Evaluating the Relationship between Two Extreme Wind Events in Southern California for Advancements in Forecasting

Alana Ginsburg

Abstract

Frequent extreme wind events in Southern California are associated with elevated risks for rapid wildfire spread. The extreme wind events analyzed in this study are Santa Ana Winds (SAWs), which impact Ventura, Los Angeles, and San Diego Counties; and Sundowners, which are particular to Santa Barbara County. This study examines the typical timing between SAW and Sundowner events and their associated large-scale meteorological conditions to provide improvements for models and forecasting. Data on pressure, temperature and wind was analyzed to create composite maps. Results demonstrated a weak correlation in the likelihood that the two events occurred within 2 days of each other, and the most likely temporal arrangement when these events occurred in close proximity to each other was found to be a Sundowner event occurring 2 days prior to a SAW event. This can be attributed to the eastern flow of air masses in the atmosphere. The composite maps suggested that atmospheric pressures at 500mb height had the most distinct patterns by wind event. Distributions of pressure at 850mb height suggested the most about lag time values and what event could be expected to occur in close proximity from the day represented on the map. The composite maps for vector winds suggested that the highest overall wind speeds observed during any wind event were when both SAWs and Sundowners occurred on the same day. Variations in results suggest that differences in topography between the regions affected by each event is critical to the development of unique characteristics for each.

I. Introduction

The frequent extreme wind events in Southern California significantly influence local communities through dangerous gale force wind conditions and rapid wildfire spread (Ryan, 1996; Blier 1998; Hughes and Hall, 2009). Two downslope wind events in the region are Santa Ana Winds (SAWs), which impact the coastal counties of Southern California located south of Santa Barbara county, and Sundowners, which occur in Santa Barbara county (Hatchett et al. 2018).

Both SAWs and Sundowners are heavily influenced by the unique and complex topography of Southern California (Figure 1); the mountains in this region are known collectively as the Transverse Ranges. The region has many peaks and valleys, and is framed by the Pacific Ocean on one side and a large desert (Mojave Desert and Great Basin) on the other side. In Santa Barbara, these features are present at a smaller scale, with the additional presence of a coastline that runs horizontally west to east for 100 km. The Santa Ynez Mountains are parallel to this stretch of the coastline and are steep, with their peak elevation reaching around 1300 m. The western mountain ranges create SAWs and the Santa Ynez mountains in Santa Barbara county create Sundowners. (Ryan, 1996; Blier, 1998; Raphael, 2003)

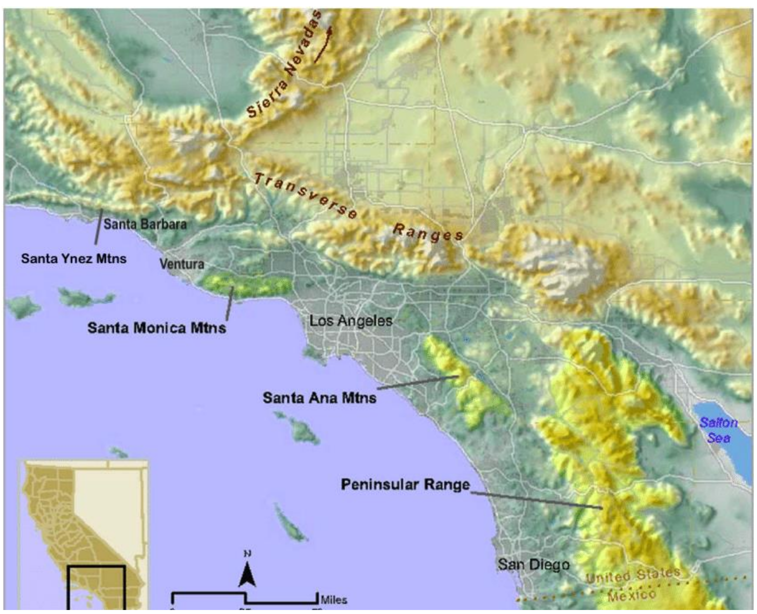

Figure 1: Map of cities and mountain ranges in focal region, Southern California USA (Ernest et al. 2014).

Mechanistically, these extreme, downslope wind events are caused by mountain wave activity, and may be associated with other meteorological phenomena such as rotors, jump zones, wave breaking regions and the adiabatic warming of air parcels (Blier, 1998). Typical air flow around a mountain barrier consists of air being trapped on the windward side of the mountain. Downslope wind events represent an extreme in the conditions at the mountain barrier. These events occur when the atmosphere above the mountains is stable and properly stratified, and the geostrophic flow in the region is across the mountain tops due to the presence of an unusually strong pressure or thermal gradient on either side of the mountain barrier. Gravity waves transfer this mid-level momentum from the geostrophic flow occurring in the mid-troposphere to the surface, which creates strong leeward-side surface winds. These winds are known to be especially strong in areas just beyond mountain gaps. The disruption in the stability of the atmosphere at the mountain barrier due to the abnormal geostrophic flow occurring in the mid-troposphere to the surface, which creates a critical level that traps the gravity waves that form on the leeward side of the mountain and causes the air parcels on that side to sink and compress quickly, creating the hot, dry winds of the downslope wind events. (Ryan, 1996; Blier, 1998; Hughes and Hall, 2009)

Sundowners and SAWs bring hot, dry air into regions on the leeward side of a mountain. These conditions create a threat for wildfires, as hot, dry air is carried over mountains from deserts on the windward side into the leeward side that has abundant fire fuel (Ryan, 1996; Raphael, 2003).

