CLIMATE CHANGE–PROJECTED SANTA ANA FIRE WEATHER OCCURRENCE

A Report From:
California Climate Change Center

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WHITE PAPER

Arnold Schwarzenegger, *Governor*

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, the Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contact the Energy Commission at (916) 654-5164.

Table of Contents

Preface.......... ii
Abstract iv
1.0 Introduction.......... 1
2.0 Approach 2
3.0 Results 5
4.0 Summary and Conclusion.......... 8
5.0 References.......... 9
6.0 Glossary 10

List of Figures

Figure 1. A four-day snapshot of the time-evolving surface pressure fields, constrained by ERA40 specific humidity, associated with the Santa Ana fires of December 19–22, 1999....... 3

Figure 2. GFDL AOGCM–derived number of SAO days, based on pressure gradient and humidity, indicate a small bias for the monthly climatological occurrences for September, October, November, December, January, and February. 4

Figure 3. AOGCM-derived SAO 1966–1994 based on GFDL pressure gradients and humidity (constrained), GFDL pressure gradients (unconstrained), and PCM pressure gradients (unconstrained) 5

Figure 4. AOGCM-derived SAO sensitivity for 2005–2034, 2035–2064, and 2070–2099 based on GFDL pressure gradients with (a) A2 forcing constrained with humidity, (b) A2 forcing without humidity constraints, and (c) B1 forcing without humidity constraints.......... 7

Figure 5. AOGCM-derived SAO sensitivity for 2005–2034, 2035–2064, and 2070–2099 based on (a) PCM pressure gradients with A2 forcing, (b) PCM pressure gradients with B1 forcing... 8

List of Tables

Table 1. Evaluation of the derived SAO using GFDL A2 constrained and unconstrained by humidity 6

Abstract

A new approach for detecting foehn weather conditions, such as the Santa Ana occurrence (SAO), was performed using two Atmosphere-Ocean General Circulation Models, the GFDL and the PCM, forced with the relatively high (A2) and low (B1) greenhouse gas emissions detailed in the IPCC *Special Report on Emission Scenarios*. Southern California Santa Ana winds were analyzed using large-scale pressure gradients and humidity fields. Results indicate a good correlation between large-scale detected Santa Ana occurrences and observed offshore winds during periods of low humidity. The sensitivity of the number of climate change–projected SAOs was analyzed for three future time periods—2005–2034, 2035–2064, 2070–2099—and ranged from 26% to 138% of historical. GFDL A2 and B1 outcomes indicate that the warmest fall month, September, has an increase in SAO days in the early part of this century, followed by a decrease, while the PCM A2 and B1 outcomes suggest fewer SAOs during September. Meanwhile, the strongest historical SAO month, December, experiences SAO decreases for all cases during 2005–2034 and increases for 2070–2099. This initial analysis suggests that Santa Ana conditions may significantly increase during California's fire season, but in general are unlikely to be radically more or less frequent than at present.

1.0 Introduction

California coastal region wildfire weather typically occurs during the fall season (September to December) prior to the winter rains, and when an inland high pressure and an offshore low pressure set up a strong pressure gradient with high offshore winds, heated air mass, and low humidity. These conditions are known locally as "Santa Ana winds" in southern California, and "Diablo winds" in northern California, but are more generally defined as foehns. The translation of the Greek root word for foehn is fire, and such conditions have a long history of being associated with high winds that spread fires. During foehn occurrences, hot downslope winds may exceed 60 miles per hour (97 kilometer per hour), are warmed by adiabatic compression at a rate of 5°F per 1000 feet (2.8°C per 305 meters), and have very low relative humidity, making these conditions the most prevalent for the spread of fires.

One of the earliest records of a southern California foehn was in 1859 (Tompkins, undated publication; Ryan 1991). The engineering boat *US Coast Survey* was anchored near Santa Barbara and ship records indicated temperatures near 85°F (29.4°C) in the late morning and no unusual weather. By 1:00 p.m. gusty northerly winds developed from the Santa Ynez peak, accompanied by a sharp rise in temperatures, and by 2:00 p.m. temperatures rose to a record-setting 133°F (56.1°C) with strong northerly winds. By 5:00 p.m. the ship thermometer indicated temperatures had dropped to 122°F (50°C), and by 8:00 p.m. the ship temperature was at 77°F (25°C).

