Guidance on Using Upper-air Profiler Report

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PREPARED BY:

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This report contains the results of the upper-air wind profiler pilot study conducted as part of the California Energy Commission (CEC) project titled Comprehensive Open-Source Development of Next Generation Wildfire Models for Grid Resiliency (CEC agreement# EPC-18-026). Sonoma Technology performed this work as part of the Extreme Weather Team (Workgroup #1), under Task 3: Optimal Configuration of Weather Stations.

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Executive Summary

Sonoma Technology deployed and operated a sodar wind profiler instrument in northern California, which was used to collect upper-air data from July through October 2020. The purpose of the pilot study was to demonstrate the value of upper-air wind measurements to supplement surface wind observations, allowing utilities to better predict the onset of strong winds. This can help inform Public Safety Power Shutoff (PSPS) decisions and improve situational awareness during extreme wind events.

The instrument chosen for this project was an Atmospheric Systems Corporation (ASC) Model 2000 Sodar, which was deployed based on several environmental and logistical siting criteria. The data collected by the Sodar 2000 show wind speed and direction by time and vertical height, with a vertical resolution of approximately 20 m from about 80 to 600 m above ground level (AGL). While operations experienced some unforeseen challenges, the Sodar collected useful data and provided valuable insights for deploying upper-air instrumentation in high wind areas.

Study results using the Sodar 2000 dataset, as well as nearby upper-air and surface wind measurements, found that aloft wind data collected during a PSPS event can provide advance information and improve forecast capabilities to better predict high wind events that impact the surface and influence fire behavior. In addition, further research indicates aloft observations are useful in validating the real-time performance of predictive meteorological models. Therefore, the addition of upper-air instrumentation to the meteorological measurement network would enhance the ability to make good decisions regarding PSPS decisions and improve situational awareness during extreme wind events; and ultimately better protect communities, fire fighter's safety, and improve resource allocations.

Introduction

Overview and Background

Over the last decade, California has experienced its largest and most destructive fires in recorded history. During the past five years, extreme wind events, such as those present during northern California's 2017 Tubbs Fire, 2018 Camp Fire, and 2020 Glass Fire, have been the driving force behind many of California's largest fires. Extreme wind events often damage power lines, which have been associated with approximately half of the most destructive fires in California history.[1] In recent years, utilities have responded to severe weather and wind events by implementing PSPS events to help prevent wildfires and protect communities. However, PSPS events can leave communities and

[1] California Public Utilities Commission (https://www.cpuc.ca.gov/psps/).

essential facilities without power, which brings its own risks and hardships, particularly for vulnerable communities and individuals.[1] Improving short-term forecasts of extreme wind events helps inform PSPS decisions and improve situational awareness before and during fire weather events.

The regional winds that primarily drive red flag warnings[2] in northern and southern California are referred to as Diablo winds and Santa Ana winds, respectively. Diablo and Santa Ana winds are most common in the late summer through early winter; it is under these wind regimes that California typically experiences its largest and most destructive fires. These winds occur as high-pressure forms in the Great Basin and drives air over the Sierra Nevada Mountains (from the east) and down toward the Pacific Ocean (to the west and south). As winds flow over the Sierra Nevada Mountains, a variety of flow effects can occur. The descending air is compressed, and its relative humidity lowered resulting in strong, dry winds that desiccate vegetation (Werth et al., 2016). As the winds accelerate through canyons, they create strong gusts. Flow of a stable boundary layer air over topography can also create other complex and poorly understood or measured local accelerations. Numerical simulations of significant Diablo wind events reveal that contributions from both small-scale downslope winds and larger-scale flow interactions with terrain contribute to the Diablo winds' complex character (Bowers, 2018).

While a wealth of meteorological observation data are currently used for operational Numerical Weather Prediction (NWP) forecasts, the availability of boundary layer wind, temperature, and moisture profiles in the observation networks is limited. In northern California, NOAA launches twice-daily radiosonde (balloon) soundings from Oakland International Airport. In addition, NOAA operates radar wind profilers at two coastal sites (Bodega Bay, and McKinleyville) and two inland sites (Twitchell Island and Oroville), and Naval Postgraduate School operates a coastal profiler at Fort Ord. These sites provide important data to support NWP and weather forecasting activities; however, the radiosonde data are not frequent enough to capture the evolution of the wind events, and the profilers are not located in regions where Diablo winds tend to pose the greatest fire weather risks. Targeted deployments of ground-based boundary layer sensors such as wind profilers show promise for improving local and regional NWP forecasts for wind energy applications (Bianco et al., 2019; Wilczak et al., 2019). These same technologies can be used to improve forecasts of high wind events and extreme fire weather.

Pilot Study Objectives

The primary objective of the upper-air pilot study was to demonstrate how utilities can use upper-air wind data to improve short-term (up to 15 hours) and very-short-term (from 0 to 3 hours) forecasts of high wind events and to enhance situational awareness during extreme weather events. A secondary objective was to determine how best to integrate upper-air data into operational data

[2] A red flag warning is a weather forecast warning issued by the National Weather Service to inform the public, firefighters, and land management agencies that conditions are ideal for wildland fire ignition and rapid spread. Red flag warnings are typically issued when winds are high, temperatures are high, and relative humidity is low.

management systems currently used by utilities and next-generation fire models in development by the Pyregence Consortium.

To meet these objectives, Sonoma Technology implemented a targeted deployment of an upper-air instrument in an area of northern California that frequently experiences easterly, offshore Diablo wind events. The upper-air instrument was sited near surface meteorological sites to augment the observational data collected by existing monitoring stations. The team used the data collected by the upper-air instrument, and surface observations and data from other upper-air instruments in the San Francisco Bay Area, to assess how well the upper-air wind data can be used by utilities to improve short-term (up to 15 hours) and very-short-term (from 0 to 3 hours) forecasts of high wind events. More accurately predicting the onset of high surface winds, both spatially and temporally, could significantly improve decision support systems for PSPS events, near real-time fire modeling, and situational awareness. The research team collaborated with Pacific Gas & Electric (PG&E), Bureau of Land Management (BLM), CalPine, and Santa Fe Geothermal Group to identify the site location for the upper-air instrument and the data parameters of greatest value to operational decision-making.

Field Data Collection Program

Overview of Upper-Air Pilot Program

The upper-air pilot deployment launched on July 25, 2020 and ran through October 26, 2020. Prior to deployment, Sonoma Technology developed a pilot study test plan; worked with PG&E, BLM, CalPine, and Santa Fe Geothermal Group to strategically identify a site location; acquired permits; and tested and deployed the instrument and data systems. Once they deployed the instrument, the team developed a data website; monitored the data and data systems throughout the study period; conducted site visits; and dismantled the site at the end of the study. Following the monitoring period, the team processed and analyzed the collected data.

Rationale for Instrument Siting

Preliminary analysis of historical weather data and burn probability performed by the *Extreme Weather Team* were used to identify general geographic areas in Northern California frequently impacted by Diablo wind events. Next, Sonoma Technology worked with PG&E to identify and verify areas that frequently experience Diablo wind events based on PG&E's 30-year Weather Climatology database. Siting criteria were established to ensure the upper-air instrument was deployed in an area that experiences Diablo winds as they flow to the west over the Sierra Nevada Mountains and down through the valleys toward the San Francisco Bay Area. Using PG&E's Weather Climatology database and fire potential parameters established by PG&E, the team identified areas of moderate elevation with surface wind speeds greater than 20 miles per hour (mph); wind gusts greater than 34 mph; relative humidity (RH) less than 25%, wind direction north to northeast (offshore); and a fire potential index greater than 14.

Using the environmental siting criteria above, several areas in Northern California were identified. Next, siting logistics were considered including:

1. Land ownership with a preference for land owned by PG&E and areas away from sensitive wildlife habitats.
2. Access to the site (e.g., condition of access road, fences, and gates).
3. Travel distance for site visits and emergency repairs.
4. Solar panel exposure and tree canopy interference; because of the possibility of a PSPS, the instrument was powered by stand-alone solar/battery power.
5. Proximity to residences and occupied buildings, as the instrumentation produces acoustic signals that can be loud and/or irritating to people
6. Noise or acoustic signal interference; because the instrument relies on multi-frequency acoustic signaling, surrounding noise and structures can interfere with the measurements.
7. Security considerations to avoid theft and/or vandalism of the equipment.

After considering the siting and logistics criteria, four potential locations were identified in the area northeast of Santa Rosa. Sonoma Technology worked with PG&E, Bureau of Land Management, CalPine, and the Geothermal Facility to conduct site visits to the four locations. After conducting site visits and considering the locations of nearby surface meteorological stations, a location near Cobb Mountain was selected (Figure 1).

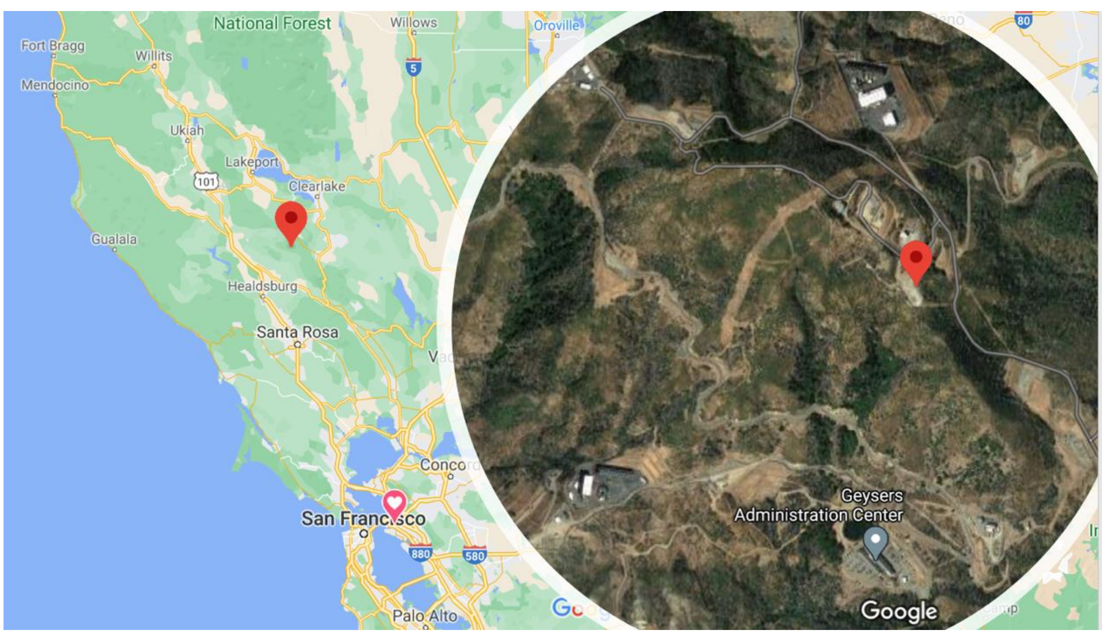

Figure 1. Location of the upper-air profiler site near Cobb Mountain in Northern California.