SAWs are defined as being easterly, offshore winds that occur in Ventura, Los Angeles, Orange and San Diego counties primarily in the winter months (Raphael, 2003; Jones et al. 2010; Figure 2). SAWs tend to be more prevalent in winter because the thermal gradient between the desert and ocean on either side of the Transverse ranges tends to be stronger, as the desert is coldest in the winter and the

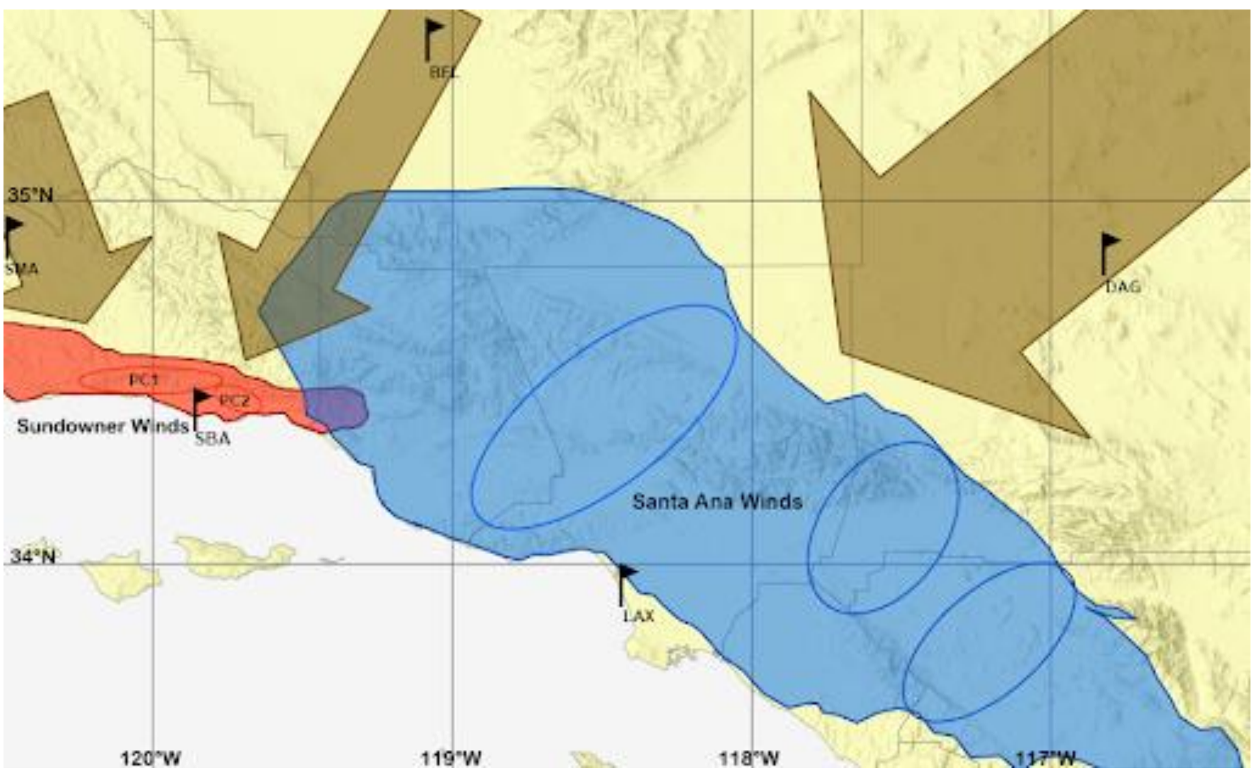

Figure 2: Map of Southern California (focal region) with blue and red areas signifying where these wind events tend to occur. The blue circles represent where the strongest Santa Ana winds typically occur, and the red circles represent regions of Sundowners developed through a principal component analysis test that are suggested to be independent. Black flags represent airport locations that are used to evaluate pressure gradients that will fuel the event, and the brown arrows represent the general direction of the pressure gradients associated with each wind event (Figure by competition entrant).

ocean stays warm (Hughes and Hall, 2009). They are known for occasionally reaching hurricane speeds in canyons and mountains and passes, and their name stems from the Santa Ana mountain range, a section of the Transverse Ranges where Santa Ana winds are particularly amplified (Hughes and Hall, 2009; Jones et al. 2010; Guzman-Morales et al. 2016). In the past, SAWs have been defined using various variables and characteristics of forecasts and observed meteorological conditions. Raphael (2003) developed a 33-year long climatology of SAWs based on observed pressure gradients at mean sea level from station data, Jones et al. (2010) identified SAW events based on 28 years of daily Fire Weather Index and Guzman-Morales et al. (2016) used mesoscale modeling that utilizes model-derived wind data exclusively.

Sundowners occur most frequently in the late spring and derive their name from their tendency to occur in the late evening into early night hours (Blier, 1998; Figure 2). As the synoptic cause of Sundowners remains unclear, the definition that has been used for the wind event has undergone many phases. The first attempt to develop a universal definition for Sundowner severity accounted for temperatures outside the normal diurnal curves, and wind speed and direction at the coast, mountains and passes (Ryan, 1996). These criteria remained confusing for researchers and forecasters as they did not help to identify the cause of Sundowner events, so the Mean Sea Level Pressure (MSLP) gradient between Bakersfield airport and Santa Barbara airport was added as a telling factor to consider (Sukup, 2013). The most recent definition relies on atmospheric model output which is calculated with temperature differences and the north-south wind component at each grid cell to study these same characteristics that had been previously determined with station data (Smith et al. 2018).

