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The Diablo Winds of Northern California: Climatology and Numerical Simulations

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THE DIABLO WINDS OF NORTHERN CALIFORNIA: CLIMATOLOGY AND
NUMERICAL SIMULATIONS

A Thesis

Presented to

The Faculty of the Department of Meteorology and Climate Science

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Carrie Bowers

December 2018

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The Designated Thesis Committee Approves the Thesis Titled

THE DIABLO WINDS OF NORTHERN CALIFORNIA: CLIMATOLOGY AND
NUMERICAL SIMULATIONS

by

Carrie Bowers

APPROVED FOR THE DEPARTMENT OF METEOROLOGY AND CLIMATE
SCIENCE

SAN JOSÉ STATE UNIVERSITY

December 2018

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ABSTRACT

THE DIABLO WINDS OF NORTHERN CALIFORNIA: CLIMATOLOGY AND NUMERICAL SIMULATIONS

by Carrie Bowers

Extreme fire behavior in the San Francisco Bay Area (SFBA) has historically been associated with strong offshore wind events referred to locally as Diablo winds. A 17-year surface-based climatological analysis was performed to establish a definition of Diablo winds and to identify their frequency and spatial distribution. Synoptic composites of events were constructed using North American Regional Reanalysis, and high-resolution Weather Research and Forecasting (WRF) model simulations were used to investigate the mesoscale dynamics of three significant Diablo wind events. Diablo winds were defined as dry northeasterly, downslope winds that occur in the SFBA with minimum sustained wind speeds of 6 m s^{-1} . Climatological analysis results illustrate that Diablo winds most frequently impact the Coast Ranges nearest the Sacramento Valley and occur, on average, 2.5 times annually. The highest monthly frequency occurs in October when live fuel moisture is at its driest, creating the most severe fire danger for the SFBA during that time. Numerical simulations of significant Diablo events revealed that Diablo winds have complex character with contributions from small-scale downslope winds, as well as large-scale mountain waves interacting with terrain.

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CHAPTER 1

The Diablo Winds of Northern California: Climatology and Spatial Characteristics

Abstract

Diablo winds are offshore wind events that flow northeasterly over Northern California's Coast Ranges, often creating extreme fire danger for the San Francisco Bay Area. A 17-year climatology of regional surface stations was used to develop a definition of Diablo wind events as well as an analysis of their spatial distribution and event frequency. A synoptic composite of the identified events illustrate that Diablo wind events are associated with an inverted surface pressure trough that develops over California, creating a pressure gradient from higher pressure over the interior northern Great Basin to lower pressure near the California coast. Results indicate Diablo winds affect regions throughout the San Francisco Bay Area with greater frequencies concentrated in the Coast Ranges nearest the Sacramento Valley. During the 17-year study period, the region experienced a mean annual frequency of 2.5 events with the highest frequency of Diablo wind events occurring in October when the live fuel moisture is already at a seasonal minimum. These events contribute to further drying of the dead fuel moisture that responds on a smaller temporal scale, leading to the most severe fire danger conditions for the San Francisco Bay Area.

1.1 Introduction

Extreme fire behavior is that which inhibits direct control measures, by a high rate of spread, spotting, the existence of fire whirls, or a strong convective column ("Glossary of Wildland Fire" 2018). In California, extreme fire behavior is often associated with strong offshore winds. Most notably, the Santa Ana winds of Southern California have been the

driving force behind many of the area's most devastating fires (Jin et al. 2014). In 2003, the Cedar Fire in San Diego County and the Old Fire in San Bernardino County together caused the deaths of 21 people, burned 364,527 acres, and destroyed 3,823 structures. In 2007, the Witch Fire and Harris Fire in San Diego county killed 10 people, burned 288,430 acres, and destroyed 2,198 structures (CalFire 2018). These foehn winds (warm dry winds that develop on the lee of mountains ranges) produce strong ridgetop winds that accelerate downslope in the lee of the Southern California mountains (Fosberg 1966). Similarly, Sundowner winds of Santa Barbara originate inland and over the Santa Ynez Mountains and accelerate downslope as they flow offshore (Blier 1998). In the San Francisco Bay Area (SFBA), an analogous situation arises when north winds flow into Northern California's Central Valley and move out over coastal terrain. Named for the Diablo Range section of the Coast Ranges (Null 2000), "Diablo winds" create the area's most extreme fire behavior with their low relative humidities, high temperatures, and very high wind speeds (Werth et al. 2011). These north winds were first reported in Daily Alta California ("North Winds" 1883) as mysterious and remarkable wind storms that are most prevalent in the winter months, but when they occur in the summer months, they can bring high temperatures and low humidity that cause damage to agriculture.

Historically, fires driven by Diablo winds in the Bay Area have attained catastrophic proportions. The foothills of the East Bay have experienced four major wildland-urban interface fires during Diablo wind conditions (Routley 1991). In the northern region of the SFBA, the recent Tubbs Fire (one of the "Wine Country Fires" of 2017) bears remarkable resemblance to the Hanly (Hanley, [sic]) Fire of 1964, also driven by Diablo

winds (McCallum 2017). Three of the Wine Country Fires (Tubbs, Redwood Valley, and Atlas) as well as the Tunnel Fire (Oakland Hills) of 1991, rank in the top twenty of California's deadliest wildfires (CalFire 2017). All four of those fires, with the addition of the Nuns Fire (2017) are also ranked in the top twenty most destructive fires (CalFire 2018) in California's history.

The mountainous terrain of California provides potential for offshore winds to transition to foehn or downslope winds associated with warming and drying of the accelerated flow. Besides high wind velocities, two very important aspects of foehn flow are the warming and drying of the air as it descends the lee of the mountain range (Whiteman 2000). Elvidge and Renfrew (2015) showed turbulent mixing and isentropic drawdown (surfacing of air of higher potential temperature) as additional mechanisms for producing the signature warm, dry air of foehn winds. While foehn winds have been studied extensively in many regions around the world, including the area east of the front range of the Colorado Rockies (Klemp and Lilly 1975; e.g.) and Southern California (Raphael 2003; Huang et al. 2009; e.g.), some areas have been neglected. For example, Blier (1998), in his study of the Sundowner winds of Santa Barbara, California argues that although the Sundowner winds are grouped under the broad category of foehn winds, a closer investigation into their mesoscale causes is warranted due to the unique topography of the region. Likewise, Monteverdi (1973) discussed the "Santa Ana Type" winds of the SFBA (later named the Diablo winds) and their major implications on fire danger. More recently, Smith, Hatchett, and Kaplan (2018) compared "Diablo-like"

conditions over the western slopes of the Sierra Nevada to the Diablo winds in the North Bay region of the SFBA.

In California, offshore foehn winds are produced when a high pressure ridge settles over the Great Basin in conjunction with a low pressure trough off the coast; air aloft is adiabatically driven to the surface, warming and drying as it descends (Werth et al. 2011). The notorious Santa Ana wind of Southern California, capable of producing wind gusts in excess of 45 m s^{-1} (Cao and Fovell 2016), occurs most frequently in the fall and winter (Raphael 2003). Fosberg et al. (1966) observed that Santa Ana winds are initiated when dry air from the Great Basin forms waves in the lee of the San Gabriel Mountains, producing high ridge top winds and accelerated downslope flow into the canyons and plains to the southwest. Raphael (2003) constructed a dataset using 32 years of daily weather charts from the National Climate Data Center (NCDC) and local weather station data to quantify the Santa Ana winds. This dataset provided empirical measures of the frequency of Santa Ana occurrence and a foundational dataset for further study.

