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Witness: Vanderburg

PREPARED DIRECT TESTIMONY OF

STEVE VANDERBURG

ON BEHALF OF

SAN DIEGO GAS & ELECTRIC COMPANY

BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF CALIFORNIA

SEPTEMBER 25, 2015

TABLE OF CONTENTS

PREPARED DIRECT TESTIMONY OF STEVE VANDERBURG

ON BEHALF OF SAN DIEGO GAS & ELECTRIC COMPANY

I. INTRODUCTION

Q. Please state your name and business address.

A. My name is Steve Vanderburg. My business address is 9060 Friars Road, San Diego, CA 92108.

Q. What is your current position?

A. I am currently employed by San Diego Gas & Electric Company ("SDG&E") as a Meteorologist.

Q. What is your educational and professional background?

A. I received a Bachelor of Science in Meteorology from the University of Oklahoma in 2004. In 2001, I began working as a student meteorologist for the National Weather Service in San Diego through the Student Career Experience Program. Upon completion of my B.S. in Meteorology in 2004, I became a full-time meteorologist at the National Weather Service in San Diego. I moved to a position with the National Weather Service in Reno, Nevada in 2010. During my tenure with the National Weather Service, I performed a variety of functions, including providing forecast and other weather information to the public and state and federal agencies; managing the Red Flag Warning Program in San Diego; coordinating weather information with various fire agencies; maintaining weather equipment and instruments; and compiling monthly event records for storm events (*e.g.*, winter storms and Santa Ana wind events). In July 2011, I was hired by SDG&E for my current position where I provide operational weather support to the company, manage one of the densest, most sophisticated weather station networks in the country, and collaborate with local universities and government agencies on a variety of weather-related projects. I directly support SDG&E's Emergency Service's group and the Emergency Operations Center (when activated) prior to and during significant weather events including dangerous fire weather conditions associated with Santa Ana wind events and Red Flag Warnings. My qualifications are set forth in Appendix 1.

Q. Have you previously testified before the California Public Utilities Commission?

A. No, I have not.

II. PURPOSE OF TESTIMONY

Q. What is the purpose of your direct testimony?

A. The purpose of my testimony is to discuss the weather conditions at the time of the massive wildfire outbreak in Southern California that began in late October 2007 ("2007 Wildfires") and the steps taken by SDG&E to better understand and predict potentially dangerous weather conditions. Our analysis, based on information that was not available before the 2007 Wildfires, demonstrates that the 2007 Wildfires occurred during the most severe fire weather event in San Diego County since at least 1984. That is to say that the weather conditions that existed in October 2007 greatly increased both the risk of a fire start and the risk that any fire would quickly spread when compared against historically normal conditions and other Santa Ana events. In fact, the weather at the time of the 2007 Wildfires made it more likely than ever before that a potential ignition source would start an uncontrollable fire.

Q. How is the remainder of your testimony organized?

A. In Section III, I provide an overview of the weather and wind conditions in SDG&E's service territory, including a discussion of the factors that make the area prone to wildfire outbreaks, such as the Santa Ana winds. Next, in Section IV, I explain the steps SDG&E and others have taken since the 2007 Wildfires to better understand the weather conditions in

SDG&E's service territory, including the development of a predictive tool for classifying the fire threat potential associated with Santa Ana wind events known as the Santa Ana Wildfire Threat Index. Lastly, in Section V, I place the 2007 Wildfires in historical context and provide support for my conclusion that this was the most severe fire weather event on record in San Diego County. I also explain that the wind gusts at the time of the 2007 wildfires were extreme.

III. THE WEATHER CONDITIONS IN SDG&E'S SERVICE TERRITORY

Q. Please describe the weather conditions in SDG&E's service territory.

A. SDG&E's service territory encompasses primarily San Diego County but also parts of Orange County. The climate of this region is characterized by mild to cool, wet winters and warm to hot, dry summers, typical of a Mediterranean climate. However, the climate of a particular location within the SDG&E's service territory is greatly influenced by its distance from the coast and topography. SDG&E's service territory, like much of Southern California, also experiences strong wind patterns known as the Santa Ana winds.

Q. What are the Santa Ana winds?

A. Santa Ana winds are dry, gusty winds that blow across coastal Southern California from the east (northeast) to the west (southwest). These winds generally occur between the months of September and May and often result when cold temperatures and surface high pressure over the interior desert regions of the Western U.S. (primarily the Great Basin) combine with upper level high pressure over Southern California. This pressure imbalance causes the desert air to rush into Southern California. As the cold, dry air passes over the mountains, it accelerates rapidly down the coastal slopes in what is called a downslope wind. As the air descends, it becomes much warmer and even more dry, hence the reason Santa Ana winds are often associated with hot, dry conditions across coastal regions of Southern California. The strongest Santa Ana winds in San Diego County generally occur in the foothills, at elevations between 2000 – 4000 feet.

Q. What role do the weather conditions have in the outbreak of wildfires in Southern California?

A. Hot, low humidity conditions, coupled with strong and gusty Santa Ana winds and dry, high fuel loads, *i.e.*, the amount dry living and dead vegetation (primarily chaparral) and native and non-native grasses,[1] create the potential for large wildfire outbreaks. Under these conditions, fire will ignite easily and spread quickly.

IV. SDG&E'S EFFORTS TO IMPROVE THE GENERAL UNDERSTANDING OF WEATHER IN SAN DIEGO SINCE THE 2007 WILDFIRES

Q. Did SDG&E take steps after the 2007 Wildfires to better understand the weather conditions in its service territory?

A. Yes. The 2007 Wildfires were obviously a catastrophic event in Southern California and were a major turning point in how SDG&E – as well as federal and state agencies and the weather community – looked at weather conditions in relation to potential wildfire outbreaks in San Diego. Prior to the 2007 Wildfires, the tools that existed for anticipating and preparing for weather conditions conducive to wildfire outbreaks in SDG&E's service territory were – as we now know – not specific enough.[2] As a result, there was insufficient information available to

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[1] Live fuel moisture and dead fuel moisture measurements are one important factor in determining when fuels are dry enough to support fire growth.

[2] As explained below, the National Weather Service has, since prior to the fire, issued weather alerts in advance of expected high fire conditions. These warnings are based on evaluation of certain expected weather conditions for a wide area, *i.e.*, the humidity, wind speed, and temperature for San Diego County, but are do not attempt to quantify the risk of fire or the threat posed in any particular location within the county.

prepare for wildfire conditions and to deploy appropriate resources in advance of those conditions.

Thus, one of the major steps SDG&E took in the aftermath of the 2007 Wildfires was to examine whether, through research and technology, it could better predict when and where wildfires were most likely to develop. I have been directly involved in the efforts to develop a better understanding of the local weather conditions – particularly Santa Ana winds – and the particular circumstances in which weather conditions become conducive to large wildfire outbreaks. I have also been involved in the development of an index that can categorize this information in a way that is useful not only to fire agencies and the general public but also to SDG&E. These efforts are unprecedented among utilities.

A. SDG&E Weather Stations

Q. How has SDG&E improved its understanding of the weather conditions in its service territory?

A. SDG&E has dramatically increased the amount and quality of real-time weather data available in its service territory. Prior to the 2007 Wildfires, there were only 30 weather stations owned by the federal government and other entities in SDG&E's service territory, many of which provided data that could only be used to understand the weather in their immediate vicinity.[3] More data was needed.

As such, since the fire SDG&E has installed an additional 170 weather stations, of two basic types. SDG&E installed five Remote Automated Weather Stations (or RAWS), which are stand-alone weather stations that monitor wind speeds, wind gusts, precipitation, dead-fuel moisture, temperature, humidity and solar radiation. Wind speeds and gusts are monitored from

[3] A weather station is the name given to a collection of weather monitoring equipment installed at a single location or facility.

20 feet above ground. The remainder of the weather stations SDG&E installed are mounted on SDG&E poles, 20 feet above the ground. These weather stations monitor wind speed, wind gusts, wind direction, temperature, humidity, and in some cases, additional information like barometric pressure. The data from these stations is transmitted to SDG&E every 10 minutes.

Q. What has SDG&E learned from the data transmitted by these weather stations?

A. The greatest benefit of these weather stations is that we know have a far clearer understanding of weather conditions at specific locations throughout the SDG&E service territory. The information derived from the new SDG&E weather stations has also allowed SDG&E to study Santa Ana winds in a way that was not previously possible. This has led to the development of the Santa Ana Wildfire Threat Index (which I describe below) and an increased understanding of how Santa Ana winds impact our service territory. For instance, we now know that the strongest Santa Ana winds in SDG&E's service territory are not being funneled through passes or canyons, as was previously assumed, but are actually downslope windstorms. This is important because it changes the way a meteorologist examines the atmospheric conditions when forecasting the severity and extent of Santa Ana winds.

We also now have a much clearer picture of the locations of the windiest areas in our service territory and an understanding that winds can vary significantly across relatively small distances within SDG&E's service territory. I have provided several examples of such variation in Appendix 2. In the first example from a recent Santa Ana wind event that transpired on February 15, 2013, at 18:22 UTC, the strongest wind gust reported by any of the 14 government-owned weather stations across the San Diego backcountry, which is all we had access to in 2007, was 36 mph at Pine Hills. But as shown on the next page, once we add in the SDG&E weather stations, which did not exist in 2007, we can see that the strongest wind gust in the area was actually in excess of 90 mph – almost three times faster than what the Pine Hills RAWS was reporting. Examples such as this can be found during every Santa Ana wind event. Thus, wind gust observations vary tremendously by location even among SDG&E weather stations that are in relatively close proximity. The most striking example is the 91 mph wind gusts at SDG&E's Sill Hill weather station and the 45 mph wind gusts a mere 1 mile south at SDG&E's Boulder Creek weather station.

Another example comes from a very strong Santa Ana wind event that occurred on April 30, 2014. At 16:01 UTC, wind gusts ranged from 37 mph at the Julian RAWS, to 74 mph at SDG&E's West Santa Ysabel weather station, to 32 mph at Ramona Airport. This example clearly highlights the downslope nature of Santa Ana winds in that the air coming into San Diego County from the east is only just beginning to accelerate as it passes Julian, reaches peak velocity several miles downslope around the Santa Ysabel area, and then decelerates significantly upon reaching the lower elevations around Ramona. This variability is not random, however, and in many cases is now predictable based on historical observations and the local, known characteristics of downslope winds. At the time of the 2007 Wildfires, however, no one had any idea how significant this variability could be across such short distances.

Q. How does SDG&E use the data provided by the weather stations in its operations?

A. The SDG&E meteorology department monitors and analyses this data, along with other weather information provided by the National Weather Service. We then provide the company with detailed information on how weather has impacted or may impact SDG&E's system, including specific weather conditions that may impact precise locations on our system. The examples I gave in my previous answer about the significant variability in wind gust observations over a short distance certainly impact how we operate the grid, since we know that wind gust readings at Pine Hills, for instance, likely don't provide meaningful information about the severity of gusts at West Santa Ysabel, or other nearby locations. We have also been able to use historical data collected from our weather stations to fine tune high resolution weather forecast models to our service territory, so that those models provide more accurate information.

Q. Does SDG&E share information obtained from its weather stations with anyone?

A. Yes. The data from SDG&E's weather stations is made available to the National Weather Service, and is publically available for free through the internet, the media, and the National Weather Service, to name a few sources. SDG&E also built a website (sdgeweather.com) to be viewed by firefighters and other first responders on their mobile devices. The intent was to provide firefighters easy access to SDG&E weather data in the event of a wildfire or other weather-sensitive emergency.

Q. To your knowledge, how have these new weather stations benefitted rate payers?

A. As noted, these weather stations allow SDG&E's meteorologists to develop a real-time, detailed knowledge of how weather impacts SDG&E's system. The National Weather Service, for instance, does not tailor its weather forecasts specifically to utility industry impacts; we do. By having the ability to inform our transmission and distribution personnel of specific weather conditions that can impact precise locations on our system in a specific time period, SDG&E can position resources such as trucks and crews more appropriately. This means that we can more quickly and effectively respond to weather and wind conditions that may impact system reliability. Moreover, through our advanced forecasting system, we have far better awareness of the timing and severity of Santa Ana wind events, which also permits SDG&E to prepare, monitor and deploy its resources more effectively and similarly leads to improved system reliability. Such improved understanding also lowers the costs of emergency operations because we are now able to ramp up those operations in a more tailored way, in response to specific threats.