California fires linked to such windy, hot, and dry offshore flow conditions have resulted in significant loss of life and property, especially in regions where development has encroached on wilderness interfaces. California Santa Ana and Diablo winds impact hundreds of miles along the coastal mountains. The 1991 Oakland fire re-ignited and spread due to hot, dry, and windy Diablo conditions. In 2003, the Cedar fire near San Diego spread from 200 to 12,500 hectares (600 to 37,375 acres) in four hours time due to the presence of Santa Ana winds. As development on coastal mountain regions expands and man-made fires continue to occur, fire weather–related loss and damage will rise.

It is largely thought that large-scale mechanisms dominate the Santa Ana and Diablo conditions, which are in turn modulated by local effects of the sea breeze and topography. Coastal California offshore flow is governed by several mechanisms, including the local sea breeze due to a diurnal land-sea temperature differential and upwelling, and large-scale atmosphere and ocean dynamics associated with pressure systems. Santa Ana conditions occur when a north-south pressure gradient is present and may be enhanced by a southward moving trough, or a high-pressure ridge moving into central California (Ryan 1991).

The evolution of the northeasterly Santa Ana wind patterns has been detected remotely by Castro et al. (2003) using Quicksat satellite observations. Hu and Liu (2003) also used remotely sensed Quicksat data to observe oceanic and thermal biologic responses to Santa Ana winds. Raphael (2003) catalogued a 33-year dataset of Santa Ana surface meteorological observations and identified days when a surface high pressure system existed over the Great Basin simultaneously with a surface low pressure offshore of southern California, with results suggesting a relationship between Santa Ana occurrence and large-scale patterns. The large-scale weather variables have been diagnosed along with other variables to understand the onset and duration of fire weather in the western US (Westerling et al. 2003, 2004). Recently, Conil and Hall (2006) used a very high resolution regional climate model forced by reanalysis data and performed a cluster analysis to determine three wind regimes in southern California—Santa Ana, onshore flow, and a common northwesterly flow—indicating that 2 to 5 days per month between October and March are Santa Ana days.

The following section discusses an approach for detecting Santa Ana Occurrences (SAOs) from large-scale variables and for determining the sensitivity of SAOs to climate change. This is followed by a section on the resulting climate change sensitivity of SAOs for three projected time periods, and a conclusion section with remarks on next steps.

2.0 Approach

In this initial study, Santa Ana conditions are analyzed using observations and simulated global climate model data for a historical period (1965–1994) and simulated climate data for projected periods (2005–2034, 2035–2064, 2070–2099). Our climate change fire weather sensitivity analyses are based on the output from two Atmosphere-Ocean General Circulation Models (AOGCMs): the NOAA GFDLv2 (developed by the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory; see Delworth et al. 2005) and the DOE/NCAR PCM (the Parallel Climate Model developed by the Department of Energy and the National Center for Atmospheric Research; see Washington et al. 2000). These two models were run with simulations forced by the high (A2) and low (B1) emissions scenarios presented in the Intergovernmental Panel on Climate Change's *Special Report on Emission Scenarios* (IPCC SRES) (Nakicenovic´ et al. 2000). These scenarios represent the range of IPCC non-intervention emissions futures, with atmospheric CO_2 concentrations reaching approximately 550 parts per million (ppm) (B1) to 830 ppm (A2) by 2100.

An approach for detecting Santa Ana occurrences within AOGCM output has been developed here for the analysis of fire weather sensitivity along coastal southern California due to climate change. The surface pressure fields were used as the available variables to determine the presence of SAOs. These data were constrained by specific humidity fields during the evaluation. The 850 hectopascal (hPa) geopotential height fields could also be used to further constrain the solution space; however, their availability was limited. The PCM AOGCM output did not include geopotential height or surface humidity fields on a daily timestep, and these height fields were only used in the evaluation phase of this study. Due to the unavailability of these data, the sensitivity analyses of projected climates were based only on the pressure fields.

The conditions necessary for the establishment of an SAO are the existence of a stationary high situated over the Great Basin and/or extending further east, an offshore Pacific low southwest off Los Angeles with a pressure difference between these centers of approximately 20 hPa or greater, and the local (fire risk area) surface level humidity below 40%.

Figure 1 shows the western U.S. domain, the search sub-domain (boxed area), and surface pressure fields for four days in December 1999, when strong Santa Anas were present. A very strong high offshore flow SAO-related fire occurred during 19–22 December 1999, in which fires spread and property loss was extensive. Figure 1 shows a four-day snapshot of the time evolving SAO using the available ERA40 surface pressure gradient, concurrent with very low ERA40 specific humidity, which represents a constraint to the solution space. A parallel analysis using this Santa Ana occurrence based on the 850 hPa geopotential height fields had near identical results (not shown).

