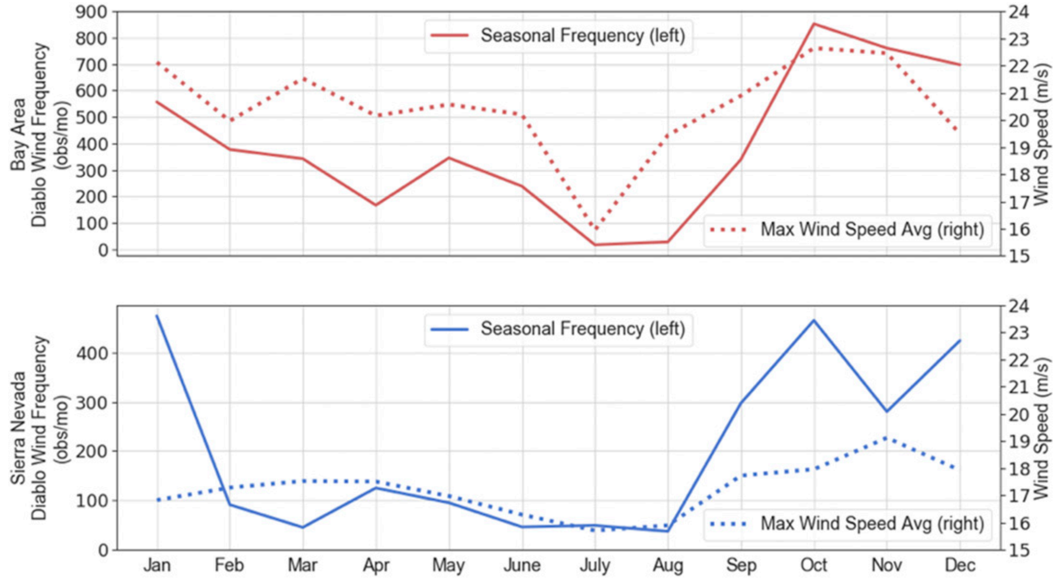

FIG. 6. Seasonal variability of the frequency of Diablo–North wind events for the (top) Bay Area and (bottom) Sierra Nevada regions. The maximum wind speeds for events in both regions are also shown.

accompanied by Diablo–North winds on the western side of the Sierra Nevada. In contrast to these results, Smith et al. (2018) found nearly the same frequency for the two regions, perhaps due to the lower number of stations considered.

Diablo–North winds have substantial seasonal modulation. Figure 6 presents the seasonal variability of such events for both the Bay Area/coastal mountain and Sierra Nevada locations. For the Bay Area, there is a minimum frequency during midsummer (July and August), with a rapid rise to an annual maximum in October, followed by a slight decline in frequency in November and December. The small dip in November is potentially the result of the relatively small sample size of

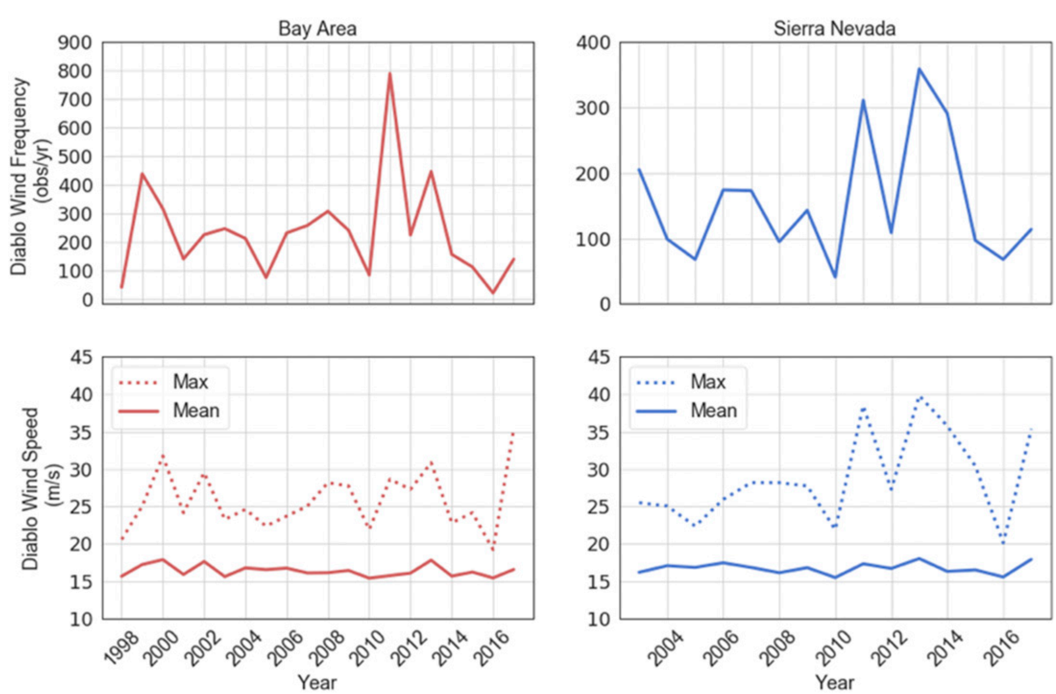

FIG. 7. (top) Annual frequency of Diablo–North wind events and (bottom) maximum and mean wind speeds during such events for the Bay Area and Sierra Nevada regions. The annual totals are the sum of the number of events for all stations in the relevant regions.

