



RESEARCH LETTER

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Key Points:

- Synoptic flow associated with stratospheric intrusions can force Santa Ana winds
- Descent of dry lower stratospheric air to the surface can foment wildfires
- Stratospheric intrusions can indirectly increase ozone by exacerbating wildfires

Correspondence to:

A. O. Langford,
andrew.o.langford@noaa.gov

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Stratospheric intrusions, the Santa Ana winds, and wildland fires in Southern California

A. O. Langford¹, R. B. Pierce², and P. J. Schultz^{1,3}

¹NOAA Earth System Research Laboratory, Boulder, Colorado, USA, ²NOAA/NESDIS Center for Satellite Application and Research, Cooperative Institute for Meteorological Satellite Studies, Madison, Wisconsin, USA, ³Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA

Abstract The Santa Ana winds of Southern California have long been associated with wildland fires that can adversely affect air quality and lead to loss of life and property. These katabatic winds are driven primarily by thermal gradients but can be exacerbated by northerly flow associated with upper level troughs passing through the western U.S. In this paper, we show that the fire danger associated with the passage of upper level troughs can be further increased by the formation of deep tropopause folds that transport extremely dry ozone-rich air from the upper troposphere and lower stratosphere to the surface. Stratospheric intrusions can thus increase surface ozone both directly through transport and indirectly through their influence on wildland fires. We illustrate this situation with the example of the Springs Fire, which burned nearly 25,000 acres in Ventura County during May 2013.

1. Introduction

The Santa Ana winds of Southern California have long been associated with severe wildfires [Mensing *et al.*, 1999; Westerling *et al.*, 2004] that contribute to poor air quality [Bytnerowicz *et al.*, 2010; Corbett, 1996] and can result in the loss of life and property [California Department of Forestry and Fire Protection, 2008]. These dry, easterly or northeasterly foehn-like katabatic winds can affect a large area typically developed between fall and early spring [Conil and Hall, 2006; Hughes and Hall, 2010; Raphael, 2003] when there is a large temperature gradient between the cold desert surface and warm ocean air [Hughes and Hall, 2010]. Major episodes can persist for several days and often follow the inland movement of a Great Basin High behind a cold front associated with an upper level trough [Sommers, 1978]. The strong northerly flow on the western flank of particularly deep troughs can substantially add to the Santa Ana winds at the surface.

The synoptic conditions described above can also lead to the formation of tropopause folds, intrusions of dry, ozone-rich lower stratospheric air that slope downward and equatorward into the free troposphere beneath the jet stream circulating around the upper level trough [Danielsen and Mohnen, 1977]. Climatological studies [Skerlak *et al.*, 2014; Sprenger and Wernli, 2003] have shown that deep tropopause folds, i.e., those that penetrate all the way to the top of the boundary layer [Bourqui and Trepanier, 2010], are particularly common above the west coast of the U.S. at the end of the North Pacific storm track, with lower stratospheric air descending to the surface as far south as Baja California. These events are most frequent in winter and spring but also occur in the fall. Most research on this deep stratosphere-to-troposphere transport (STT) has been motivated by the potential impacts on surface ozone [Langford *et al.*, 2012, 2015; Lin *et al.*, 2012], but the northerly winds and extremely dry air descending to the surface on the western flank of these troughs can also potentially foster the explosive development of wildland fires in Southern California. In this paper, we present a case study of the May 2013 Springs Fire near Camarillo, CA, that supports this hypothesis and suggest that a stratospheric intrusion may also have contributed to the extremely destructive Santa Ana-driven fire outbreak of October 2007.

2. Springs Fire

The Springs Fire burned about 75 km west of Los Angeles in Ventura County, California, during early May 2013. April of 2013 was exceptionally dry in Southern California with near-normal temperatures but no measurable rainfall in Ventura County (http://www.wrh.noaa.gov/lox/archive/pns_2013summary.pdf). The Springs Fire occurred unusually early in the year, starting along the grassy shoulder of the Ventura