The monitoring site was located on a ridge top approximately 10 miles southwest of Clear Lake and just southwest of Cobb Mountain. The site elevation was approximately 3,720 ft (Figure 2).

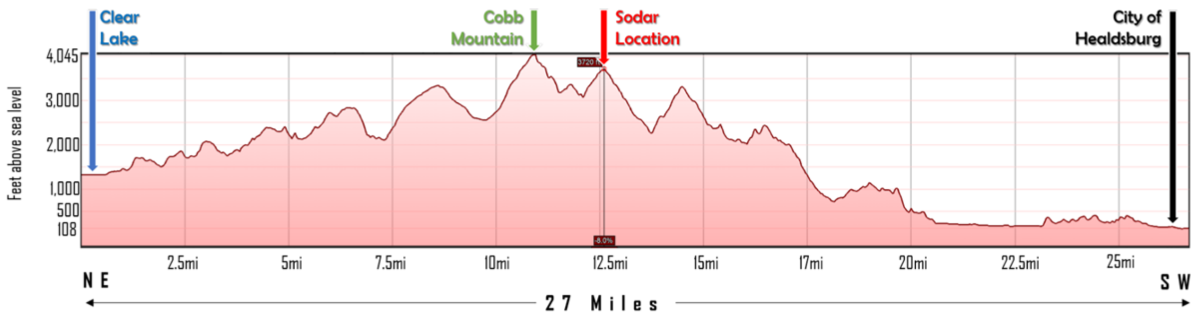

Figure 2. Location and elevation of the upper-air profiler site near Cobb Mountain in Northern California.

During the same period as the upper-air pilot study, the *Extreme Weather Team* conducted analyses to define Fire Weather Regions throughout the state. Within each Fire Weather Region, extreme fire weather types (XWTs) were defined (Figure 3) to characterize fires by type and to detect days with potentially extreme fire growth.

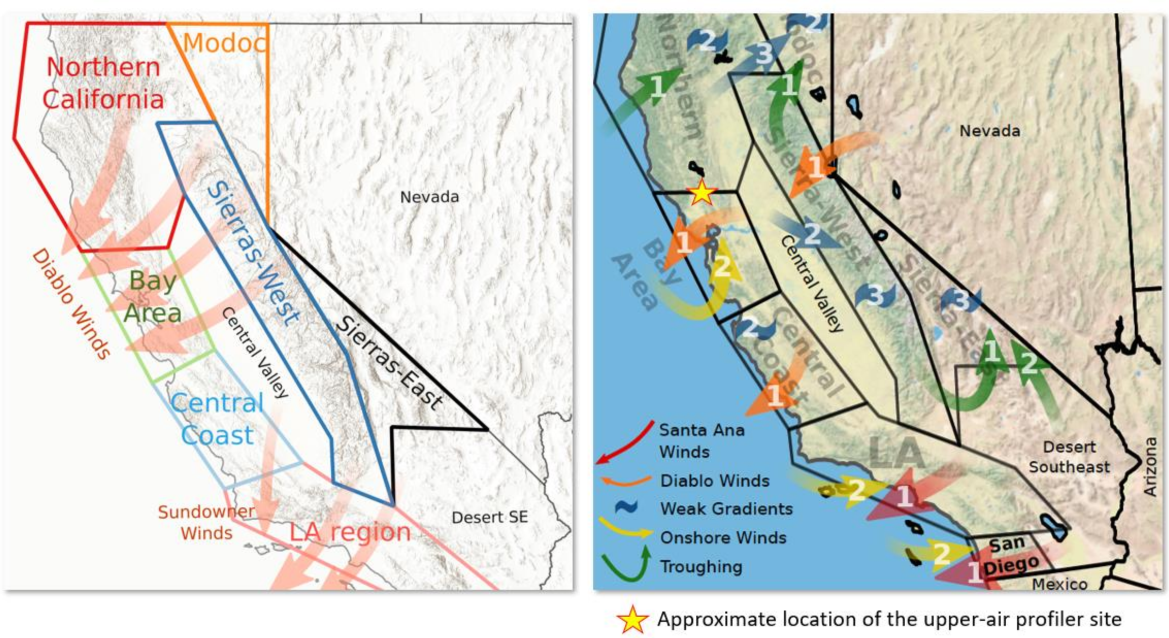

Figure 3. Fire Weather Regions (left) and XWTs (right) defined by the *Extreme Weather Team*. The yellow star on the map (right) indicates the approximate location of the upper-air profiler site in relation to the Fire Weather Regions.

Instrumentation

Sonoma Technology installed and operated an Atmospheric Systems Corporation (ASC) Model 2000 Sodar (**Figure 4**) at the location shown in Figure 1. A sodar sends out sound pulses and records the sound that reverberates from atmospheric turbulence back to the sodar. After the sound pulse is transmitted, the sodar records scattered sound to determine wind speed, direction, inflow angle, and height. The resulting data provide information about the atmospheric wind profile.

Figure 4. Photograph of the ACS Model 2000 Sodar at the upper-air monitoring site near Cobb Mountain, California.

The Sodar 2000 uses three parabolic dishes with a compression driver at the focal point of each dish to generate audible acoustic pulses (i.e., chirps or beeps every 4 to 6 seconds). The parabolic dishes are situated so that two orthogonal horizontal wind components (u, v) and one vertical wind component (w) are sampled to compute the reported wind profile. A receiver measures the small amounts of transmitted sound that scatter back toward the sodar. These backscattered signals are received at a slightly different frequency than the transmitted signal. This difference, called the Doppler frequency shift, is directly related to the velocity of air moving toward or away from the sodar in the direction the beam is pointing. The radial velocity measured by the tilted beams is the vector sum of the horizontal motion of the air toward or away from the sodar, plus any vertical motion present in the beam. Using trigonometry, the three-dimensional meteorological velocity components (u, v, w), wind speed, and wind direction are calculated from the radial velocities. The Sodar 2000 operates at a frequency of ~1,800 Hz, and the emitted sound is ~90 dbA.

The data collected by the Sodar 2000 show wind speed and direction by time and vertical height. Figure 5 shows an example of data collected by the Sodar 2000. The hourly wind data have a vertical resolution of approximately 20 m from about 80 to 600 m AGL. The upper-air data was collected on a continuous, hourly basis and was periodically reviewed by a trained data analyst throughout the pilot study period to monitor the instrument and ensure that the instrument and data systems were functioning properly.

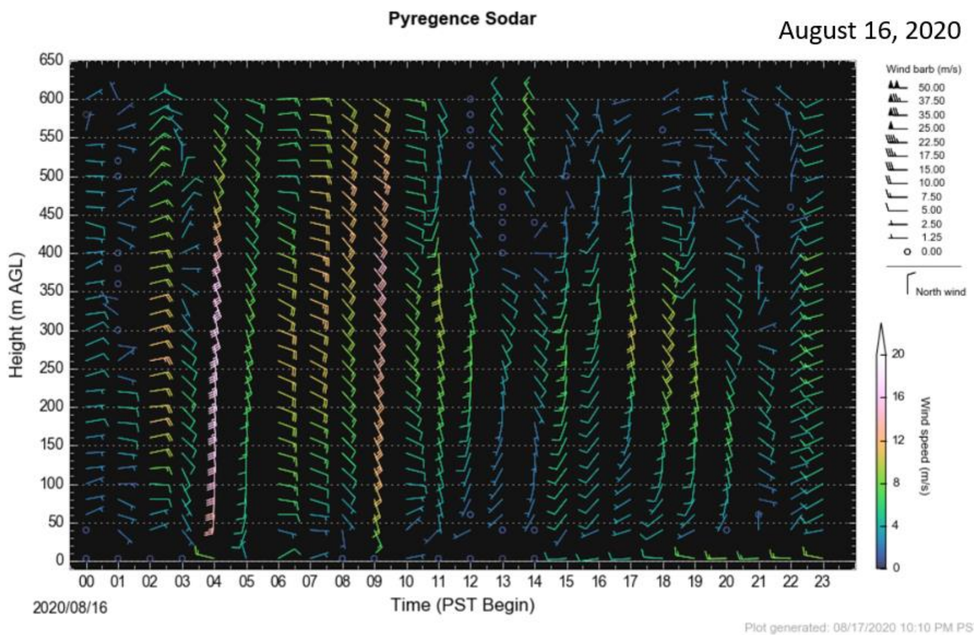

Figure 5. Example of wind speed and direction data by time and vertical height collected by the Sodar 2000 on August 16, 2020.

Instrument Preparation, Installation, and Operations

For programs involving routine instrument operations, it is critical to ensure that the data captured are high-quality and as complete as possible for the monitoring period. Operations for this project were divided into two main elements: (1) pre-deployment instrument interface and testing, and (2) routine operations.

To prepare the Sodar 2000 for deployment, the power source, computer, data management system, and communications were tested and verified at Sonoma Technology's headquarter offices in Petaluma, California. Instrument updates and system corrections were made as needed. Prior to deployment, Sonoma Technology's team confirmed that all systems, from data collection to data delivery and archiving, were working together properly.

Sonoma Technology's field operations team installed the Sodar 2000 at the pilot-study field site on July 25, 2020, in accordance with manufacturers' guidelines and field installation experience and best practices. Once the Sodar 2000 was installed at the site, field operators thoroughly tested the equipment and verified that all components were working properly.

Throughout the duration of the pilot study, Sonoma Technology's field operators conducted remote monitoring of the Sodar 2000's operation and performance. When needed, Sonoma Technology's team conducted on-site visits to perform maintenance or adjust the instrument. During these on-site visits, Sonoma Technology staff performed the following inspections and maintenance:

- Visually inspected the instrument and cables.
- Verified that the instrument was collecting reasonable data for the current weather conditions.
- Inspected the instrument base to ensure that it was securely mounted.
- Verified the instrument orientation and level.
- Verified disk space was available on the instrument and data logger.
- Verified that the Sodar speakers were operating properly.
- Made instrument repairs when needed.

Meteorologists at Sonoma Technology's Weather Operations Center periodically compared the upper-air data collected by the Sodar 2000 with external data sources such as the North American Mesoscale Model (NAM), the Global Forecast System (GFS), and surface meteorological observations as a quality control measure. This allowed the Sonoma Technology team to identify operational and/or equipment problems.

Data Acquisition and Processing

Reliable communication with field sites is a fundamental requirement to (1) ensure high data recovery rates, (2) monitor instrument performance, (3) remotely diagnose instrument problems, and (4) make instrument system changes as needed. Cellular communications and file transfer protocol (FTP) were used to support instrument communications for this pilot study.