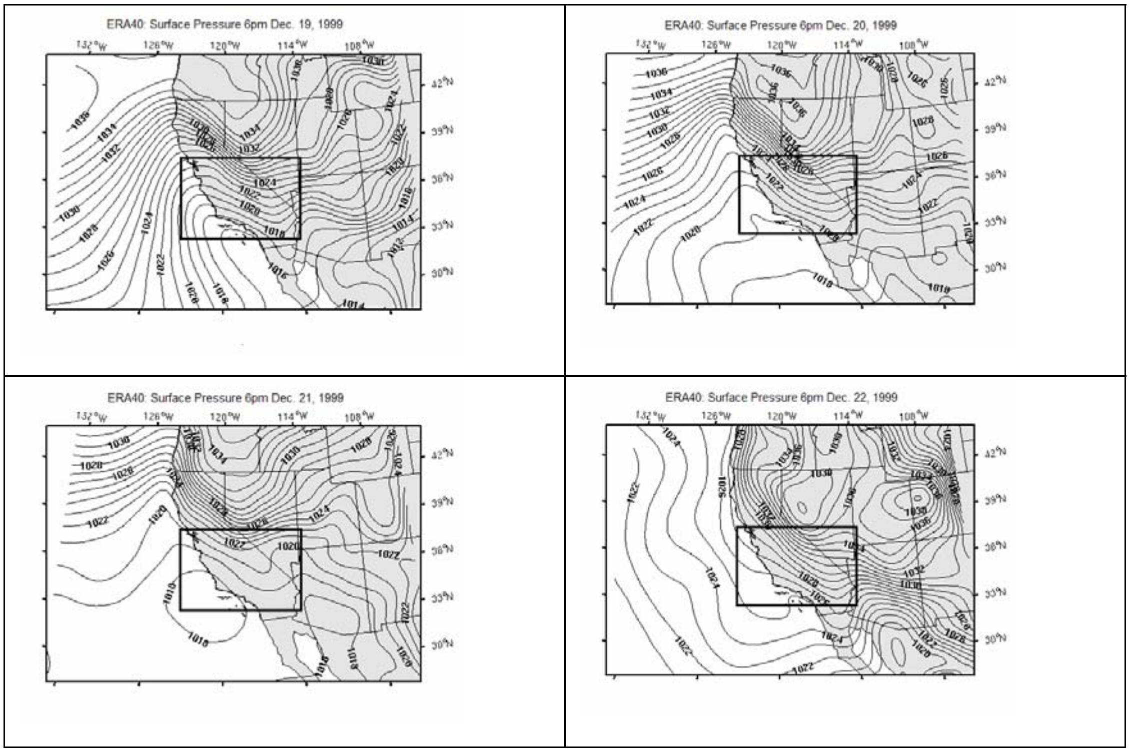

Figure 1. A four-day snapshot of the time-evolving surface pressure fields, constrained by ERA40 specific humidity, associated with the Santa Ana fires of December 19–22, 1999. The boxed area shown is the search domain used in the analysis.

This initial SAO analysis was performed using hourly wind and humidity NCDC (National Climatic Data Center) Surface Airways Observations (1992) for California, Arizona, and the western United States, and the ERA40 Reanalysis 850 hPa geopotential height, surface pressure, and specific humidity fields. An additional number of significant SAO days were identified from the observations and reanalysis data, and a search domain was configured with latitudinal coordinates ranging from 33N to 39N, and longitudinal coordinates ranging from 125W to 113W.

Station data representing local temperature, wind, and humidity were obtained from Raphael (2003) for 1965 to 1994 and used as part of the evaluation along with the ERA40 Reanalysis data. The combined data, observations, and reanalysis were used for a 30-year (1965–1994) bias study of the GFDL output–derived SAO days, resulting in a good fit between the humidity-constrained, pressure-gradient-derived SAO days and the observed number of high-offshore-wind, low-humidity SAO days. Figure 2 indicates that climatological (30-year average) September, October, November, December, January, and February GFDL-simulated SAO days were 1.2, 3.5, 6.5, 7.1, 8.7, and 5.8, respectively, representing 112%, 76%, 93%, 81%, 70%, and 69% of observations, respectively. It is important to note that the trends match well, with September having the lowest number of SAO days and with an increasing trend toward the maximum in December, along with a decreasing trend for the period during January and February.