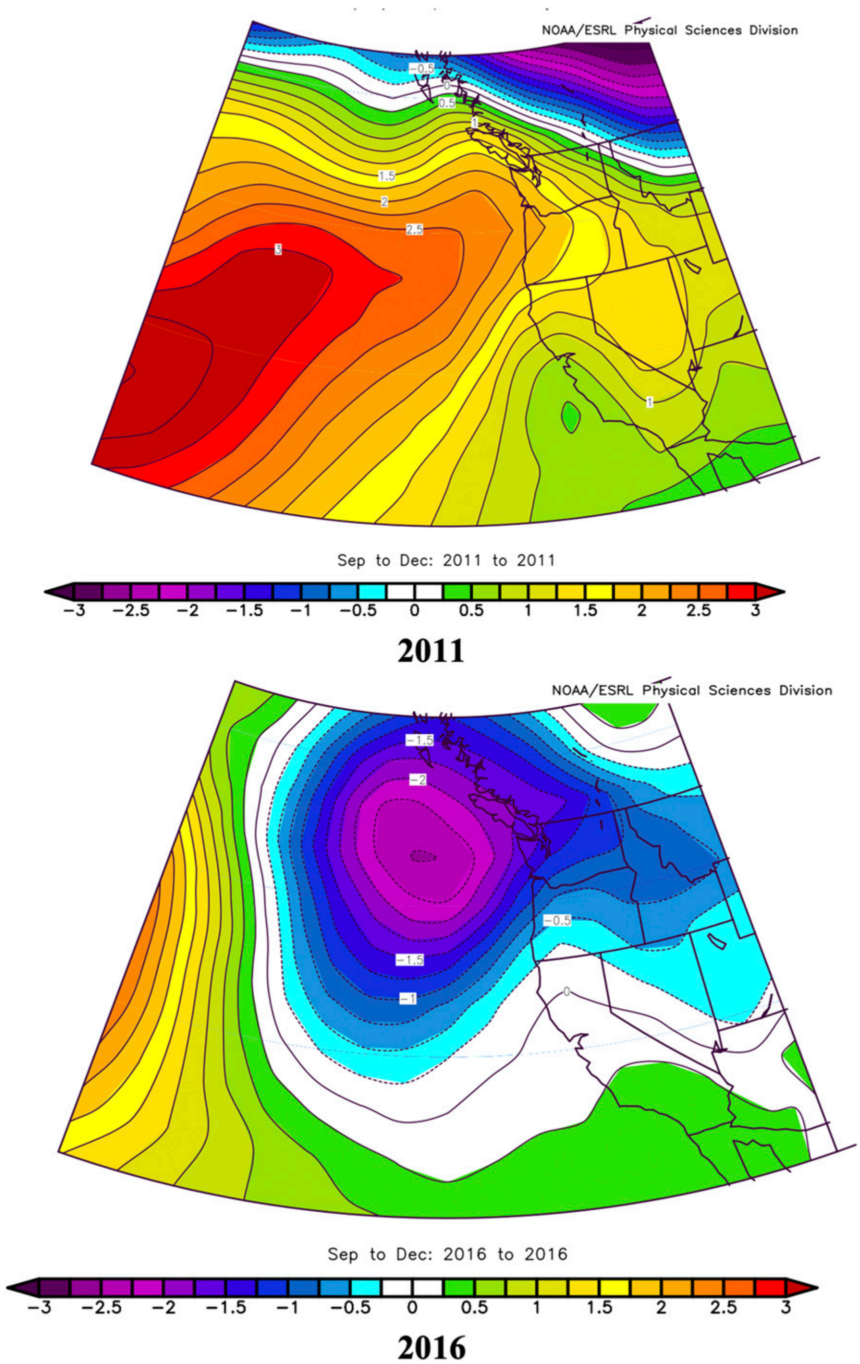

FIG. 8. Sea level pressure anomalies (hPa) from climatology (1980–2010) for (top) 2011 and (bottom) 2016 over September–December. Graphics based on NCEP–NCAR reanalysis grids and produced using the online facilities of NOAA/ESRL.

Sierra Nevada events and might disappear if a longer dataset was available. For the Sierra Nevada locations, there are relatively few events from February through August, followed by a steady rise to a maximum in October, a modest decline in November, followed by a secondary maximum in January. As described later, the midsummer frequency minimum experienced in both areas results from the building of sea level high pressure over the eastern Pacific from late June through early September, with lower pressure over the warm Great Basin during summer. The result is a strong onshore pressure gradient during summer that forces onshore (westerly) flow, resulting in cooler temperatures and higher humidity over central and Northern California. In October, the movement of cooler air and associated lower-tropospheric high pressure into