B. Santa Ana Wildfire Threat Index

Q. You also mentioned that you have developed a Santa Ana Wildfire Threat Index. Please describe what that is.

A. The Santa Ana Wildfire Threat Index is an index that categorizes Santa Ana wind events with respect to the anticipated potential for a large fire to occur (referred to as "Large Fire Potential"[4]) in much the same way that hurricanes and tornadoes have been categorized. It was developed through a collaboration involving SDG&E, the U.S. Forest Service (Predictive Services), the Department of Oceanic and Atmospheric Sciences at UCLA, Vertum Partners. It is now maintained by the U.S. Forest Service and was made available to the public in the fall of 2014.[5]

Q. What are the categories of the Santa Ana Wildfire Threat Index?

A. There are five categories:

(1) <u>No-Rating</u>: Santa Ana winds are not expected or will not contribute to significant fire activity.

(2) <u>Marginal</u>: Upon ignition, fires *may* grow rapidly.

(3) <u>Moderate</u>: Upon ignition, fires *will* grow rapidly and *will* be difficult to control.

(4) <u>High</u>: Upon ignition, fires will grow very rapidly and will be very difficult to control.

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[4] Large Fire Potential refers to the likelihood of an ignition reaching or exceeding 250 acres, or approximately 100 hectares.

[5] *See* http://sawti.fs.fed.us/

(5) Extreme: Upon ignition, fires will have extreme growth and will be uncontrollable.

Q. Please describe the methodology used to determine how specific events fall within these five categories?

A. The Santa Ana Wildfire Threat Index uses a comprehensive, state-of-the-art predictive model to create a detailed daily assessment of the fuel conditions across Southern California. This information is coupled with calibrated weather model output (comprised of wind speed and atmospheric moisture), to generate a 6-day forecast of Large Fire Potential. The Large Fire Potential output is then compared to climatological and historical fire occurrence data extending back to January 1, 1984 to establish the index rating. Further information about the Santa Ana Wildfire Threat Index is included in a white paper that I have attached as Appendix 3, which I co-authored with my colleague Brian D'Agostino, Tom Rolinski and Scott Capps of the U.S. Forest Service, and Robert Fovell and Yang Cao of UCLA. In addition, Appendix 4 provides an overview of the development and validation of the index and was originally presented at a weather industry conference.

Q. Why is historical information dating back to 1984 taken into consideration?

A. We looked back 31 years because in order to understand fire potential in the present you have to compare the current conditions with the conditions that existed on prior days. Past time periods in which there actually were wildfire outbreaks are particularly important in this regard; if we have a present fire potential on our index that matches the fire potential of a previous instance in which wildfires occurred, this confirms there is a strong likelihood of a wildfire outbreak.

Q. Doesn't the National Weather Service monitor the weather conditions that could lead to wildfire outbreaks?

A. Yes. The National Weather Service issues fire weather forecasts every day. The National Weather Service will issue a Fire Weather Watch or a Red Flag Warning when weather conditions are forecast to become conducive to rapid fire growth. These watches and warnings, however, do not provide any quantification of the fire risk and are usually too high level to be helpful in any particular area with respect to the decision making process at the utility.

Q. When does the National Weather Service issue a Red Flag Warning?

A. In San Diego County, the criteria for a Red Flag Warning is sustained winds of 25 mph or greater and/or frequent gusts of 35 mph or greater with relative humidity of equal to or less than 15 percent for six or more hours. A Fire Weather Watch is issued when critical fire weather conditions are forecast to occur within 24 to 72 hours. A Red Flag Warning is issued when critical fire weather conditions are occurring or are expected to occur within 24 hours. In other words, such warnings are issued when it is expected to be windy and dry for a sustained period.[6]

Q. Does a Red Flag Warning tell you anything about the likelihood of a wildfire outbreak that exists at a particular point in time?

A. No. A Red Flag Warning only tells you that weather conditions are forecast to become (or have already become) conducive to rapid fire growth. A Red Flag Warning does not rate the severity of the fire potential or give any indication as to how the event compares with past events. In a sense, it is comparable to issuing a Hurricane Warning but without the Saffir-Simpson Scale (Category 1-5 scale). In addition, Red Flag Warnings do not indicate what specific locations within, for example, San Diego County are most at risk for wildfire ignitions.

[6] A Red Flag Warning is also issued for Dry Lightning.

For example, while a Red Flag Warning may state that wind gusts are expected to be strong in the mountains and foothills, that forecast does not pinpoint which mountains and foothills will experience the greatest gusts.

Q. Has the Santa Ana Wildfire Threat Index been used successfully as a predictive tool?

A. Yes. A beta test version provided important guidance to SDG&E's operations in mid-May 2014. At that time, the Santa Ana Wildfire Threat Index forecasted extreme weather and fuel conditions in parts of Southern California up to five days in advance. In fact, the Large Fire Potential associated with that Santa Ana wind event was forecast to be the fourth greatest since 1984 with a high probability of large wildfires should ignitions occur. As predicted, Southern California experienced several major wildfire outbreaks at that time (*e.g.*, the Bernardo, Cocos and Poinsettia wildfires). It was the most significant outbreak of wildfires in San Diego County since October 2007.

Q. Have members of the firefighting and weather communities recognized the benefit of the Santa Ana Wildfire Threat Index?

A. Yes. I have had many first-hand conversations with federal and state agencies, meteorologists, and the media about the Santa Ana Wildfire Threat Index and have received a lot of positive feedback. When it was first unveiled in September 2014, a number of commentators provided positive reactions. U.S. Forest Service Chief Bob Bell stated: "It's worked very well for us. We've been able to prepare for a couple past events, and it's with that tool we've been able to get the resources where they really should be."[7] Dr. Robert Fovell, who was at the time the chair of the department of atmospheric and oceanic sciences at UCLA, and who, along with others in that department were involved in high-resolution weather modeling that was used,

[7] http://abc7.com/weather/santa-ana-wildfire-threat-index-unveiled/313399/

stated: “This effort has led to an enhanced understanding of the evolution of Santa Ana winds, their potential for sparking and spreading fires, and their spatial and temporal variation. We not only have a new, deeper understanding of how the San Diego-area terrain influences weather, especially wind, which is crucial to SDG&E’s operations, but we also have been able to make improvements in weather monitoring that will benefit forecasters around the world.”[8]

V. APPLYING SDG&E’S IMPROVED KNOWLEDGE TO THE 2007 WILDFIRES

Q. Have you done any analysis of the wind speeds during the 2007 Wildfires?

A. Yes. I have performed an analysis of the relationship between the Julian RAWS, which existed in October 2007, and the SDG&E weather station at West Santa Ysabel (near the ignition point of the Witch Fire), which did not exist at that time. Based on the known relationship between those two weather stations collected over the past several years, I can calculate what the wind speed would have been in the area of the Witch Fire ignition on October 21, 2007. According to my calculations, the peak wind gust at West Santa Ysabel in October 2007 would have been 1.56 times stronger than what was observed at the Julian RAWS. This means that the peak wind gusts at West Santa Ysabel were likely to have been approximately 92 mph at that time.

Q. Earlier, you mentioned that in developing the Santa Ana Wildfire Threat Index, you analyzed Large Fire Potential back to 1984. Did you learn anything about the 2007 Wildfires in connection with that analysis?

A. Yes. We learned that at the time of the 2007 Wildfires, the Large Fire Potential was by far the greatest Large Fire Potential in the entire study period. The spikes on Figure 1 correspond to periods of elevated fire danger associated with Santa Ana wind events. As one can

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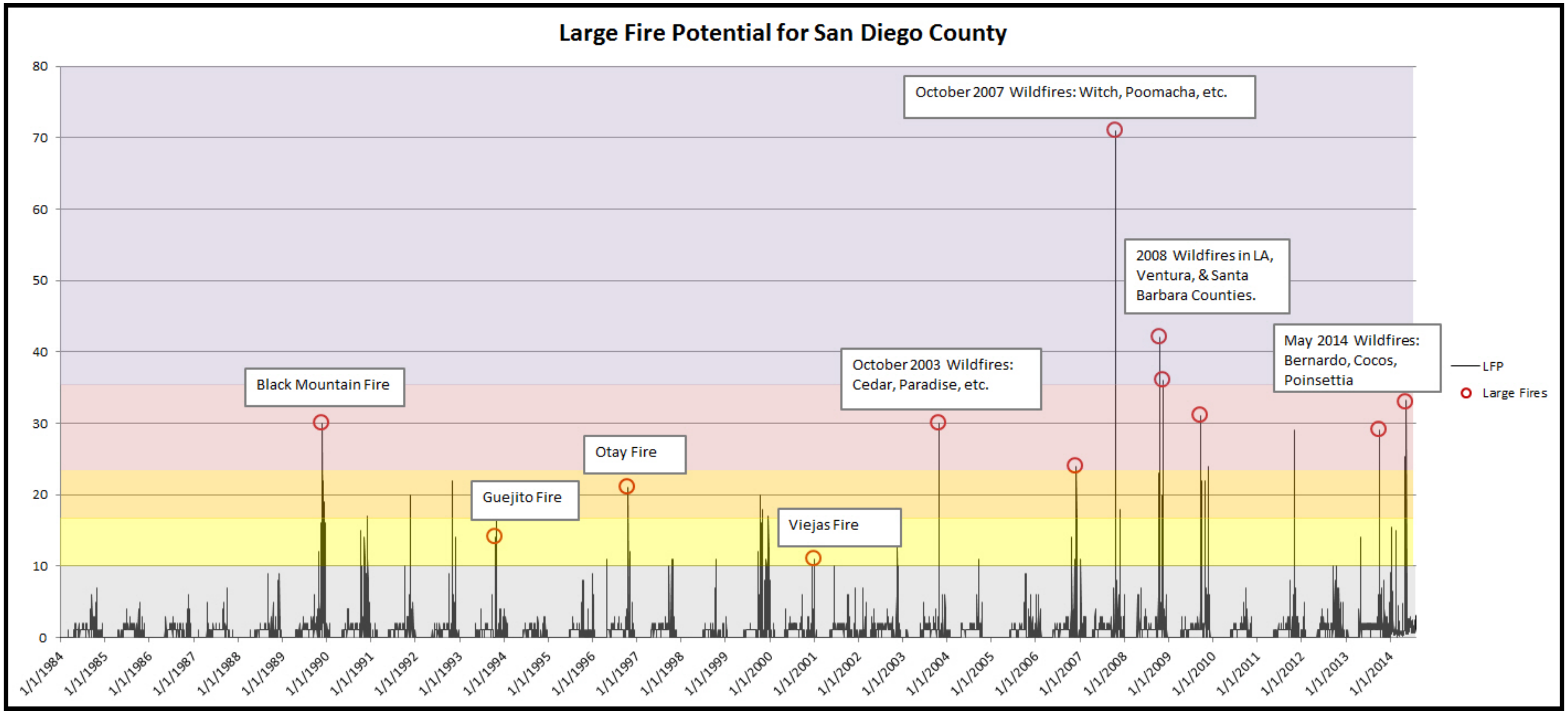
[8] http://newsroom.ucla.edu/releases/ucla-scientists-play-key-role-in-developing-new-santa-ana-wildfire-threat-index

see, the greatest Large Fire Potential occurred during October 21-23, 2007. To put this into context, the Large Fire Potential at the time of the 2007 Wildfires was 2.4 times greater than the Large Fire Potential at the time of the 2003 wildfires, which burned approximately 750,000 acres acres and 3,700 homes.

FIGURE 1



No-Rating	Marginal	Moderate	High	Extreme
Santa Ana winds are not expected or will not contribute to significant fire activity.	Upon ignition, fires *may* grow rapidly.	Upon ignition, fires *will* grow rapidly and *will* be difficult to control.	Upon ignition, fires will grow *very* rapidly and will be *very* difficult to control.	Upon ignition, fires will have extreme growth and will be uncontrollable

Q. What conclusions do you draw from this analysis?

A. From these numbers, I conclude that October 2007 was an unusually strong, damaging, and unprecedented Santa Ana wind event in San Diego County, which, when coupled with the high heat, low humidity, and extremely low fuel moisture, created an environment that fostered the start and spread of fire. This is undoubtedly a major reason why some 300 fires ignited at that time, and why several of those fires spread rapidly across great distances.