Diablo winds occur in a region bounded by low lying hills and a frequent marine inversion. Additionally, the erosion or displacement of the marine layer during offshore wind events with air of continental origin and very low specific humidity likely contributes more to the warming and drying of the air mass than adiabatic compression. Prior to the present study, there has been no concrete definition of Diablo winds. The goals of this study are to define and characterize Diablo wind events using a 17-year climatology of surface weather stations in order to assess event frequency and spatial distribution in northern California. Additionally, this study describes the synoptic

environment conducive to their onset and dissipation, and utilizes a synoptic composite for characterization of large scale forcing associated with strong offshore Diablo wind events. The structure of the paper is as follows: Section 1.2 describes the methods used, Section 1.3 details the results and their relationship to fire danger conditions, and Section 1.4 presents a summary and conclusions of the paper.

1.2 Methods

While there has been no formal definition of a Diablo wind event, a couple of studies have established criteria for their identification. In his study of the "Santa Ana Weather Type" winds of the Bay Area, Monteverdi (1973) used a minimum wind speed threshold of 10 mph (4.5 m s^{-1}) to represent the speed at which flaming debris from a fire could become airborne and accelerate the spread of the fire. This threshold was based on the Beaufort Wind Scale, at a wind speed expected to move leaves and small twigs. Smith et al. (2018) considered a "Diablo-like" event to have wind speeds greater than 11.17 m s^{-1} , a wind direction between 315° and 135° , and a relative humidity less than 30%. As the entire SFBA needs to be considered in defining Diablo events, and a northwest wind would advect moisture from the San Francisco Bay and Pacific Ocean, the directional component necessarily should be offshore. For this study then, it is useful to reference Santa Ana wind criteria for guidance. Sergius and Huntoon (1956) defined a Santa Ana wind as 20 mph (8.9 m s^{-1}) or greater from the northeast quadrant with a relative humidity at 1630 PST of less than 40 percent. Edinger et al. (1964) identified possible Santa Ana events if one or more of the following were present: 3 mb pressure gradient from Palmdale to Santa Monica, California, 9°C or greater temperature gradient from

Palmdale to Santa Monica, northerly winds in Riverside, California in excess of 30 mph (13.4 m s^{-1}), and a relative humidity in the Los Angeles area of 30 percent or less. The National Weather Service in Los Angeles/Oxnard operationally defines a Santa Ana wind as a northeasterly to easterly wind over 25 knots (12.9 m s^{-1}) (Small 1995). In an effort to establish a historical dataset of Santa Ana wind occurrence, Raphael (2003) found that identifying Santa Ana wind events using surface pressure gradients on weather maps was comparable to a study using wind speed only at a selected weather station. Our study identifies Diablo wind events using wind speed and direction, and relative humidity in order to create a foundation for event identification.

In this study, we define a Diablo wind event using a threshold of 6 m s^{-1} , a value between Monteverdi's (1973) approach, and the higher values from Smith et al. (2018). The value represents the wind speed that can support fire spread by transport of firebrands while also allowing for higher average wind speeds common in the Coast Ranges. Sustained wind speeds such as those that occur during Santa Ana wind events are not frequently observed in the SFBA, even during a Diablo wind event. Sustained winds of 6 m s^{-1} or greater from the northeast quadrant (0-90 degrees), persisting 6 consecutive hours or more, were considered to meet Diablo wind criteria. The criteria were further restricted by taking the minimum relative humidity reached during each event and omitting those that did not drop below 20 percent. When events were identified within 24 hours of each other, those two events were combined into one, as synoptic forcing is unlikely to evolve enough in time to form a second event within 24 hours. In

order for an event to qualify for analysis, it must have impacted at least 4 of the 18 stations used (or 22 percent) in the SFBA.

A 17-year climatology from 2000 to 2016 was used to assess the frequency and spatial distribution of Diablo wind events in the SFBA. Forty-two weather stations from the National Weather Service (NWS) and Remote Automated Weather Station (RAWS) network were initially examined to quantify the spatial distribution of Diablo wind events (Fig. 1, Table 1). Wind speed, wind direction, and relative humidity were extracted from the station data for analysis. RAWS reports wind speed at a height of 20 feet (approximately 6.1 meters) while NWS stations report wind speed at a height of 10 meters, a difference of nearly 4 meters. In order to insure adequate spatial coverage, stations from both networks were utilized. Stations indicating 2 or more events (defined below) over the study period and having greater than 14 years of data were used for further analysis. Only one station (Poverty) used in the secondary analysis had less than 17 years of data, and the frequency of events at that location justified its use as beneficial to the study. A total of 18 stations were used for event frequency assessment. Many of the RAWS around the Bay Area were installed in 1999 and their data were made available in MesoWest in 2000 (Horel et al. 2002), providing 17 years of continuous, high-quality weather data. Not all weather stations are sited to effectively capture northeast winds. Atlas Peak, for example, has a cluster of trees to the northeast and poorly represents northeast wind events, so some caution must be used in considering data quality and site location.

Fig 1. Map of the San Francisco Bay Area showing elevation (shading), weather station locations (circles), and spatial distribution (coloring of circles).

Table 1. Diablo wind event statistics and spatial distribution based on station location.

Station ID	Station Name	Elevation (m)	Total Events	Events/Yr	Latitude	Longitude	Start Date	Years of Data
AATC1	Altamont	437.69	0	0.00	37.693	-121.609	05/22/09	7.5
ATLC1	Atlas Peak	589.48	1	0.17	38.475	-122.265	01/20/11	6
BBEC1	Barnaby	246.89	0	0.00	38.028	-122.702	01/01/00	17
HSPC1	Spring Valley	327.66	13	0.76	37.563	-122.436	01/01/00	17
HWKC1	Hawkeye	616.92	31	1.82	38.735	-122.837	01/01/00	17
KAPC	Napa County Airport	10.06	15	0.88	38.208	-122.279	01/01/00	17
KCCR	Concord, Buchanan Field	7.01	11	0.65	37.992	-122.052	01/06/00	17
KDVO	Novato / Gness Field	0.91	3	0.34	38.142	-122.555	02/15/08	8.8
KE16	South County Airport of Santa Clara Count	85.65	10	1.92	37.082	-121.597	11/10/11	5.2
KHAF	Half Moon Bay Airport	19.81	6	0.86	37.514	-122.500	01/19/10	7
KHWD	Hayward Air Terminal	14.02	7	0.41	37.661	-122.118	01/01/00	17
KLVK	Livermore Municipal Airport	121.01	0	0.00	37.693	-121.814	01/01/00	17
KNUQ	Mountain View, Moffett Field	10.06	2	0.12	37.406	-122.048	01/01/00	17
KNXC1	Knoxville Creek	670.56	128	7.53	38.862	-122.417	01/01/00	17
KO69	Petaluma Municipal Airport	27.13	6	1.15	38.258	-122.605	10/20/11	5.2
KOAK	Metro Oakland International Airport	0.91	8	0.47	37.718	-122.233	01/01/00	17
KSFO	San Francisco International Airport	3.05	0	0.00	37.620	-122.366	01/01/00	17
KSJC	San Jose International Airport	17.98	0	0.00	37.359	-121.924	01/01/00	17
KSTS	Santa Rosa Sonoma County Airport	38.10	9	0.53	38.500	-122.817	01/01/00	17
KSUU	Fairfield / Travis Air Force Base	18.90	0	0.00	38.267	-121.950	01/01/00	17
KVCB	Vacaville Nut Tree Airport	32.00	0	0.00	38.378	-121.959	01/01/00	17
LAHC1	La Honda	245.06	0	0.00	37.305	-122.255	01/01/00	17
LOAC1	Los Altos	164.29	0	0.00	37.355	-122.142	01/01/00	17
LSGC1	Los Gatos	561.44	1	0.06	37.204	-121.951	01/01/00	17
LTRC1	Las Trampas	536.45	46	2.71	37.834	-122.067	01/01/00	17
LVFC1	Livermore Fire Department	95.71	0	0.00	37.655	-121.823	08/15/11	5.3
LVMC1	Mallory Ridge	593.75	2	0.12	37.817	-121.779	01/01/00	17
MDEC1	Middle Peak	712.93	1	0.08	37.928	-122.587	05/17/04	12.5
MIPC1	Poverty	629.72	30	2.07	37.443	-121.771	05/11/02	14.5
NBRC1	Big Rock	457.20	0	0.00	38.039	-122.570	09/30/03	13.3
OKSC1	Oakland South	333.76	10	0.59	37.786	-122.145	01/01/00	17
ONOC1	Oakland North	427.63	35	2.06	37.865	-122.221	01/01/00	17
OVYC1	Olema Valley	11.28	0	0.00	38.043	-122.796	05/23/05	11.5
PEAC1	Calaveras Road	374.90	52	3.06	37.553	-121.844	01/01/00	17
PIBC1	Black Diamond	487.68	0	0.00	37.950	-121.884	01/01/00	17
PLEC1	Briones	441.96	4	0.24	37.934	-122.118	01/01/00	17
PUGC1	Pulgas	196.29	0	0.00	37.475	-122.298	01/01/00	17
RJSC1	San Jose	205.74	0	0.00	37.398	-121.807	03/10/08	8.8
RSAC1	Santa Rosa	182.58	2	0.12	38.478	-122.712	01/01/00	17
RSPC1	Rose Peak	932.69	64	3.76	37.502	-121.736	01/01/00	17
TT119	Cordoza Ridge	710.49	0	0.00	37.168	-121.528	12/21/11	5
WDAC1	Woodacre	426.72	0	0.00	37.991	-122.645	05/24/03	13.5

