

1 **Stratospheric intrusions, the Santa Ana winds, and wildland fires in southern California**

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

4

5 ¹NOAA Earth System Research Laboratory, Boulder, Colorado 80305, USA.

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7 ²NOAA/NESDIS Center for Satellite Application and Research, Cooperative Institute for
8 Meteorological Satellite Studies, Madison, Wisconsin, 53706, USA.

9

10 ³Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder,
11 Colorado, 80309, USA.

12

13

14 Corresponding author: Andrew O. Langford, NOAA Earth System Research Laboratory, 325 Broadway, R/CSD3,
15 Boulder, CO 80305, USA. (andrew.o.langford@noaa.gov)

16

1 **Key points**

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3 Descent of dry lower stratospheric air to the surface can exacerbate wildland fires.

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5 Synoptic flow associated with deep stratospheric intrusions can force Santa Ana-like winds.

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7 Stratospheric intrusions can indirectly contribute to surface ozone by influencing wildland fires.

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1 **Abstract:**

2 The Santa Ana winds of southern California have long been associated with wildland fires
3 that can adversely affect air quality and lead to loss of life and property. These katabatic winds
4 are driven primarily by thermal gradients, but can be exacerbated by northerly flow associated
5 with upper level troughs passing through the western U.S. In this paper, we show that the fire
6 danger associated with the passage of upper level troughs can be further increased by the
7 formation of deep tropopause folds that transport extremely dry ozone-rich air from the upper
8 troposphere and lower stratosphere to the surface. Stratospheric intrusions can thus increase
9 surface ozone both directly through transport, and indirectly through their influence on wildland
10 fires. We illustrate this situation with the example of the Springs fire, which burned nearly
11 25,000 acres in Ventura County during May 2013.

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14 **Index Terms**

15

16 3362 Stratosphere/troposphere interactions

17 0468 Natural Hazards

18 0368 Troposphere: constituent transport and chemistry

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1 **1. Introduction**

2 The Santa Ana winds of Southern California have long been associated with severe wildfires
3 [*Mensing et al.*, 1999; *Westerling et al.*, 2004] that contribute to poor air quality [*Bytnerowicz et*
4 *al.*, 2010; *Corbett*, 1996] and can result in the loss of life and property [*California Department of*
5 *Forestry and Fire Protection*, 2008]. These dry, easterly or northeasterly foehn-like katabatic
6 winds can affect a large area typically develop between fall and early spring [*Conil and Hall*,
7 2006; *Hughes and Hall*, 2010; *Raphael*, 2003] when there is a large temperature gradient
8 between the cold desert surface and warm ocean air [*Hughes and Hall*, 2010]. Major episodes
9 can persist for several days, and often follow the inland movement of a Great Basin High behind
10 a cold front associated with an upper level trough [*Sommers*, 1978]. The strong northerly flow on
11 the western flank of particularly deep troughs can substantially add to the Santa Ana winds at the
12 surface.

13 The synoptic conditions described above can also lead to the formation of tropopause folds,
14 intrusions of dry, ozone-rich lower stratospheric air that slope downward and equatorward into
15 the free troposphere beneath the jet stream circulating around the upper level trough [*Danielsen*
16 *and Mohnen*, 1977]. Climatological studies [*Skerlak et al.*, 2014; *Sprenger and Wernli*, 2003]
17 have shown that *deep* tropopause folds, i.e. those that penetrate all the way to the top of the
18 boundary layer [*Bourqui and Trepanier*, 2010], are particularly common above the west coast of
19 the U.S. at the end of the North Pacific storm track, with lower stratospheric air descending to
20 the surface as far south as Baja California. These events are most frequent in winter and spring,
21 but also occur in the fall. Most research on this deep stratosphere-to-troposphere transport (STT)
22 has been motivated by the potential impacts on surface ozone [*Langford et al.*, 2012; *Langford et*
23 *al.*, 2015; *Lin et al.*, 2012], but the northerly winds and extremely dry air descending to the

1 surface on the western flank of these troughs can also potentially foster the explosive
2 development of wildland fires in southern California. In this paper, we present a case study of the
3 May 2013 Springs Fire near Camarillo, CA that supports this hypothesis, and suggest that a
4 stratospheric intrusion may also have contributed to the extremely destructive Santa Ana driven
5 fire outbreak of October 2007.