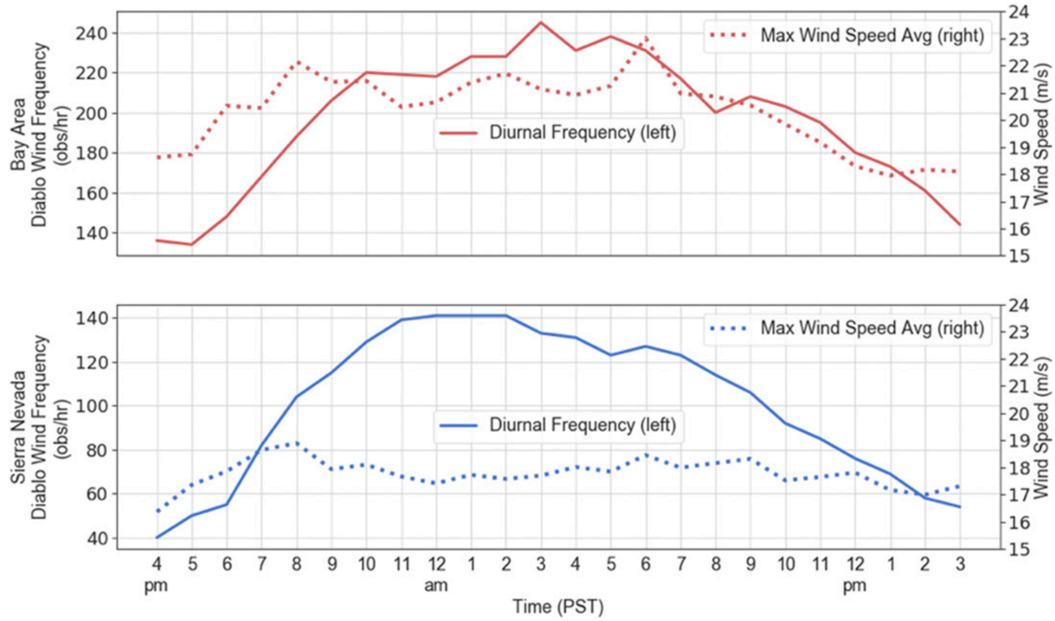

FIG. 9. Diurnal variability of Diablo–North wind event frequency (solid lines) and maximum wind speeds (dotted lines) for the (top) Bay Area and (bottom) Sierra Nevada regions.

the Great Basin region and the weakening of the east Pacific high results in the reversal in the pressure gradient and the strengthening of low-level offshore flow. These reversals support the development of Diablo–North winds, with conditions remaining favorable into early winter. Smith et al. (2018) found a generally similar annual variation for Bay Area and Sierra Nevada slope stations, but with maxima in December, compared to maxima in October (Bay Area) and January (Sierra Nevada) found in this study.

The seasonal variation of the maximum wind speed observed during Diablo–North events is also shown in Fig. 6. For the Bay Area, the weakest Diablo–North winds occur in midsummer (July), when the climatological onshore pressure gradient is large, while the strongest Diablo–North winds occur in October, November, and January (~22 m s^{-1}). Diablo–North winds are generally weaker for the Sierra Nevada locations, with less seasonal variation and the strongest winds (~19 m s^{-1}) in November.

The recent decadal trend of Diablo–North wind events for both regions is shown in Fig. 7, encompassing 1998–2017 for the Bay Area and 2003–17 for the Sierra Nevada locations (gaps in station data resulted in a later start for the Sierra Nevada locations). The results for neither area suggest an overall trend over the period, although there is substantial interannual variability. Both regions had frequency peaks in 2011. Figure 7 also shows the trends in the average maximum and mean wind speeds during Diablo–North events for both regions. There is little trend in the mean winds during such events (~17 m s^{-1}) but considerable variability in the average maxima, with the highest maxima (38 and 40 m s^{-1}) observed in 2011 and 2013, respectively, over the western slopes of the Sierra Nevada.

To examine the origins of the interannual variations in Diablo–North winds, sea level pressure anomalies were calculated over the season of greatest event frequency (September through December) for a year with a large numbers of Diablo–North wind events (2011) and a year of relatively low frequency (2016). These synoptic anomalies were calculated using the NCEP/NCAR reanalysis grids and are shown in Fig. 8. For a year with many Diablo–North wind events (2011), a high pressure anomaly over the eastern Pacific extends into the Pacific Northwest and the Great Basin, with a pressure trough along the coast, a highly favorable synoptic pattern for producing northeasterly or easterly winds over Northern California and the northern Sierra Nevada. This configuration has much in common with the canonical Diablo–North wind pressure distribution (presented later in Fig. 11). In contrast, for a year with few Diablo–North events (2016), anomalous low pressure off the Northwest coast extends to the southeast. This pressure pattern would result in reduced dry downslope flow and enhanced geostrophic southwesterly winds over Northern California, both inimical to Diablo–North wind occurrence.