Spatiotemporal trends for both wind events, SAWs more so than Sundowners, are generally well understood. However, much still remains unclear about the overlap of these two events both temporally and spatially.

In previous studies, only surface station data was available and/or used to examine Sundowners and SAWs (Ryan, 1996; Blier, 1998; Raphael, 2003; Sukup, 2013). While station data is still utilized, atmospheric reanalysis data is commonly used to further study climatological and meteorological questions. Reanalysis is created using weather observations and atmospheric model output to produce reconstructions of past weather conditions (Parker, 2016). In recent years, programs and computational models such as the Weather Research Forecasting model (WRF) have been developed and applied to allow for the collection of data in higher resolution for locations where winds cannot be detected with station data (Cannon et al. 2017).

In this study, reanalysis data was utilized to compare synoptic conditions between Sundowner and SAW events. The purpose of this study was to improve knowledge on the relationship between

Sundowners and SAWs on spatial and temporal scales, which may ultimately advance the forecast skill of atmospheric models.

II. Methodology

All of the below protocols were completed by the competition entrant unless otherwise noted.

a. Data Sets

This study utilized various databases to provide information about days with Sundowners and SAWs and the associated synoptic conditions. The SAW database was provided by Dr. Leila Carvalho using the methodology from Jones et al. (2010), and includes data from 1948-2017. The Sundowner database was provided by Dr. Charles Jones and was produced by running a Principal Components Analysis (PCA) on wind components from the Weather Research Forecasting (WRF) model output. The Sundowner database included data for a shorter 30-year time span at which this study followed as well (1987-2017). PC1 Sundowners exhibit generally northwesterly winds and are found to occur in the western region of Santa Barbara, and PC2 Sundowners exhibit generally northeasterly winds and occur in the eastern region (anticipated publication date 2020; Figure 2).

In this study, Sundowner wind events were considered in 3 ways: all Sundowner wind events that were accounted for by the first PCA only (PC1 Sundowners), Sundowner wind events that were accounted for by the second PCA only (PC2 Sundowners), and Sundowners that were accounted for by either of the PCAs or by both PCAs (Sundowners). To clarify, the term Sundowner wind events can be assumed to account for the last of these options unless otherwise noted.

b. Data Grouping

In Figure 3, the model calendar, red circles represent dates of SAW events and green circles represent dates of Sundowner wind events. Blue ovals represent times when both events occurred in close proximity to each other and yellow circles represent times when they occurred on the same day. This experiment used numbered groups to represent lists of dates where wind events occurred in close temporal proximity to each other. The dates included in the event represent the latter event that was preceded by a wind event of the other type. For

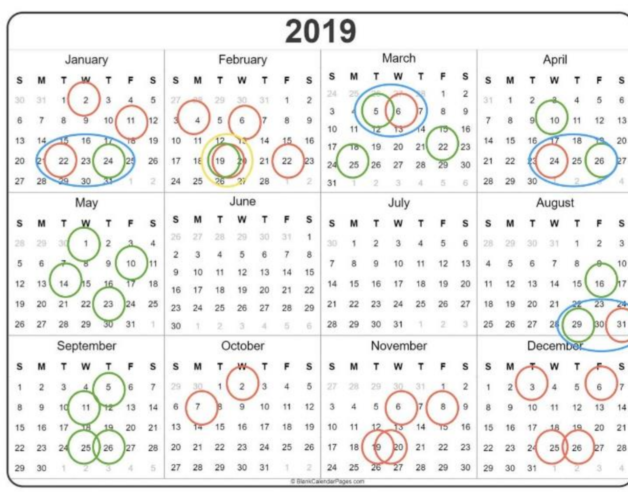

Figure 3: Calendar with hypothetical occurrences of wind events demonstrating the temporal relationships that define the groups analyzed in this study. All data analysis in this study represents instances where a "blue oval" was present (Figure by competition entrant).

example, Group 1 represents a list of dates where a Santa Ana Wind event was recorded 1 day after a Sundowner (PC2) was recorded.

Group #	Event on Date	Preceding Event	Difference in Days
1	Santa Ana Wind	PC2 Sundowner	1
2	Santa Ana Wind, PC2 Sundowner		0
3	Santa Ana Wind	PC2 Sundowner	2
4	Santa Ana Wind, PC1 Sundowner		0
5	Santa Ana Wind	PC1 Sundowner	1
6	Santa Ana Wind	PC1 Sundowner	2
7	Santa Ana Wind, Sundowner		0
8	Santa Ana Wind	Sundowner	1
9	Santa Ana Wind		2
10	PC1 Sundowner	Santa Ana Wind	1
11	PC1 Sundowner	Santa Ana Wind	2
12	PC2 Sundowner	Santa Ana Wind	1
13	PC2 Sundowner	Santa Ana Wind	2
14	Sundowner	Santa Ana Wind	1
15	Sundowner	Santa Ana Wind	2

Table 1: Table of Group Characterizations based on the temporal arrangement and shift between a SAW event and some type of Sundowner wind event (Table by Competition Entrant).