To better contextualize and understand the impact of Diablo wind events on wildfires and fire season in northern California, live fuel moisture data from the National Fuel Moisture Database (<https://www.wfas.net/index.php/national-fuel-moisture-database-moisture-drought-103>) were used to illustrate the state of the fuels throughout the year and how they correspond with identified Diablo wind event frequency. Three Chamise (*Adenostoma fasciculatum*) sampling sites were used: Clayton Ranch (2008-2016), Blackberry Hill (2009-2016), and Saratoga Summit (2012-2016). Monthly averages were

computed for both old and new growth for each site, and then both were averaged across all stations to get one representative monthly live fuel moisture value for the SFBA (Fig. 2).

Fig 2. Average number of events per month. Dashed line is monthly average fuel moisture content (LFM) obtained from three sites in the SFBA.

Finally, the 32-km resolution North American Regional Reanalysis (NARR) model was used to construct a synoptic composite using the events identified through wind speed, direction, and relative humidity. NARR output was analyzed at the closest hour available to the time of maximum wind speed of each event.

1.3 Results

1.3.1 Spatial Distribution

Geographical extent of Diablo winds has been poorly defined in previous studies. Monteverdi (1973) described the Santa Ana Weather Type (later named “Diablo winds”) as a phenomenon local to the eastern region of the SFBA, specifically the Oakland-Berkeley Hills. Similarly, Routley (1991) described Diablo winds as local to the Oakland area. As far back as 1883, Diablo winds have been recognized as dangerous wind storms within a larger region of Northern California (“North Winds” 1883). Fig. 1 illustrates that Diablo wind events occur throughout the SFBA (including the northern region) with a heavy concentration of events along the higher elevations of the Coast Ranges. While events at near-coastal stations were infrequent, it is important to consider the impact these northeasterly winds could have on areas more prone to a coastal wind and marine influence. The spatial distribution of Diablo wind events is summarized in Fig. 1 and Table 1. Diablo wind events most frequently impact stations at the higher elevations of the Coast Ranges, particularly in the Diablo Range which is east of the San Francisco bay. There are also a higher number of events in the northern region including Hawkeye RAWS (HWKC1) at 616 m MSL and even at lower elevations in the region at the 27 m MSL (KO69). Overall, the spatial extent of Diablo events is limited to the higher elevation sites in the Coast Ranges of the SFBA.

1.3.2 Event Frequency

The mean annual frequency of events over the 17-year climatology was 2.5 (Fig. 3). The most active year was 2014 with 6 events, 3.5 above the mean. The most inactive year

was 2016 with no recorded events. There were no recorded events during the months of July and August during the study period, though events did occur in June. The months of October, January, and November show the highest frequency of Diablo wind events, while summer events are much less common (Fig. 2).

Fig 3. Total number of recorded events per year. Annual mean indicated by dashed line.

The station with the highest frequency of Diablo wind events was the Knoxville Creek (KNXC1) RAWS with just over 7.5 events per year on average. While not the highest elevation station, it is the furthest north. KNXC1 may be more sensitive to north winds that commonly flow through the Sacramento Valley, causing it to record a much higher frequency of events. Rose Peak (RSPC1), the highest elevation station, recorded 3.76 events per year. Calaveras Road RAWS (PEAC1), at only about 375 m in elevation, had the third highest average annual event frequency, at 3.06 events per year. Six of the remaining stations had between 1 and 3 events per year. Sixteen stations had at least one

event in the 17-year climatology but averaged less than one event per year. The remaining 17 stations had no recorded events over the 17-year climatology, or during the station's history for those with less than 17 years of data (Table 1).

From March until November, seasonal warming and increased solar angle causes fuel temperatures to rise, as well as curing and dehydration of dead and live fuels, bringing them closer to their ignition point (Rolinski et al. 2016). May through October in the SFBA represents a higher fire danger due to lower fuel moistures and higher fuel temperatures. Diablo wind events that occur during this time present an extreme fire danger to even urbanized areas, as multiple past fires have demonstrated. The most recent fire events of Napa and Sonoma counties (October 8-9, 2017) were driven by Diablo winds and were nearly identical to the Northern California fires of September 1964 (McCallum 2017). The East Bay Hills has experienced at least four major fires, all intensified by Diablo winds, that destroyed multiple structures in the wildland urban interface (Routley 1991). Three of those fires: Berkeley Fire (September 17, 1923), Fish Canyon Fire (September 22, 1970), and the Berkeley Hills/Tunnel Fire (October 19-20, 1991), occurred during this season of high fire danger. An additional fire, the Wildcat Canyon Fire (December 14, 1980), occurred during the winter and was contained fairly quickly as the wind was not as strong and persistent as the other cases. The most critical time of fire danger in the SFBA is during the months of October and November when Diablo events are more likely to occur within the season of low fuel moistures and higher fuel temperatures (Fig. 2). Not only are live fuel moistures lower during the autumn months, Diablo events tend to cause drying of the one and ten hour dead fuel moistures,

increasing fire potential even further. Drier winters in Northern California can present the same fire danger for May when Diablo events are still frequent, as well as the summer months in the rare occasion of a summer Diablo. Additionally, in years with low winter precipitation, increased fire danger can occur during the winter season when Diablo wind event frequency is also high.

1.3.3 Synoptic Composite

Synoptic composites are used to understand the overall distribution of pressure systems that give rise to Diablo wind events. The synoptic composite in Fig. 4 shows an inverted pressure trough along the coast of California during the time of maximum wind speed for the 43 recorded events. The inverted trough occurs near the surface and extends northward from an area of low pressure that is located in the southwestern US and southern California (Brewer et al. 2012). Fig. 4 shows the mean sea level maximum is located over the Northern Great Basin and Columbia Plateau in Eastern Oregon and Southern Idaho. A steep surface pressure gradient exists between central Oregon and central California as the most northern extent of the trough is near the Oregon and California border. The 500 mb geopotential height contours run nearly parallel to the California coast where the upper-level ridge is positively tilted transitions to a trough over the Intermountain West.

Fig 4. NARR reanalysis composite of mean sea level pressure (colored contours) and 500 mb geopotential heights (black contour lines) for time of maximum wind speed.