The diurnal variation of the frequency of Diablo–North wind events is shown in Fig. 9. For the Bay Area, the peak frequency is in the early morning hours, with a decline to a minimum during the late afternoon (1600–1700 PST). The Sierra Nevada also has an overnight peak in event frequency but phased 3–4 h earlier compared to the Bay Area (2300–0200 PST). The Sierra Nevada locations also possess a late afternoon minimum. Smith et al. (2018) also found maximum frequency during the overnight hours for both Bay Area and Sierra Nevada locations. Figure 9 also presents the diurnal variation of maximum wind speed during Diablo–North wind events. For the Bay Area, Diablo–North winds are strongest during the evening and morning hours, with a minimum during early afternoon. In contrast, there is little diurnal wind

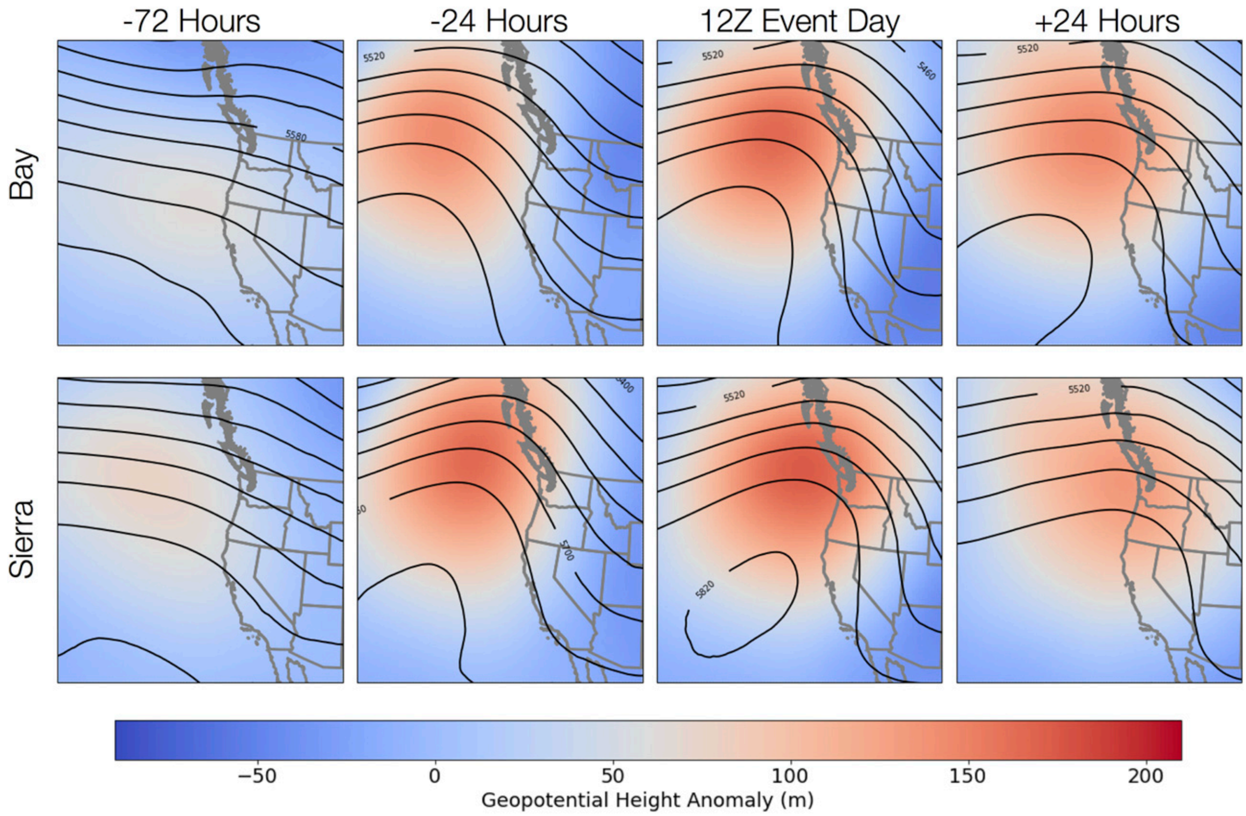

FIG. 10. The 500-hPa geopotential height (m) composite evolution for (top) Bay Area and (bottom) Sierra Nevada events. Black contours are geopotential height in meters, contoured every 60 m. Geopotential height anomalies from climatology (m) are color shaded.

variation for the maximum Diablo–North winds over the western slopes of the Sierra Nevada, with a minor minimum at 1600 PST.

The nighttime maximum in frequency for both the Bay Area and Sierra Nevada locations is consistent with both mountain-wave theory and observations in other locations (e.g., Colle and Mass 1998a,b; Gaffin 2009), which generally found both higher amplitude and more frequent surfacing of strong mountain-wave winds during the night when low-level stability is typically larger. Furthermore, daytime heating over land and terrain would tend to lessen the frequency of crest-level stable layers and could enhance onshore (westerly) diurnal winds from the west, generally opposing downslope flow.

4. Synoptic evolution associated with Diablo–North wind events

This section explores the synoptic evolution of 500-hPa geopotential height, sea level pressure (MSLP), 850-hPa temperature, and 925-hPa relative humidity from 72 h prior to 24 h after Diablo–North wind events. Composites were constructed using grids from the North American Regional Reanalysis dataset (NARR) (Mesinger et al. 2006), with a horizontal grid spacing of 0.3° (32 km) and a temporal resolution of 3 h. The dates chosen for compositing were based on periods when Diablo–North wind events occurred at a minimum of two stations within the Bay Area or Sierra Nevada collection of stations.[8]

Figure 10 presents the composite evolutions for the Sierra Nevada and Bay Area locations at 500 hPa, with the deviation from climatology shown by color shading. Both regions possess a similar temporal evolution at 500 hPa, with a small difference in phasing (a slight westward displacement for the Bay area composites). The 72 h before the Diablo–North wind events, there is relatively zonal flow over the eastern Pacific, and during the subsequent 48-h substantial ridging occurs immediately west of the North America coast. By event day, the ridge intensifies further and makes landfall along the coast of southwest Canada. During the subsequent 24 h, there is modest weakening and eastward movement of the ridge. The areas of stronger positive anomalies for each of the composites were statistically significant at the 95% confidence level using a Student's *t* test (not shown in the figure).