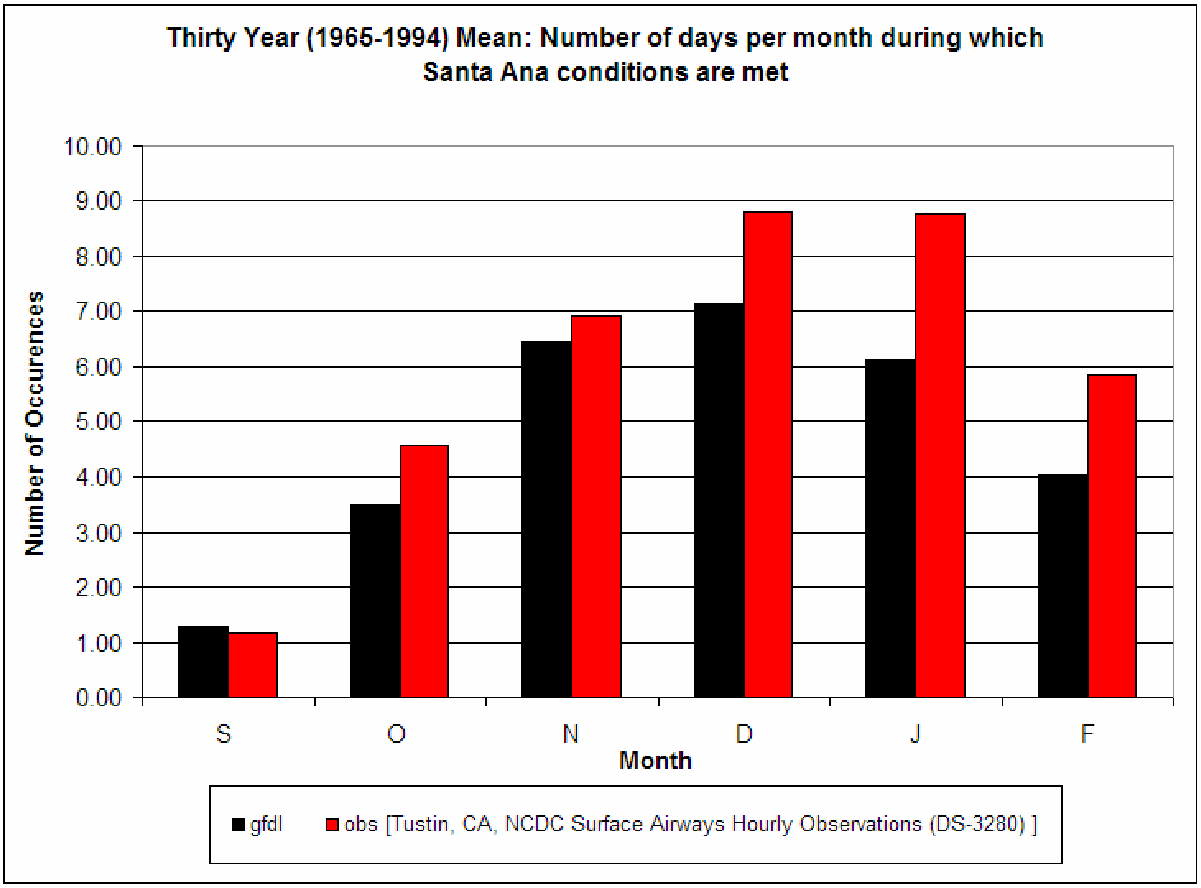

Figure 2. GFDL AOGCM–derived number of SAO days, based on pressure gradient and humidity, indicate a small bias for the monthly climatological occurrences for September, October, November, December, January, and February.

This bias study analyzed the GFDL pressure gradients with and without humidity constraints for 1965–1994 and found that the humidity reduces the number of September to February SAOs detected to 52% of those detected without humidity constraints. Figure 3 shows the monthly differences between the GFDL constrained and unconstrained days, along with the mean-monthly unconstrained PCM number of SAO days. The approximate 100% overestimation by the unconstrained data is consistent (Table 1), indicating that this approach is valid for sensitivity studies based on the relative ratios of simulated projections to the present day, and will provide new information on fire weather sensitivity under future climates.

In this approach it was determined that the search domain was sufficient for analysis of this type, and that a larger domain could be neglected for now. A larger search domain extending further west and north will yield additional information on teleconnections that may influence the local phenomena. However, this study has taken on an intentional regional analysis to detect SAO signals and determine their distribution as projected out in time under various forcing scenarios. Understanding the position and magnitude of pressure systems external to the search domain will lend information on how SAOs set up, but detecting the presence of the pressure gradient driving force associated with SAOs can be reduced to an analysis of the immediate high and low systems that set up locally.