Fig. 5 shows the synoptic composite of surface dew point temperature and 10-m winds for the same time as in Fig. 4. During the time of maximum wind speed, surface winds are northerly in Sacramento Valley while winds in the Coastal Ranges are northeasterly, including the Diablo Range east of the SFBA. Additionally, winds are easterly over the western slope of the Sierra Nevada and Cascade Mountains in northern California. The northeasterly surface winds develop in south central Oregon near the boundary of the inverted pressure trough and extend through most of northern California. In addition to the northeasterly winds over the SFBA Coastal Ranges, a decrease in dewpoint (from 0 to -8 °C) occurs in the higher elevation areas. The lowest dewpoints are observed to occur in the higher elevations of the central Sierra Nevada, as expected due to drier air aloft. The highest dewpoints occur in the Sacramento Valley and are

associated with lower elevation and marine influence with the drier air overriding the more humid near-surface air mass. Overall, the synoptic composite indicates that Diablo wind events are associated with an inverted pressure trough that causes offshore, easterly winds to occur over the Coastal Ranges of the SFBA bringing drier air to the region.

Fig 5. NARR reanalysis composite of dewpoint temperature (colored contours) and 10-m winds at time of maximum wind speed.

The synoptic composite generated from the 17-year climatology is consistent with Monteverdi's (1973) synoptic compilation of "Santa Ana Weather Type" (Diablo) events that demonstrated anticyclone placement either in the Pacific Northwest or in the Great

Basin. In contrast, Santa Ana wind events occur when the center of a high pressure ridge is over the Great Basin, and a surface low is off the coast of California (Raphael 2003; Abatzoglou et al. 2013). The synoptic analysis presented here may be of value for forecasters and fire managers if applied operationally.

1.4 Discussion and Summary

Diablo wind events are strong, dry northeasterly, offshore winds local to the SFBA, driven by a surface pressure gradient that forms in response to an inverted surface pressure trough that develops over California. The synoptic characteristics are associated with a positively-tilted 500 mb ridge centered over the California coast. A 17-year climatology was conducted to understand the frequency and develop criteria for this wind phenomena. Winds from the NE quadrant of 6 m s^{-1} or greater with the relative humidity below 20 percent were identified as Diablo wind events. While Diablo winds occur nearly year-round, they are absent during the months of July and August, and most frequent in October, January, and November. The mean annual frequency of Diablo events was 2.5 and the highest monthly frequency occurred in October which corresponds to critical low live fuel moistures in California that increase the potential for wildfire ignitions and potential for extreme fire behavior. The strong winds and low relative humidity during Diablo wind events create an environment for extreme fire behavior in the SFBA.

Although Diablo winds have historically been grouped under “Santa Ana Type” events limited to the Oakland-Berkeley Hills region, Diablo winds, in fact, occur throughout the SFBA including the Coastal Range north of the SFBA and exhibit some

differences from the Santa Ana winds. Santa Ana wind events require surface high pressure to be located over the central Great Basin, Diablo wind events, however, occur when an inverted trough forms over California and extends through central Oregon with lower surface pressure near the California coast. At times, Diablo wind events can precede a Santa Ana event by about 12- 24 hours.

Extreme fire behavior in the SFBA is often associated with Diablo wind events of varying intensities. For example, the Tunnel fire that occurred in the East Bay Hills on October 20, 1991 was a devastating fire where 3,354 structures were destroyed and 25 lives were lost (Routley 1991). During this event, Diablo winds were responsible for causing a flare up from a small grass fire the day before. The maximum recorded wind speed at KOAK, southwest of the Tunnel Fire, was 10 m s^{-1} and it was estimated that winds in the East Bay Hills were in excess of 10 m s^{-1} (Pagni 1993). The resulting blaze was one of the worst catastrophes in California's history in regards to lives lost (CalFire 2017) and structures destroyed (CalFire 2018). The recent 2017 Wine Country Fires occurred during a more intense Diablo wind event with sustained winds in excess of 20 m s^{-1} in some areas. Collectively, the Wine Country Fires are now among the deadliest and most destructive fires in California's history.

While this study presents a classification of Diablo wind events, it was limited to 17 years of surface station data, as few stations in the SFBA were installed prior to that time. In that regard, some stations used for the analysis of the spatial distribution of Diablo events may be prone to exposure errors caused by poor siting of the station such that the station does not sample northeasterly winds well. This can be a result of tall vegetation

upwind of the station, for example. Furthermore, while the goals of this study were to characterize the climatology and spatial characteristics of Diablo wind events, further research focused on the local dynamical forcing driving Diablo winds is needed to better understand their impact on fire behavior in and around the populated regions of the San Francisco Bay Area.

CHAPTER 2

Numerical Simulations and Mesoscale Dynamics of Diablo Winds

Abstract

Diablo winds are dry downslope wind events that can generate extreme fire behavior in the San Francisco Bay Area of Northern California. Mesoscale numerical simulations of three Diablo wind events were used in conjunction with surface observations to examine how mesoscale processes affect the location and intensity of Diablo winds. All three events were associated with significant drying and sustained wind speeds of 13 to 22 m s⁻¹. Only one of the events initiated an increase in air temperatures, consequently, Diablo events are not always associated with warming. Mean sea level pressures showed an inverted trough over the California coast, with pressure gradients directed down the Sacramento Valley. Numerical simulations of the three events were able to capture mountain lee waves, downslope winds, and in two of the cases, a hydraulic jump structure.

2.1 Introduction

Extreme fire behavior in California is often associated with strong offshore wind events produced when a ridge of high pressure moves over the Great Basin, that can lead to downslope winds in the lee of mountainous terrain (Werth et al. 2011). A version of these winds local to the San Francisco Bay Area (Fig. 6) are called “Diablo” winds and have a history of generating catastrophic wildfires (Routley 1991; Smith et al. 2018). The most devastating fires in the area’s history have been driven by Diablo winds, most notably the Tunnel Fire of 1991 and the Wine Country Fires of 2017. On October 19, 1991, the Tunnel Fire started in the hills to the east of Oakland and Berkeley under fairly

benign weather conditions and was quickly brought under control. The next morning, a Diablo wind event surfaced, rekindling the fire and leading to a massive conflagration that killed 25 people and destroyed over 3,000 structures (Routley 1991). The Tunnel Fire has also been referred to as the East-Bay Hills Fire or Oakland Hills Fire. The Tubbs Fire, one of the “Wine Country Fires” of October 2017, began in Calistoga and raced into Santa Rosa within about four hours of ignition, some 20 km away. Driven by a particularly strong Diablo wind event, the Tubbs Fire killed 22 people and destroyed nearly 6,000 structures (CalFire 2018). A lesser recognized, but very strong Diablo event occurred in October of 2000, causing widespread damage to trees and power lines, forced airport delays, cut power to approximately 80,000 customers, and fanned the flames of several wildfires (Shallwani, DelVecchio, Jones, & Martin 2000). Wind gusts at Las Trampas RAWS in the hills east of Oakland measured 43 m s^{-1} while gusts of 37 m s^{-1} were recorded on Mt. Diablo. Not being associated with a historical fire, this event will be referred to in this paper as the Severe Diablo wind event.

Fig 6. San Francisco Bay Area of Northern California with weather station location depicted as black diamonds.

While the existence of Diablo winds has been acknowledged for some time, until recently little research has been done to understand them. Monteverdi (1973) introduced the “Santa Ana Type” winds and their resultant fire hazard to the East-Bay Hills region of the San Francisco Bay Area (SFBA). Since the 2017 fires of Northern California, the increased interest in Diablo winds has highlighted a need for further research into their climatology and dynamics. Smith et al. (2018) analyzed Diablo-like wind conditions across a broader range of California and found that occasionally Diablo winds occur in conjunction with Diablo-like winds in the Sierra Nevada. While more research is needed

to classify these events across the whole of Northern California, this study focuses on the dynamics of Diablo wind events local to the SFBA through high resolution numerical modelling and synoptic analysis. The structure of this paper is as follows: Section 2.2 describes research methods used, Section 2.3 details the results, and Section 2.4 presents a summary and conclusions of the paper.