To evaluate the relationships between Sundowners and SAWs, 15 total possible setups of overlap between SAWs and each type of PC-classified Sundowner were defined as groups (Table 1). These group definitions are based on an event that occurs on the recorded date, an event that precedes that date, and the lag time between those two events. Three control groups not listed in the table were also developed so the synoptic conditions found for these important situations could be compared to the typical climatology of the general region. Seasons for the control groups were determined based on the established typical monthly frequencies of each wind event (Hughes and Hall, 2009; Jones et al. 2010; Raphael, 2003).

c. Map Creation

For each group, 5 composite maps were created for the following parameters: 500 and 850 hPa (or mb) geopotential height (GPH), 1000 hPa (surface) vector winds, air temperature in degrees Kelvin at 2m, and mean sea level pressure (MSLP). These variables were chosen for specific reasons. When predicting these winds, sea level pressure gradients and upper level wind support are evaluated to forecast these wind events (Gomberg). Vector winds at the surface give the best indication of what effects the wind events actually had on the area, and how severe they were in terms of a spatial perspective. MSLP and temperature allow for stronger interpretations to be made relating to what variables are actually used for forecasting. Looking at geopotential height allows for a sense of understanding of the effect of upper level atmospheric dynamics on these downslope wind events (Mills, 2012).

Composite maps were created to evaluate synoptic conditions when Sundowners and SAW events occurred within days of each other. Data for these maps was sourced using North American Regional Reanalysis data (Mesinger et al. 2006) through the Earth System Research Laboratory (ESRL) Daily Average Composite Map creator.

d. Data Analysis

i. Temporal Analysis

JupyterLab (version 0.35.4) with Python languages (Numpy, Pandas, CSV) was used to identify dates to create the lists for each group. Datasets were subset accordingly.

To evaluate the frequency of overlap between the two wind events, descriptive statistics were utilized. The frequency for how many times each group occurred was recorded and plotted through pyplot.Matplotlib.

ii. Spatial (Map) Analysis

The composite maps created were analyzed quantitatively and qualitatively in order to fully identify similarities and patterns in atmospheric setups during periods with the two wind events occurring in close temporal proximity.

Trends and features present in the map were identified based on the colors and pattern shown in the ESRL model and were then discussed (Mills, 2013).

III. Results

a. Frequency Analysis

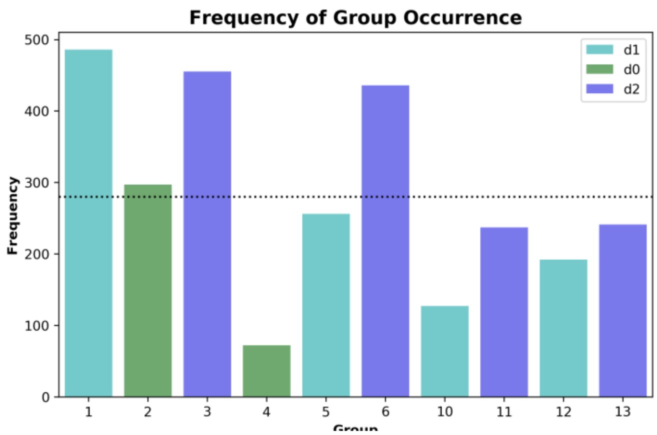

Figure 4: Counts of each possible wind event relationship from 1987-2017 based on UCSB criteria. Green bars indicate the wind events occurred on the same day, cyan bars have a 1-day difference, and blue groups have a 2-day difference. The dashed line indicates the mean value (280) (Figure by competition entrant).

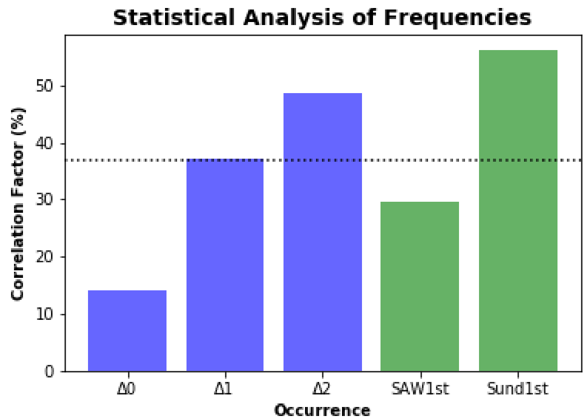

Figure 5: Percentages of occurrence for various situations in datasets. Dashed line indicates the mean value of 36.8%
(Figure by competition entrant).

The frequencies for each group were recorded and examined. Group 1 (PC2 Sundowners preceding SAWs by 1 day) was observed most frequently (486 dates from 1987 to 2017; Figure 4). However, as shown in Figure 5, groups with a 2-day difference between the wind events (PC1 or PC2 preceding SAW, and vice versa) were observed most frequently when considering only the difference in days between groups. Additionally, Sundowners more frequently preceded SAWs compared to SAWs preceding Sundowners (56% versus 29%).