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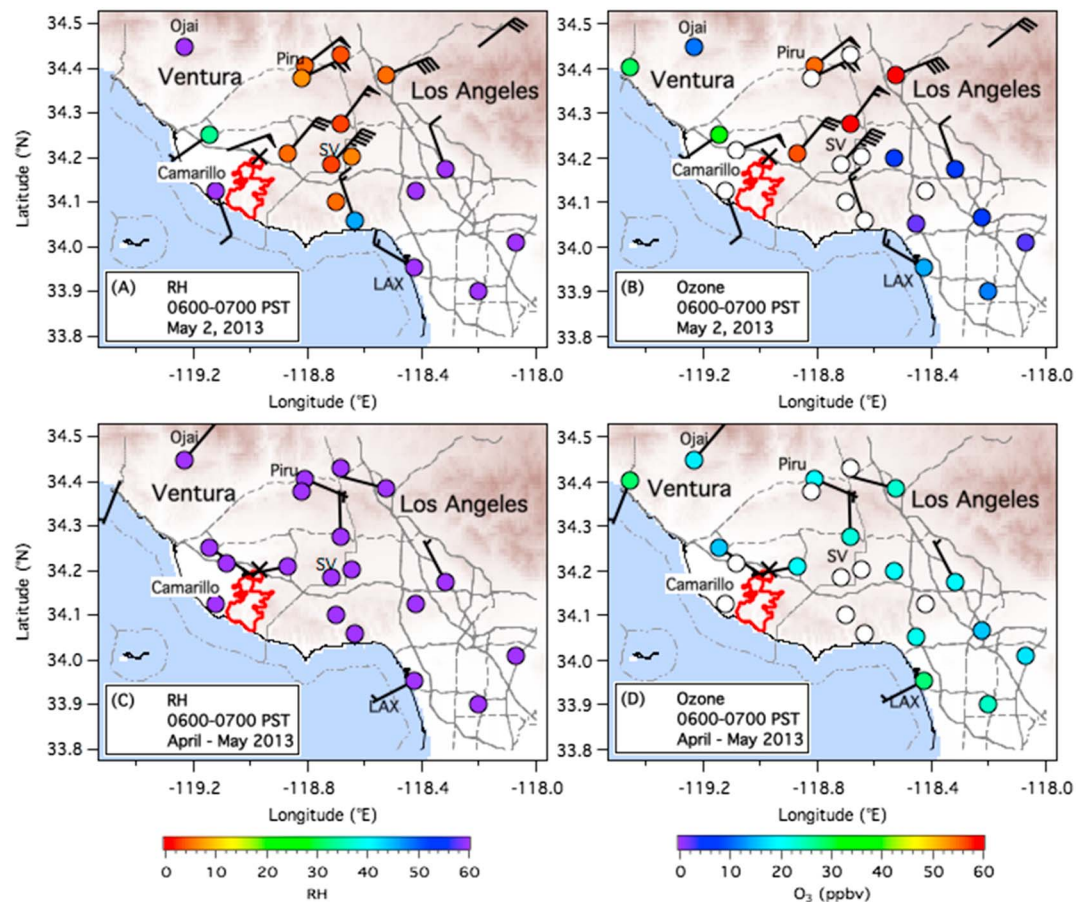


Figure 1. (a) Topographic map of Ventura County and surrounding areas showing the mean hourly winds (each barb=2 m/s, each flag=10 m/s) and RH measured by California Air Resources Board monitors between 0600 and 0700 PST on 2 May. Simi Valley (SV) lies near the center of the map. (b) Same as Figure 1a but with the corresponding hourly O₃ concentrations. (c and d) Same as Figures 1a and 1b but with the 0600 to 0700 PST April–May 2013 mean RH and O₃ values. The cross in all four panels marks the origin of the Springs Fire, and the red outlines show the final footprint of the burned area on 6 May 2013.

Highway (“cross” in Figures 1a–1d) at about 0530 Pacific standard time (PST) during early rush hour traffic on May 2. The fire grew rapidly, ultimately scorching 24,251 acres of mostly brush-covered land between the highway and the Pacific Ocean (red outlines in Figures 1a–1d). The fire threatened 4000 structures and burned 15, involving the efforts of more than 2100 firefighters supported by 117 fire engines, 11 helicopters, and 8 air tankers (California Department of Forestry and Fire Protection, 2013, http://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=780) at a cost of nearly \$12 million [Ventura County, 2014] before being extinguished by rain on May 6.