2.2 Methods

Surface observations of wind speed, wind direction, temperature, and dewpoint temperature were taken from a combination of National Weather Service (NWS) stations and Remote Automated Weather Stations (RAWS). In using both networks, it must be remembered that NWS stations take wind measurements at a height of 10 m, while the RAWS measure winds at 6.1 m. During the time of the Tunnel Fire, the RAWS network had not yet been put into the Mesonet (Horel et al. 2002), so the Oakland Airport (KOAK) and Travis Air Force Base (KSUU) were used for surface observations. To extend the spatial extent of the observations, four additional stations were added to the analysis of the severe wind event of October 2000 and the Tubbs Fire of 2017. Lacking the RAWS to better compare the Tunnel Fire with these two events, surface variables of wind, temperature, and dewpoint temperature were calculated using the WRF model simulations in lieu of actual observations. The Oakland North RAWS (ONOC1) is located in the Berkeley Hills near the origin of the Tunnel Fire (Pagni 1993) which allows for a verification of Monteverdi's (1973) analysis of the fire hazard Diablo wind events can cause for this area. To the west of ONOC1 lies the ridge-top Las Trampas RAWS (LTRC1), slightly higher in elevation. The Santa Rosa RAWS (RSAC1) is

located on a hillside just above Coffey Park, Santa Rosa, a neighborhood completely devastated by the Tubbs Fire. Northwest of Santa Rosa is the Hawkeye RAWS (HWKC1) just to the northeast of Geyserville, located on a flat ridge. Synoptic analysis of each event was completed using 32 km North American Regional Reanalysis (NARR) model output.

High resolution Weather Research and Forecasting (WRF) model simulations were conducted on three Diablo wind events: the Tunnel (East Bay Hills) Fire of Berkeley, California in October, 1991, the Tubbs Fire of the Santa Rosa, California area of October, 2017, and the Severe Diablo wind event in October of 2000. The three simulations featured two-way nesting over three domains (Fig. 7) of 10.8 km, 3.6 km, and 1.2 km horizontal resolution, with 60 vertical levels. Physics and boundary layer parameterizations are outlined in Table 2. The simulations were initialized with North American Regional Reanalysis (NARR) 32 km reanalysis data. Two vertical cross sections were taken from the simulations to compare across events and for two main areas frequently impacted by Diablo wind events. Cross section A (Fig. 7) intersects Coffey Park, crossing Mt. Saint Helena roughly perpendicular to the Mayacamas Mountains at a 30-degree bearing and ends in the Sierra Nevada Range. Cross section B crosses approximately perpendicular to the Diablo Range of the Coast Ranges at a 50-degree bearing after passing through the Berkeley Hills of the San Francisco Bay Area. Both A and B use data from the 3.6 km resolution domain. Cross sections C and D (shown in red) utilize the 1.2 km resolution domain and enable a finer scale inspection of

wind processes in the lee of the mountain ranges, at the same angles as corresponding cross sections A and B.

Fig 7. WRF domain configuration. Vertical cross sections A and B shown in black, and C and D shown in red.

Table 2. Summary of WRF physics schemes

Parameter	Scheme
Microphysics	WRF Single-Moment 3 class (WSM3) scheme
Long Wave Radiation	Rapid Radiative Transfer Model (RRTM)
Short Wave Radiation	Dudhia
Surface Layer	Eta similarity theory
Land Surface	Noah Land Surface Model
Boundary Layer	Mellor-Yamada-Janjic (MYJ)

2.3 Results

2.3.1 WRF Model Validation

Numerical simulations of all three events matched observations well at all stations used in the analysis. Sample model validations are shown in Figs. 8, 9, and 10 for KSUU, which besides KOAK, was the only station available for all three events. There was an occasional discrepancy between the model and the observed variables, particularly with temperatures and dewpoint temperatures. For the Tunnel Fire event, the model showed a difference from observed temperatures (Fig. 8c) of approximately 7 °C, and a dewpoint temperature (Fig. 8d) discrepancy of about 6 °C. There was also a significant difference in dewpoint temperature for the Severe event (Fig. 9d) where the WRF simulation was unable to capture the variation in moisture and produced values that were too dry. This may be related to land surface model or radiation parameters, and would be something to investigate in future simulations. Overall, the model was able to reproduce surface observations to a degree sufficient to verify its usefulness.

Fig 8. WRF model validation at KSUU for the Tunnel Fire event for (a) wind speed, (b) wind direction, (c) temperature, and (d) dewpoint temperature.

Fig 9. WRF model validation at KSUU for the Severe Diablo event for (a) wind speed, (b) wind direction, (c) temperature, and (d) dewpoint temperature.

Fig 10. WRF model validation at KSUU for the Tubbs Fire event for (a) wind speed, (b) wind direction, (c) temperature, and (d) dewpoint temperature.

2.3.2 Surface Observations

a) Tunnel Fire

On October 20, 1991 at 0700 UTC, a Diablo wind event started at KSUU and registered at KOAK at 1900 UTC. Sustained wind speeds reach a maximum of 13 m s^{-1} at KSUU (Fig. 11a) and remained steady from the northeast quadrant throughout the event (Fig. 12a). A corresponding 6°C increase in temperature (Fig. 13a) and a 4°C decrease in dewpoint temperature (Fig. 14a) at KSUU can be seen, even though the event started during night hours. While winds were primarily northeasterly at KOAK (Fig. 12a), there was more directional variability throughout the event. KOAK did not experience the same disruption in nocturnal cooling as KSUU (Fig. 13a), though the temperature was 6°C higher during the peak hours than the day before. At KOAK, there

was also a more brief dewpoint temperature drop (Fig. 13a) than that of KSUU, and it corresponded with the increase in wind speed and air temperature.

Fig 11. Tunnel Fire event (a) observed wind speed, (b) WRF simulated wind speed, and observed wind speed during the (c and d) Severe Diablo event, and (e and f) the Tubbs Fire event.

Fig 12. Tunnel Fire event (a) observed wind direction, (b) WRF simulated wind direction, and observed wind direction during the (c and d) Severe Diablo event, and (e and f) the Tubbs Fire event.

Fig 13. Tunnel Fire event (a) observed temperature, (b) WRF simulated temperature, and observed temperature during the (c and d) Severe Diablo event, and (e and f) the Tubbs Fire event.

Fig 14. Tunnel Fire event (a) observed dewpoint temperature, (b) WRF simulated dewpoint temperature, and observed dewpoint temperature during the (c and d) Severe Diablo event, and (e and f) the Tubbs Fire event.

The WRF simulation of surface variables showed a maximum sustained wind speed of 17.5 m s^{-1} at HWKC1, about 13 m s^{-1} at RSAC1 and ONOC1, and 10.5 m s^{-1} at LTRC1 (Fig. 11b). Simulated wind direction (Fig. 12b) reveals a wind shift to the northeast quadrant across all stations except RSAC1, which remained variable throughout the event. Temperatures (Fig. 13b) showed a less discernible pattern and dewpoints, though they did show a decrease during the event, weren't significantly different than the day before (Fig. 14b).

b) Severe Diablo Event

On October 21, 2000 at 2015 UTC, a Diablo wind event began at LTRC1. The remaining stations followed a number of hours later, with the exception of RSAC1 that maintained southwesterly winds throughout the event. At KSUU, the maximum sustained wind speed was 15 m s^{-1} (Fig. 11c), slightly higher than during the Tunnel Fire, though the event lasted longer. The event was again shorter at KOAK than KSUU, though at 20 m s^{-1} , this event recorded the highest sustained wind speed for KOAK during a Diablo wind event from 1985 to present. LTRC1 had a maximum sustained wind speed of 18 m s^{-1} with HWKC1 and ONOC1 following closely behind at 16.5 m s^{-1} and 15 m s^{-1} respectively (Fig. 11d). KOAK experienced a 5°C drop in dewpoint temperature (Fig. 14c), while KSUU was more variable. The dewpoint temperature at the remaining stations (Fig. 14d) gradually began decreasing, then had a sharp drop, then a subsequent gradual decrease. RSAC1 experienced the same drop in dewpoint temperature, even though winds were generally southwesterly. Temperatures followed a diurnal pattern, though the lows were slightly warmer than the night before (Fig. 13c, d).