6

7 **2. Springs Fire**

8 The Springs Fire burned about 75 km west of Los Angeles in Ventura County, California,
9 during early May 2013. April of 2013 was exceptionally dry in Southern California with near
10 normal temperatures, but no measurable rainfall in Ventura County (www.ncdc.noaa.gov). The
11 Springs fire occurred unusually early in the year, starting along the grassy shoulder of the
12 Ventura Highway (“x” in **Figures 1A-D**) at about 0530 Pacific Standard Time (PST) during
13 early rush hour traffic on May 2. The fire grew rapidly, ultimately scorching 24,251 acres of
14 mostly brush-covered land between the highway and the Pacific Ocean (red outlines in **Figures**
15 **1A-D**). The fire threatened 4000 structures and burned 15, involving the efforts of more than
16 2100 firefighters supported by 117 fire engines, 11 helicopters, and 8 air tankers [*California*
17 *Department of Forestry and Fire Protection, 2013*] at a cost of nearly \$12 million [*Ventura*
18 *County, 2014*] before being extinguished by rain on May 6.

19 The synoptic situation at the start of the fire is shown in **Figure 2A**, which displays the
20 lower tropospheric (310K) O₃ distribution (colors) and mean vector winds (black arrows) above
21 the continental United States at 1200 UT (0400 PST) on May 2, 2013 from the NOAA Realtime
22 Air Quality Modeling System (RAQMS) model. The white lines show the Montgomery stream
23 functions for the geostrophic winds on the 310K surface. **Figure 2B** displays the corresponding

1 latitude-height distributions of O₃ (colors) and dew point (black contours) through Ventura
2 County (dashed line in **Figure 2A**). The NOAA/NESDIS RAQMS is a unified (stratosphere-
3 troposphere) online global chemical and aerosol assimilation/forecasting system that has been
4 used to support several airborne field missions [*Pierce et al.*, 2003]. Forecasts are initialized
5 daily at 1200 UT with real-time assimilation of OMI cloud cleared total column ozone and MLS
6 ozone profiles from the NASA Aura satellite, and MODIS aerosol optical depth from the NASA
7 Terra and Aqua satellites. The O₃ and CO distributions over the North Pacific (10 to 72°N, -110
8 to -50°E) were predicted at 6-hour intervals for the next 4 days. RAQMS has been run routinely
9 since 2010 with 2° x 2° resolution analyses and forecasts prior to 2012 and 1° x 1° resolution
10 after 2012. RAQMS plots are archived online (<http://raqms-ops.ssec.wisc.edu>).

11 The stream functions in **Figure 2A** show a deep trough with high O₃ concentrations
12 stretching southward from Canada to New Mexico before curving westward over southern
13 California. Cyclonic circulation around this low-pressure system and anticyclonic circulation
14 around the Great Basin High that followed produced strong northerly winds with maximum
15 values above western Arizona and Utah on the 310K isentropic surface in Figure 2A. The
16 transect in **Figure 2B** exhibits the classic appearance [*Danielsen and Mohnen*, 1977] of a deep
17 tropopause fold, with a tongue of air characterized by high O₃ (yellow-red colors) and very low
18 dewpoints (T_d, black contour lines) that slopes downward and equatorward from the lower
19 stratosphere. RAQMS indicates that the intrusion brought lower stratospheric air with T_d < -20°C
20 and O₃ > 75 ppbv to within 1 km of the surface as far south as Baja California. The circled
21 region in **Figure 2B** shows air with T_d = -20°C and 60-70 ppbv of O₃ just above Ventura County
22 (arrow). This dew point corresponds to a relative humidity (RH) < 3% at 30°C. This region and
23 the more distinct stratospheric layer above are consistent with the dry stable layers characteristic

1 of stratospheric intrusions seen at ~1 and 4 km above sea level (ASL) in the nearby San Diego,
2 CA sounding plotted in **Figure 2C**.