At the monitoring site, dual-band cellular modems were configured to automatically push data from the Sodar 2000 to FTP servers every hour. Once the data were uploaded to the FTP servers, automated processes imported the raw data to a Microsoft® SQL Server® database, effectively combining all data into a single, unified data set. The raw data files were stored and backed up daily.

Real-Time Data Website

A real-time data website was developed and linked to the Pyregence Consortium website. Automated processes generated images from the raw Sodar data files, and the images were uploaded to the Pyregence Sodar website (https://cecsig.sonomatech.com/windsodar.jsp). A screen shot of the Pyregence Sodar website is shown in Figure 6. The Pyregence Sodar website was used to monitor the upper-air data throughout the pilot-study period, especially during high wind, fire weather events.

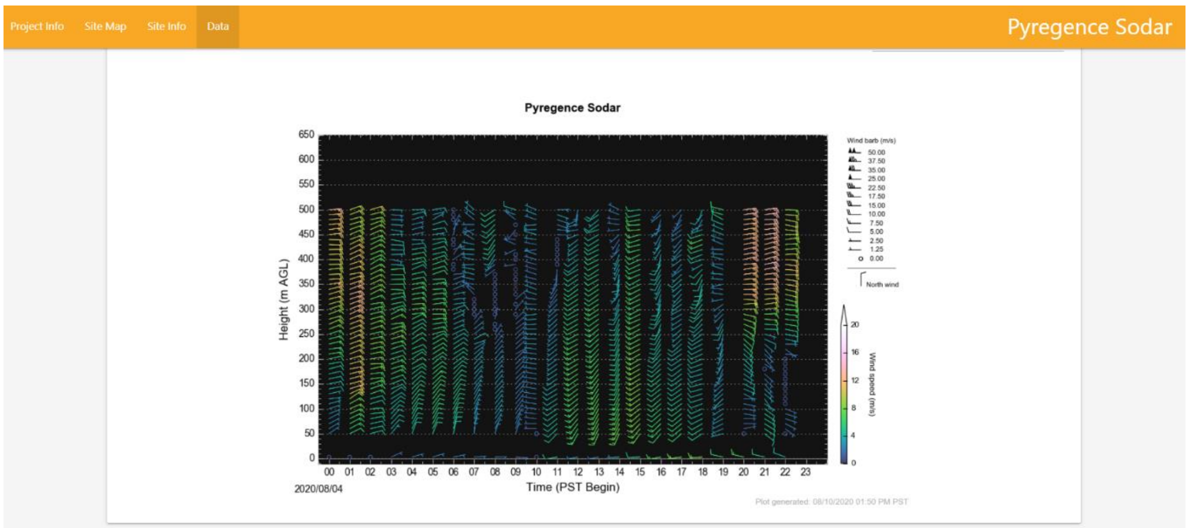

Figure 6. Screen shot of the Pyregence Sodar project website that was used to display and monitor the data collected by the Sodar 2000 during the pilot study.

Unanticipated Challenges

As described above, the team considered several site logistics to determine the location for the Sodar 2000, including potential noise and acoustic signal interferences. During the initial site visits, Sonoma Technology field staff verified that the proximity of the site to geothermal-related activities would not impact measurement operations. Sonoma Technology field staff also verified that nearby above-ground piping did not contain venting valves that could create noise, and therefore impact measurement operations. However, during routine monitoring, daily data quality control (QC) checks, and operational feedback from PG&E meteorologists, the team discovered that during times of high surface winds, the upper-air measurements were suspect. After all possible quality checks were performed remotely, Sonoma Technology field staff scheduled a site visit coinciding with a high wind event to help diagnose the issue. During the site visit, they determined that when surface winds reached ~20 mph and above, the physical orientation and structure of the nearby above-ground pipes created a whistling effect. This was an unanticipated issue, as the initial site assessment and instrument deployment occurred on days when wind speeds were relativity low.

Over the course of the monitoring period, Sonoma Technology field staff conducted numerous site visits and performed a series of corrective measures to reduce the impact of noise interference on data collection and data quality. These corrective measures included:

1. Relocating the Sodar 2000 as far away as possible from the above-ground pipes, without introducing other noise or tree canopy interference.

2. Reorienting the Sodar 2000 to better mask noise interference from the direction of the above-ground pipes.
3. Working with the instrument manufacturer to develop software-based correction factors during high wind events.
4. Installing additional acoustic instrument parts to help address the noise interference.

While efforts were made to determine a new location for the Sodar 2000 during the study period, the relativity short duration of the study did not provide enough time to deploy the instrumentation to a new location. However, despite these unanticipated challenges, the Sodar collected useful data (as described in the Data Analysis and Results section below) and provided valuable insights for deploying upper-air instrumentation in high wind areas.

Summary of Data Completeness

At the conclusion of the upper-air pilot study, the Sonoma Technology team assembled and processed the data collected from the upper-air instrument. Time-height wind profiles were produced for each day from July 25, 2020, through October 26, 2020. The deployment spanned a total of 94 days with one time-height wind profile recorded every hour. Sonoma Technology meteorologists inspected these profiles for data completeness and to ensure the data and time-height plots looked physically realistic. For example, the data were reviewed for each day to determine if the data displayed physically realistic wind behavior, such as a generally logarithmic increase in wind speed from the surface to the upper end of the wind profile. They also inspected the plots to verify that changes in wind speed and direction (in both time and height) looked physically realistic. To be considered for further investigation, at least 50% of the data for a 24-hour period was required. A total of 75 of the 94 daily profiles met data completeness requirements. Of these, 9 contained invalid data, leaving the 66 daily profiles that were used for the data analyses described below.

Data Analysis and Results

Following the upper-air profiler pilot deployment, Sonoma Technology analyzed the data collected during the study period. Time-resolved vertical wind profiles from the Sodar 2000 provide important detail about the local vertical atmospheric structure in the lower boundary layer and the evolution of those structures in time. The analyses performed were focused on demonstrating the value of upper-air wind data to supplement synoptic-scale and surface data to better predict the occurrence and timing of high winds reaching the surface. This information can allow utilities to improve short-term (up to 15 hours) and very short-term (from 0 to 3 hours) predictions of extreme surface wind events.

To help verify the data collected from the pilot study sodar, and to improve understanding of the variability in winds aloft at different locations throughout the region, Sonoma Technology's meteorologists analyzed similar datasets from other sodars and radar wind profilers in the San Francisco Bay Area. The additional sodar sites are in Benicia and Richmond, while additional radar wind profilers are located at Bodega Bay along the coast and at Twitchell Island in the Sacramento Delta region.

Analysis of Upper-Air Data and Integration with Surface Data

Several high-wind events occurred at the sodar study site during the pilot study period. Periods of high winds that coincided with PG&E PSPS events (shown in **Table 1**) provided the starting point for selecting case study dates.

Table 1. PSPS days issued by PG&E in 2020.

2020 PG&E PSPS Events	
August 15 - 16	October 14 - 17
September 7 - 10	October 21 - 23
September 26 - 29	October 25- 28

Data completeness and quality assurance requirements were met for two of these wind events: August 15 to 16 and September 26 to 29. During these events, meteorologists were interested in the evolution of winds aloft and if those winds translated to the surface. A new website run by the National Weather Service (NWS) provides access to historical data from a variety of surface-based meteorological instruments (NWS Weather & Hazards [noaa.gov]). The surface meteorological station closest to the pilot study sodar was the Santa Fe Geothermal meteorological site (SFG), which was approximately 400 m from the pilot study sodar. Surface measurements were also available from a station near the Benicia Sodar located on the Union Pacific Railroad bridge between Benicia and Martinez, CA. Sonoma Technology meteorologists also reviewed co-located surface measurements at the Bodega Bay and Twitchell Island radar wind profiler sites.

There are subtle differences when interpreting sodar and radar wind profiler plots (shown in **Figure 7**). The x-axis of the sodar plots shows the date the observations were taken, as well as hourly timestamps in Pacific Standard Time (PST) from left to right. The x-axis on the radar wind profiles has hourly timestamps in Universal Coordinated Time (UTC) and read from right to left. The y-axis of the sodar plot displays the height of the observations in meters AGL while the y-axis on the radar wind profiler plot displays height in kilometers AGL. Wind barbs on both the sodar and wind profiler plots use standard meteorological wind-barb notation (knots); however, the associated color scaling and legend on the sodar plots show speeds in meters per second (mps). Surface wind plots from SFG and Benicia show windspeed and gusts in knots. Surface data from Twitchell Island displays wind speeds in mps.

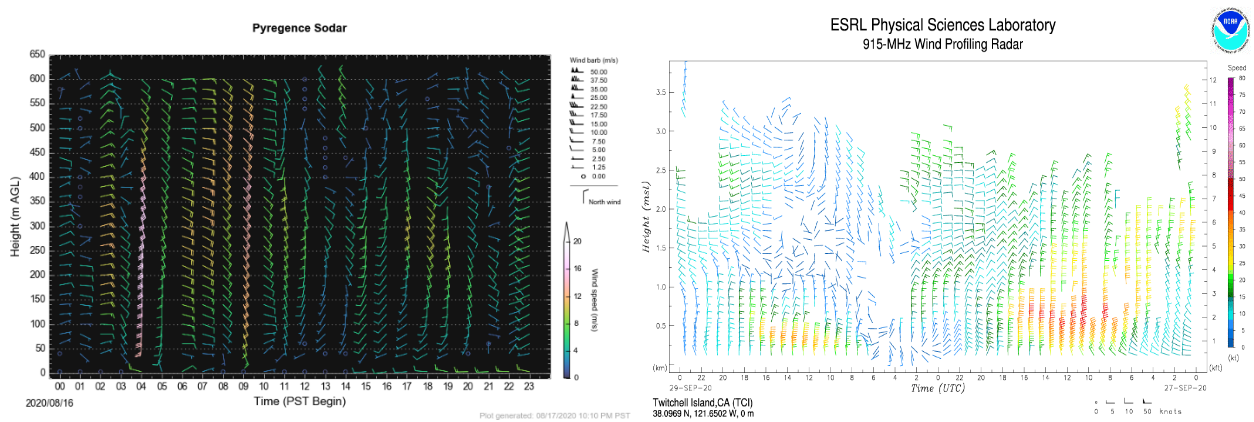

Figure 7. Example of a sodar plot (left); example of a radar wind profiler plot (right).

Case Study Analysis and Results

August 15-16, 2020, Event

Synoptic weather conditions during the August 15-16, 2020, event featured a strong upper-level ridge of high pressure over the Great Basin (**Figure 8**) and a weak surface high pressure system over the northern Rockies (**Figure 9**).