b. Spatial Analysis

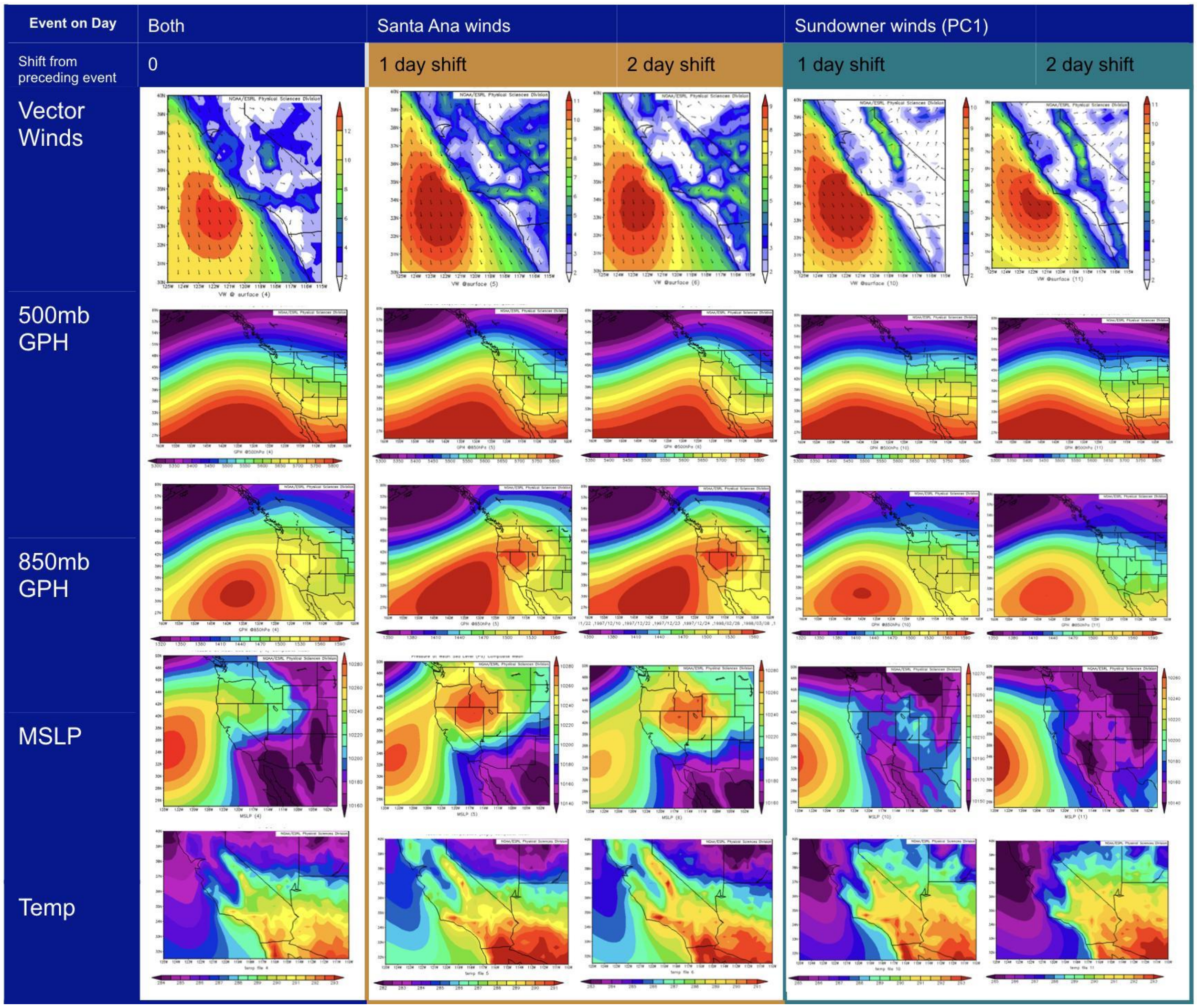

Figure 6: Chart of maps created for groups 4, 5, 6, 10 and 11, which includes all analyzed setups of Santa Ana Winds and PC1 Sundowners. The rows are sorted by different, yet pertinent meteorological variables and the columns are sorted according to different temporal relationships (Figure by competition entrant).

i. Observed Patterns and Central Findings from Composite Maps:

Composite maps featuring all evaluated setups between PC1 Sundowners and SAWs were used to demonstrate relationships observed in the following map analysis. Groups 4,5,6,10 and 11 are included above from left to right. All include different variations of Santa Ana Winds and PC1 Sundowners occurring in close proximities, organized in columns based on the temporal setup of the events.

The main findings are as follows:

a. The pattern for each wind event at 500mb height was the most uniform across all maps representing the same wind event out of all meteorological variables evaluated, regardless of the preceding event or lag time relevant to that map. The pattern in the 500mb height map served as an effective way to identify each wind event height due to the distinctness in the patterns according to which wind event was represented in the map.

b. Ridge shape at 500mb height during Sundowners is more dependent on the Sundowner type (PC1 or PC2) rather than the lag between the Sundowner and SAW event. It should be noted that the northward position of the ridges are evidently related to lag times, as the d1 days exhibit slightly more northern ridges than the d2 days for all Sundowner groups.

c. Similarities in temperature, vector winds, and 850mb height seem to exist based on lag times, especially among d1 SAW groups compared to d2 SAW groups. In contrast, most pressure variables do not seem to exhibit similarities on the basis of lag times solely.

d. The setup of high pressure regions in the composite maps for SAW days at 850mb height demonstrate more similarities based on what the preceding wind event is rather than lag time.

e. No maps of Sundowners have distinct anticyclone centers over the Great Basin at 850mb height. At MSLP, this feature is only evident for days of PC2 Sundowners.