The sea level pressure composite evolutions for the Diablo–North wind events for both areas are shown in Fig. 11. At 72 h before the event, high pressure is found west of California

[8] Thus, for the Bay Area composites only dates when two Bay Area stations fulfilled the Diablo–North wind threshold are used. This is done to ensure that only generally significant events were included and did not only reflect conditions at one station.

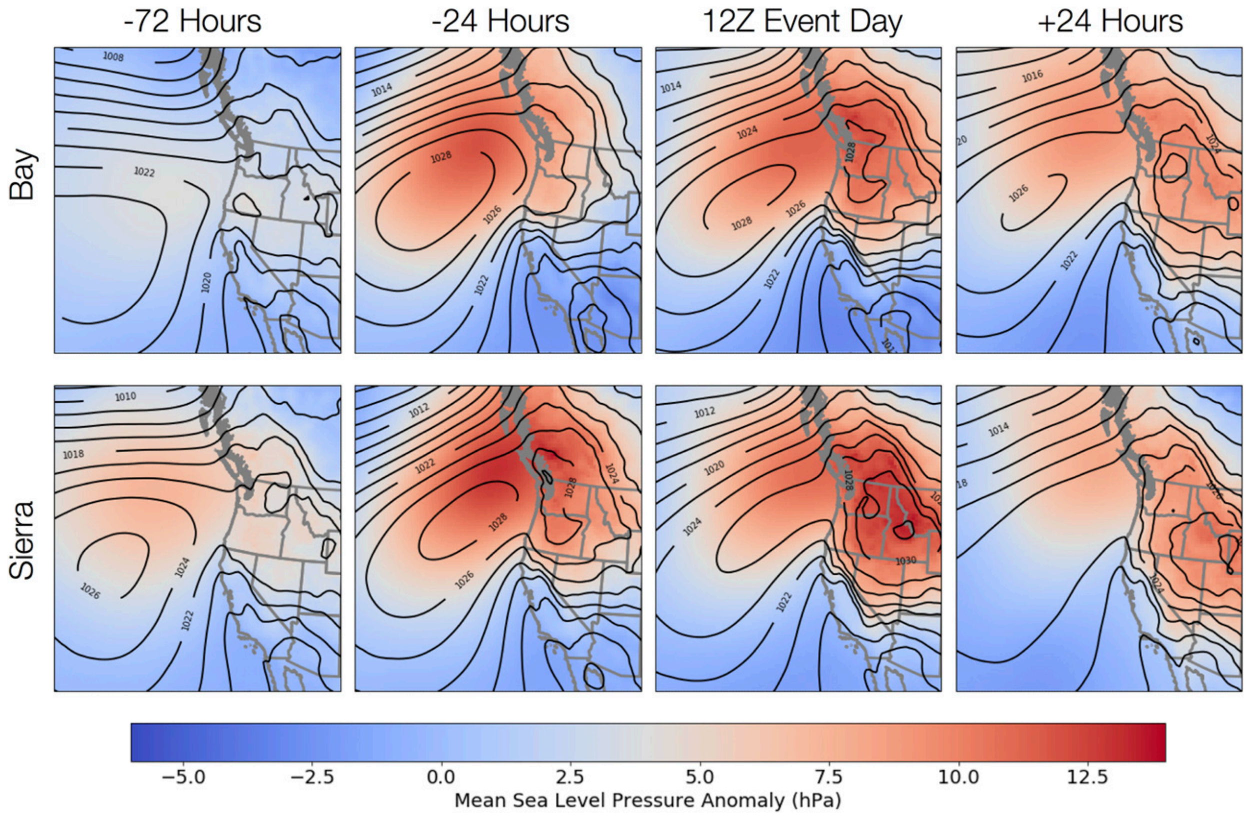

FIG. 11. As in Fig. 10, but for mean sea level pressure, contoured every 2 hPa.

for both regions, with a more northward extension for the Sierra Nevada events. At 24 h prior to the event day, the eastern Pacific ridge has greatly amplified and extends into the Pacific Northwest, while a pressure trough has been established along the California coast. There is greater inland extension of high pressure for the Sierra Nevada events. By the time of Diablo–North wind initiation (event day), high pressure has not only moved into the Pacific Northwest but has also progressed southward into the Great Basin region, with a farther southward extension for the Sierra events. As a result of these changes, a large pressure gradient is found over the Sierra Nevada and Northern California for events in both regions, one that is favorable for northeasterly flow. The inland high pressure anomaly weakens and moves southeastward during the subsequent 24 h. Bowers (2018) composited sea level pressure at the time of Diablo–North wind events for stations around the Bay Area and found a similar pressure distribution.