c) Tubbs Fire

As with the Severe case in 2000, this Diablo event first began at LTRC1. Over the next 16 hours, the event registered at the remaining stations, with the exception of KOAK that did not experience high winds with this event. Maximum sustained wind speed at HWKC1 reached 21.5 m s^{-1} , LTRC1 was the second windiest at 15 m s^{-1} , while RSAC1 and ONOC1 reached a maximum of 12 and 11 m s^{-1} respectively (Fig. 11e, f). Though KOAK did not have strong wind speeds, the dewpoint temperature dropped nearly 16°C

over three hours (Fig. 14e). HWKC1 and RSAC1 experienced the same 16 °C decrease over about five hours (Fig. 14f). The remaining stations dropped off more gradually, with approximately the same decrease in dewpoint temperature (Fig. 14e, f). At 1100 on the 9th, the Tubbs Fire front passage can be seen at RSAC1 as a sharp increase in temperature (Fig. 13f), wind shift (Fig. 12f), and small increase in dewpoint temperature (Fig. 14f).

2.3.3 Synoptic Analysis

Fig. 15 a-c shows the mean sea level pressure (MSLP) at the closest hour to the start of each event. For the Tunnel Fire (Fig. 15a), the MSLP at the start of the event exhibits an inverted trough pattern. The beginning of both the Severe event and the Tubbs Fire event show a more north-south gradient configuration, however, as Fig. 15e and 15f show, both of these events obtained the inverted trough pattern at the surface within a few hours of the start time.

Fig 15. Mean sea level pressure for the onset of (a) Tunnel Fire event, (b) Severe event, (c) Tubbs Fire event, and demonstration of inverted trough for (d) Tunnel Fire event, (e) Severe event, and (f) Tubbs Fire event.

A positively tilted ridge can be seen in the 300 mb, 500 mb, and 700 mb geopotential heights in Fig. 16, with California wedged situated between a ridge to the west and a trough to the east, favoring northerly geostrophic flow over California. At the beginning of the Diablo event that led to the rapid growth of the Tunnel Fire (Fig. 16a), the geostrophic flow runs parallel to the Sacramento Valley down the center of California. At the start of the Severe event (Fig. 16b), the 300 mb and 500 mb height lines also run parallel along the length of the valley, though a sharp trough has formed immediately east

of the ridge, with a closed low at 700 mb. The height contours at the start of the Tubbs Fire event (Fig. 16c) are not quite as parallel to the state as with the previous two events.

Fig 16. Geopotential height at 300 mb, 500 mb, and 700 mb, for the onset of (a) the Tunnel Fire event, (b) the Severe event, and (c) the Tubbs Fire event.

2.3.4 Numerical Simulation Analysis

Vertical cross sections of dewpoint temperature and wind barbs are shown in Figs. 17-19 with cross section A (Fig. 7) on the left and cross section B on the right. At the beginning of all three events, surface winds were flowing north through the Sacramento Valley. During the onset of the Tunnel Fire and Severe events (Figs. 17,18 a,b), winds aloft were likewise north, with a slight down sloping off the Sierras as seen in the isentropes. Mountain waves propagated vertically through the atmosphere over the North Bay Coast Ranges early in both events, though wave propagation was more shallow over the Diablo Range during the Tunnel Fire event than the Severe event. At the start of the Tubbs Fire wind event (Fig. 19 a,b), winds aloft were west-northwest and downslope winds off the Sierras had yet to begin, indicating that a connection to downslope flow across the Sierras is not a necessary condition for the onset of strong Diablo winds. Downslope winds off the Sierras are a more prominent feature in cross section B (Figs. 17-19 b, d, f) than in cross section A (Figs. 17-19 a, c, e) across all three events. Wind speeds aloft

were higher during the Severe event (Fig. 18) than during either of the other two, demonstrating stronger upper level support and synoptic forcing than was available for the Tunnel Fire and Tubbs Fire events.

Fig 17. Vertical cross section of WRF simulation at 3.6 km horizontal resolution during the Tunnel Fire wind event. Dewpoint temperatures in colored shading. Plots on the left are through Coffey Park, and plot on the right are through the Berkeley Hills. Wind barbs are in m s⁻¹ and contour lines are potential temperature.

Fig 18. Vertical cross section of WRF simulation at 3.6 km horizontal resolution during the Severe Diablo wind event. Dewpoint temperatures in colored shading. Plots on the left are through Coffey Park, and plot on the right are through the Berkeley Hills. Wind barbs are in m s⁻¹ and contour lines are potential temperature.

Fig 19. Vertical cross section of WRF simulation at 3.6 km horizontal resolution during the Tubbs Fire event. Dewpoint temperatures in colored shading. Plots on the left are through Coffey Park, and plot on the right are through the Berkeley Hills. Wind barbs are in m s⁻¹ and contour lines are potential temperature.

Surface dewpoint temperatures (Figs. 17-19) were similar across all three events, though the Severe event (Fig. 18) had slightly lower dewpoints at the surface. The Severe event also had the driest air aloft particularly in comparison with the Tunnel Fire event (Fig. 17) which maintained dewpoints above -45 °C throughout most of the troposphere.

A layer of very dry air was present around 4 km AGL in both the Severe and Tubbs Fire events, with an area of isentropic drawdown over the Coast Ranges shown clearly in Fig. 16c.

Near the start of the Tunnel Fire event, strong north to northeast winds began to downslope over Mt. Saint Helena (at 25 km mark in Fig. 20 a, b) as seen in the terrain following isentropes. A hydraulic jump structure on the lee side is evident as the isentropes ascend sharply as they near the base Mt. Saint Helena (Fig. 20b), leading to a decoupling of surface winds and nearly straight-line downstream of the jump. Above the region of downslope flow, a self-induced critical level can be seen as a layer of wind shear where the wind speed is approximately 0 m s^{-1} . A self-induced critical level (or wave-induced critical layer) occurs as mountain waves break, leading to wave amplification and reflection towards the surface (Clark and Peltier 1984). At the same time over the Diablo Range (Fig. 21 a, b), winds were north-northeast with no indication of mountain waves. As wind speeds increased, winds over the Berkeley Hills (Fig. 21c) began to downslope with decoupling in the lee of the slope. A self-induced critical layer formed west of both ranges (Figs. 20, 21 d), directing wave energy towards the surface, which caused trapped lee waves in the North Bay and northeasterly winds to surface in the East Bay. As the critical layer extended further over Santa Rosa (Fig. 20e) wind flowed along the surface, decoupling to the west of Coffey Park. Towards the end of the event, the core of the strongest winds (Figs. 20, 21 f) detached from the surface.

Fig 20. Vertical cross section of streamwise winds from 1.2 km horizontal resolution WRF domain for Tunnel Fire event for the North Bay. Contour lines are potential temperature (K) and wind barbs are in m s^{-1} .

Fig 21. Vertical cross section of streamwise winds from 1.2 km horizontal resolution WRF domain for Tunnel Fire event for the East Bay. Contour lines are potential temperature (K) and wind barbs are in m s^{-1} .

Unlike the Tunnel Fire event, as downslope winds begin over Mt. Saint Helena during the Severe Diablo event (Fig. 22), there was no hydraulic jump formation and winds remained north to slightly northwest. Winds aloft approached 40 m s^{-1} and mountain waves formed in the lee of Mt. Saint Helena. Further south, over the Berkeley hills, strong north winds were present through the lower 8 km of the atmosphere and

reached speeds of 10 to 15 m s^{-1} at the surface (Fig. 23). At 0600 UTC on October 22, winds of 15 to m s^{-1} surfaced over both areas and reached 35 to 50 m s^{-1} from 6 km to 8 km AGL. Below the crests of the mountain waves over Santa Rosa, winds were calm (Fig. 22 d). A layer of directional wind shear appeared between 1 and 3 km AGL over both the North and East Bay, causing winds to surface (Figs. 22, 23 e). Shortly after, wind speeds decreased, and the event dissipated.