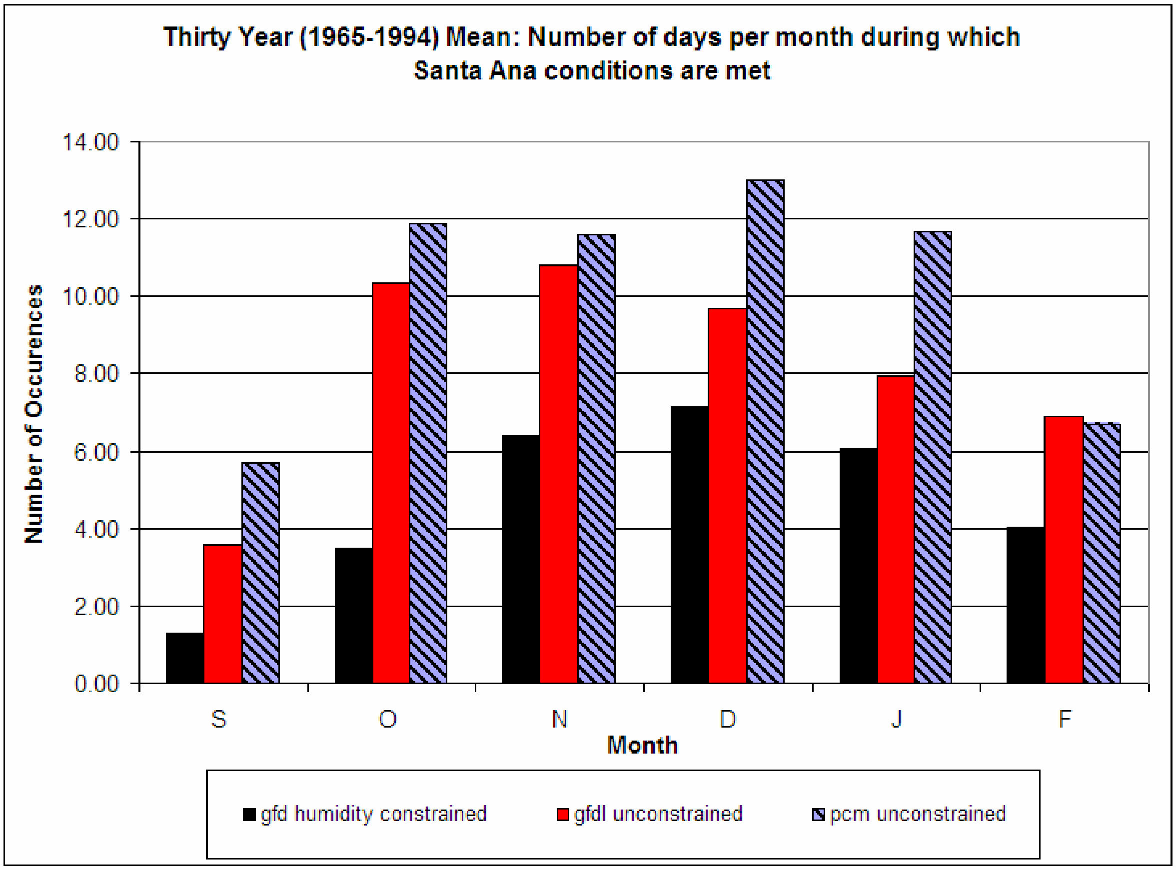

Figure 3. AOGCM-derived SAO 1966–1994 based on GFDL pressure gradients and humidity (constrained), GFDL pressure gradients (unconstrained), and PCM pressure gradients (unconstrained)

3.0 Results

SAO sensitivity (projected/historic) results for the three projected time periods (2005–2034, 2035–2064, 2070–2099) are presented in Figures 4 and 5. Figure 4a was calculated with the inclusion of the available surface humidity as a constraint to the GFDL pressure gradient, both for the projected and historical periods, but Figures 4b and 4c did not include humidity constraints for historical or projected periods. It is important to note that the mean-seasonal ratio between the constrained and unconstrained number of SAO days for all cases, including 1965–1994, is 52% (Table 1), verifying that for projected periods the constrained case remains about half the value of the unconstrained case. This is an important result, as it indicates there is a consistent and relative overestimation for the unconstrained analyses, as compared to the constrained. There are insufficient AOGCM output data (i.e., specific humidity, geopotential heights) at the time of this study to impose a bias correction, hence this study evaluates the results as relative sensitivities (percent change) of the unconstrained simulations.