f. Patterns for MSLP, 850mb height and 500mb height during PC2 Sundowners are more similar to SAW patterns than PC1 Sundowner patterns. However, vector wind patterns at the surface do not exhibit this trend (More similarities with Sundowner days than with SAW days exist according to vector winds at the surface).

g. An eastward shift of high pressure centers is evident in the “evolution” of d1 maps to d2 maps in the 850mb height and MSLP variables (for Santa Ana days).

h. A broadening and weakening of pressure systems is evident in the shift between d1 and d2 maps for 850mb height and MSLP on Sundowner days.

i. Highest average wind speeds throughout the region encompassed by the maps are observed when SAW and Sundowner events are occurring on the same exact day, rather than in any other instance.

j. Vector winds tend to be stronger on the maps with a d2 shift than maps with a d1 shift.

k. File 5 has the coldest desert temperatures (~287K; ~14C) of any group, and has the highest onshore wind speeds of any SAW-only group.

l. Datasets for PC1/PC2 Sundowners were developed using mesoscale analysis models, yet the predicted wind direction assigned to each type is clearly depicted in this study (Northeasterly for PC2 and Northwesterly for PC1).

m. The highest temperatures are located near mountain peaks and are surrounded by steep gradients on the slopes. This is very different from season 2 and 3 controls, where temperature consistently increases inland from the ocean to the desert.

n. General seasonal analysis conclusion: Clear and distinct differences exist between setups for each season, yet the pattern shown in the composite map is echoed in each one.

ii. Pattern Observations:

500mb Geopotential Height

Both composite maps for SAW-representing days in Figure 6 have a ridge (high pressure) extending to 30-33°N that is titled east, creating a southwesterly gradient and resulting northeasterly winds in the focal region. This ridge is present during PC1 Sundowner days although it only extends to 30-31°N, and the resulting wind over the focal region is northerly. On days with both SAW and PC1 events, the ridge reaches around 33-36°N and does not have an eastern tilt, indicting more north-north easterly winds for the focal region.

850mb Geopotential Height

Maps for SAW-representing days have two separate high pressure centers: off the West Coast, and in Northern California and Southern Oregon, as seen on the maps for both SAW-representing days with lag from PC1 Sundowner events in Figure 6. The pattern observed in these maps was echoed in the maps of PC2 Sundowner-representing days with lag from SAW events. The secondary center over the contiguous United States (CONUS) is likely due to the influence of high-elevation mountains, which may result in surface pressure around or below 850mb. The resulting 850mb height flow in the focal region is between westerly and northerly, depending on the placement of the centers and the exact region of interest. For maps of PC1 Sundowner-representing days, the ridge over the CONUS is less amplified for the 1-day lag maps than the 2-day lag maps. This implies that the 850mb heights near the ridge are lower during the 1-day lag than the 2-day lag, while the heights over the CONUS are higher in the 1-day lag maps than the 2-day lag maps with the high pressure center as observed on SAW-representing days. The maps showing conditions when both wind events are occurring contain only a high pressure center off of the West Coast as well as ridges over the CONUS, more closely resembling PC1 Sundowner-representing maps.

MSLP

All composite maps for MSLP featured strong high pressure systems in the Pacific Ocean and a low pressure system south of the focal region, as seen in all maps for MSLP in Figure 6. The presence of a high pressure system around the Great Basin occurs in all maps except in PC1 Sundowner-representing maps. For maps of SAW-representing days with a 1-day (2-day) lag time, the offshore (onshore) center is stronger, a pattern evident in Figure 6 as well. The scale for the map of SAW-representing days with a 2-day lag time from a PC1 Sundowner event goes slightly higher than the scale for the map of SAW-only days with a 1-day lag time with a PC1 Sundowner event, and this trend holds for all SAW-representing days. When comparing only maps representing PC1 Sundowner days, the high pressure off the coast and the low pressure in the Great Basin is more amplified during the 2-day lag than the 1-day lag.

Surface Air Temperature

Temperature distributions are similar for all maps studied. As shown in Figure 6, the maps from SAW-representing days have the overall coldest temperatures, and the 1-day lag SAW days have the coldest temperatures in the desert more specifically. The coldest temperatures for the domain are around the western border to central Colorado. The scales for maps of PC1 Sundowner days rise to 293K and feature the warmest temperatures in the corner by the desert and coldest temperatures in the ocean in the left corner. The Santa Ynez region in mid-Santa Barbara (Figure 1) has higher temperatures overall during PC1 Sundowner days with a shorter lag time near Central California. The map for days where both wind events occur has a scale similar in value to the PC1 Sundowners.

Vector Wind at Surface

The prevailing wind pattern in all maps was northeasterly over Southern California, however the maps for days of PC1 Sundowner occurrences had northwesterly flow present as well, as seen in the maps for both lag times of PC1 Sundowners in Figure 6. Additionally, all groups demonstrated that the Los Angeles Basin had lower speed winds throughout all maps, and that wind speed quickly decreased moving offshore. As expected, maps created for Sundowner dates show stronger winds in Santa Barbara than on SAW days. The fastest wind speeds were observed in the northern portion of the Southern California region on the days where both events were occurring simultaneously. As demonstrated in SAW-representing maps (see Figure 6), the highest wind speeds were observed near the mountains and valleys in Ventura County. For PC1 Sundowner-representing days, the maps demonstrate that 2-day lag times between the events typically result in stronger winds than 1-day lag time. Lastly, both of these Sundowner-representing maps feature an offshore gradient producing northwesterly winds in the focus region, which can be identified by studying the direction of the included vector on the map.