Fig 22. Vertical cross section of streamwise winds from 1.2 km horizontal resolution WRF domain for Severe Diablo wind event for the North Bay. Contour lines are potential temperature (K) and wind barbs are in m s^{-1} .

Fig 23. Vertical cross section of streamwise winds from 1.2 km horizontal resolution WRF domain for Severe Diablo wind event for the East Bay. Contour lines are potential temperature (K) and wind barbs are in m s^{-1} .

The Diablo event that led to the Tubbs fire behaved very similar to that of the Tunnel Fire. In the North Bay, downslope winds began in the lee of Mt. Saint Helena, forming a hydraulic jump structure about 5 km west of the base of the mountain, and decoupling the strong northeast winds from the surface (Fig. 24 a, b). Meanwhile, winds over the East Bay were north and lacked high amplitude wave structures (Fig. 25 a, b). As the winds

strengthened, the hydraulic jump downstream of Mt. Saint Helena dissipated underneath a layer of wind shear, with shooting flow remaining connected to the surface for some distance downstream (Fig. 24 c, d). Winds over the East Bay became downslope and intensified (Fig. 25 c, d). Subtle changes in the speed and direction of cross barrier flow over Mt. Saint Helena (Fig. 24 b, c, d) disrupted the wave-induced critical layer, once again decoupling the strong winds from the surface (Fig. 24 e, f).

Fig 24. Vertical cross section of streamwise winds from 1.2 km horizontal resolution WRF domain for Tubbs Fire event for the North Bay. Contour lines are potential temperature (K) and wind barbs are in m s^{-1} .

Fig 25. Vertical cross section of streamwise winds from 1.2 km horizontal resolution WRF domain for Tubbs Fire event for the East Bay. Contour lines are potential temperature (K) and wind barbs are in m s^{-1} .

The three theories on the initiation of downslope windstorms (Durrán 1990) are evident in the three simulations above. Long's (1953) hydraulic theory can be seen clearly in each event in the lee of Mt. Saint Helena (Figs. 20a,b, 22a, 24b) as winds accelerate downslope, transition to a jump structure, and cause an offshoot of strong winds above the surface on the other side. The absence of a hydraulic jump structure over

the East Bay Hills during these events (except possibly near the end of the Tubbs Fire event in Fig. 25f) supports the conclusion of Durran (1990) that downslope windstorms will occur only if the mountain height is greater than that of a threshold determined by stability and wind speed. The breaking of vertically propagating waves (Figs 20 and 24), consistent with Clark and Peltier (1984), create the “wave-induced critical layer” that propagates across the domain, causing the core of strong winds to surface. The Severe event in October of 2000 (Fig 22) appears to be an example of vertically propagating mountain waves reflecting downward toward the surface, as discussed in Eliassen and Palm (1960). Vertically propagating waves (Fig. 23c) transition to trapped lee waves (Fig. 23d) as a layer of wind shear appears at around 1 km AGL, limiting wave energy transfer to higher levels (Crook 1987).

2.3.5 Fire Behavior Analysis

The Tunnel Fire (also called the East Bay Hills Fire) began on October 19, 1991 just after noon on a warm, calm day in the Berkeley Hills region of the San Francisco Bay Area (Routley 1991). In just over an hour, responding agencies had the fire under control and continued monitoring and “mopping up” the fire overnight. The next morning, winds started to increase and caused a number of flare-ups within the fire perimeter. By 11 am, a Diablo wind had surfaced over the area as evident by the sharp increase in wind speed at KOAK (Fig. 11a) and corresponding drop in dewpoint temperature (Fig. 14a), and the fire quickly grew to a massive conflagration. When the winds finally abated around 7:30 pm, the fire’s forward rate of spread halted.

Approximately 27 years later, in Napa County, California, the Tubbs Fire started during a strong Diablo wind event. The ignition occurred around 9:43 pm on October 8, 2017 and within three hours, had reached the city of Santa Rosa (Watkins et al. 2017) roughly 20 km away. Radiance data from the Geostationary Satellite (GOES) 16 (Fig. 26) chronicles the fire progression over six hours. The fire jumped a major highway and completely decimated the community of Coffey Park, an urbanized residential area in Santa Rosa. Similar to the Tunnel Fire, the forward advance of the Tubbs Fire was halted when Diablo winds abated, having decoupled from the surface as shown in Fig. 24e.

Fig 26. Progression of Wine Country Fires derived from LB1 Radiance data from GOES 16. Tubbs Fire is circled in white.

Both the Tunnel and Tubbs fires exhibited extreme fire behavior with long range spotting and very rapid rates of spread that quickly exceeded control efforts by responders. The Tunnel Fire was fairly benign before the onset of Diablo winds, but fire behavior escalated quickly with the arrival of these strong, dry, downslope winds. The Tubbs Fire began during a strong Diablo wind event and rapidly raced out of control. Forward rate of spread was halted on both fires only when Diablo winds abated.

2.4 Summary and Conclusions

The three Diablo wind events in this study began as north winds driven by a surface pressure gradient with the ridge located to the north and west of the SFBA. As winds intensified and shifted northeasterly, the flow was directed across the Coast Ranges and driven downslope on the lee side. Structurally, the Tunnel Fire wind event and Tubbs Fire wind event were similar in their hydraulic jump formation and establishment of a self-induced critical level that attached the flow to the surface. The Severe event had minimal directional wind shear throughout the lower atmosphere until near the end of the event, when winds became southwest at 1 km AGL, causing the winds to run downslope and attach to the surface. As Smith et al. (2018) found, while these events produced high wind speeds and significant drying of the air, there was not always a corresponding temperature increase. The exception was the Tunnel Fire event that brought nocturnal warming to Travis Air Force Base (KSUU) and an increase in daily maximum temperature at Oakland International Airport (KOAK) of 6 °C. As seen in the model simulations, air from the surface to 8 km AGL became drier with the onset of the events

and in some cases, the very dry air aloft was mixed to the surface through downslope winds.

From past events, it is clear that Diablo winds can produce extreme fire behavior from strong winds transporting embers and initiating spot fires, as well as inducing fire spread that is too rapid to be contained by responders. In addition to the Tunnel Fire, the East Bay Hills has experienced 3 other notable wildland fires associated with Diablo winds: the Berkeley Fire of 1923, Fish Canyon Fire of 1970, and the Wildcat Canyon Fire of 1980 (Routley 1991). All of those, with the exception of the Wildcat Canyon Fire, occurred during the fall when live and dead fuels tend to be dried out and primed for ignition. The Wildcat Canyon Fire happened in December and winds were not as intense as during the other three fires. The Wine Country Fires of 2017 bore a remarkable resemblance to the Northern California Fires of September 1964, resulting in nearly identical fire perimeters (McCallum 2017). As discussed by Nauslar, Abatzoglou, and Marsh (2018), land development in California's steep terrain introduces an ever-increasing number of people to fire hazards in the wildland-urban interface. As areas scorched by fire during the 2017 fire season begin to rebuild, it is even more important to study and understand the winds that drive these catastrophic wildfires.

Chapter 3

Summary and Future Work

3.1 Summary

This thesis provided an in-depth analysis of the Diablo winds of the SFBA, which has been sparsely studied in scientific literature. Chapter 1 provided the background behind offshore downslope wind events as they relate to other regions in California as well as a 17-year climatology and synoptic composite of 43 Diablo wind events. The strong, dry, downslope winds are driven by surface pressure gradients and with an upper level ridge contributing to strong northerly flow. The SFBA receives an average of 2.5 events per year, with the majority of events occurring in October when live fuel moisture is at its driest. Should a fire occur during one of these events, particularly during the dry season, extreme fire behavior can result in the form of very rapid fire growth and long range spotting.