The evolution of 850-hPa geopotential heights, temperatures, and winds associated with Diablo–North wind events (Fig. 12) indicates that higher heights and cooler than normal air pushes eastward into the Pacific Northwest and then south into the Great Basin area during the three days prior to events, while warmer than normal air and troughing develop along the coast. During the same period, northeasterly winds strengthen over northeastern California. Thus, the downslope flow associated with Diablo–North winds originates in a region that is cooler than normal, with the air warming by compression as it descends to lower elevations. The 850-hPa temperatures over the western slopes of the Sierra Nevada are near normal during Diablo–North wind events, while the 850-hPa temperatures over the Bay region are above normal.

The associated evolution in geopotential height and relative humidity anomaly from climatology at 925 hPa (Fig. 13) indicates modestly (~10%) higher than normal relative humidity over the interior of the western United States between 72 and 24 h prior to the events for both regions. By event time, 925-hPa coastal relative humidity plummets to ~40% below normal due to increasing downslope flow, with drier conditions spreading eastward during the subsequent 24 h.

5. Discussion and conclusions

This work examines the climatology and synoptic evolution of strong, dry, downslope winds over central and Northern California. Often termed Diablo or North winds, these events are defined in this paper to be associated with surface winds exceeding 25 kt and a coincident relative humidity of less than 20% for 3 h or more, over a directional range encompassing 80% of climatological occurrences. Observations for 20 years (1998–2018) from both FAA/NWS ASOS and USDA Forest Service RAWS stations were used in this study. Two regional collections of stations are considered. One encompasses the coastal mountains of central/Northern California near San Francisco Bay, while the other includes the western slopes and

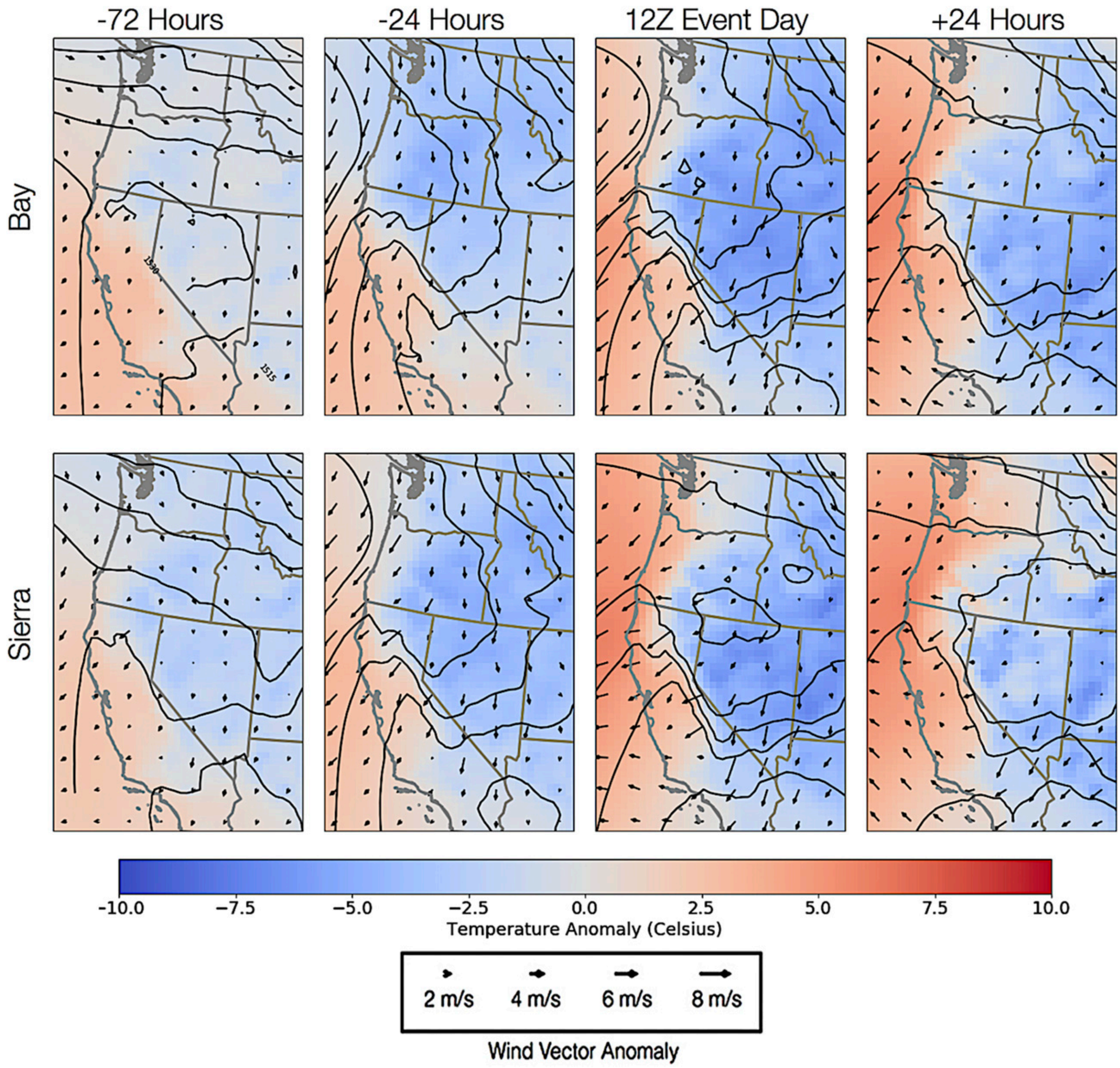

FIG. 12. Evolution of 850-hPa geopotential heights (m) contoured every 15 m, 850-hPa wind anomalies from climatology (arrows), and 850-hPa temperature anomalies (°C; shading).

adjacent lowlands of the Sierra Nevada. For the Sierra Nevada stations, Diablo–North wind events were defined as possessing surface (10 m) wind directions from 10° to 100°, while from 320° to 70° was used for the Bay Area sites.