The synoptic situation at the start of the fire is shown in Figure 2a, which displays the lower tropospheric (310 K) O₃ distribution (colors) and mean vector winds (black arrows) above the continental United States at 1200 UT (0400 PST) on 2 May 2013 from the NOAA Realtime Air Quality Modeling System (RAQMS) model. The white lines show the Montgomery stream functions for the geostrophic winds on the 310 K surface. Figure 2b displays the corresponding latitude-height distributions of O₃ (colors) and dew point (black contours) through Ventura County (dashed line in Figure 2a). The NOAA/National Environmental Satellite, Data, and Information Service RAQMS is a unified (stratosphere-troposphere) online global chemical and aerosol assimilation/forecasting system that has been used to support several airborne field missions [Pierce *et al.*, 2003]. Forecasts are initialized daily at 1200 UT with real-time assimilation of Ozone Monitoring Instrument (OMI) cloud cleared total column ozone and Microwave Limb Sounder ozone profiles from the NASA Aura satellite and Moderate Resolution Imaging Spectroradiometer aerosol optical depth from the NASA Terra and Aqua satellites. The O₃ and CO distributions over the North Pacific

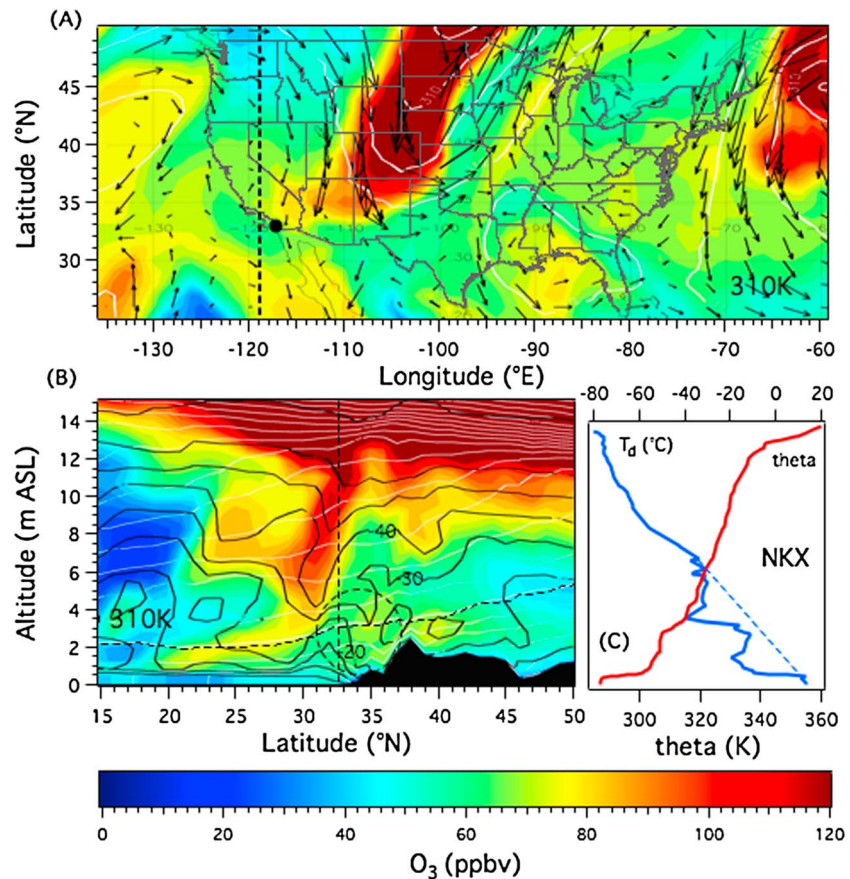


Figure 2. (a) RAQMS ozone distribution (colors) and mean winds (arrows) on the 310 K isentropic surface (~2 to 4 km asl) at 1200 UT on 2 May 2013. The white contours show the Montgomery stream functions ($\times 10^3 \text{ m}^2 \text{ s}^{-2}$) for the geostrophic wind. The filled circle marks the location of the San Diego (NKX) radiosonde station. The vertical dashed line corresponds to Figure 2b. Latitude-height transect of the RAQMS O_3 (colors) and T_d (black contours) through Simi Valley, CA, at 119°W. (b) The white contours show the isentropes with the dashed curve extending across Figure 2b indicating the 310 K surface. The dashed circle encloses an area of dry, ozone-rich air above Ventura County, CA, and the vertical dashed line shows the (c) location of the 1200 UT NKX sounding.