VI. CONCLUSION

Q. Does this conclude your prepared direct testimony?

A. Yes, it does.

APPENDIX 1

STATEMENT OF QUALIFICATIONS OF STEVE VANDERBURG

My name is Steve Vanderburg. I am currently employed by San Diego Gas & Electric Company ("SDG&E") as a Senior Meteorologist.

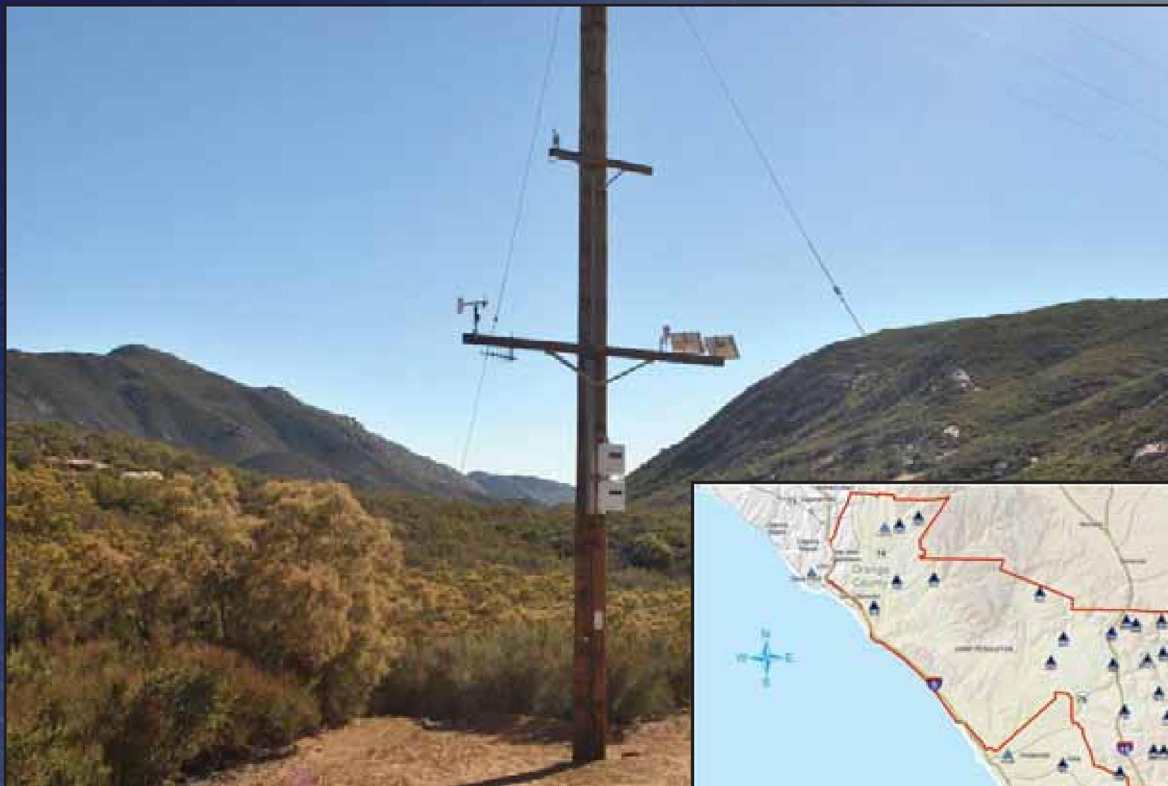
In 2001, I began working as a student meteorologist for the National Weather Service in San Diego through the Student Career Experience Program. I received a Bachelor of Science in Meteorology from the University of Oklahoma in 2004. Upon completion of my B.S. in Meteorology in 2004, I became a full-time meteorologist at the National Weather Service in San Diego. I moved to a position with the National Weather Service in Reno, Nevada in 2010. During my tenure with the National Weather Service, I performed a variety of functions, including providing forecast and other weather information to the public and state and federal agencies; managing the Red Flag Warning Program in San Diego; coordinating weather information with various fire agencies; maintaining weather equipment and instruments; and compiling monthly event records for storm events (*e.g.*, winter storms and Santa Ana wind events).

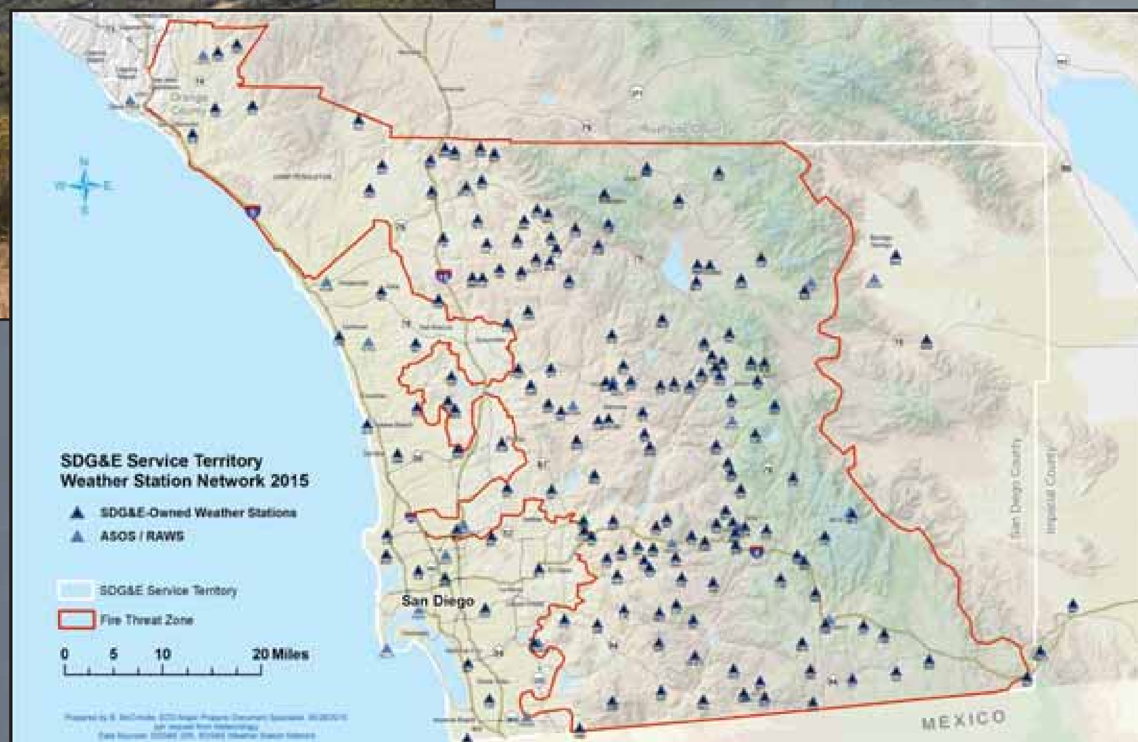
In July 2011, I was hired by SDG&E for my current position where I provide operational weather support to the company, manage one of the densest, most sophisticated weather station networks in the country, and collaborate with local universities and government agencies on a variety of weather-related projects. I directly support SDG&E's Emergency Service's group and the Emergency Operations Center (when activated) prior to and during significant weather events including dangerous fire weather conditions associated with Santa Ana wind events and Red Flag Warnings.

I have not previously testified before the California Public Utilities Commission.

APPENDIX 2

SDG&E MESONET





SDG&E MESONET: SUPERIOR SITUATIONAL AWARENESS

Example from recent Santa Ana wind event – 02/15/2013 @ 18:22 UTC …without SDG&E Weather Stations

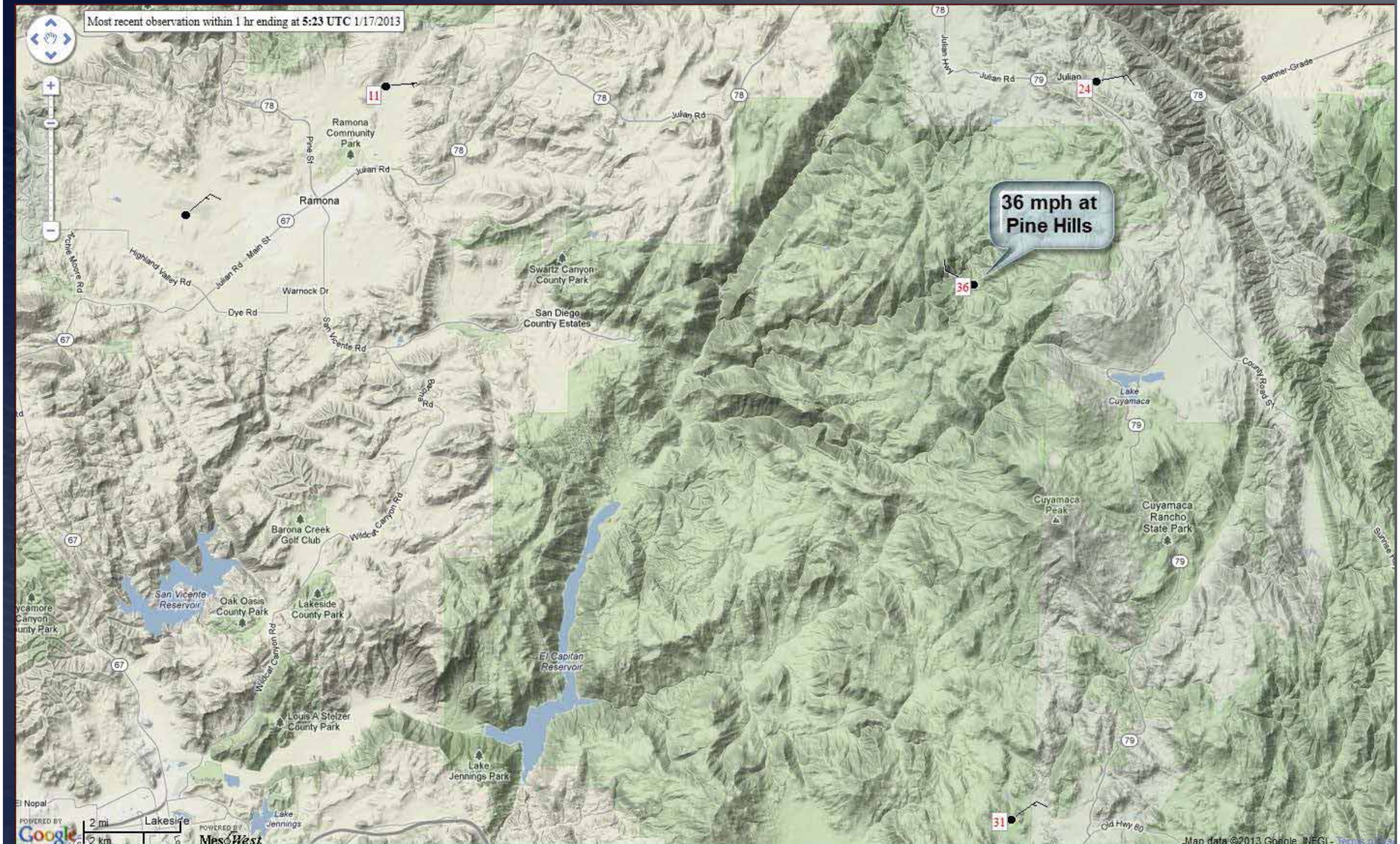
SDG&E MESONET: SUPERIOR SITUATIONAL AWARENESS

Example from recent Santa Ana wind event – 02/15/2013 @ 18:22 UTC …with SDG&E Weather Stations