Based on the above definitions, it was found that Diablo–North wind events are more frequent for the Bay Area/coastal mountain locations than along the western slopes of the Sierra Nevada. While strong downslope winds can reach to near sea level for the relatively modest, but often steep, terrain in the Bay Area, strong downslope winds associated with the far higher Sierra Nevada, with its extended western slopes, rarely reach the lower slopes or the adjacent Central Valley (Fig. 3). Thus, the largest number of Sierra Nevada events occur on the midslopes on the western side of the barrier. There is great spatial variability for the Bay Area events, with the greatest frequency on midslopes on both sides of the coastal range.

About half of the Sierra Nevada Diablo–North wind events are accompanied by simultaneous events over the Bay Area terrain, while only about 30% of the more numerous Bay Area Diablo–North wind events are accompanied by Diablo–North winds along the western slopes of the Sierra Nevada.

An examination of Diablo–North wind seasonal variability finds that for the Bay Area locations there is a minimum frequency during midsummer (July and August), a maximum in October, and a declining trend from November to June. The Sierra Nevada locations have maximum frequency from

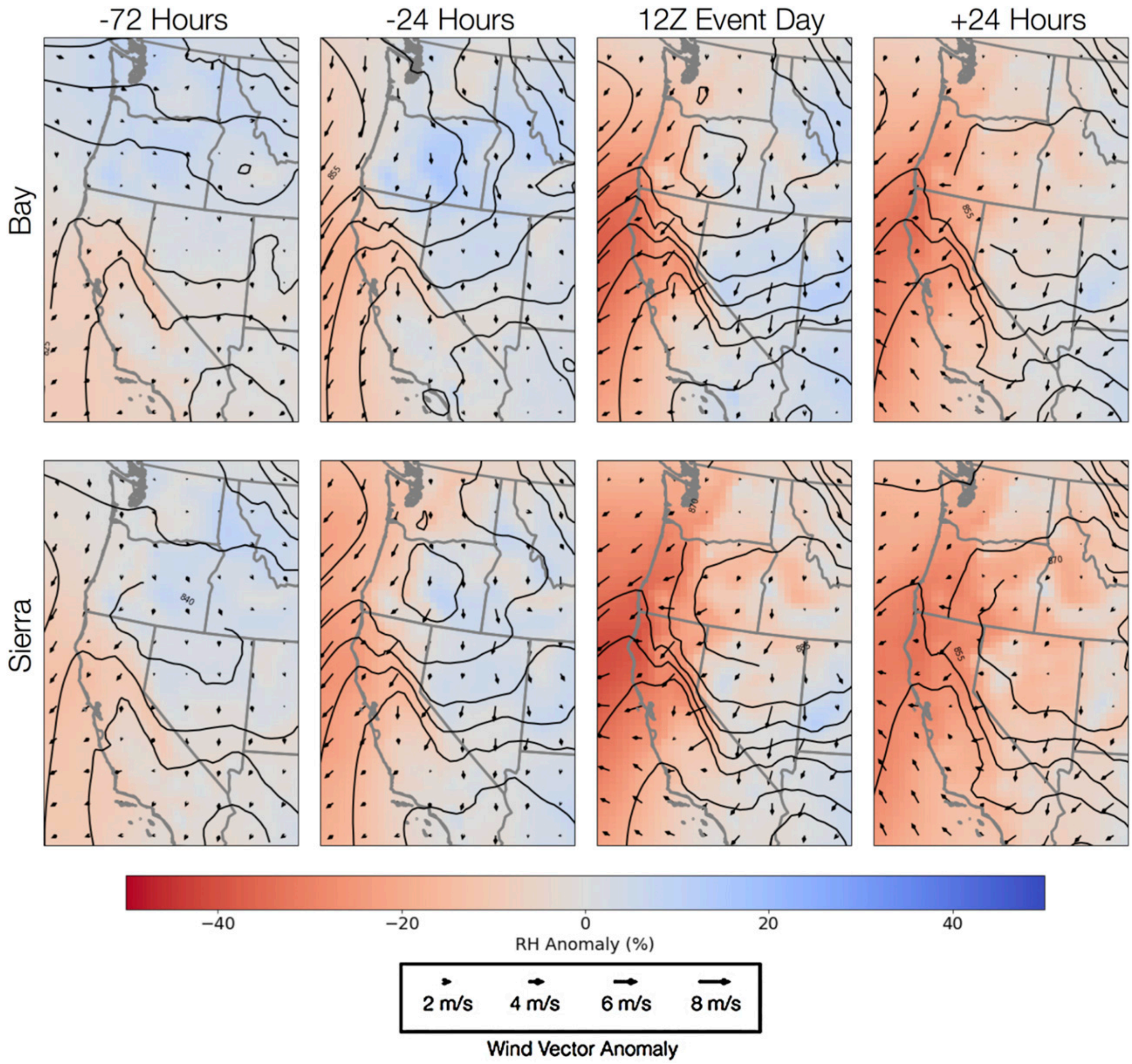

FIG. 13. The 925-hPa relative humidity anomaly from climatology (%; color shading), geopotential heights (m; solid lines) contoured every 15 m, and 925-hPa wind anomalies (arrows).