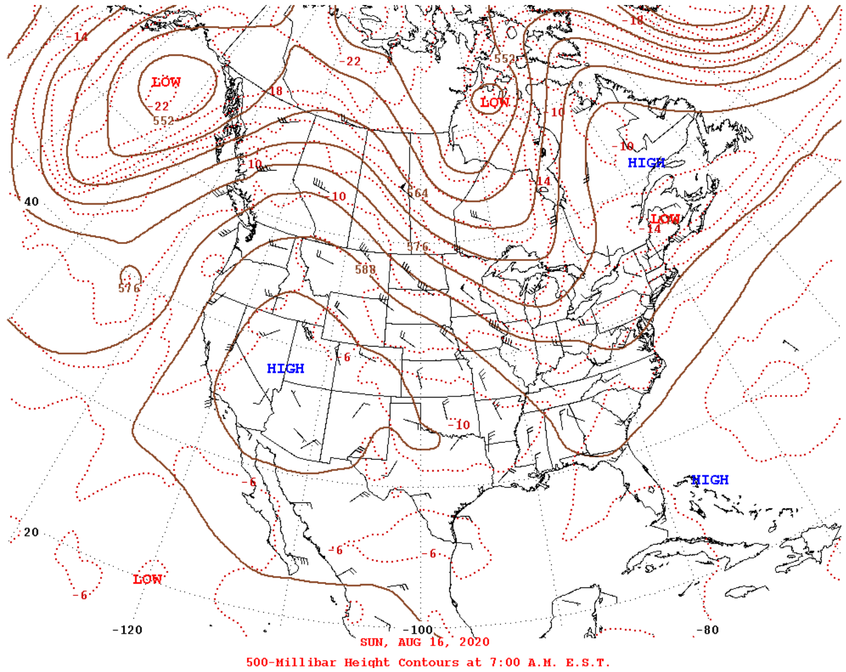

Figure 8. 500-Millibar heights and winds at 7:00 a.m. EST on August 16, 2020.

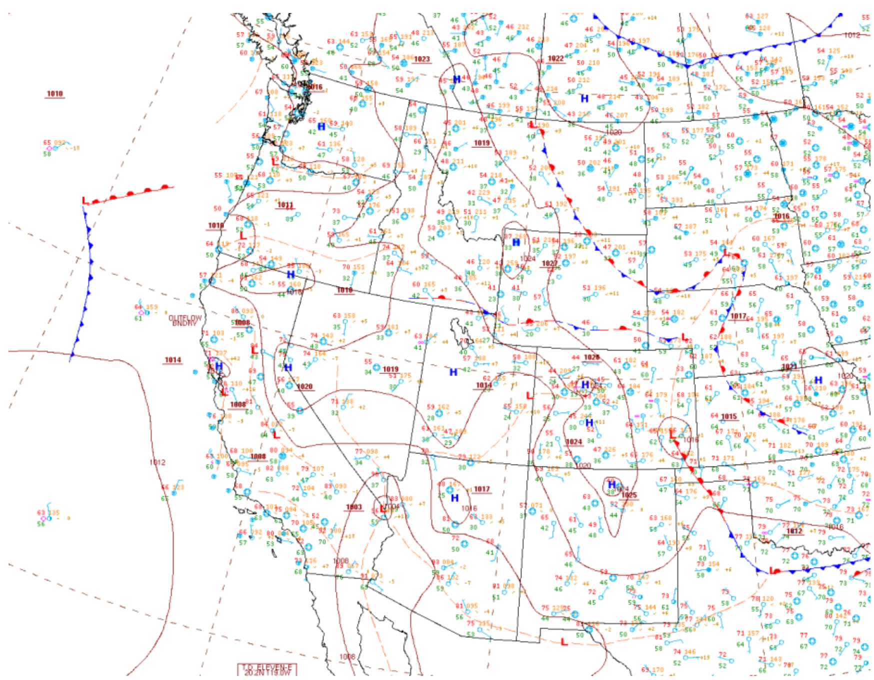

Figure 9. Surface map depicting surface pressure and fronts, 7:00 a.m. EST on August 16, 2020. Tropical depression Eleven-E (remnants of Tropical Storm Fausto) noted just offshore Baja California.

The strong high-pressure system aloft allowed temperatures to rise above normal for the entire region, with widespread readings over 100°F across California. The southerly winds around the western side of the high-pressure system aloft also transported moisture northward from remnants of Tropical Storm Fausto. The combination of the abnormal heat and increased moisture produced strong to severe thunderstorms early on August 16 across the Bay Area. The storms brought intense lightning and gusty winds that created dangerous fire weather conditions. Figure 10 shows the progression of hourly radar images from 4:00 to 9:00 a.m. PST on August 16, as waves of thunderstorms moved across the Bay Area from the south. Thunderstorm activity continued through the early afternoon.

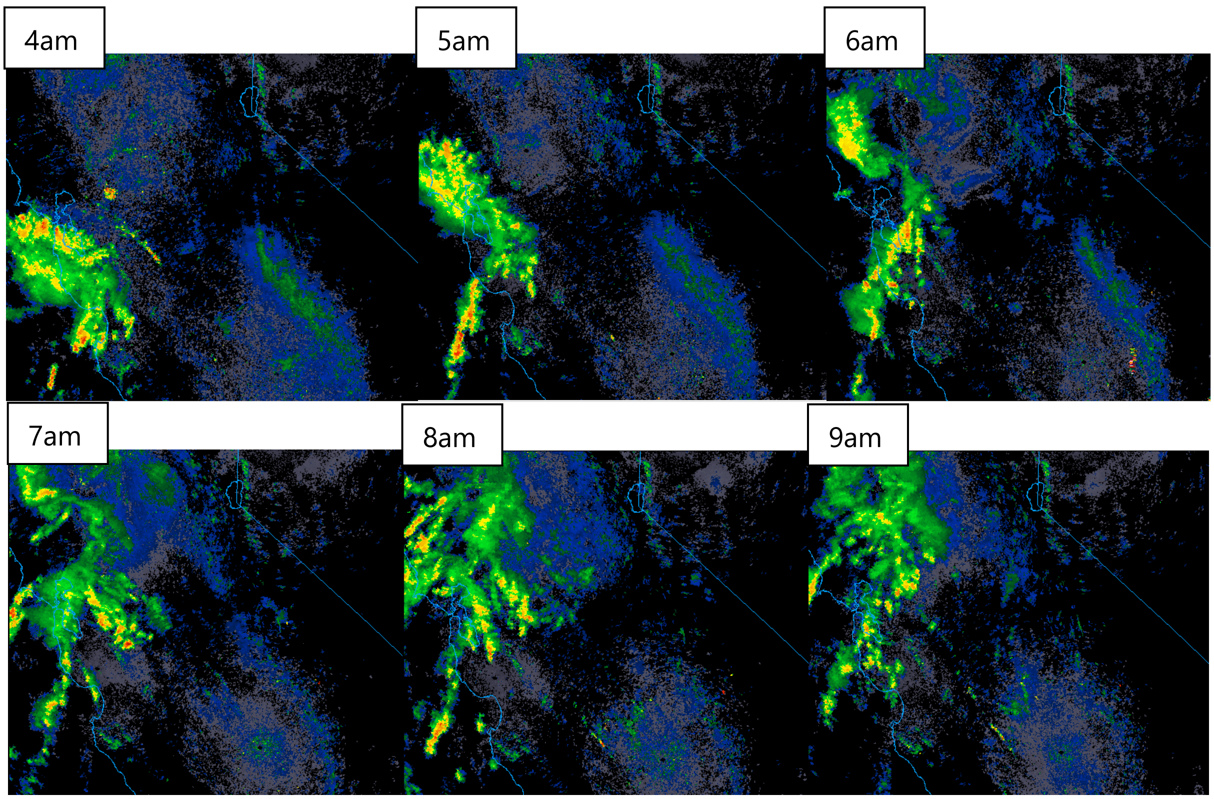

Figure 10. Hourly composite radar images from 4:00-9:00 a.m. on August 16, 2020.

As shown in Figure 11, sodar plots from the pilot study site show rapidly changing winds aloft as the thunderstorms approached and moved over the site. The wind speed and direction measured at the pilot study site changed almost every hour during the morning of August 16, and winds were strongest (> 30 mph) between 4:00 a.m. and 5:00 a.m. PST as the first wave of thunderstorms approached the site. Changes in wind speed and direction appear throughout the vertical column simultaneously. This erratic behavior is expected in a thunderstorm environment, where wind speed and direction are highly variable and dependent on the exact location of storms, as well as the interaction of thunderstorm outflow boundaries.

While wind speeds increased aloft with the initial round of storms, wind gusts at SFG did not increase until a second round of storms moved through around 8:00 a.m. PST (Figure 12). These gusts were most likely the result of strong thunderstorm outflows as precipitation evaporated in the dry, lower levels of the atmosphere where relative humidity was less than 20%. Though rainfall was minimal, thunderstorm outflows moistened the lower atmosphere, evidenced by the higher values of relative humidity after 7:00 a.m. PST (Figure 12). Similar conditions were observed at the Benicia Sodar site on August 16 (Figure 13). Wind speed and direction were highly variable as the storm system moved through the region.

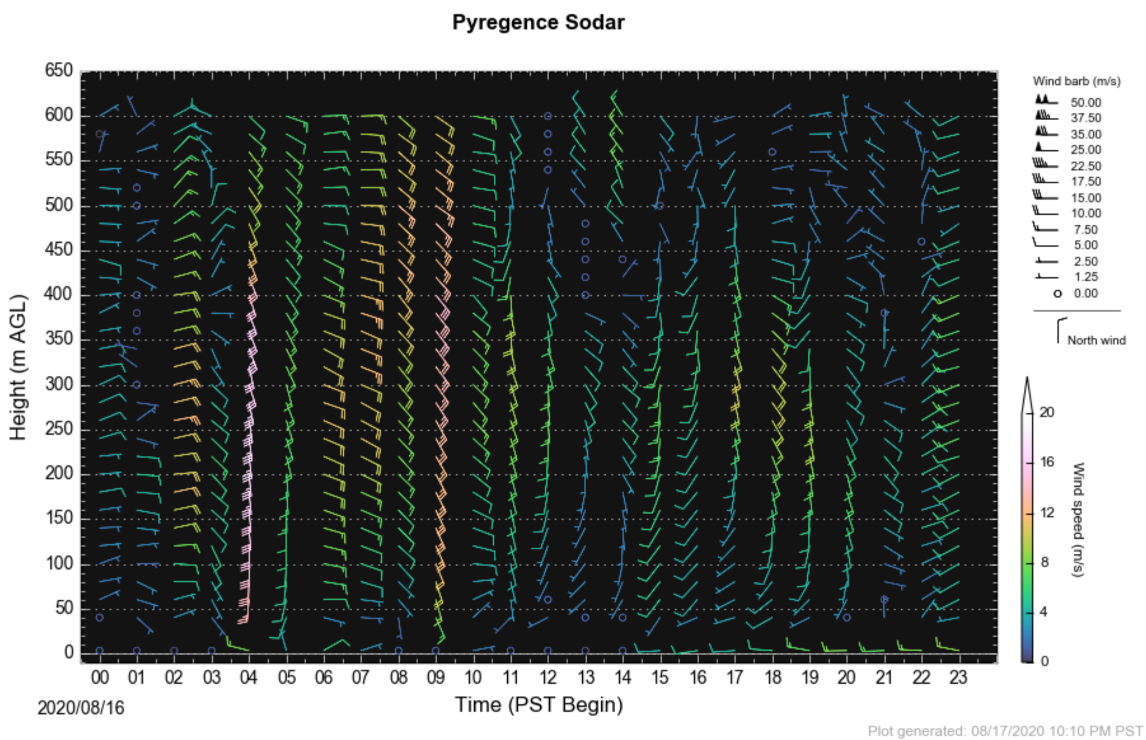

Figure 11. Study site sodar time-height wind profile from August 16, 2020.