(10 to 72°N, -110 to -50°E) were predicted at 6 h intervals for the next 4 days. RAQMS has been run routinely since 2010 with $2^\circ \times 2^\circ$ resolution analyses and forecasts prior to 2012 and $1^\circ \times 1^\circ$ resolution after 2012. RAQMS plots are archived online (<http://raqms-ops.ssec.wisc.edu>).

The stream functions in Figure 2a show a deep trough with high O_3 concentrations stretching southward from Canada to New Mexico before curving westward over Southern California. Cyclonic circulation around this low-pressure system and anticyclonic circulation around the Great Basin High that followed produced strong northerly winds with maximum values above western Arizona and Utah on the 310 K isentropic surface in Figure 2a. The transect in Figure 2b exhibits the classic appearance [Danielsen and Mohnen, 1977] of a deep tropopause fold, with a tongue of air characterized by high O_3 (yellow-red colors) and very low dew points (T_d , black contour lines) that slopes downward and equatorward from the lower stratosphere. RAQMS indicates that the intrusion brought lower stratospheric air with $T_d < -20^\circ\text{C}$ and $\text{O}_3 > 75$ ppbv to within 1 km of the surface as far south as Baja California. The circled region in Figure 2b shows air with $T_d = -20^\circ\text{C}$ and 60–70 ppbv of O_3 just above Ventura County (arrow). This dew point corresponds to a relative humidity (RH) $< 3\%$ at 30°C . This region and the more distinct stratospheric layer above are consistent with the dry stable layers characteristic of stratospheric intrusions seen at ~1 and 4 km above sea level (asl) in the nearby San Diego, CA, sounding plotted in Figure 2c.

Descent of dry O_3 -rich air to the surface in Southern California is evident in Figures 1a and 1b, which show the (0600 to 0700 PST) hourly winds (flags), RH (colored filled circles, Figure 1a), and O_3 (colored filled