Table 1. Evaluation of the derived SAO using GFDL A2 constrained and unconstrained by humidity

Evaluation	Season-Mean
GFDL (1965–1994) constrained/unconstrained	0.57
GFDL (2005–2034) constrained/unconstrained	0.52
GFDL (2035–2064) constrained/unconstrained	0.52
GFDL (2070–2099) constrained/unconstrained	0.52

The unconstrained GFDL-derived and PCM-derived SAOs for each month are shown in Figure 3. The relative SAO sensitivities range from 26% of historical (GFDL/A2 2070–2099 September) to 138% (PCM/A2 2070–2099 November). GFDL A2 and B1 outcomes indicate that the warmest fall season month, September, has an increase in SAO days in the early part of this century (120% of historical for both A2 and B1 during 2005–2035), followed by a decrease (26% for A2 and 88% for B1 during 2070–2099), while the PCM A2 and B1 outcomes suggest decreases in SAOs during September (82% historical for A2 and 61% for B1 during 2005–2034; 45% historical for A2 and 82% for B1 during 2070–2099). Meanwhile, the strongest historical SAO month, December, decreases for all cases during the period 2005–2034 (GFDL/A2 89%, GFDL/B1 74%, PCM/A2 83%, PCM/B1 100.1%), and increases for the period 2070–2099 (GFDL/A2 110%, GFDL/B1 110%, PCM/A2 100.3%, PCM/B1 102.3%).

These initial findings indicate striking differences between early century and late century, and high-emission and lower-emission SAO sensitivities. The PCM results suggest an increase during October and November, with the greatest October increase (120%) during the 2005–2034 period with A2 emissions, and the greatest November increase (125%–135%) at 2070–2099 for both A2 and B1. PCM additionally shows significant decreases for September, a month with about one SAO, and slight decreases for December, a month with more than eight SAOs. The GFDL SAO sensitivities are very different, with early century increases (125%) in SAOs during September with a steady decrease toward the end of the century. October has increases in SAOs for the B1 emissions scenario and decreases for the A2 scenario for all projected periods. November A2 is below the historical SAO for all periods, while the B1 emissions SAO results are at 100% during 2005–2034, 90% during 2035–2064, and 110% during 2070–2099. Finally, there are increased SAOs for December at the end of the century, with below-historical values for early and mid-century periods.

In terms of fire weather threats in the future, this initial study suggests that there may be SAO increases during critical dry periods, leading to more extensive wildfire. However, caution needs to be used with regard to these early results.