SDG&E MESONET: SUPERIOR SITUATIONAL AWARENESS

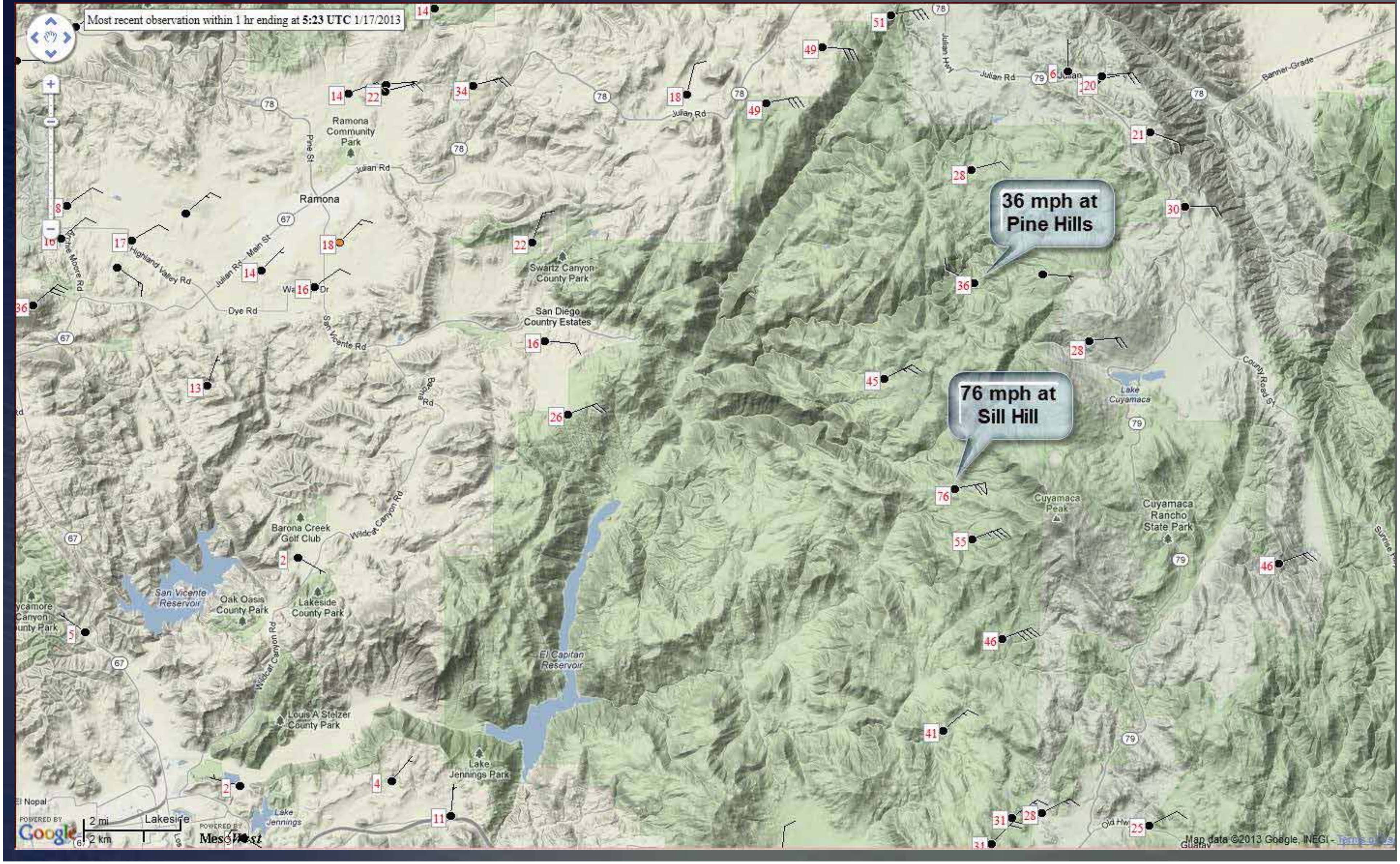
Example from recent Santa Ana wind event – 01/17/2013 @ 5:23 UTC

…without SDG&E Weather Stations…



SDG&E MESONET: SUPERIOR SITUATIONAL AWARENESS

Example from recent Santa Ana wind event – 01/17/2013 @ 5:23 UTC
…with SDG&E Weather Stations



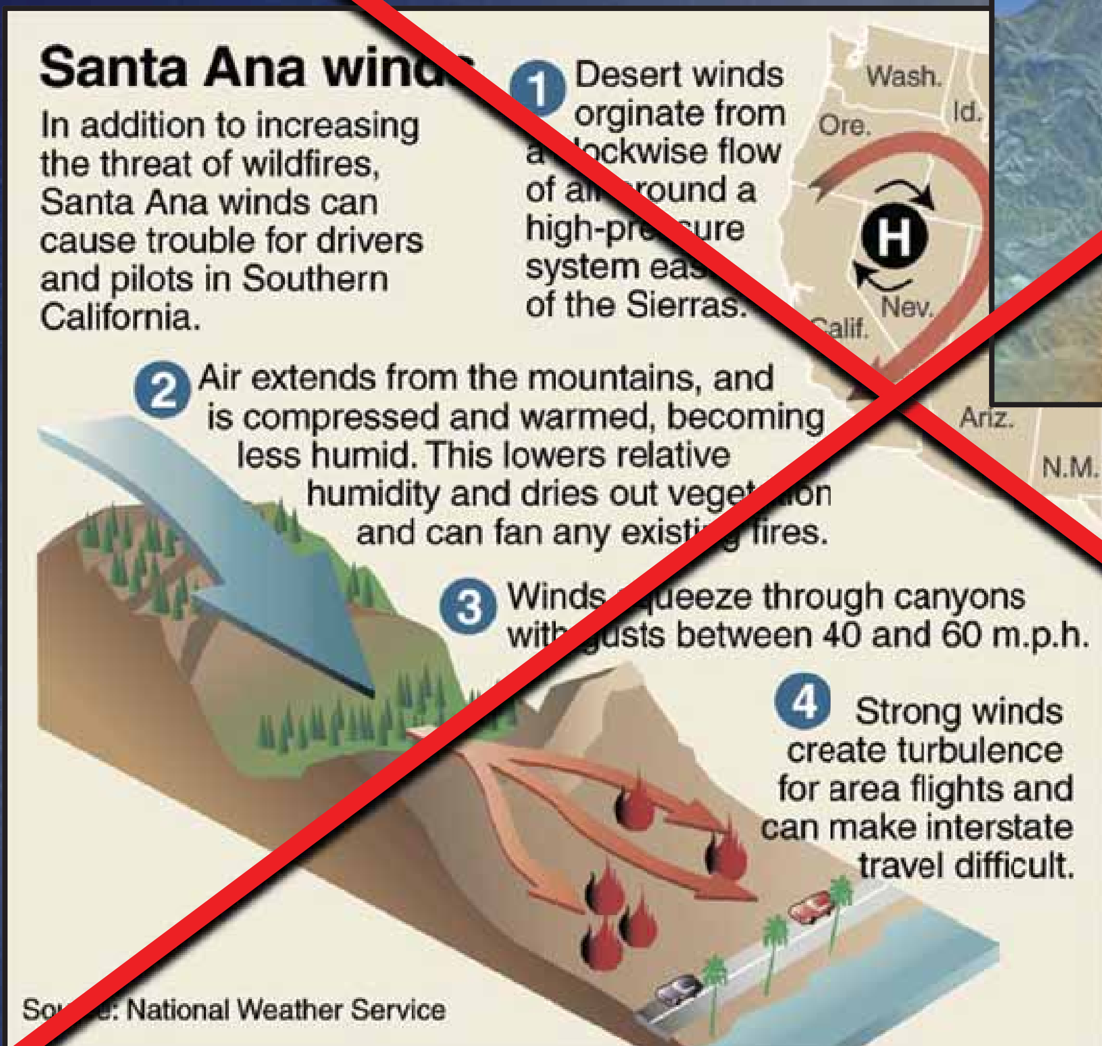
SDG&E MESONET: SUPERIOR SITUATIONAL AWARENESS

Example from recent Santa Ana wind event – 04/30/2014 @ 16:01 UTC
…without SDG&E Weather Stations…

SDG&E MESONET: SUPERIOR SITUATIONAL AWARENESS

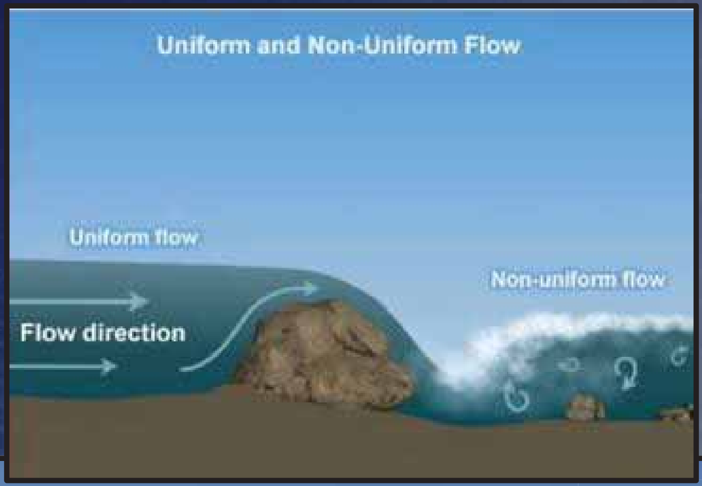
Example from recent Santa Ana wind event – 04/30/2014 @ 16:01 UTC
…with SDG&E Weather Stations

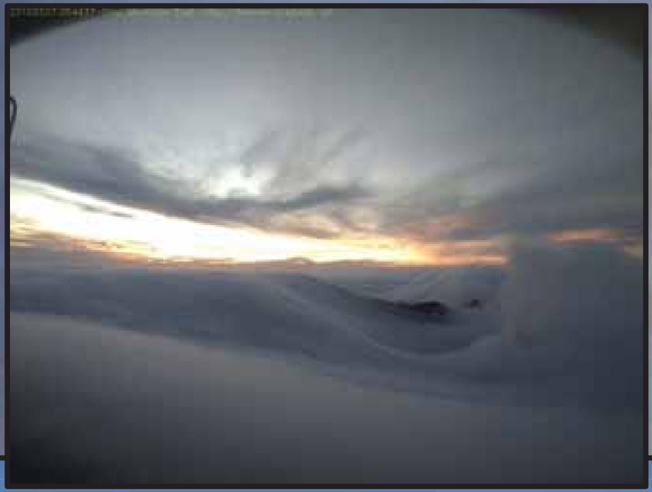
SANTA ANA WINDS DEFINED:



Courtesy of AccuWeather

SANTA ANA WINDS: ATMOSPHERIC RAPIDS

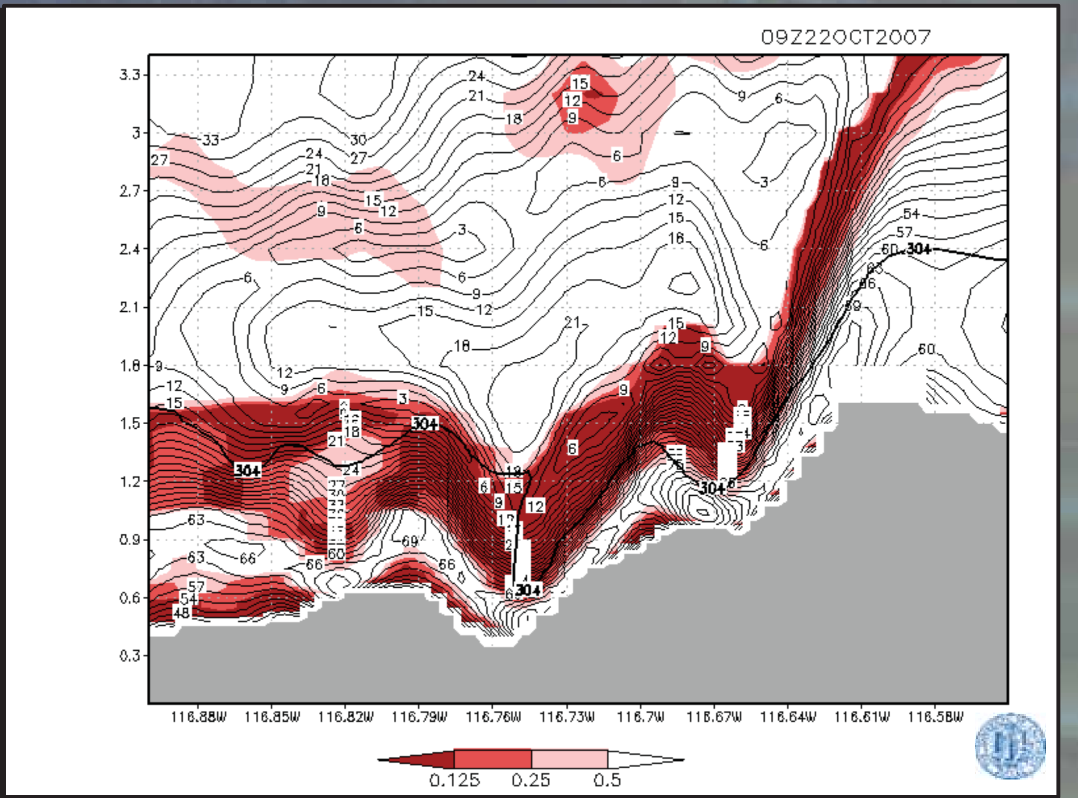




SILL HILL (C79/TL626, BOULDER CREEK RD)