IV. Discussion

The purpose of this study was to compare synoptic conditions between Sundowner and SAW events, as well as between the categorizations of Sundowner wind events via PCA by Dr. Charles Jones (anticipated publication date 2020), to improve knowledge on the relationship between the two events on spatial and temporal scales, which may ultimately advance the usefulness of atmospheric models in forecasting.

Temporal analysis completed in this study signified that of all times any Sundowner or SAW events occurred during the time span covered by the datasets, a relevant possibility of the wind event of the other type occurring in close proximity either preceding or following that first wind event existed. The quantitative correlation factor for this situation was determined to be at a 26% possibility. A stronger correlation (56%) existed when looking at that 26% of dates specifically, of Sundowners preceding SAW events with a 1-2 day lag time.

These percentages indicate that analyzing conditions in the periods where both events occur in close proximity can offer unique perspectives into the mechanisms related to both wind events. The inclusion of data relating to how one downslope wind events relates to other downslope wind events in terms of their effects and synoptic causes allows for a better understanding of the characteristics that make each of these downslope wind events unique. Using composite maps to study these relationships is beneficial because these maps gives an average of synoptic conditions, which are best observed qualitatively rather than quantitatively and easiest for trend extraction (Hatchett et al. 2018). Beyond comparing these maps for each event to each other, comparing the maps created here to maps in previous studies also provides insight into the forces that drive these wind events.

Three general setups were observed in the composite maps created for groups at the 500mb geopotential height. These setups all had a ridge far off the coast of California, however the wind event represented in the map, the type of wind event that had preceded that wind event, and the lag time between those two all related to identifiable trends that varied the exact structure and location of this feature. As with most of the analyzed variables, patterns in the appearance of jet can be most strongly related to the difference in the wind event that was represented in the map. The jet identified by Hatchett et al. (2018) resembled the jet pattern visible for SAW dates (Figure 6), however the pattern shown in Hatchett et al. (2018) was mapped for dates when both SAWs and Sundowner winds were simultaneously occurring. This difference may be due to Hatchett et al. (2018)'s seasonal subsetting of the data.

The gradient exhibited in the jets at 500mb geopotential height always runs directly opposite to the direction of the vector winds at the surface, which is apparent in the maps for these two variables included in Figure 6. This signifies that all of these wind events are receiving upper level support. The reversal in atmospheric flow closer to the surface can be explained by the sinking of air at the higher elevation that results in a high pressure region developing directly below a lower pressure region at a higher level due to the movement of air according to the gradient that exists higher up (Cannon et al. 2017). This connection further support that the occurrence of these wind events can be attributed to synoptic factor-related causes, over just local forcing of winds (Hughes and Hall, 2008; Jones et al. 2010).

Geopotential height analysis at 850mb provided insight on the importance of synoptic features during these extreme wind events as well. The 850mb maps in this study resembled the MSLP maps, as can be noticed in a comparison between the rows in Figure 6, and the differences that did exist between these variables further suggest that synoptic conditions do have an important influence on wind mechanisms for both Sundowners and SAWs. Although the trends observed between groups in the maps of 850mb geopotential height tended to be most closely related to which wind event was directly represented by the map, these maps had a closer relationship to uniform differences based on lag time than other variables. Two anticyclones existed in each map with SAW days represented, and the stronger anticyclone shifted to be more further with the higher lag time, which is evident in the maps for SAW-only days at 850mb height in Figure 6. This suggests that Sundowners that form as a result of higher pressure centers are most likely to occur two days before a SAW event than 1 day before. On Sundowner days, the opposite is present, where Sundowners that occurred 2 days after SAW events tended to form, occurred from lower and larger geographical regions of high pressure than their counterpart occurring with a 1-day lag time. Other interesting features observed in these maps were the semi-permanent Aleutian low and Pacific high, which cause the general prevailing westerly flow in this section of the Northern Hemisphere (Mills, 2012).

Analysis at 850mb height is critical, as it is similar to one of the factors used for the actual forecasting of these wind events. One of the variables that meteorologists account for in their forecasting is wind support at the top elevations of the mountains that the downslope wind event formation is attributed to. Geopotential height at 850mb gives a good idea of the direction of pressure gradients that exist at the peaks of these mountains (the Transverse ranges more accurately than the Santa Ynez range), and this gradient demonstrates the direction of the winds at that level below that specific region (Gomberg). Additionally, this level represents the planetary boundary layer, where surface features start having an effect on the flow of the atmosphere as perceived from Earth’s surface (Mills, 2012).

MSLP was the first synoptic factors used to evaluate both wind events, and it is still the most important factor considered in forecasting today (Ryan, 1996; Raphael, 2003; Gomberg). Figure 2 indicates the locations of each pressure gradient used to forecast these wind events currently. The black flags all represent locations of the relevant airports that are used. Forecasters currently consider the pressure difference between Barstow-Daggett (DAG) Airport and Los Angeles (LAX) Airport for SAW forecasting, and both the pressure gradient between Santa Maria (SMA) and Bakersfield (BFL) Airports and Santa Barbara (SBA) airport for Sundowner forecasting (Raphael, 2003; Blier, 1998; Sukup, 2013; Gomberg). These pressure gradients are evident between these areas in Southern California in the MSLP composite maps. This study supports the use of both the BFL-SBA and SMA-SBA gradients in the forecasting of Sundowners, as very different synoptic conditions for each of the variables existed for each of the separate geographical regions covered by these gradients.