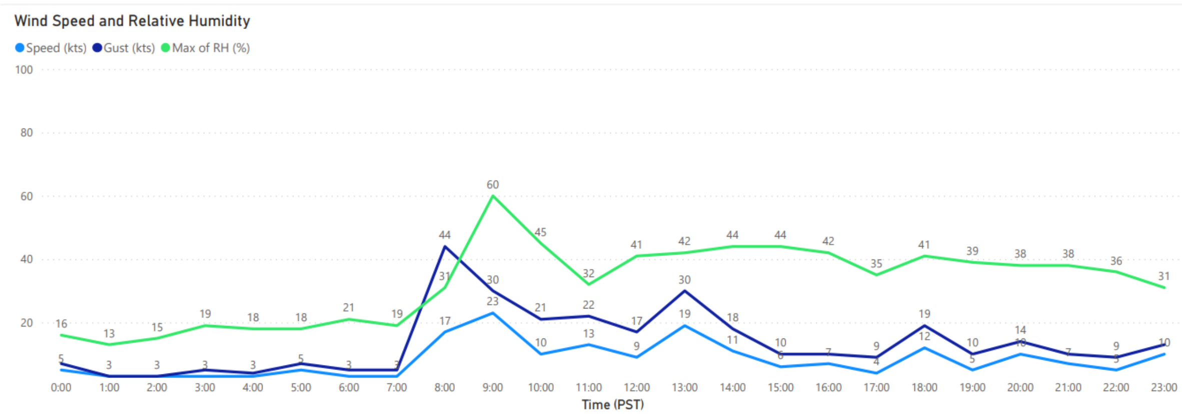

Figure 12. Hourly wind speeds, wind gusts, and relative humidity on August 16, 2020, at SFG.

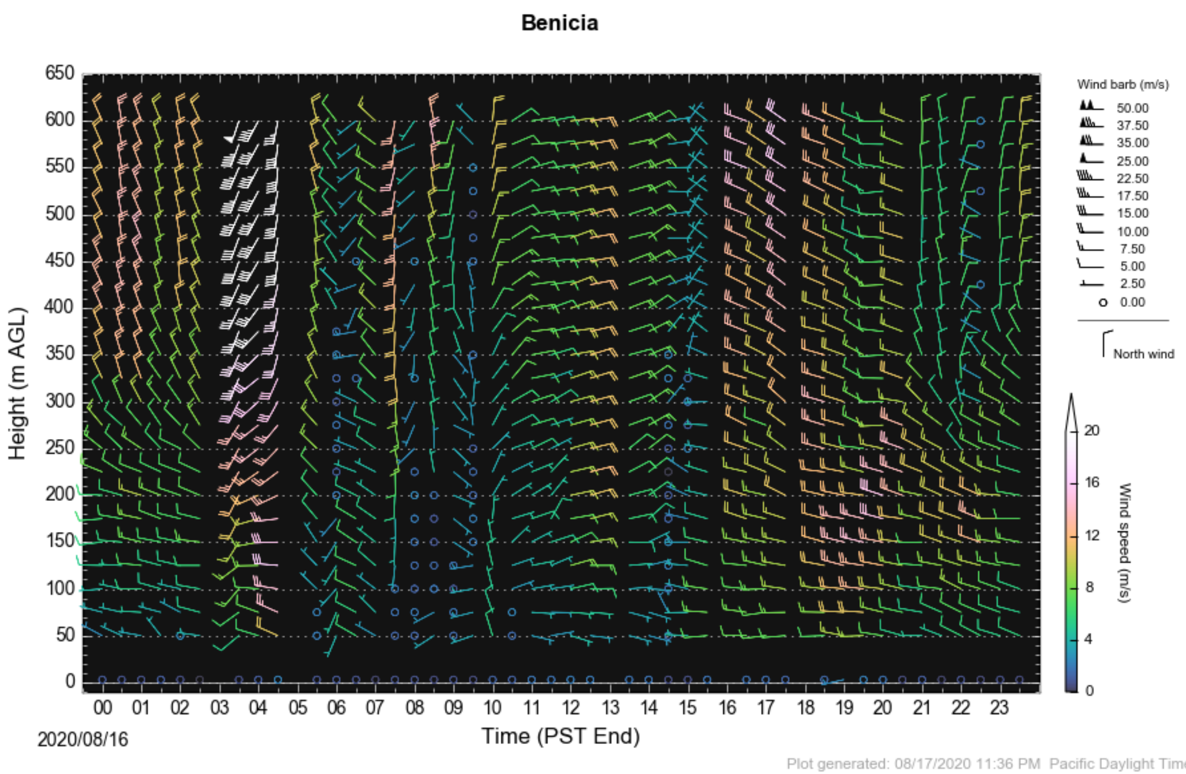

Figure 13. Benicia Sodar time-height wind profile, August 16, 2020.

Surface winds at Benicia (Figure 14) followed a similar pattern with maximum gusts associated with the second round of thunderstorms, even though higher winds aloft were observed between 3:00

and 5:00 a.m. PST. In fact, the strongest gusts at the surface around 9:00 a.m. PST are correlated with a relative minimum in wind speeds aloft at Benicia.

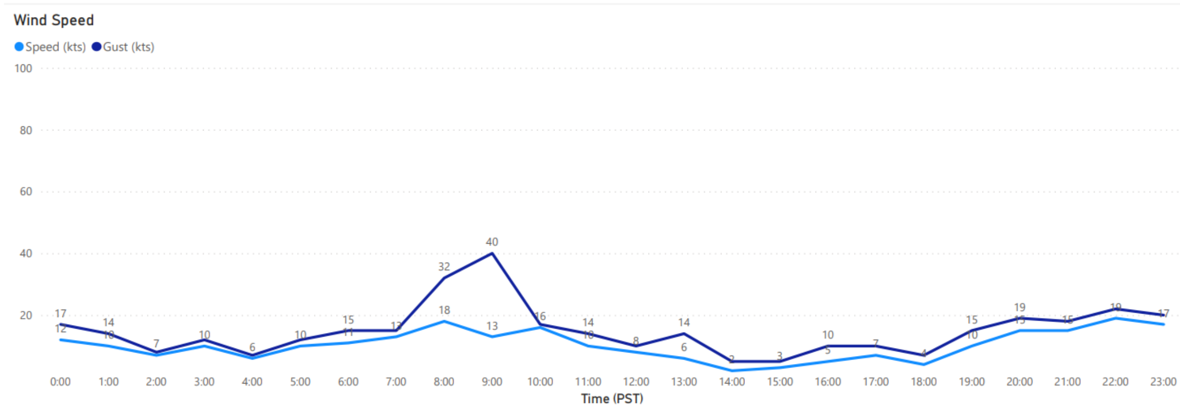

Figure 14. Wind speed and gusts observed at Benicia, August 16, 2020.

The sodar data analyzed from this thunderstorm event did not show the onset of strong surface winds. However, the data do depict how variable wind direction and speed can be in these unstable weather conditions. Interference from thunder during this event was not quantified.

September 26-29, 2020, Event

The September 26-29 event was the result of strong Diablo offshore winds. The synoptic weather pattern during this event (shown in Figure 15) featured a strong trough of low pressure aloft digging southward from the Rockies into the central Plains. Behind this trough, a strong surface high pressure system developed over the Pacific Northwest before slowly shifting into the Rockies. The air mass associated with the surface high was characterized by cool and dry conditions, with temperatures generally in the 30s and 40s °F, while temperatures were still in the 70s °F across Northern California. This set up a strong pressure gradient across the Sierra Nevada mountains, creating several periods of strong northerly to northeasterly winds across the upper elevations during the episode.