Wind Gust Stats for Sill Hill during the 2013-14 Santa Ana wind season

- 258 hours of 50+ mph winds
- 128 hours of 60+ mph winds
- 50 hours of 70+ mph winds
- Peak Wind Gust of 101 mph on April 30th, 2014



APPENDIX 3

The Santa Ana Wildfire Threat Index: Methodology and Operational Implementation

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ABSTRACT

Santa Ana winds, common to Southern California during the fall through early spring, exhibit characteristics similar to katabatic winds and originate from a direction generally ranging from 360°/0° to 100° and is usually accompanied by very low humidity. Since fuel conditions tend to be driest from late September through the middle of November, Santa Ana winds occurring during this time have the greatest potential to produce large, devastating fires when an ignition occurs. Such catastrophic fires occurred in 1993, 2003, 2007, and 2008. Because of the destructive nature of such fires, there has been a growing desire to categorize Santa Ana wind events in much the same way that tropical cyclones have been categorized. The Santa Ana Wildfire Threat Index (SAWTI) is an index that categorizes Santa Ana wind events with respect to anticipated fire potential. The latest version of the index has been a result of a three and a half year collaboration effort between the USDA Forest Service, SDG&E, and UCLA. SAWTI uses several meteorological and fuel moisture variables at 3 km resolution using the Weather Research and Forecasting (WRF) model to generate the index out to 6 days. In addition to the index, a 30-year climatology of weather and fuels data, along with the index itself has been developed to help put current and future events into perspective. This paper will outline the methodology for developing the SAWTI, including a discussion on the various datasets employed and its operational implementation.

1. Introduction

From the fall through early spring, offshore winds, or what are commonly referred to as Santa Ana winds, occur over Southern California from the coastal mountains westward, from Ventura County southward to the Mexican border. These synoptically driven wind events vary in frequency, intensity, and spatial coverage from month to month and from year to year, thus making them difficult to categorize. Most of these wind events are associated with mild to warm ambient surface temperatures $\geq 18\,^{\circ}\mathrm{C}$ and low surface relative humidity $\leq 20\,\%$. However, during the late fall and winter months, these events tend to be associated with lower surface temperatures due to the air mass over the Great Basin originating from higher latitudes and other seasonal effects. There are a variety of ways to define a Santa Ana event through the analysis of local and synoptic scale surface pressure and thermal distributions across Southern California (Raphael 2003). We view these offshore winds from a wildfire potential perspective, taking into consideration both the fuel characteristics and weather. As we have found, the index described herein provides a robust descriptor of both Santa Ana Winds and potential wildfire activity. Used in conjunction with an MSLP map type, this is a powerful method to separate Santa Ana Wind events from the more typical nocturnal offshore flows that occur throughout the coastal and valley areas (i.e, land breeze) during the year.

October 21^{st} through the 23^{rd}, 2007, Santa Ana winds generated multiple large catastrophic fires across Southern California (Moritz et al. 2010). Most notable was the Witch Creek fire in San Diego County, where wind gusts of $26\,\mathrm{m\,s^{-1}}$ were observed at the Julian weather station along with relative humidity values of $\approx 5\,\%$. However, high resolution model simulations at 667 m showed that wind velocities were much higher in unsampled areas (Fovell 2012). This event became the catalyst for the development of a comprehensive wildfire potential index to better inform fire agencies, first responders, private industry, and the general public about the severity of an approaching event. This index could also help augment Fire Weather Watches and Red Flag Warnings from the National Weather Service by providing value added information about an impending event.

The Predictive Services Unit, functioning out of the Geographic Area Coordination Center (GACC) in Riverside, California, is comprised of several meteorologists employed by the USDA Forest Service. In 2009, Predictive Services developed the Offshore Flow Severity Index (OFSI), which categorizes Santa Ana wind events according to the potential for a large fire to occur (Rolinski et al. 2011). This unique approach addresses the main impact Santa Ana winds can have on the population of Southern California beyond the casual effects of windy, dry weather. During the past three and a half years, the Forest Service (through Predictive Services) has collaborated with the San Diego Gas and Electric utility (SDG&E) and the University of California at Los Angeles (UCLA) to develop the Santa Ana Wildfire Threat Index (SAWTI) which is a more mature version of the Offshore Flow Severity Index (OFSI). Both versions of the index relate Santa Ana winds to anticipated fire potential (i.e., wind, humidity, and fuel moisture). However, the big difference between the two versions is that the OFSI ingests meteorological data from a single point and uses a simple model to address the state of the fuels. In contrast, the SAWTI uses gridded 3 km resolution model data to assess meteorological conditions and employs a more comprehensive fuel moisture model to determine the likelihood of rapid fire growth.

The SAWTI domain covers the coastal, valley, and mountain areas of Southern California from Point Conception southward to the Mexican border. This area has been divided into 4 zones based in part on the different offshore flow characteristics that occur across the region (Figure 1). For instance, Santa Ana winds across Zone 1 and Zone 2 are primarily a result of offshore surface pressure gradients (locally and/or synoptically) interacting with the local terrain to produce gap winds through the Soledad Canyon, the Cajon Pass, and the Banning Pass (Hughes and Hall 2010; Fovell 2012). These winds also tend to precede the Santa Ana winds that occur across San Diego County by 12 to 24 hours. Across Zone 3, offshore winds take on a more "downslope windstorm" characteristic driven largely by the tropospheric stability (Fovell 2012). Other factors that led to the division of zones were changes in terrain, National Weather Service Forecast Office boundaries, and local news media market areas. The SAWTI is more than a tool for meteorologists and fire agency managers to assess the severity of Santa Ana winds; it is also a tool for the general public to help better prepare for impending events that could lead to catastrophic fires. Therefore, the idea of displaying the product via zones keeps the index simple and easy to understand for all user groups. The following discussion centers around the assessment of fire potential related to Santa Ana winds, the methodology behind the weather and fuel components of the index, and its operational implementation.

2. Methodology

a. Large Fire Potential - Weather Component

The potential for an ignition to reach or exceed 100 hectares (i.e., a large fire) depends on a number of components: e.g., various meteorological and fuel conditions, suppression strategy, topography, accessibility, and resource availability. The value of 100 hectares was achieved by compiling a database of historical fire records containing information such as ignition date, acres burned, containment date, etc., from all the fire agencies across California, and taking the 95^{th} percentile of daily largest fires. The determination of this semi-empirical threshold was also guided by decades of experience guiding coordinated attacks on wildfires throughout Southern California. Moreover, in most cases when this threshold is exceeded, the GACC becomes engaged in resource mobilization to assist in fire suppression. Current methods to evaluate fire potential include various indices from the National Fire Danger Rating System (NFDRS) and from the Canadian Forest Fire Danger Rating System (CFFDRS) (Preisler et al. 2008). The Fosberg Fire Weather Index (FFWI) is one such index which is a function of wind speed, humidity, and temperature with output values ranging from 0 to 100 (Fosberg 1978). While the FFWI may show elevated output values for a Santa Ana wind event, it can also show elevated values for *any* day therefore making it too generic for our purposes.

Assuming an aggressive suppression strategy is employed with adequate resource availability in an easily accessible area where topography is uniform; Large Fire Potential (LFP) becomes a function of the fuel and weather conditions preceding, during, and following the time of ignition. Based on experience, observations, and model data, it has been noted that a non-linear relationship exists between wind speed and fire growth (Rothermel 1972). Supposing for the moment that fuels are fully receptive to ignitions and will support large fire growth, the weather component of LFP during a Santa Ana wind event can be expressed by the following equation:

$$\mathrm{LFP_w} = 0.001\mathrm{W_s}^2\mathrm{D_d} \tag{1}$$

where $\mathrm{W_s}$ is the near surface (10 m AGL) sustained wind speed (mph), and $\mathrm{D_d}$ is the near surface dew point depression (°F). It should be noted that this equation was derived by examining the relationship between multi-decadal historical fire occurrence data and dynamically downscaled reanalysis data. It has been suggested that wind speed has an exponential effect on the spread of fire among finer fuels such as grass and brush, and that wind can also have the same effect on fire spread as a fire burning upslope with little or no wind (Rothermel 1972). Dew point depression ($T-T_d$) depicts the dryness at the surface well, and affects the moisture content of both the live and dead vegetation. Also, dew point depression can sometimes differentiate better between warm and cold offshore events than relative humidity can. In our dataset, it has been noted that larger dew point depression values ($D_d \geq 24\,^{\circ}C$) have mainly been associated with warm events. While this may seem trivial, cold Santa Ana wind events (surface ambient temperatures $< 16\,^{\circ}C$) are usually not associated with large fires (according to our historical fire database previously mentioned). This may be due in part to lower fuel temperatures because in those cases more time would be needed to reach the ignition temperature. Another reason is that colder events are sometimes preceded by precipitation either by a few days or by a few weeks which would cause fuels to be less receptive to new ignitions. These are the primary reasons why temperature was excluded from (1) although it has been incorporated indirectly through the use of D_d, and in the fuels component that will be discussed in the following section. Finally, we note that while (1) bears some resemblance to the FFWI, a comparison of daily outputs of FFWI and LFP_w revealed that LFP_w provides significantly greater contrast between Santa Ana days and non-Santa Ana days. Therefore, these results favored LFP_w as being the more appropriate equation for our purpose.

b. Large Fire Potential - Fuel Moisture Component

In addition to the meteorological conditions, LFP is also highly dependent on the state of the fuels. Given the complexity of the fuel environment (i.e., fuel type, continuity, loading, etc.), we decided to focus more specifically on fuel moisture since that aspect plays a critical role in the spread of wildfires (Chuvieco et al. 2004). For our purpose, we have condensed fuel moisture into three parameters: 1) dead fuel moisture, 2) live fuel moisture, and 3) the state of green-up of the annual grasses. Each of these aspects of fuel moisture is complex and will be defined more specifically later. We combined these moisture variables into one term which we refer to as the Fuel Moisture Component (FMC). While the variables within FMC often act in concert with each other, there are times when they are out of phase with one another due to the variability in precipitation (frequency and amount) across Southern California in the winter. Through a comprehensive empirical investigation, the governing equation for FMC can be expressed as follows:

$$\mathrm{FMC} = \left[0.1\left(\left(\frac{\mathrm{DL}}{\mathrm{LFM}} - 1\right) + \mathrm{G_{ag}}\right)\right]^{1.7} \tag{2}$$

where DL is the Dryness Level consisting of the Energy Release Component (ERC) and the ten hour dead fuel moisture time lag (10 hr). Live Fuel Moisture (LFM) is a sampling of the moisture content of the live fuels indigenous to the local region, and G_{ag} is the degree of green-up of the annual grasses. Currently we are making the assumption that all the terms in (2) have equal weight, but further study may lead to future modification.

1) Dryness Level

The dryness level is a function of ERC and 10 hr DFM (DFM_{10hr}) calibrated to historical fire occurrence across Southern California with unitless values ranging from 1 to 3. ERC is a relative index of the amount of heat released per unit area in the flaming zone of an initiating fire and is comprised of live and dead fuel moisture as well as temperature, humidity, and precipitation (Bradshaw et al. 1983). While ERC is a measure of potential energy, it also serves to capture the intermediate to long term dryness of the fuels with unitless values generally ranging from 0–100 (using NFDRS fuel model G). The 10 hr dead fuel moisture time lag represents fuels in which the moisture content is exclusively controlled by environmental conditions (Bradshaw et al. 1983). Output values of DFM_{10hr} are in g/g expressed as a percentage ranging from 0–60. In the case of the DFM_{10hr}, this is the time required for dead fuels (0.64–2.54 cm in diameter) to lose approximately two-thirds of their initial moisture content (Bradshaw et al. 1983). Thus a DL of 1 indicates that dead fuels are moist, 2 represents average dead fuel dryness, and a 3 indicates that the dead fuels are drier than normal.