October through January, followed by a rapid decline in February to very low frequency through August. As noted earlier, a minimum frequency of Diablo–North wind events during midsummer is expected, resulting from onshore (westerly) flow forced by a prominent low-level east Pacific high and a ‘‘thermal low’’ over the Great Basin. This situation reverses in autumn with the rapid weakening of the east Pacific high and the intrusion of cool, continental air and attendant high pressure over the Great Basin, producing an offshore pressure gradient that forces easterly/northeasterly Diablo–North winds.

During the 20-yr period considered, there is little overall trend in the number of Diablo–North wind events or associated strong winds for either the Bay Area or Sierra Nevada locations. There is substantial interannual variability in the number of Diablo–North wind events and associated maximum winds, but minimal annual variability for the mean winds accompanying such events. Diurnal variability of the frequency of Diablo–North wind events for both the Bay Area and Sierra Nevada sites is characterized by a nighttime/early morning maxima, with the Sierra Nevada events phased a few hours earlier (2300–0200 PST). In both regions, minimum frequency occurs during the late afternoon.

Synoptic composites constructed using NOAA/NWS NARR grids from 72 h before to 24 h after Diablo–North wind events indicate a generally similar synoptic evolution for both Bay Area and Sierra Nevada locations, but with some subtle differences. At 500 hPa, ridging over the eastern Pacific amplifies and slowly moves eastward to the coast during the three days prior to the events, while the sea level pressure composites for both regions show strengthening of the east Pacific High, its extension into the Pacific Northwest, and the southeastward expansion of high pressure into the Great Basin. At the same time, a sea level pressure trough develops along the coast, resulting in strong pressure gradients over the Sierra Nevada and Northern California that produce the strong, dry downslope flow characteristic of Diablo–North winds. High pressure builds farther south into southern Nevada for the Sierra Nevada events.

Regional composites show that Diablo–North wind events for both areas were accompanied by colder than normal 850-hPa temperatures over Oregon and Nevada, transitioning to warmer than normal conditions along the coast. At 925 hPa, there was substantial drying west of the Sierra Nevada crest prior to Diablo–North wind events, with higher than normal relative humidity to the east, where cool air was moving in from the north. At both 925 and 850 hPa, winds during the events were northeasterly over the Sierra Nevada and Northern California.

Although the synoptic evolution associated with San Francisco Bay and Sierra Nevada locations are similar, there are small synoptic differences at the time of Diablo–North wind initiation. The 500-hPa synoptic ridge is shifted westward for the Bay Area composites compared to those of the Sierra Nevada events, with Sierra Nevada events having higher pressure extending southward into the Great Basin. The similarity in the synoptic conditions associated with coastal (Diablo) and Sierra Nevada (North or Mono) wind events suggests that they should be considered a single phenomenon, leading to the use of the term Diablo–North wind events in this paper.

There are substantial variations in the strength and frequency of Diablo–North winds by location, elevation, and exposure. As suggested in several earlier studies (e.g., Mass and Ovens 2019; Nauslar et al. 2018; Smith et al. 2018; Bowers 2018) mountain-wave dynamics play an important role in producing strong, localized, winds in the region, with downslope flow associated with mountain waves being a significant feature of many Diablo–North wind events. The amplitude and location of the strongest downslope flow associated with mountain waves are highly sensitive to subtleties of the incoming flow (e.g., magnitude and locations of stable layers, critical levels, etc.) and terrain configuration, and small variations of flow characteristics result in shifting locations and changing amplitude of the strongest winds. The importance of mountain-wave dynamics might also explain the low frequency of Diablo winds at the western base of the Sierra Nevada. Since the Sierra Nevada is relatively high, with a gentle and extended western slope, it is difficult for downslope flow associated with mountain waves to reach lower elevations (e.g., Miller and Durran 1991).

A useful follow-on to this study could examine the mesoscale dynamics associated with Diablo–North winds over both the coastal terrain in the Bay Area and the western slopes of the Sierra Nevada. To what degree does the mesoscale evolution differ for these two locations and how can these differences be explained by variations in upwind terrain, characteristics of the incoming flow, and the amplitude and location of mountain-wave-related downslope acceleration? Such studies may be greatly enhanced by the availability of thousands of new surface observing stations being installed across the region by Pacific Gas and Electric or the analysis of multidecade high-resolution simulations over the region. Another possible study would compare the results described above to the conditions associated with actual wildfires in the region, an examination what would be challenged by the relatively low number of major wildfire events. Finally, using century-long, high-resolution dynamic downscaling runs, the impacts of anthropogenic global warming on the frequency, intensity, and distribution of Diablo–North winds should be explored.

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