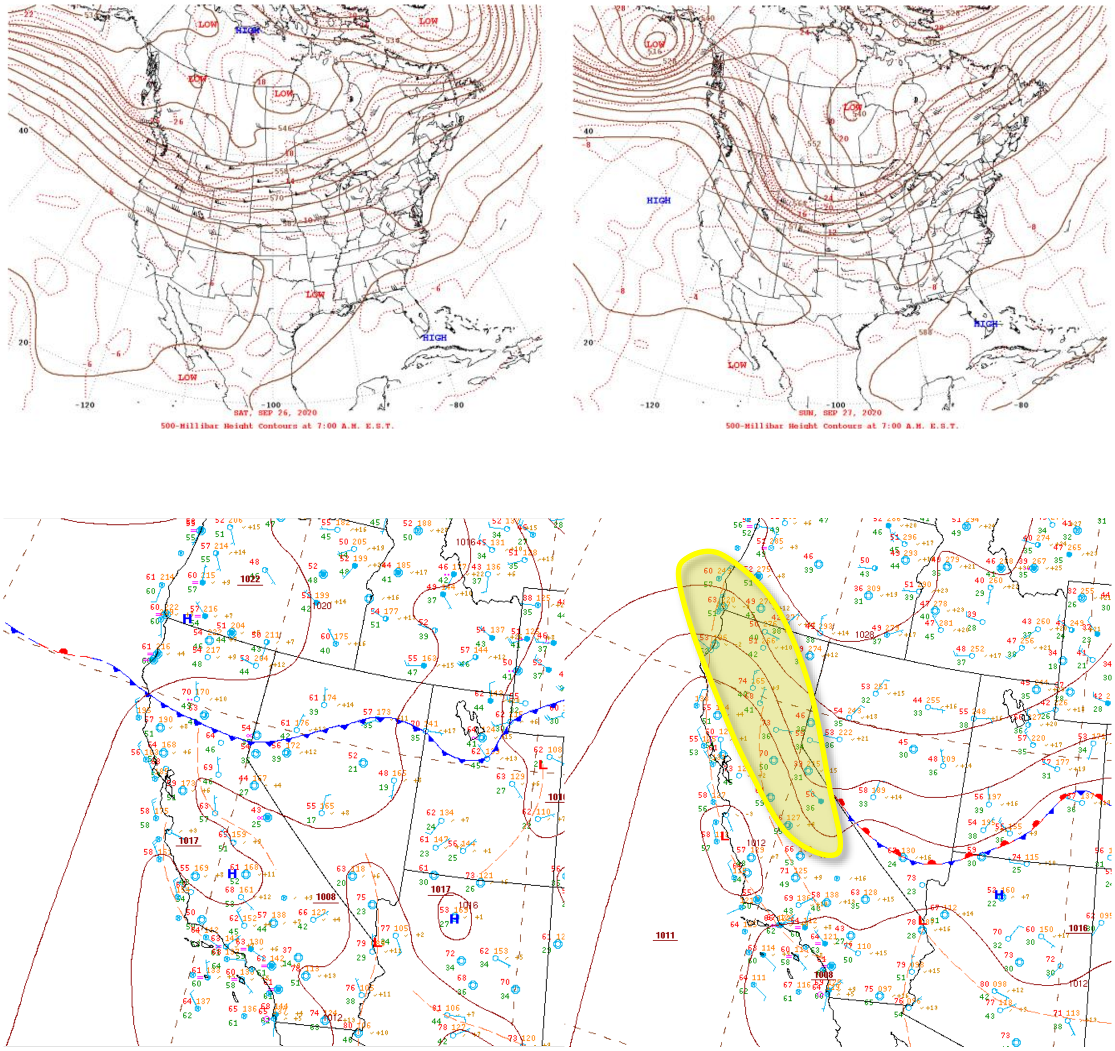

Figure 15. 500-millibar heights and winds at 7:00 a.m. PST on September 26, 2020, and 7:00 a.m. PST on September 27, 2020 (top left to right); surface pressure pattern and fronts 7:00 a.m. PST on September 26, 2020, and 7:00 a.m. PST on September 27, 2020 (bottom left to right); strong pressure gradient annotated in yellow.

During this event, stronger winds developed gradually aloft as the regional pressure gradient tightened. Figure 16 shows stronger winds were first detected from 300-600 m AGL between 15:00 and 16:00 PST on September 25. Over the course of several hours, the stronger winds descended closer to the surface (yellow annotation notes descent of stronger winds) but did not increase significantly at the surface until 1:00 to 2:00 on September 26 (Figure 17). Wind gusts near 30 knots were common throughout the morning of September 26 at the SFG surface meteorological site. These wind speeds match the speeds sampled by the Sodar in the lowest 200 m AGL. The sodar profiles show upper-level winds decreased significantly during the late morning on September 26.

Surface winds responded accordingly, with gusts dropping below 20 knots by 12:00. This first round of wind had an onshore component from the north-northwest, so relative humidity levels remained mainly above 50%.

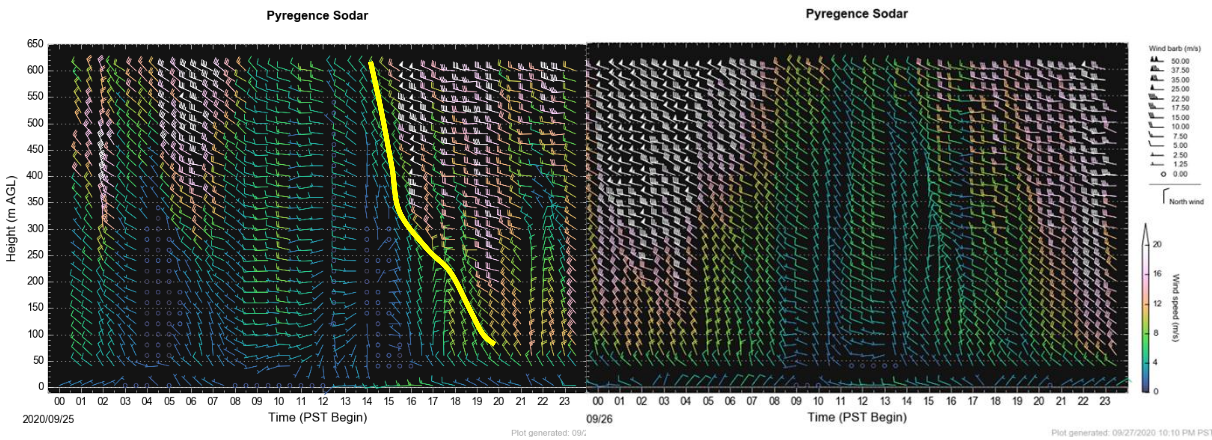

Figure 16. Sodar time-height wind profiles at the study site from September 25-26, 2020. The yellow line indicates the boundary of stronger winds that start at the top of the wind profile on September 25 at 15:00 PST and descend toward the surface over several hours.

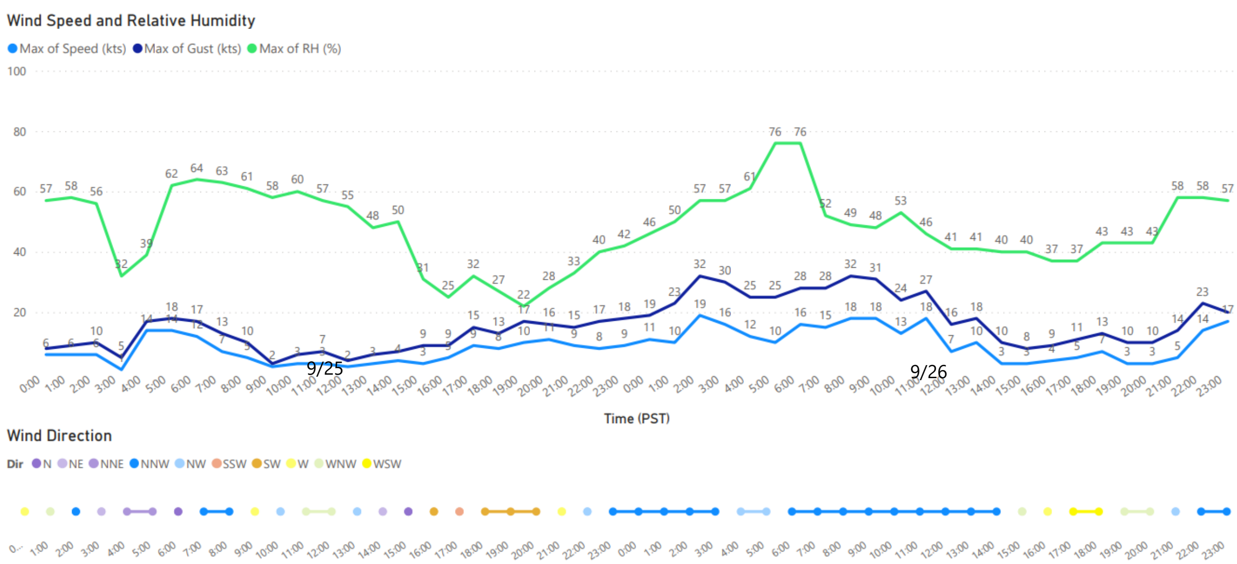

Figure 17. Wind speed (knots), gusts (knots), direction, and relative humidity at SFG, from September 25-26, 2020. Note that surface wind speeds were only 3-9 knots from 3:00 p.m. to 4:00 p.m. PST on September 25 when stronger winds were first sampled by the Sodar between 300-600 m AGL.

After the lull in strong winds on the afternoon of September 26, a similar pattern to the previous evening developed, with wind speeds increasing aloft between 14:00 and 16:00 PST (as shown in Figure 18), before gradually descending toward the surface just before midnight.

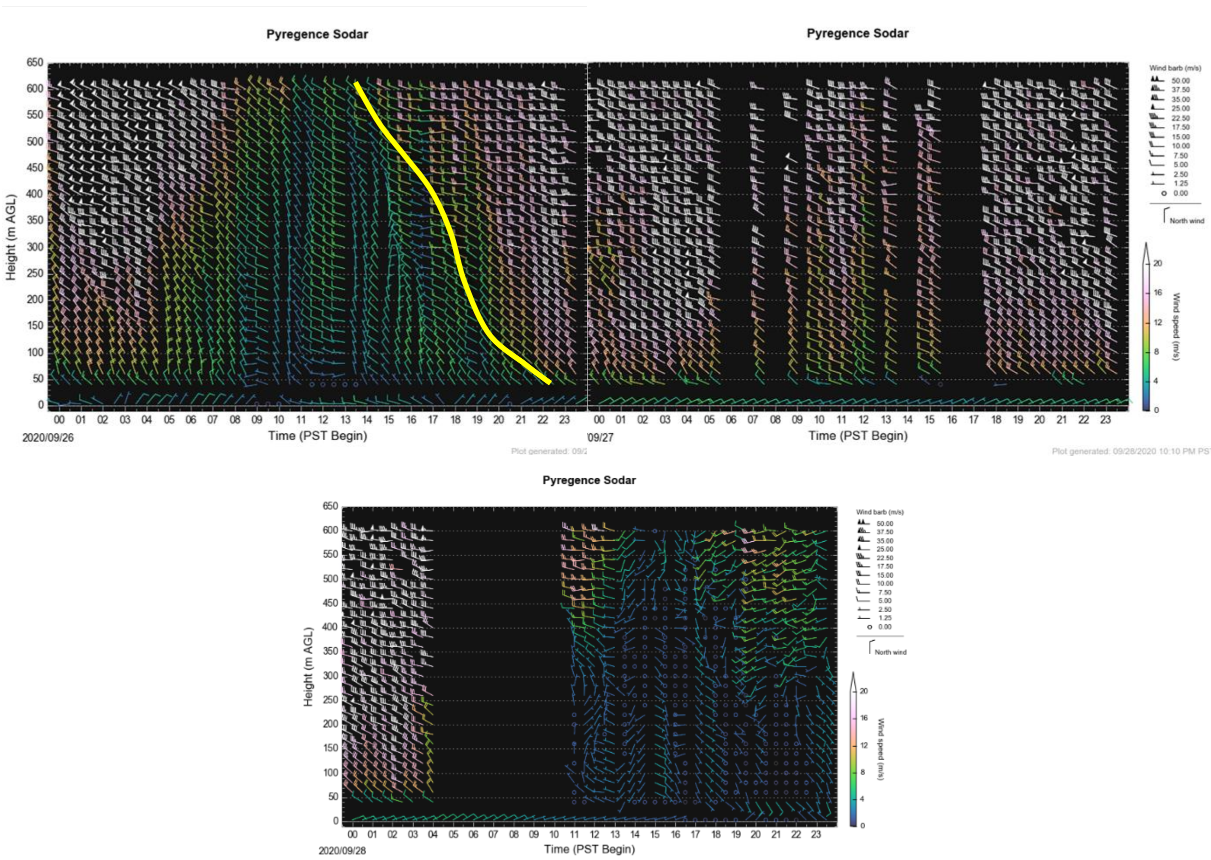

Figure 18. Sodar time-height profiles at the study site from September 26-28, 2020. The yellow line indicates the boundary of stronger winds that start at the top of the wind profile on September 26, 2020 at 15:00 PST and descend toward the surface over several hours.