Additionally, no distinct discrepancies between the directions of the vector winds indicated on the map and the direction of MSLP pressure gradients were observed to exist, as evident in the maps of the relative rows in Figure 6. Lastly, the same evolutionary pattern for pressure shifts which were observed to exist in 850mb maps for geopotential height existed according to lag time as well for the MSLP composite maps.

The analysis of vector winds at the surface allowed for an assessment of the PCA Sundowner criteria as well as the extreme surface winds produced during Sundowners and SAWs. Hatchett et al. (2018), Blier (1998), Hughes & Hall (2009), and Jones et al. (2010) include comparable vector wind composite maps of Sundowner and SAW events. Cross-analysis between these studies shows the large spatial variability of Sundowners, that may be attributed to varied synoptic conditions. Analysis of vector winds at 1000mb allowed for an association of the other synoptic factor variables analyzed in the study with the severity of each wind event, by highest wind speed. It also provides insight into the relationship between local factors and synoptic factors, because it demonstrates the direction of the winds that were observed at the surface.

Clear differences in the direction of wind vectors over Santa Barbara were observed between the two categories of Sundowners, with maps of PC1 Sundowners exhibiting northwesterly winds over the region (Figure 6), and maps of PC2 Sundowners exhibiting northeasterly winds over the region. Although the map depicted in Figure 6 that represents MSLP on days where both wind events occurring appears to lack a second definitive anticyclone onshore, that group has the highest observed wind speeds in the region than any map for any other group evaluated, which indicates that MSLP is not the most indicative factor of the severity of wind events. However, the map for vector winds representing SAW days that occurred 1 day after PC1 Sundowner days in Figure 6 were the second highest wind speed values reported in this study (equivalent with speeds on both of the other days where two wind events were occurring besides group 4) and this day had the lowest temperatures in the deserts southeast of the region, indicating that the role of temperature advection may be more critical than MSLP in regards to event severity.

The first suggestion that thermodynamic forcing played a critical role in the development and strength of SAW events was by Hughes and Hall (2009). Since then, studies including Jones et al. (2010) and Guzman-Morales et al. (2016) have attributed the strength of SAW events back to temperature-related forcing, specifically focusing on the existence of anomaly cold temperatures in the Mojave Desert southeast to the relevant portion of the Southern California coast included in Figure 2. This idea helps explain why SAWs are more common in the winter than in other months of the year, because the desert reaches its coldest temperatures in the winter (Guzman-Morales et al. 2016). The results related to differences in temperature evaluated in the maps of this study further supported these ideas. A possible flaw in the temperature data evaluated in this study was the course resolution of the reanalysis data, which can cause for the effect of the mountains to be lost, as they take up a space smaller than the grids utilized in reanalysis. As the Santa Ynez range is smaller and lower in elevation than the Transverse range, this flaw becomes more important when evaluating temperatures related to Sundowner wind events (Abatzoglou et al. 2013; Hatchett et al. 2018). Overall, temperature distributions throughout maps (ignoring the scale values) tended to appear similar to each other for all groups evaluated, yet the minute differences in which ones were closer lead to observable increases in the vector wind speeds, as evident in the maps in Figure 5. This similarity is notable, as this relatively uniform temperature pattern observed in the maps for the groups listed in Table 1 did not resemble the patterns for temperature distribution in any of the control group maps based on seasons.

Sundowner and SAW events both play a significant role in the development and devastating nature of the wildfires of the Southern California region, so developing a better understanding of them and a stronger ability to forecast them is crucial to increasing public safety during these events. Knowing whether a wind event of the other type will precede in close proximity to the first wind event is especially relevant in this context. These wind events do occur very close to each other spatially, so the shift in wind direction that will overcome the region heightens the dangers as it may cause the fire to spread in a completely opposite direction than expected. Fires like the Thomas Fire of 2017 (Carvalho et al. 2019) represent situations of fires spread by both wind events.

V. Conclusion

Results indicated a weak temporal correlation between the timing of the two events, with the highest frequency of events occurring in close temporal proximity to each other being a PC2 Sundowner event preceding a SAW event by 2 days. Variations within the results, specifically within groups with similar lag times, suggest that the difference in topography between the regions affected by each event is critical to the development of unique spatial and temporal characteristics for each wind event. However, the patterns detailed in this study are likely closely tied to the major causes of these downslope wind events, more importantly than mesoscale features, and typically can also be accounted for the severity of each event, with MSLP and surface air temperatures being most closely tied to it.

VI. Future Works

More insight could be provided in to the relationship between PC2 Sundowners and SAWs through analysis of the same variables analyzed here but on smaller spatial scales. Looking at a smaller spatial scale would give more detail on the role of certain geographical features such as the Santa Ynez Mountains, which are too small to be represented by the coarse resolution in the reanalysis data. The study could also be expanded to include the consideration of longer lag times between the events. Seasonal and yearly analyses could also be evaluated further to gain more definitive perspectives on extreme wind events in Southern California, and how these wind events may evolve in the future with the changing climate. Lastly, composite maps for additional variables, such as 850mb vector winds and the evaluation of surface winds in terms of anomaly values (to better quantify each event by the wind gusts that were observed), for more insight into the processes involved in the creation of these wind events.

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