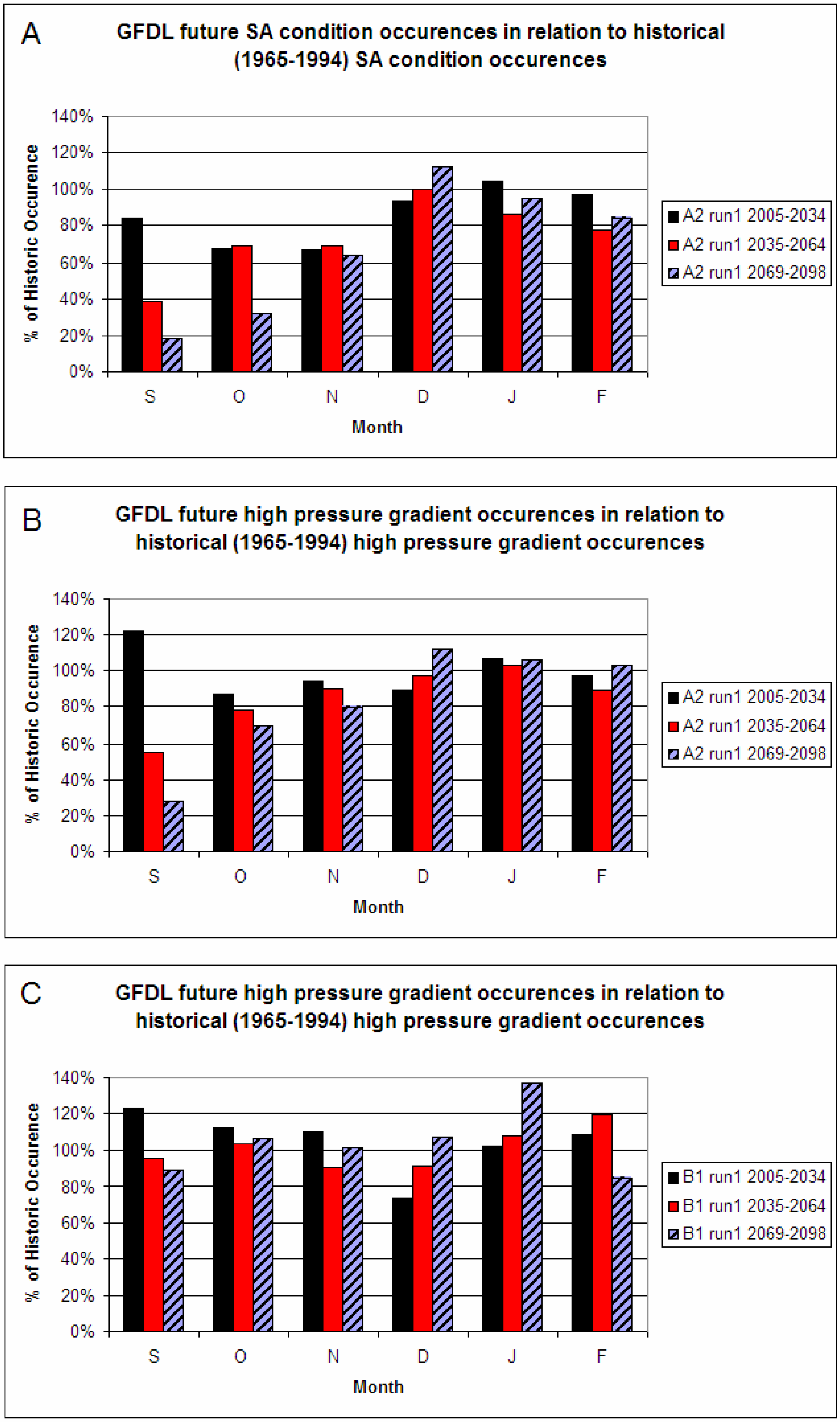

Figure 4. AOGCM-derived SAO sensitivity for 2005–2034, 2035–2064, and 2070–2099 based on GFDL pressure gradients with (a) A2 forcing constrained with humidity, (b) A2 forcing without humidity constraints, and (c) B1 forcing without humidity constraints.