High resolution numerical simulations of three significant Diablo events were presented in Chapter 2, with model validation showing good agreement with surface observations across all six weather stations used for analysis comparison. Event comparison demonstrated that Diablo events can occur with or without upper level support. Downslope winds occurred in all three events, though not always at the peak of the event. Self-induced critical levels can be produced by mountain wave activity on the lee of the mountain, reflecting wave energy back towards the surface. Two of the three events studied showed a hydraulic jump type structure downwind of the mountain that effectively decoupled the core of the strong winds from the surface. All three theories on

the production of downslope windstorms as discussed by Durran (1990) were observed in the three event simulations.

3.2 Future Work

In comparing the mountain wave dynamics between the North Bay and the East Bay, it is evident that regional flow characteristics can differ during a Diablo wind event. A number of explanations for this may exist (such as mountain height differences as well as contrasts in atmospheric stability due to proximity to the bay or ocean) and are worth further examination. Additional work will include calculation of the Froude number upstream from both the Diablo Range and the Coast Ranges of the North Bay during the three events presented here, which will describe the expected flow characteristics and help explain differences in outcome.

As the climatology conducted in this study used a limited number of surface weather stations, a more complete analysis could be gained from using reanalysis data to fill gaps left by surface stations and may possibly remove bias from station siting errors.

References

- Abatzoglou, J. T., R. Barbero, and N. J. Nauslar, 2013: Diagnosing Santa Ana winds in Southern California with synoptic-scale analysis. *Wea. Forecasting*, 28, 704–710, doi:<https://doi.org/10.1175/WAF-D-13-00002.1>.
- Blier, W., 1998: The sundowner winds of Santa Barbara, California. *Wea. Forecasting*, 13(3), 702-716.
- Brewer, M.C., C.F. Mass, & B. E. Potter, 2012: The West Coast Thermal Trough: Climatology and Synoptic Evolution. *Mon. Wea. Rev.*, 3820-3843.
- CalFire, 2017: Top 20 Deadliest California Wildfires. Accessed 15 December 2017, http://calfire.ca.gov/communications/downloads/fact_sheets/Top20_Deadliest.pdf
- CalFire, 2018: Top 20 Most Destructive California Wildfires. Accessed 21 February 2018, http://www.fire.ca.gov/communications/downloads/fact_sheets/Top20_Destruction.pdf
- Cao, Y., & Fovell, R. G., 2016: Downslope windstorms of San Diego County. Part I: a case study. *Mon. Wea. Rev.*, 144(2), 529-552.
- Clark, T. L., & Peltier, W. R., 1984: Critical level reflection and the resonant growth of nonlinear mountain waves. *J. Atmos. Sci.*, 41(21), 3122-3134.
- Crook, N. A., 1988: Trapping of low-level internal gravity waves. *J. Atmos. Sci.*, 45(10), 1533-1541.
- Durran, D. R., 1990: Mountain waves and downslope winds. *Atmospheric processes over complex terrain*, Amer. Meteor. Soc., 59-81.
- Eliassen, A., 1960: On the transfer of energy in stationary mountain waves. *Geophys. Publ.*, 22, 1-23.
- Fosberg, M. A., O'Dell, C. A., & Schroeder, M. J., 1966: Some characteristics of the three-dimensional structure of Santa Ana winds. *Res. Paper PSW-RP-30 Berkeley, CA: Pacific Southwest Forest & Range Experiment Station, Forest Service, US Department of Agriculture*; 35 p, 30.
- Horel, J., Splitt, M., Dunn, L., Pechmann, J., White, B., Ciliberti, C., ... & Burks, J., 2002: Mesowest: Cooperative mesonets in the western United States. *Bull. Amer. Meteor. Soc.* 83(2), 211-225.

- Jin, Y., Randerson, J. T., Faivre, N., Capps, S., Hall, A., & Goulden, M. L., 2014: Contrasting controls on wildland fires in Southern California during periods with and without Santa Ana winds. *J. Geophys. Res.: Biogeosciences*, 119(3), 432-450.
- Long, R. R., 1953: A laboratory model resembling the " Bishop-wave" phenomenon. *Bull. Amer. Meteor. Soc.*, 205-211.
- McCallum, K., 2017: Fire-scorched Fountaingrove in Santa Rosa focal point of debate over rebuilding. *The Press Democrat*, <http://www.pressdemocrat.com/news/7572376-181/fire-scorched-fountaingrove-in-santa-rosa?sba=AAS>
- Monterey, J. P., 1973: The Santa Ana Weather Type and Extreme Fire Hazard in the Oakland-Berkeley Hills. *Weatherwise*, 26(3), 118-121.
- National Wildfire Coordinating Group, 2018: *Glossary of Wildland Fire*. Accessed 9 September 2018, <https://www.nwcg.gov/glossary/a-z>
- Nauslar, N., Abatzoglou, J., & Marsh, P., 2018: The 2017 North Bay and Southern California Fires: A Case Study. *Fire*, 1(1), 18.
- NOAA, 2018: GOES-16 Lb1 Radiance. Comprehensive Large Array-Data Stewardship, accessed 16 May 2018, <https://www.bou.class.noaa.gov/saa/products/welcome>
- NOAA, 2017: National Operational Model Archive and Distribution System, accessed 08 November 2017, <http://nomads.ncdc.noaa.gov/>
- North Winds. (1883, June 11). *Daily Alta California*, 35. Accessed 22 August 2017, <https://cdnc.ucr.edu/cgi-bin/cdnc?a=d&d=DAC18830611.2.50>
- Null, J., 2000: Winds of the World. *Weatherwise*, 53(3), 36-40.
- Pagni, P. J., 1993: Causes of the 20 October 1991 Oakland hills conflagration. *Fire Saf. J.*, 21(4), 331-339.
- Raphael, M. N., 2003: The Santa Ana winds of California. *Earth Interact.*, 7(8), 1-13.
- Rolinski, T., Capps, S. B., Fovell, R. G., Cao, Y., D'Agostino, B. J., & Vanderburg, S., 2016: The Santa Ana wildfire threat index: methodology and operational implementation. *Wea. Forecasting*, 31(6), 1881-1897.
- Routley, J.G., 1991: The East-Bay Hills Fire. *U.S. Fire Administration Technical Report*, 060.

- Shallwani, P., DelVecchio, R., Jones, C., & Martin, M., 2000: Fear, Wind and Fire/ Gusts fan flames and, in Oakland hills, bring nervous flashbacks. *The San Francisco Chronicle*. Accessed 12 January 2017, <https://www.sfgate.com/bayarea/article/Fear-Wind-and-Fire-Gusts-fan-flames-and-in-2732493.php>
- Small, I., 1995: Santa Ana winds and the fire outbreak of fall 1993, *NOAA Technical Memorandum* NWS, WR-230.
- Smith, C., Hatchett, B., & Kaplan, M., 2018: A Surface Observation Based Climatology of Diablo-Like Winds in California's Wine Country and Western Sierra Nevada. *Fire*, 1(2), 25.
- United States Forest Service- Wildfire Assessment System, 2018: National Fuel Moisture Database. Accessed 14 April 2017, <https://www.wfas.net/index.php/national-fuel-moisture-database-moisture-drought-103>
- Watkins, D., Griggs, T., Lee, J.C., Park, H., Singhvi, A., Wallcae, T., & Ward, J., 2017: How California's Most Destructive Wildfire Spread, Hour by Hour. *The New York Times*. Accessed 15 January 2018, <https://www.nytimes.com/interactive/2017/10/21/us/california-fire-damage-map.html>
- Werth, P. A., and Coauthors, 2011: *Synthesis of knowledge of extreme fire behavior: volume I for fire managers*. USDA Forest Service, 144 pp.
- Whiteman, C. D., 2000: *Mountain meteorology: fundamentals and applications*. Oxford University Press.