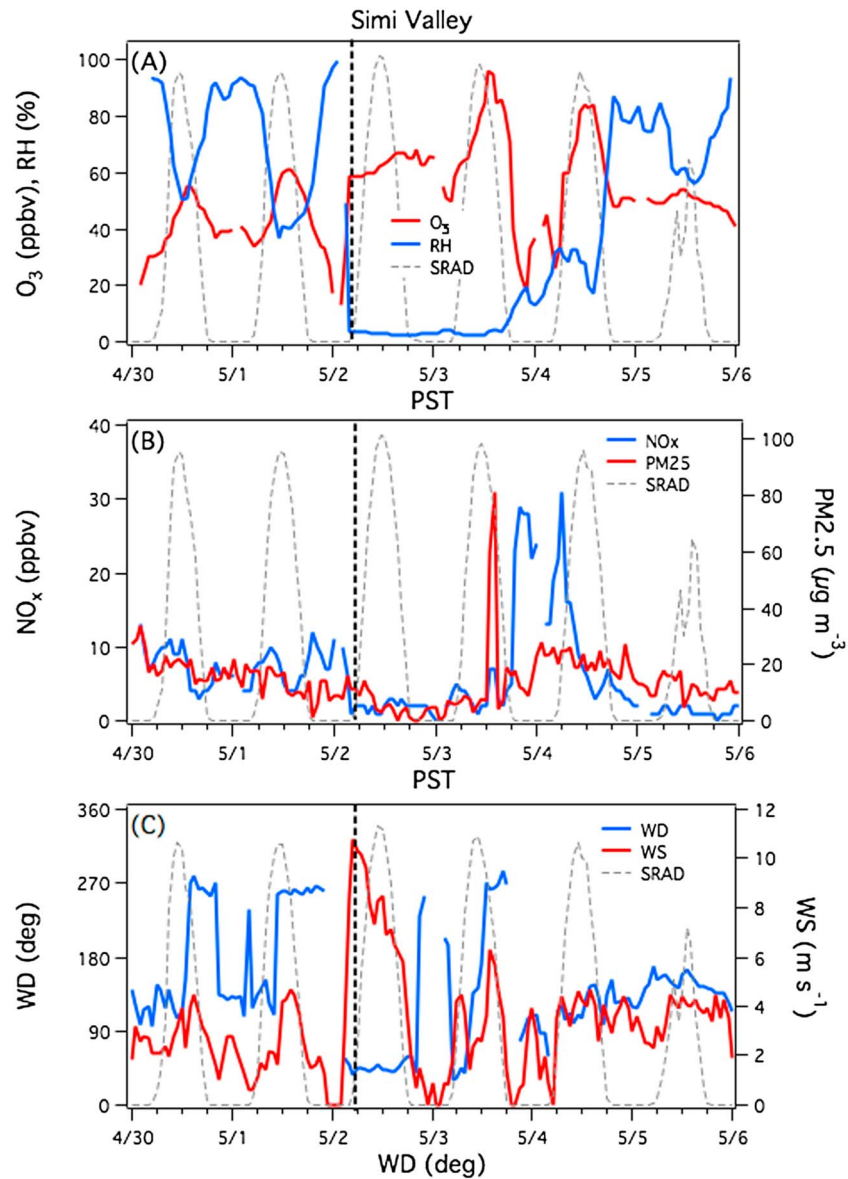


Figure 3. Time series of (a) relative humidity (RH) and O₃, (b) NO_x and PM_{2.5}, and (c) wind speed and direction measured at the Simi Valley-Cochran Street monitoring station (34.28°N, -118.68°E, 316 m asl) before and during the Springs Fire. The dashed gray traces represent the normalized solar radiation. The vertical black dashed line shows the start of the Springs Fire.

circles, Figure 1b) from monitoring sites in Los Angeles and Ventura counties. Figures 1c and 1d show the April–May 2013 mean values for the same early morning time period. Unusually high O₃, low RH, and strong northeasterly winds of 8 to 13 m/s were measured at several sites upwind of the fire. The much lower O₃, higher RH, and weak, ill-defined winds comparable to the April–May norm for 0600–0700 PST (Figure 1b) in the surrounding areas show that this dry, O₃-rich air was not advected from the Los Angeles Basin. The arrival of the diluted lower stratospheric air at the surface on the morning of 2 May is also seen in Figure 3, which plots time series of hourly O₃ and other parameters from the Simi Valley monitoring station operated by the California Air Resources Board (SV in Figure 1). The relative humidity fell abruptly to 3% (dew point from 13 to -21°C) between 0500 and 0600 PST when the fire started and O₃ increased to 60 ppbv as the winds shifted to the northeast, disrupting the normal land-sea breeze seen the previous 2 days. Small-diameter fuels such as the dry grass found along the Ventura Highway respond quickly (<1 h) to changes in relative humidity, and the probability of ignition and rapid expansion of wildfires through spotting increases dramatically at low relative humidities and high wind