2) Live Fuel Moisture (LFM)

The observed LFM is the moisture content of live fuels, e.g., grasses, shrubs, and trees, expressed as a ratio of the weight of water in the fuel sample to the oven dry weight of the fuel sample (Pollet and Brown 2007). Soil moisture as well as soil and air temperature govern the physiological activity which results in changes in fuel moisture (Pollet and Brown 2007). LFM is a difficult parameter to evaluate because of the irregularities associated with observed values. For instance, samples of different species of native shrubs are normally taken twice a month by various fire agencies across Southern California. However, the sample times often differ between agencies and the equipment used to dry and weigh the samples may vary from place to place. In addition, sample site locations are irregular in distribution and observations from these sites may be taken sporadically. This presents a problem when we attempt to assess LFM over the region shown in Figure 1.

Apart from taking fuel samples, there are several ways of estimating LFM using meteorological variables, soil water reserve, solar radiation, etc. (Castro et al. 2003). In particular, (Fovell et al. 2015) developed an approach to modeling the LFM of chamise or greasewood (*Adenostoma fasciculatum*), a common shrub that grows within the chaparral biome in Southern California and is particularly flammable due to its fine, needle-like leaves and other characteristics (Countryman and Philpot 1970). Their strategy made use of historical observed LFM data from 10 sampling sites across Southern California and soil moisture from the 40-100 cm layer ($\mathrm{SMOIS}_{40-100\mathrm{cm}}$) from the North American Land Data Assimilation System, Phase 2 ($\mathrm{NLDAS}-2$). At each sampling site, LFM deviations from climatology are predicted using $\mathrm{SMOIS}_{40-100\mathrm{cm}}$ departures from its own annual cycle. A key element of the model is the incorporation of a 22 day lag between

$SMOIS_{40-100cm}$ and LFM which improved the model fits. LFM observed now is relatable to gridded NLDAS − 2 soil moisture anomalies from about three weeks earlier.

That approach, although quite skillful, results in site-specific equations not easily generalized across Southern California. The SAWTI index presently makes use of a simplified version of the (Fovell et al. 2015) strategy, applied to all grid points in the domain. For a given day, the model can be expressed as follows:

$$\mathrm{LFM} = \left(\mathrm{SMOIS}_{40-100\mathrm{cm}\ 22\mathrm{days}} - \mathrm{SMOIS}_{\mathrm{m}}\right) + 82, \quad (3)$$

where $SMOIS_{40-100cm\ 22days}$, is the soil moisture of the 40–100 cm layer from 22 days earlier, and $SMOIS_m$, is the mean soil moisture from 2009 to 2012 for that same date. The empirically selected constant of 82 roughly approximates the annual mean LFM over a large variety of sites.

3) Annual Grasses (G_{ag})

Following the onset of significant wetting rains, new grasses will begin to emerge in a process called green-up. While the timing and duration of this process fluctuates from year to year, some degree of green-up usually occurs by December across Southern California. During the green-up phase, grasses will begin to act as a heat sink, thereby preventing new ignitions and/or significantly reducing the rate of spread among new fires. By late spring these grasses begin to cure with the curing phase normally completed by mid-June. In (3), G_{ag} is a value that quantifies the said green-up and curing cycles of annual grasses.

G_{ag} is derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data at a resolution of 250 meters for select pixels consisting solely of grasslands. NDVI is further defined by red and near-infrared (NIR) bands in the following equation:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{b}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{b}}} \quad (4)$$

where b is the reflectance in band b (Clinton et al. 2010). It can be shown that NDVI values for Southern California grasslands generally range from about 0.25 ($\pm$0.05) to 0.75 ($\pm$0.05) for an average rainfall year (Figure 2). There is evidence that NDVI is affected by soil color (Elmore et al. 2000), which may explain the NDVI differences ($\pm$0.05) seen among the selected Southern California grassland locations.

G_{ag} is given a rating of 0 to 5 based on NDVI data, where 0 is green and 5 is fully cured. When applying the methodology discussed by White (White et al. 1997) to the general range of Southern California grasslands, green-up is estimated to have occurred when NDVI exceeds 0.50. However, we have found that this value can be closer to 0.64 for some sites, and therefore NDVI values greater than 0.64 are assigned a value of 0, or green. Furthermore, NDVI values less than or equal to 0.39 are assigned a value of 5. This is because NDVI values are observed to be below 0.39 for all grassland sites during the dry season when grasses are known to be fully cured. A linear relationship exists between NDVI-derived values of $G_{ag}$and fire occurrence in Southern California (Figure 3). For this reason, the transition between green and fully cured (or vice versa) was given a rating of 1 to 4 in NDVI increments of 0.05 (Table 1).

To model NDVI, we used MODIS-derived NDVI biweekly data observed at 19 stations shown in Figure 4, interpolated to daily frequency using cubic splines. The data availability period was January 2004-June 2012. For the ease of implementation, our goal was to create a simple, yet skillful equation to capture the temporal variation of NDVI:

$$\begin{aligned} \mathrm{NDVI} = \alpha + \beta_1 \cos(2\pi \mathrm{DOY}/\mathrm{LOY}) + \beta_2 \mathrm{PRECIP_{accum}} \\ + \beta_3 \mathrm{RH_{avg}} + \beta_4 \mathrm{VEG_{frac}} + \beta_5 \mathrm{SMOIS_{40-100cm}} \end{aligned} \tag{5}$$

where DOY = January 1st-based day of year and LOY is the length of year in days. The regressor $\mathrm{PRECIP_{accum}}$ is the September 1st-based annually accumulated precipitation [mm], $\mathrm{RH_{avg}}$ is the

30-day running averaged to relative humidity, VEG_{frac} is the surface vegetation fraction $(0-1)$, and $SMOIS_{40-100cm}$ is the soil moisture content of the $40-100$ cm depth [kg/m^3]. This equation was the result of the "random forest" selection and stepwise regression applied to a large number of meteorological candidate regressors; see Cao (2015) for more information. The R^2 of the model is 0.73; see Table 2 for coefficient values.

We applied this model to the 19 sites in the three zones shown in Figure 4. It is recognized that at some stations and times, the NDVI predictions are somewhat out of phase (i.e., the up and down ramps are too early or too late) with the observations, and the peaks are over or under predicted at different locations and times. The marked drought year of 2007 is clearly a problem at some locations, especially in Zone 2. However, considering the fact that this is a simple universal model with only 5 regressors applied across Southern California, we believe it has shown adequate skill overall (Cao 2015).

3. **Operational** SAWTI

Given our derived expression for fuel characteristics we can now predict large fire potential during Santa Ana wind events taking into consideration both the weather and the fuels. FMC modifies (1) in cases where fuels have not fully cured and are still inhibiting fire spread. Output values of FMC range from 0 to 1, where 0 represents wet fuels and 1 denotes dry fuels. This modifier can become so influential that it will greatly reduce or even eliminate the potential for large fire occurrence despite favorable meteorological conditions for rapid fire growth. So the final equation for large fire potential becomes:

$$\mathrm{LFP} = 0.001\mathrm{W_s}^2\mathrm{D_d}\mathrm{FMC} \qquad (6)$$

The value of the incorporation of fuel moisture predictions into the index is illustrated in Figure 5. For example, examination of the period between September 2008 and May 2009 shows a number of significant Santa Ana wind events indicated by the spikes in LFP_w. The difference between LFP_w and LFP is small during the fall months attributed to high FMC values. This is confirmed by viewing the relatively close spatial agreement between LFP_w and LFP (Figure 6). In contrast, large differences occur after significant winter rains commence (Figure 7). Large wildfires had occurred during each of the spikes noted in the fall while little fire activity was recorded despite the LFP_w spikes during January. This is precisely due to low FMC values which illustrates the critical role that fuels play in this index.

The data ingested to compute the four-zone, six-day LFP operational forecasts comes from multiple sources at different temporal and horizontal resolutions ranging from hourly to daily, and 3 km to 12.5 km, respectively (Figure 8). To reduce the exposure to error in fields with long accumulation periods, we sourced input variables for LFM and NDVI from the NLDAS – 2 data (constructed using a land surface model in conjunction with assimilated observations and atmospheric model output). In contrast, hourly DFM and ERC values are predicted using offline models ((Nelson 2000) and NFDRS, respectively) forced by WRF weather output.

DFM and ERC are calculated from meteorological variables predicted using WRF version 3.5 (Skamarock et al. 2008), run at 3 km and 6 km horizontal resolution. We selected a WRF configuration which minimized errors with respect to near-surface temperature, winds, and dew point during Santa Ana Wind events. This configuration consists of 51 vertical atmospheric levels using the simple WRF Single-Moment 3-class microphysics scheme (Hong et al. 2004), RRTMG shortwave and longwave radiation schemes (Iacono et al. 2008), the MM5 Monin-Obukhov surface layer scheme, and the Asymmetrical Convective Model version 2 boundary layer scheme (Pleim 2007). The Noah land-surface model (Tewari et al. 2004) with 4 soil layers was used in conjunction with the Moderate Resolution Imaging Spectroradiometer (MODIS) land use dataset. Each operational WRF forecast dynamically downscales the 00Z and 12Z North American Mesoscale Forecast System (NAM) 12 km resolution output (1-3.5 day forecasts at 3 km), and the Global Forecast System (GFS) (3.5-6 day forecasts at 6 km). To help determine bounds and behavior of the SAWTI equations and place forecasts in historical perspective, we dynamically-downscaled North American Regional Reanalysis (NARR) to 3km resolution using WRF over the historical period spanning from January 1984 through December 2013. This provided us with an unprecedented 30-year climatology of fuel characteristics related to wildfires across SAWTI zones in Southern California.

Hourly $\mathrm{LFP_w}$ ($\mathrm{W_s}^2\ \mathrm{D_d}$) is calculated at all WRF grid points across the domain as a product of 10 m wind speed squared and 2 m dewpoint depression using (1). The following equation was used to calculate $\mathrm{LFP_w}$ at each grid point:

$$\mathrm{LFP_{w,gpx}} = \frac{\mathrm{LFP}_{\mathrm{w}hour1} + \mathrm{LFP}_{\mathrm{w}hour2} + ... + \mathrm{LFP}_{\mathrm{w}hour8}}{8} \tag{7}$$

where $\mathrm{LFP_{w,gpx}}$ is an average $\mathrm{LFP_w}$ value over an eight-hour time period at grid point x. An eight hour time period was chosen because that is ample time for the finer fuels (i.e., 10 hr) to respond to the ambient atmospheric conditions. Once an average $\mathrm{LFP_w}$ had been calculated for each grid point, the maximum eight hour average $\mathrm{LFP_w}$ for each day is then spatially averaged over each zone as follows:

$$\mathrm{LFP_{w,zone}} = \frac{\mathrm{LFP}_{\mathrm{w}gp1} + \mathrm{LFP}_{\mathrm{w}gp2} + ... + \mathrm{LFP}_{\mathrm{w}gpx}}{Number\ of\ grid\ points\ per\ zone} \tag{8}$$

where $\mathrm{LFP_{w,zone}}$ is the maximum 8 hr averages at each grid point within the model domain. It is important to note that (7) was calculated for five different eight consecutive hour time periods with the highest value chosen to represent each zone for the day (Figure 9). This is to ensure that the worst conditions are being captured on a daily basis. For instance while most Santa Ana wind events peak during the morning hours, some events can peak later in the day or at night depending on the arrival time of stronger dynamical support. Thus calculating LFP_w for only one consecutive eight-hour time period may fail to capture the worst conditions of the day.

Recall that DL relates ERC and DFM to historical fire activity. To provide a DL forecast, DFM and ERC are computed across the spun-up WRF forecast period. To avoid the potentially long spin-up times required by DFM, the DFM must be initialized at each grid point across the WRF domain. Since a publicly-available gridded observed DFM product does not exist, DFM is initialized using the previous day's DFM forecast valid at the 4^{th} hour of the current WRF forecast. The first four hours of each WRF forecast are removed to allow for model spin-up and avoid contamination of DFM and ERC due to relatively unrealistic atmospheric inputs. Due to the need for this continuous spun-up DFM time series, WRF forecasts must be uninterrupted. However, if any WRF forecasts are missed, DFM forecasts could be initialized using output from earlier WRF/DFM forecasts which are archived for at least a month.