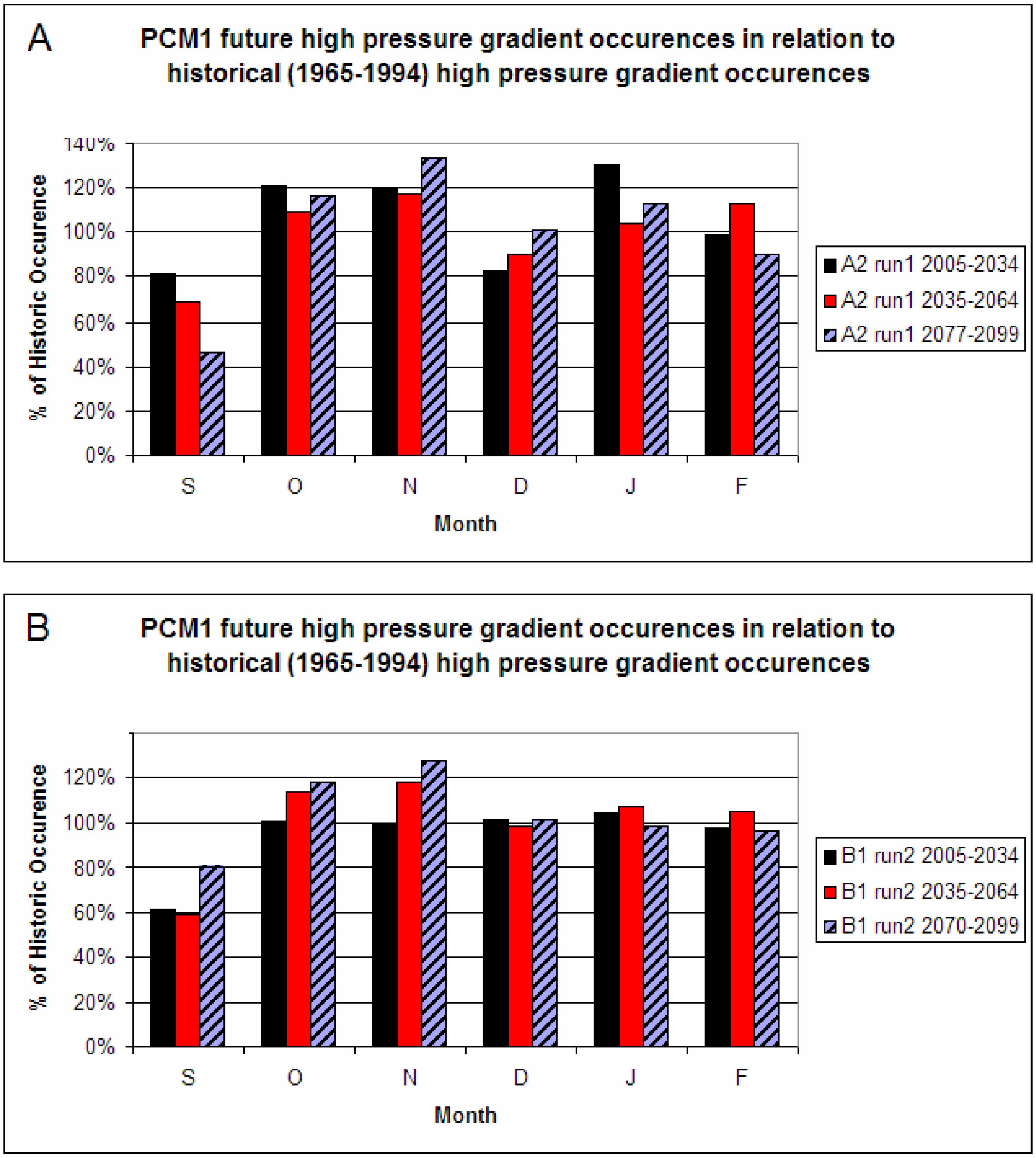

Figure 5. AOGCM-derived SAO sensitivity for 2005–2034, 2035–2064, and 2070–2099 based on (a) PCM pressure gradients with A2 forcing, (b) PCM pressure gradients with B1 forcing

4.0 Summary and Conclusion

An initial analysis of pressure gradient–derived Santa Ana occurrences has been described. Results suggest that during the fall season, SAOs may increase for some scenarios and decrease for others. More research is required to fully establish the sensitivity of this mechanism under greenhouse gas forcing. Large-scale pressure and sea surface temperature (SST) variability have a teleconnection to SAOs that remains poorly understood. There is a significant shift in the relationship between these two variables during the 1976 Pacific multi-Decadal Oscillation (PDO) shift that may additionally play a role in the rate and strength of such offshore flow occurrences along California coastal regions. This suggests that the role of natural variability in ocean temperatures, along with climate change SST variations, will play a significant role in the increase or decrease of the number of SAO days detected. Further analyses of climate types (positive El Niño Southern Oscillation (ENSO)/positive PDO; negative ENSO/positive PDO; positive ENSO/ negative PDO; negative ENSO/negative PDO), as well as other natural climate modes, will need to be decomposed to fully understand the sensitivity of SAOs.

This initial study begins to investigate an important climate impact on society, ecology, and economy. This study only indicated the relative change in the number of SAO days and did not analyze the change in intensity and duration in consecutive SAO days. These aspects are proposed for investigation as phase two of this study, which will include more AOGCM output fields.

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6.0 Glossary

A2	A future scenario with relatively high greenhouse gas emissions as detailed in the *Special Report on Emission Scenarios* by the Intergovernmental Panel on Climate Change
AOGCM	Atmosphere-ocean general circulation model (the NOAA GFDLv2 and the DOE/NCAR PCM are two such models)
B1	A future scenario with relatively low greenhouse gas emissions as detailed in the *Special Report on Emission Scenarios* by the Intergovernmental Panel on Climate Change
DOE	U.S. Department of Energy
DOE/NCAR PCM	A parallel climate model developed by DOE/NCAR. This is one of the atmosphere-ocean general circulation models used in this study.
ENSO	El Niño Southern Oscillation
ERA40	European Center for Medium Range Forecasting, Reanalysis 40-year data
foehn weather	"Fire weather" conditions of hot temperatures, high offshore winds, and low humidity
GFDL	Geophysical Fluid Dynamics Laboratory
hPa	Hectopascal, a unit of pressure equivalent to 1 millibar
IPCC SRES	*Special Report on Emission Scenarios* by the Intergovernmental Panel on Climate Change. This report is the source of the greenhouse gas emissions assumptions used in this study.
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NOAA	National Oceanic & Atmospheric Administration
GFDLv2	Geophysical Fluid Dynamics Laboratory version 2, one of the atmosphere-ocean general circulation models used in this study

PCM	Parallel Climate Model, one of the atmosphere-ocean general circulation models used in this study
PDO	Pacific Decadal Oscillation
SAO	Santa Ana occurrence. "Santa Ana" is the southern California term for foehn conditions; in northern California, an SAO is often referred to as "Diablo winds."
SST	Sea surface temperature