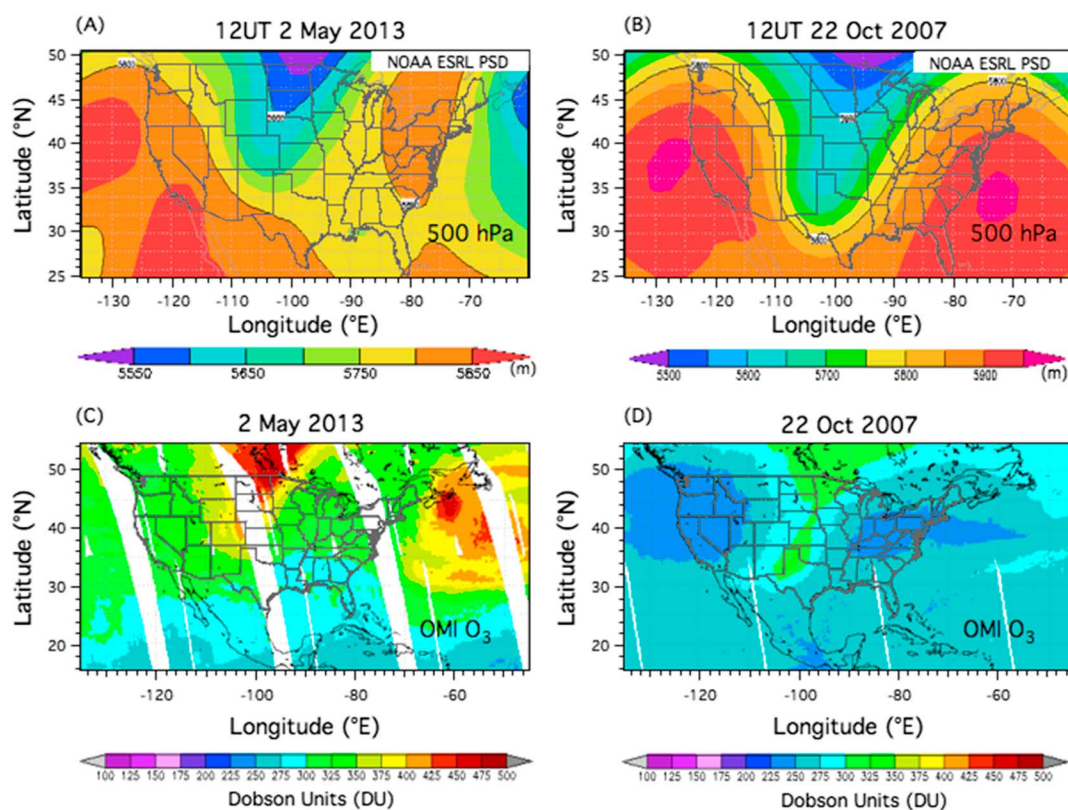


Figure 4. National Centers for Environmental Prediction Reanalysis [Kalnay *et al.*, 1996] 500 hPa geopotential heights for 12 UT on (a) 2 May 2013 and (b) 22 October 2007 from the NOAA Earth System Research Laboratory Physical Sciences Division. Daily mean total column O₃ for (c) 2 May 2013 and (d) 22 October 2007 from the NASA Ozone Monitoring Instrument (OMI) aboard the Aura satellite showing stratospheric intrusions. The lower total column ozone in Figure 4d compared to Figure 4c reflects normal fall-spring differences.

speeds [Weir, 2007]. The extremely low moisture content of larger-diameter brushy fuels caused by the ongoing drought further enhanced the spread of the fire.

The influence of the descending lower stratospheric air increased over the next several hours as the wind blew the fire plume offshore, and the NO_x and PM_{2.5} measured at Simi Valley fell below the stated precision of the Environmental Protection Agency-certified sensors (0.5 ppbv and 2 μg m⁻³, respectively). The unusual clarity on the afternoon of 2 May led to a 7% increase in solar irradiance (dashed gray traces) compared to the previous day, and adiabatic warming of the descending air raised the surface temperature to 36.7°C (98°F) at the Camarillo Airport, eclipsing the previous (60 year) record for 2 May (NOAA National Climatic Data Center, 2014, http://www.wrh.noaa.gov/lox/archive/pns_2013summary.pdf) by more than 2°C (4°F). The high winds persisted throughout the day, and the dew point dropped to -27°C (RH ~ 1%) at both Simi Valley and Camarillo Airport in the late afternoon as the O₃ concentrations climbed to nearly 70 ppbv. Note that these concentrations are not exceptionally high for the polluted Los Angeles Basin where stratospheric intrusions can actually *decrease* surface ozone compared to normal concentrations [Langford *et al.*, 2012].

The sea breeze resumed on 3 May (Figure 3c), recirculating air with recent and aged emissions from the fire and the nearby urban areas inland. Fires also emit the NO_x and VOC precursors of O₃ although ozone production in fire plumes often becomes NO_x limited [Jaffe and Wigder, 2012]. A narrow plume of fine particulates (smoke) with low RH (~7%) and O₃ concentrations up to 96 ppbv was sampled at Simi Valley on the afternoon of 3 May. Relatively high PM_{2.5} levels lingered for several more days as the fire continued to burn. The maximum daily 8 h average (MDA8) O₃ concentration of 85 ppbv was the second highest value recorded at Simi Valley in all of 2013. Ozone also exceeded the 2008 national ambient air quality standard (NAAQS) of 75 ppbv for the MDA8 on the afternoon of 4 May when the local winds rotated to the

southeast bringing both aged fire and urban emissions to the site. The concentrations finally returned to normal on 5 and 6 May when cloudy skies, cooler temperatures, and widespread rain moved ashore to help extinguish the fire.