Quasi-observational data (NLDAS – 2) is available for estimating LFM and NDVI using equations introduced earlier. The 22-day lagged soil moisture required for LFM is provided from the Noah land surface model output of the NLDAS – 2 dataset. For NDVI, the latest NLDAS – 2 output is used (typically a five day lag) which provides vegetation fraction, 2 m relative humidity, and soil moisture. Archived NLDAS – 2 data is needed going back to the previous September 1 for cumulative precipitation. Both LFM and NDVI are re-gridded from the NLDAS – 2 12.5 km to the 3 km horizontal resolution matching the WRF domain using bilinear interpolation and held constant across the 6-day forecast period.

a. Public Dissemination

Social science was incorporated during the early stages of the developmental process of SAWTI. The Desert Research Institute provided a social scientist to conduct an in-depth survey of 5 communities across Southern California. Much of the survey centered on questions regarding how the public obtains weather and fire information, and their associated responses to that information. The results of the survey were used to help determine the type of information that would be presented in the product. In conjunction with the social science, historical weather and fuels data were correlated to historical fire occurrence records to develop index threat level categories. For example, for each SAWTI zone we compared daily FMC values along with daily LFP_w values from (1) for the historical period (1992–2011) to whether or not a fire had occurred. We repeated the process this time equating the output to whether or not a 100 hectare fire or greater occurred (Figure 10). Comparing these two results yielded a conditional probability for an ignition to reach or exceed 100 hectare based on FMC and LFP values. By assessing and employing these probabilities, LFP breakpoints could easily be determined.

The SAWTI has 5 categories of severity ratings ranging from "No-Rating" to "Extreme". A "No-Rating" can either mean Santa Ana winds are not expected, or that if Santa Ana winds are forecast, they will not result in significant fire activity. So it could be possible that if a strong Santa Ana wind event were to transpire after appreciable rains occurred or when fuels are wet, the event would be categorized as a No Rating. For definitions of other threat levels, see Table 3. Tied to each threat level is a list of recommended actions suggested to the public to better prepare for an impending event. Examples include: "Clean debris away from your house, charge your cell phone and make sure you have plenty of gas". The list of recommended actions expands as the threat levels increase. This aspect of the product is critical as it serves to link categories of severity with public awareness.

The product consists of an online webpage (`http://sawti.fs.fed.us`) that displays a 6-day forecast of the above mentioned categories for each of the 4 zones across Southern California (Figure 11). A map of the region stands as the centerpiece of the page and graphically shows the categories which are colorized ranging from grey (No Rating) to purple (Extreme). The product is issued once daily but will be updated more frequently if conditions warrant. The webpage allows users to obtain more information such as viewing the latest weather observation from select stations when zoomed in on the map. The page will also display active and non-active fires (via icons) on the map when such activity is present. Selecting one of these icons will provide the user with specific fire information such as acreage burned, percent contained, and links to more data.

The product was beta tested for a year prior to it becoming a public product in the fall of 2014. During the beta test phase, the index performed well in capturing all events that occurred during the fall of 2013 through the spring of 2014 which ranged from “No Rating” to “High”. Several notable events include: 16 January 2014 (Colby fire), 29 April 2014-1 May 2014 (Etiwanda fire), and 13-14 May 2014 (the San Diego fires). Fire agencies that were granted access to the index during this time used the product to make critical decisions regarding the allocation and mobilization of shared fire resources prior to when these fires occurred. Specifically, the event that occurred on 13-14 May 2014 was especially notable due to the fact that winds were unusually strong during this period, and that multiple large fires occurred as a result. Figure 12 shows a map of the fires across San Diego County, while Figure 13 shows the SAWTI in beta test form for this event. The product was officially released to the public on September 17, 2014 via a press release and an associated press conference. Since that time, the product has been used by local news media across the San Diego and Los Angeles metropolitan areas, as well as being shown on The Weather Channel.

4. Summary and Conclusions

As the Wildland Urban Interface (WUI) continues to expand across Southern California, the source of ignitions will increase leading to a greater probability for large and destructive fires during Santa Ana wind events. This puts the public and firefighter safety at risk, thus the increasing need to categorize such events in terms of their effect on the fire environment.

While the initial OFSI proved to be generally successful, its ability to capture the complexity of Santa Ana wind events was limited. This however led to the development of a new methodology for a redefined index. Expressing large fire potential as a function of wind velocity, dew point depression, and fuel moisture has allowed high resolution model and satellite derived variables to be incorporated into the index. A discussion about this methodology has been presented highlighting the weather and fuels components that comprise the index. Challenges surrounding the assessment of fuel conditions include the difficulty in determining different types of fuel moisture parameters. Improvements to the fuel moisture component of the index is possible in the future as more data becomes available and new methodologies for determining fuel moisture are developed. Similar products can be developed using the methodology described in this paper in areas impacted by katabatic and foehn winds.

Fire agencies and first responders, private industry, the general public, and the media now have a new operational tool that determines the severity of Santa Ana wind events. They will have a clearer understanding of the severity of an event based on the potential for large fires to occur. Specifically, a more effective media response will result in the general population (particularly those living within the WUI) being more proactive in its response to an impending event.

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LIST OF TABLES

TABLE 1: Relationship between NDVI and greenness.

NDVI	G_{ag} *Number*	*Description*
$NDVI > 0.64$	0	Green
$0.59 < \text{NDVI} \leq 0.64$	1	
$0.54 < \text{NDVI} \leq 0.59$	2	
$0.49 < \text{NDVI} \leq 0.54$	3	
$0.39 < \text{NDVI} \leq 0.49$	4	
$0 \leq \text{NDVI} \leq 0.39$	5	Cured

TABLE 2: Selected NDVI Regressors.

Coefficient	*Subscript Number*	*Value*
α		-0.314867
β	1	0.11253592
β	2	1.44E-05
β	3	0.00355647
β	4	0.911360168
β	5	0.002412815

TABLE 3: Categories of threat levels and their descriptions.

Category	*Description*
NO RATING	Santa Ana winds are either not expected, ***or*** will not contribute to significant fire activity.
MARGINAL	Upon ignition, fires ***may*** grow rapidly.
MODERATE	Upon ignition, fires ***will*** grow rapidly and ***will*** be difficult to control.
HIGH	Upon ignition, fires will grow ***very*** rapidly, will burn intensely, and will be ***very*** difficult to control.
EXTREME	Upon ignition, fires will have explosive growth, will burn ***very*** intensely, and will be uncontrollable.

LIST OF FIGURES

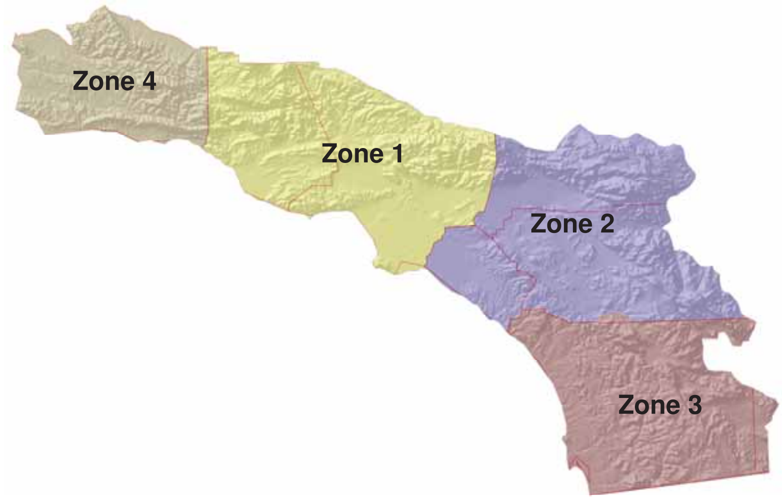

FIG. 1: Map of SAWTI zones.

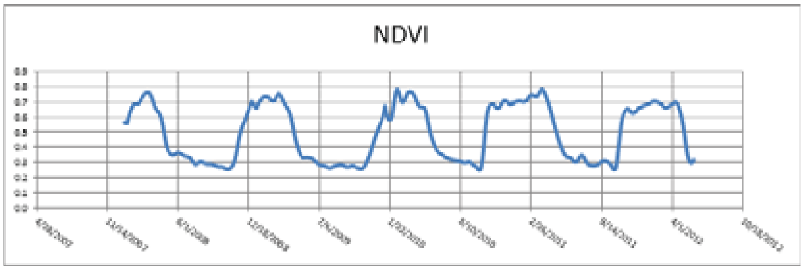

FIG. 2: Sample annual NDVI output.

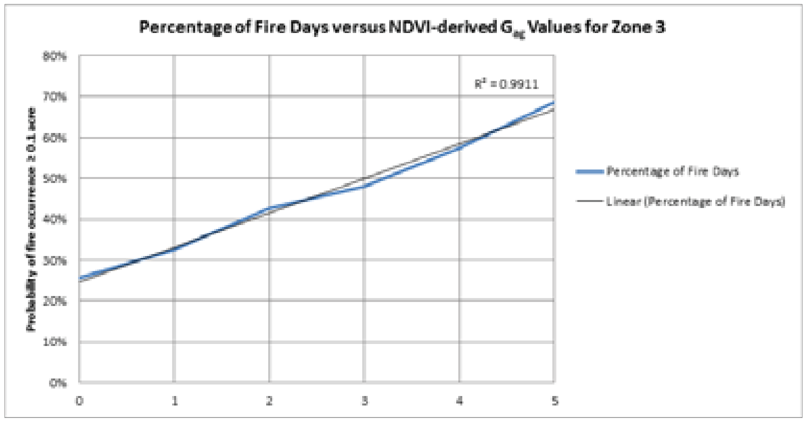

FIG. 3: Probability of fires ≥ 0.1 acre predicted by NDVI-derived G_{ag} for zone 3.

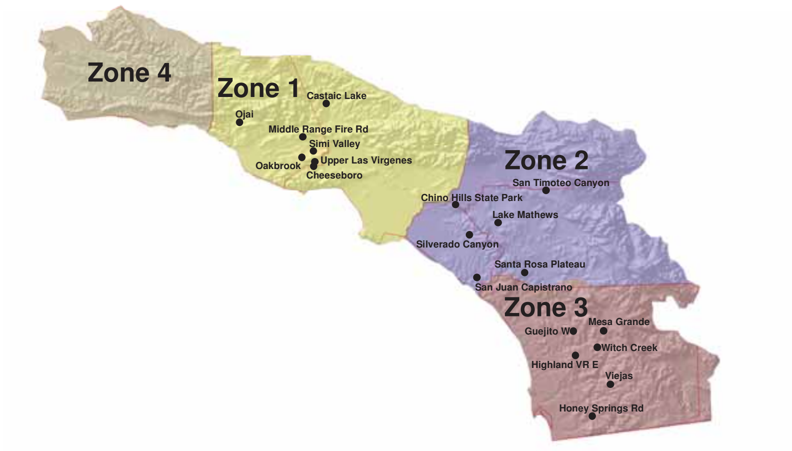

FIG. 4: NDVI surface station locations (black dots) with underlying topography shaded.

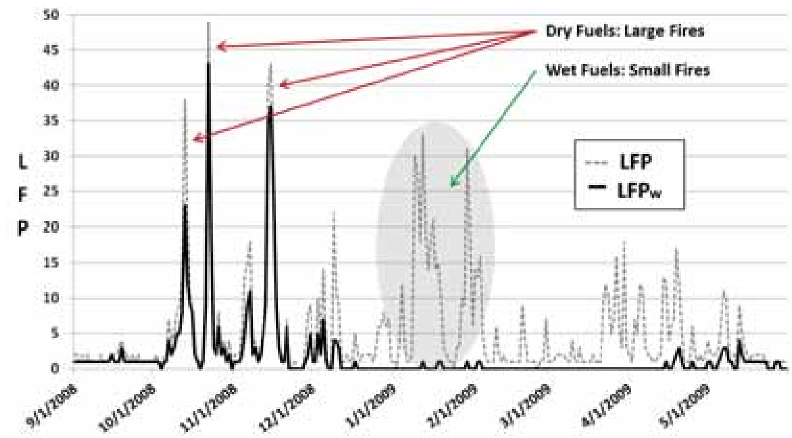

FIG. 5: Comparison of LFP_w and LFP timeseries for zone 1 during the period spanning September 2008 through May 2009. For large fires that occurred in October and November of 2008, relatively dry fuels (LFP, solid black line) accompanied the dry and windy weather (LFP_w, dashed grey line). In contrast, January through February of 2009, experienced peaks of windy and dry conditions (LFP_w) accompanied by moist fuels (LFP) and, as a result, no fires grew larger than 100 ha.