Like the previous night, there was an 8- to 10-hour lag between when the wind began increasing at 500-600 m AGL as seen in the sodar data, and when the surface winds began increasing at SFG between 1:00 and 2:00 a.m. PST on September 27 (shown in Figure 19). Unlike the previous day, once the wind started on September 27, strong gusts persisted through the day and did not subside until the afternoon of September 28. Sodar profiles show wind speeds of 50 knots lower to within 200 m AGL before the data became intermittent and surface interference became evident. This matches the magnitude of gusts measured at the surface, as 50-60 knot gusts were common at SFG on September 27 and 28. Winds associated with this second wave were offshore from the north-northeast, and relative humidity dropped below 20% at SFG accordingly. In addition to the sodar data becoming intermittent on September 27, Sonoma Technology meteorologists noted a directional shift between the north-northeasterly winds observed at SFG and the northwesterly winds observed by the Sodar. These issues are believed to be the result of the sound interference described in the "Unanticipated Challenges" section of this document. Despite this directional bias in the sodar winds, the wind speed profiles were physically realistic.

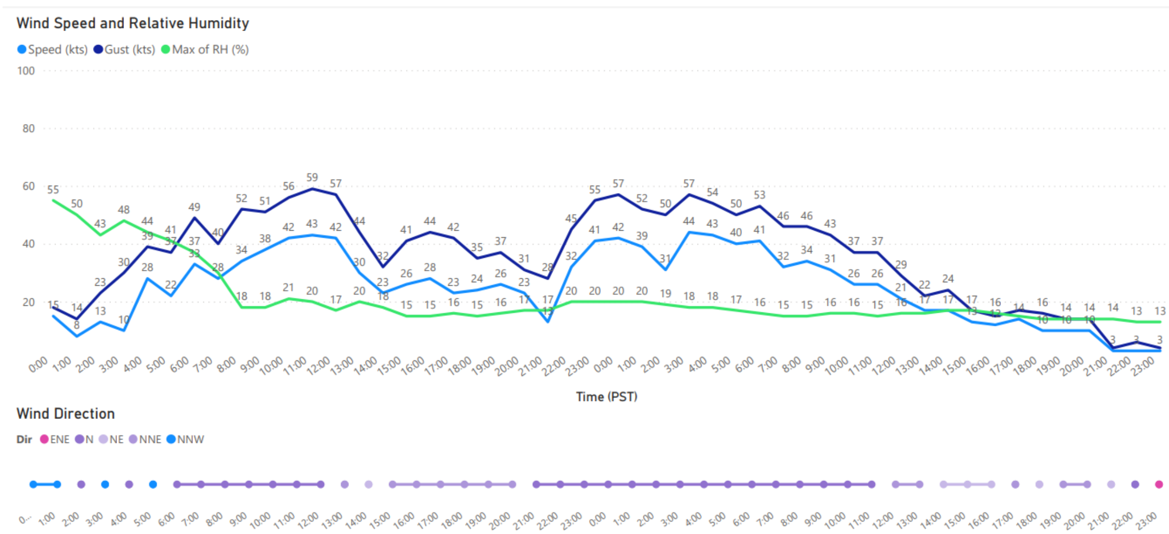

Figure 19. Wind speed (knots), gusts (knots), direction, and relative humidity at SFG, from September 27-28, 2020.

Radar wind profile data from other sites can help corroborate the findings from the pilot study sodar observations and provide additional context. The radar wind profiler at Twitchell Island captured a similar descending wind pattern late on September 26 and into early September 27 (**Figure 20**). Surface winds arrived approximately 4 to 5 hours later at SFG, around 10:00 UTC (5:00 a.m. PST) on September 27. The surface meteorological data at Twitchell Island is evidence that this was a downslope wind as relative humidity dropped from near 70% to around 40%, and temperatures increased several degrees.

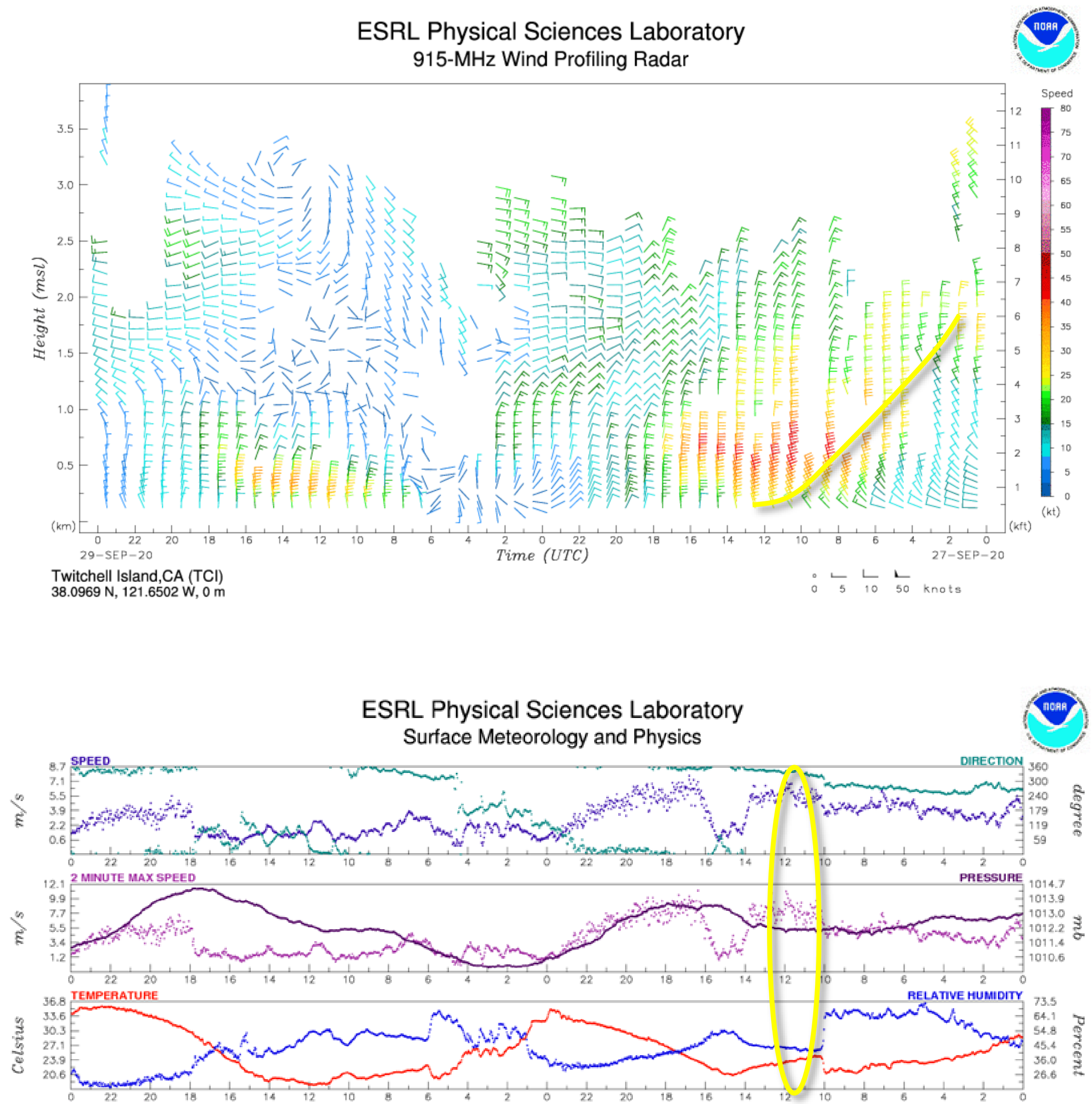

Figure 20. Time-height wind plot from radar wind profiler at Twitchell Island from September 27-28, 2020 (top). Meteorological surface measurements at Twitchell Island from September 27-28, 2020 (bottom). Arrival of downslope winds are annotated in yellow. Time in these plots progresses from right to left.

The sodars located at Richmond and Benicia also detected increasing winds aloft during this event, however, the descending wind signatures were less apparent (Figure 21). The Richmond and Benicia sodars are located at lower elevations than the pilot study sodar near the San Francisco Bay. As a result, they do not sample the higher magnitude winds observed by the pilot study sodar located at a higher elevation. Note that the easterly winds increase aloft at Richmond on the evening of September 26, but then quickly decrease, whereas the pilot study sodar observed a persistent strong wind from the evening of September 26 through midday September 28. Also note that at Benicia, the sea breeze dominates the lower half of the profile before northeasterly winds appear midday on September 27 during the peak of the offshore wind event.