The measured RH and O₃ in Figure 3a are consistent with the RAQMS transect in Figure 2b, supporting the conclusion that the air sampled on 2 May had a significant influence from the lower stratosphere. The large (20 ppbv) increase in the MDA8 O₃ on the following day when the fire plume recirculated inland reflects the combined influence of the fire and regional urban emissions. Although NO_x in fire plumes often becomes sequestered in more stable forms (e.g., peroxyacetyl nitrates [Alvarado *et al.*, 2010]) that decompose slowly and limit O₃ production, significant local production can occur if the plume mixes with NO_x-rich air from urban areas such as Los Angeles [Singh *et al.*, 2012]. In all of 2013, 3 May was one of only two O₃ exceedance days at Ojai and Piru (cf. Figure 1) and the only exceedance day at Thousand Oaks, Compton, Lompoc, and Los Angeles International Airport. Altogether, the NAAQS was exceeded at 24 monitoring sites across Southern California on 3 and 4 May and at six monitoring sites 400 km downwind in Clark County, Nevada, on 4 May. The unusual nature of the exceedances in Ventura and western Los Angeles counties argues against a strictly local or regional anthropogenic influence and suggests that the high O₃ observed there was at least partly due to the combined effects of the stratospheric intrusion and Springs Fire.

3. Discussion and Conclusions

Stratospheric intrusions have previously been implicated in the explosive development of wildland fires in New Jersey [Charney *et al.*, 2003] and Michigan [Zimet *et al.*, 2007] but have not previously been connected to fires in Southern California or to the Santa Ana winds. The frequent occurrence of stratospheric intrusions above the west coast during the winter and spring suggests that similar circumstances may have played a role in other major Southern California fires. This hypothesis is supported by Figure 4, which compares the 500 hPa geopotential heights and total column ozone measured at the onset of the Springs Fire with those from 22 October 2007 near the start of the most destructive fire episode in Southern California history. The October 2007 outbreak consisted of at least 30 fires, which burned nearly 1 million acres between 20 October and 9 November, destroying more than 1500 homes with 14 deaths. The estimated total cost was about \$1.4 billion [California Department of Forestry and Fire Protection, 2008]. These fires also led to exceedances of the PM_{2.5} and O₃ NAAQS at multiple monitoring sites in Santa Barbara, Ventura, and San Diego counties [Pfister *et al.*, 2008]. Figure 4 shows that the synoptic conditions on 22 October 2007 were even more favorable (i.e., deeper trough, larger Great Basin High, and stronger upper level winds) for tropopause folding and synoptic forcing of the Santa Ana winds. Radiosonde profiles (not shown) from San Diego, CA, acquired on that day exhibit stable, dry layers consistent with stratospheric intrusions in the lower troposphere [Langford *et al.*, 2009]. Similar synoptic conditions also occurred at the beginning of the Cedar Fire, the single largest fire in Southern California history, which started on 25 October 2003 and led to widespread O₃ and PM_{2.5} exceedances on 26 and 27 October. (http://www.arb.ca.gov/research/chs/fire/report_revised_Sept2010.pdf).

Our findings suggest that modern forecast models with the capacity to predict stratospheric intrusions such as RAQMS (<http://raqms-ops.ssec.wisc.edu>) or the NOAA Rapid Refresh Air Quality Model (http://ruc.noaa.gov/wrf/WG11_RT/Welcome.cgi) [Grell *et al.*, 2005] may provide valuable lead time for agencies to issue air quality alerts and Fire Weather Warnings and to reallocate fire fighting resources before these extreme events occur. All three of the fires mentioned above occurred during La Niña periods when the polar front jet was shifted relatively far southward leading to more frequent deep STT events above the southwestern U.S. [Lin *et al.*, 2015]. These events may become more numerous in the future as wildland fires are expected to become more frequent in a warmer, dryer climate [Yue *et al.*, 2014] and global circulation models suggest that STT will also increase due to a stronger Brewer-Dobson circulation [Hegglin and Shepherd, 2009].

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