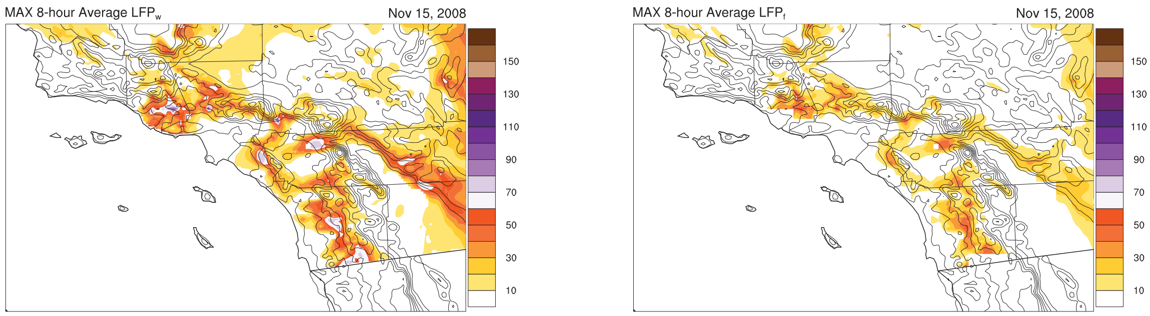

FIG. 6: Average LFP$_w$ (left) and LFP (right) from 8am to 3pm during a Santa Ana event on November 15, 2008. This offshore event was accompanied by the Freeway Complex Fire which burned over 30,000 acres while destroying 187 homes and damaging 117 others (http://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=305).

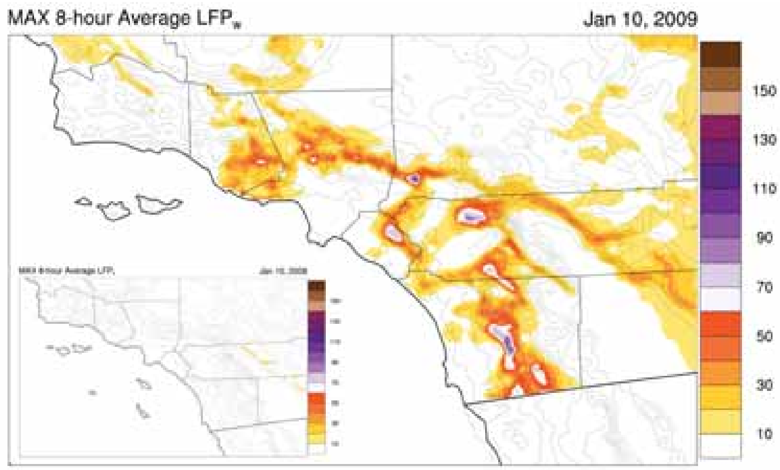

FIG. 7: Average LFP$_W$ (large) and LFP (lower left) from 8am to 3pm during a Santa Ana event on January 2009.

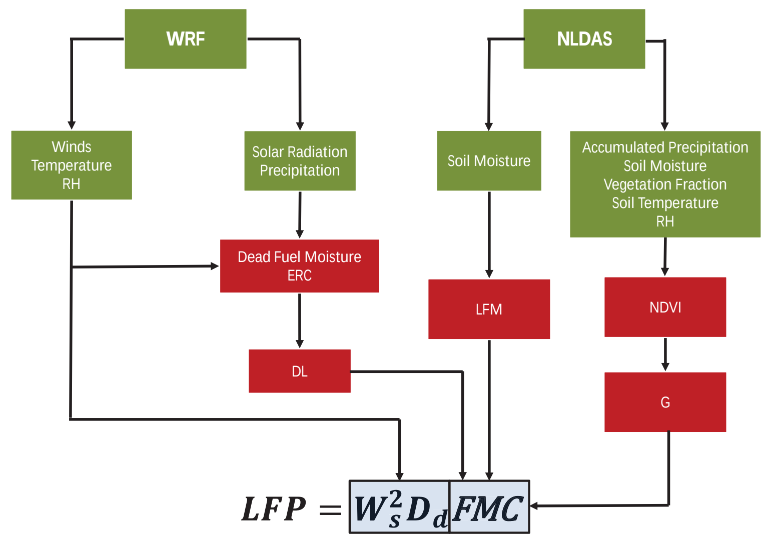

FIG. 8: Flowchart depicting operational LFP input models and datasets, derived variables and final LFP equation.

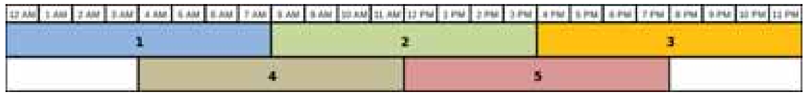

FIG. 9: Time periods over which LFP_w is averaged.

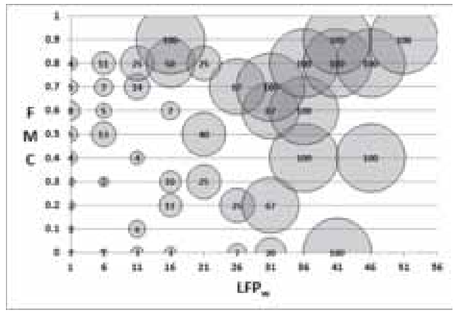

FIG. 10: Using historical fire occurrence data between 1992–2011, we show the relationship between binned FMC, LFP_w and fire activity for zone 1. Tickmarks indicate starting bin values for both FMC (bin size of 0.099) and LFP_w(bin size of 5). Bubble size indicates the conditional probability for an ignition to meet or exceed 100 hectares. For instance, 100% of fires which ignited during conditions characterized with FMC ≥ 0.7 and $LFP_w \geq 36$ grew into large fires.

FIG. 11: Online operational SAWTI product.

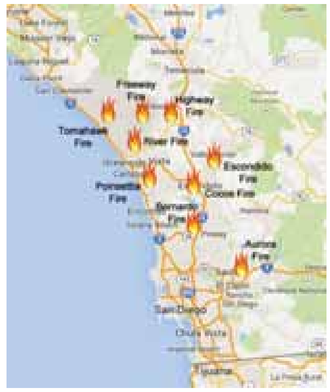

FIG. 12: Map of active fires (icons) on May 14, 2014 across San Diego County.

FIG. 13: SAWTI (in beta test) during May 14-15, 2014.

APPENDIX 4

Developing and Validating the Santa Ana Wildfire Threat Index

Tom Rolinski[1], Robert Fovell[2], Scott B Capps[3], Yang Cao[2], Brian D"Agostino[4], Steve Vanderburg[4]

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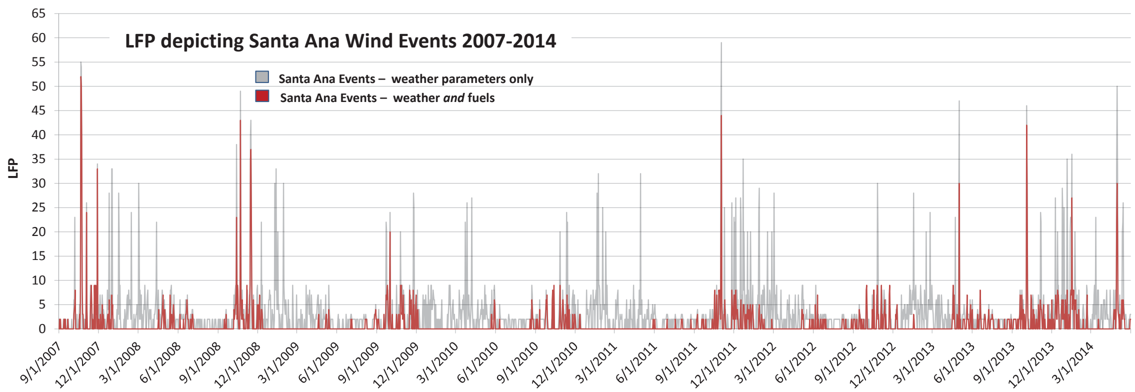


1- Introduction

From the fall through spring, offshore winds, commonly referred to as "Santa Ana" winds, occur across southern California from Ventura County south to Baja California and west of the coastal mountains and passes. Each of these synoptically driven wind events vary in frequency, intensity, duration, and spatial coverage, thus making them difficult to categorize. Since fuel conditions tend to be driest from late September through the middle of November, Santa Ana winds occurring during this time have the greatest potential to produce large, devastating fires when an ignition occurs. Such catastrophic fires occurred in 2003, 2007, 2008, and 2014. Because of the destructive nature of such fires, there has been a growing desire to categorize Santa Ana wind events in much the same way that tropical cyclones and tornadoes have been categorized.

Major passes in southern California that favor Santa Ana winds. Zones were used in beta test product.

High resolution satellite image showing the fires that occurred across southern California in 2003

During the past three and a half years, the Forest Service (through Predictive Services) has collaborated with the San Diego Gas and Electric utility (SDG&E) and the University of California at Los Angeles (UCLA) to develop the Santa Ana Wildfire Threat Index (SAWTI), which categorizes Santa Ana wind events according to the potential for a large fire to occur. This unique approach addresses the main impact Santa Ana winds could have on the population of southern California beyond experiencing the casual effects of windy, dry weather.

2- Methodology

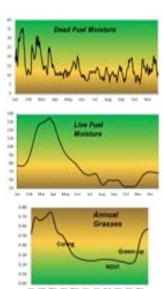
- The SAWTI which predicts Large Fire Potential (LFP) during Santa Ana wind events, is informed by both **weather** and **fuels** information.
- We define LFP to be the likelihood of an ignition reaching or exceeding 250 acres or approximately 100 ha.
- For SAWTI, the following equation was formulated:

$$LFP = W_s^2 D_d FMC$$

Where W_s is the near surface wind speed, D_d is the near surface dew point depression, and FMC is the Fuel Moisture Component expressed by this equation:

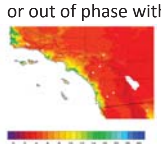
$$FMC = \left\{\left(\frac{DL}{LFM} - 1\right) + G\right\}^{1.7}$$

Where DL is a Dryness Level index (a function of the Energy Release Component [ERC] and Dead Fuel Moisture [DFM]). LFM is the Live Fuel Moisture of Chamise (Adenostoma fasciculatum), and G is the green-up/curing of the annual grasses using the Normalized Difference Vegetation Index (NDVI).



3- Fuels

Fuel moisture plays a critical role in the propagation of wildfires. FMC incorporates 3 kinds of fuel moisture (DFM, LFM, and G) because each component can be in phase or out of phase with each other.



Considering any one component alone may give a false representation of fuel moisture.

Used by fire agencies and the general public, the Santa Ana Wildfire Threat Index (SAWTI) was made publically available on September 17, 2014. The product can be accessed at: santaanawildfirethreat.com

The SAWTI shown on The Weather Channel (TWC) on the day of the press conference (September 17, 2014).

KUSI news in San Diego showing a direct link to the product on their main web page.

Google search provides a list of news articles on the release of the SAWTI

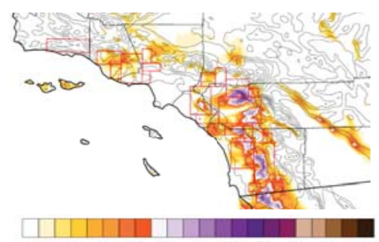
4- Operational SAWTI

In 2013, the SAWTI was beta tested through a controlled release via a password protected website. On September 17, 2014, the USDA Forest Service conducted a press conference at which time the product was made publically available. Since then it has been featured on numerous southern California news stations and on The Weather Channel. When discussing upcoming Santa Ana wind events, The Weather Channel uses the SAWTI output.

5- APPLICATION

SAWTI in beta test mode provided operational guidance during 13-14 May 2014

- Extreme weather and fuel conditions (map below left) were forecasted for this event up to 5 days in advance
- Multiple fires occurred over San Diego County on 13-14 May 2014



Map above depicts fire potential during the May 14, 2014 Santa Ana event. Colors represent the product of wind speed squared (mph) and the dew point depression (˚F)

Map depicts active fires (icons) on May 14, 2014 across San Diego County.

The authors acknowledge:
Dr. Robert Fovell and Dr. Yang Cao, UCLA Brian D'Agostino and Steve Vanderburg, San Diego Gas and Electric

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