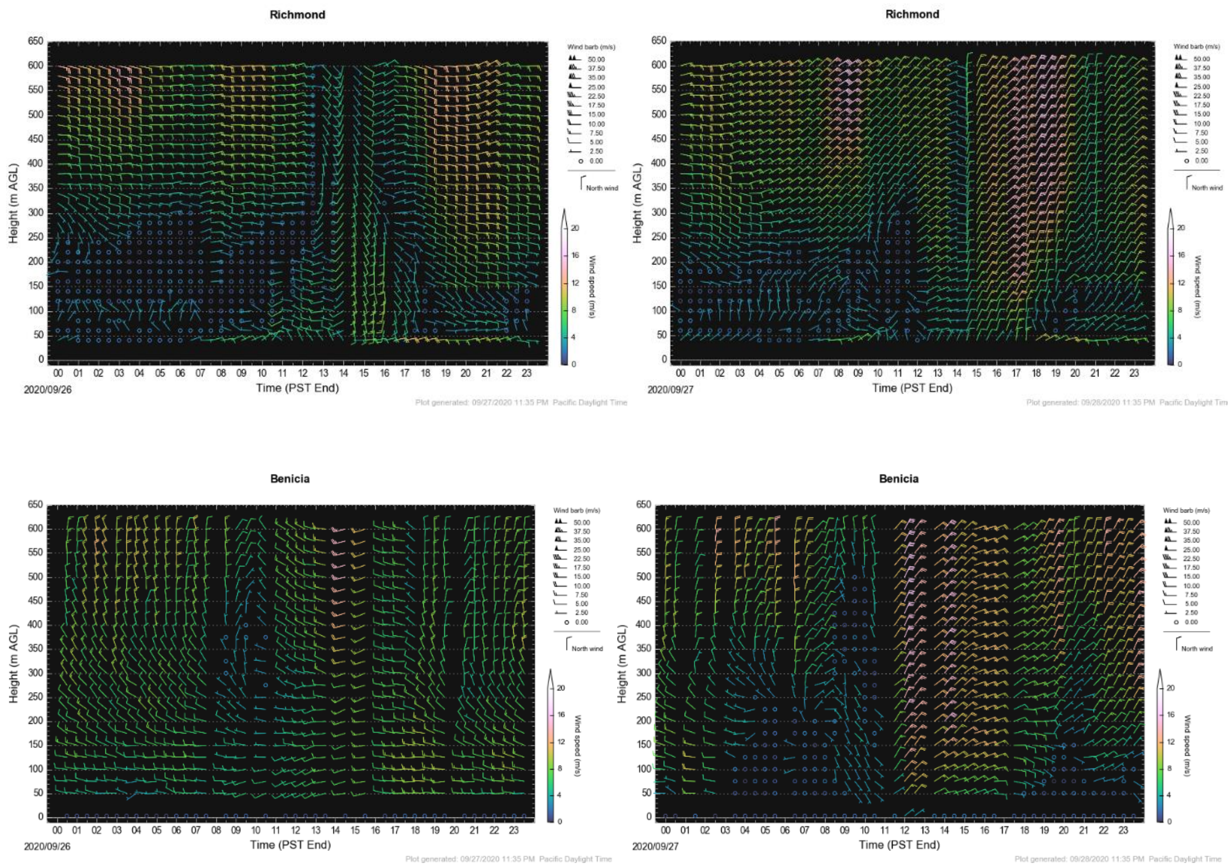

Figure 21. Sodar time-height wind profiles from Richmond (top) and Benicia (bottom) from September 26-27 (left to right), 2020.

Due to the Benicia site's coastal proximity, the rapid appearance of easterly winds was to be expected. Easterly winds most likely pushed the sea breeze front westward and resulted in very different conditions once the front passed.

Pilot Study Results

Overall data from the pilot study sodar collected during the September 26-29 Diablo wind event demonstrate the value of sodar wind profilers in the prediction of surface wind events. Data from the pilot study sodar showed increasing winds aloft well before these winds reached the surface. The increase in winds aloft late on September 25, and again on September 26, both occurred approximately 8 to 10 hours before increased winds were observed at the surface. This event also shows how wind profiles can differ dramatically at higher and lower elevations within the same region highlighting the need for a robust monitoring network. Specific results of the pilot study are summarized below.

- The Sodar 2000 deployed during the pilot study successfully measured winds from 80-600 m above ground during several off-shore wind events and during one wind event triggered by thunderstorm activity.

- During the September 26-29 offshore Diablo wind event, the Sodar captured a pattern of higher winds aloft that descended toward the surface several hours prior to the onset of the strongest wind gusts at the surface. This descending wind pattern was observed with two distinct periods of increased surface and aloft winds during the two-day wind event.

- The placement of the wind profiler at a mountaintop location was advantageous for characterizing offshore wind events and provided information that could not be obtained by nearby profilers sited at low elevations. The 600-m vertical reach of the Sodar was sufficient to capture the evolution of strong winds above the surface at SFG and was useful for anticipating the occurrence of strong winds at the surface.

- During the August 15 to 16 thunderstorm-induced wind event, the pilot study sodar showed rapidly changing winds aloft as thunderstorms approached and moved over the site. Changes in wind speed and direction appeared throughout the 600-m vertical column simultaneously. The Sodar was less useful for anticipating the occurrence of strong surface winds from thunderstorm activity as the thunderstorm outflow boundaries propagated rapidly through the SFG site.

Opportunities to Integrate Upper-Air Data to Improve Fire Weather Forecasts

Upper-air profilers have been used for decades to help forecast extreme weather events. Wind profilers have a much higher sampling resolution (e.g., hourly) than traditional upper-air weather measurement techniques such as radiosonde, which measures at synoptic times. They also provide more detailed information throughout the lowest levels of the atmosphere (i.e., up to approximately 1 km above the surface) - the region of highest impact. This not only allows for accurate mapping of vertical wind profiles but provides larger, more refined datasets for weather models. Forecasters can run high-resolution numerical models more frequently and on a more spatially resolved scale to improve regional and local weather predictions. Additionally, numerical model results can be calibrated against these measurements for improved model performance.

During its 23 years of operation (1992-2014), the National Oceanic and Atmospheric Administration (NOAA) Profiler Network (NPN) provided profiler data to Weather Forecasting Offices (WFOs) within the area, aiding in synoptic analysis, mesoscale analysis, and discerning short-term weather changes

(Benjamin et al., 2004). Among the many instances reported by WFOs where profiler data were used, the advantage of profiler data in fire weather predication can be demonstrated through its use during a wildland fire in June 2003 in Albuquerque, NM (Frederick, 2005). The Tucumcari wind profiler detected intensifying winds that were missed in nearby radiosonde observations. Forecasters were able to accurately predict a midnight wind surge that caused fire to spread rapidly. The forecasters were able to inform the fire management crew in time to contain the spread. Wind profilers can also help predict the movement of smoke and air toxics. Wind profiler data was key to making accurate forecasts during the Quebec (Canada) forest fires in July 2002.

With increased fire activity in the western United States, efforts are underway to measure and develop models that couple the atmosphere with fire behavior to understand and predict complex fire behavior. Wind profilers play an important role on both fronts. Brewer (2020) investigated the meteorological conditions for the 2018 Camp Fire (California) using both observations (Doppler lidar included) and numerical modeling. The observed vertical wind profiles were also used to compare against simulation results from the high-resolution Weather Research and Forecasting (WRF) model. Recent field campaigns that aim to study fire-atmosphere interactions during wildfire events often deploy upper-air wind profilers (Clements et al., 2018; Prichard et al., 2019; Conner et al., 2018). These observations contribute to boundary layer profiling of the near-fire environment and to measurements of smoke plume dynamics. The measurements collected during these wildfire field campaigns provide valuable evaluation datasets for new models and operational systems, which in turn provide important tactical decision support information about fire behavior and thus improve fire weather forecasting (Murdoch et al., 2019; Coen, 2018).

Conclusions and Recommendations

Data collected by the pilot study sodar during the September 25-29, 2020, Diablo wind event proved valuable in predicting the onset of high surface winds approximately 8 to 10 hours before they were observed at the surface. Data from other sodars and radar wind profilers in the region helped to corroborate this result. While the pilot study only spanned four months, the data collected demonstrate the value of upper-air profilers to help improve short-term forecasts of high surface winds. Additionally, valuable lessons were learned about siting upper-air instruments for high-wind, fire-weather applications.

Results from this pilot study and recent scientific literature demonstrate that a statewide network of strategically placed upper-air profilers could help to better predict extreme fire weather events and could help scientists understand fire-atmosphere interactions during wildfire events. Sonoma Technology was in communication with PG&E during the study period, as PG&E staff were actively viewing the data collected by the upper-air profiler. However, because of the short duration of the pilot study, the data were not integrated into PG&E’s operational systems. The integration of upper-air instrumentation into PG&E’s (and other utility) surface weather network and short-term forecasts could prove useful for predicting the occurrence and timing of extreme wind events.

Recommendations for Designing and Deploying a Profiler Network

It is difficult (and expensive) to develop a sensor network that can anticipate all possible wind forecasting scenarios and satisfy all possible objectives over large spatial extents. Targeted sensors that measure the right meteorological parameters in the right places, address specific and prevalent meteorological scenarios (e.g., Diablo wind regimes), and fill significant data gaps (horizontally and vertically) can improve upon wind forecasts generated by state-of-the-art NWP systems (Cooperman et al., 2018).

Profiler network design (i.e., which sensors should be deployed, and where they should be deployed) should be guided by the intended scientific and operational objectives. For example, as shown in this pilot study, one profiler located in a data-sparse region prone to strong winds from Diablo wind events can provide improved situational awareness of local winds that may be affecting critical assets and can provide insight for forecasting the occurrence of stronger winds at the surface. A small number of well-placed profilers can improve localized NWP and statistical forecasts for specific situations, such as predicting the occurrence of surface wind-ramp events (e.g., Cooperman et al., 2018). On the other hand, a dozen or more radar wind profilers within a project area spanning several hundred kilometers might be needed to achieve improvements in regional short-term NWP wind forecasts (Wilczak et al., 2015, 2019, Djalalova et al., 2016).

The decision for deploying a Sodar versus a Radar Wind Profiler (RWP) is guided by the location of potential available sites and the scientific and operational objectives of the deployment. This pilot study demonstrated that operating a Sodar (with limited vertical reach compared to RWP) on a ridgetop was an appropriate and cost-effective choice for observing wind profiles from Diablo events, noting that Sodars are less expensive and have reduced power requirements compared to RWP systems. For a regional profiler network, an optimized mix of RWP and sodar instruments could be valuable.

An observation targeting study could be a worthwhile investment to define the scientific and operational objectives of a profiler network, and to better understand the locations where NWP and statistical forecasts may be most sensitive to new observational data. Such a study could leverage the wealth of data, resources, analytical methods, and experience available from the scientific community, utilities, and potential stakeholders. The steps to designing and deploying an upper-air profiler network could include:

1. **Identify candidate locations for siting upper-air profilers to capture the onset of extreme wind events.** Using the fire weather regions and extreme fire weather type (XWT) information developed by the Pyregence Extreme Weather Team (Figure 3) combined with information from utilities regarding fire weather climatology and assets at risk, general locations can be identified for siting upper-air profilers.

2. **Assess the locations of existing upper-air profilers and surface meteorological monitoring sites.** Develop maps of existing upper-air profilers and surface meteorological

monitoring sites relative to the candidate sites identified in Step 1 and conduct detailed meteorological analyses to identify areas where the addition of upper-air profilers can fill data gaps and help improve extreme wind forecasts. Ensemble sensitivity analysis approaches could be used to further refine areas where new observations may benefit NWP forecasts (Zack et al., 2010).

3. **Conduct an observation targeting study or expanded pilot study.** Deploy several upper-air profilers to better understand the locations where NWP-based forecasts and statistical forecasts may benefit most from new observational data.

4. **Analyze the data from the targeting/pilot study to inform a statewide network design.** Using the results from the targeting/pilot study (Step 3), develop an expanded, statewide network design.

In parallel with these activities, it would also be important to define the stakeholders for the planned sensor network, develop a strategy for disseminating data to meet stakeholder needs, and secure resources that can be committed for long-term operations and maintenance of the profiler network.

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