3 Descent of dry O₃-rich air to the surface in southern California is evident in **Figures 1A** and
4 **1B**, which show the (0600 to 0700 PST) hourly winds (flags), RH (colored filled circles, **Figure**
5 **1A**), and O₃ (colored filled circles, **Figure 1B**) from monitoring sites in Los Angeles and
6 Ventura counties. The bottom panels (**Figures 1C** and **1D**) show the April-May 2013 mean
7 values for the same early morning time period. Unusually high O₃, low RH, and strong
8 northeasterly winds of 8 to 13 m s⁻¹ (15 to 25 knots) were measured at several sites upwind of the
9 fire. The much lower O₃, higher RH, and weak, ill-defined winds comparable to the April-May
10 norm for 0600-0700 PST (**Figure 1B**) in the surrounding areas show that this dry, O₃-rich air
11 was not advected from the Los Angeles Basin. The arrival of the diluted lower stratospheric air
12 at the surface on the morning of May 2 is also seen in **Figure 3**, which plots times series of
13 hourly O₃ and other parameters from the Simi Valley monitoring station operated by the
14 California Air Resources Board (SV in **Figure 1**). The relative humidity fell abruptly to 3%
15 (dewpoint from 13 to -21°C) between 0500 and 0600 PST when the fire started and O₃ increased
16 to 60 ppbv as the winds shifted to the northeast, disrupting the normal land-sea breeze seen the
17 previous two days. Small diameter fuels such as the dry grass found along the Ventura Highway
18 respond quickly (<1 h) to changes in relative humidity, and the probability of ignition and rapid
19 expansion of wildfires through spotting increases dramatically at low relative humidities and
20 high wind speeds [*Weir, 2007*]. The extremely low moisture content of larger diameter brushy
21 fuels caused by the ongoing drought further enhanced the spread of the fire.

22 The influence of the descending lower stratospheric air increased over the next several hours
23 as the wind blew the fire plume offshore, and the NO_x, and PM_{2.5} measured at Simi Valley fell

1 below the stated precision of the EPA-certified sensors (0.5 ppbv and $2 \mu\text{g m}^{-3}$, respectively).
2 The unusual clarity on the afternoon of May 2 led to a 7% increase in solar irradiance (dashed
3 gray traces) compared to the previous day, and adiabatic warming of the descending air raised
4 the surface temperature to 36.7°C (98°F) at the Camarillo Airport, eclipsing the previous (60
5 year) record for May 2 [*NOAA National Climatic Data Center, 2014*] by more than 2°C (4°F).
6 The high winds persisted throughout the day and the dew point dropped to -27°C ($\text{RH} \sim 1\%$) at
7 both Simi Valley and Camarillo Airport in the late afternoon as the O_3 concentrations climbed to
8 nearly 70 ppbv. Note that these concentrations are not exceptionally high for the polluted Los
9 Angeles Basin where stratospheric intrusions can actually *decrease* surface ozone compared to
10 normal concentrations [*Langford et al., 2012*].

11 The sea breeze resumed on May 3 (**Figure 3C**), recirculating air with recent and aged
12 emissions from the fire and the nearby urban areas inland. Fires also emit the NO_x and VOC
13 precursors of O_3 although ozone production in fire plumes often becomes NO_x limited [*Jaffe and*
14 *Wigder, 2012*]. A narrow plume of fine particulates (smoke) with low RH ($\sim 7\%$) and O_3
15 concentrations up to 96 ppbv was sampled at Simi Valley on the afternoon of May 3. Relatively
16 high $\text{PM}_{2.5}$ levels lingered for several more days as the fire continued to burn. The maximum
17 daily 8-h average (MDA8) O_3 concentration of 85 ppbv was the second highest value recorded at
18 Simi Valley in all of 2013. Ozone also exceeded the 2008 National Ambient Air Quality
19 Standard (NAAQS) of 75 ppbv for the MDA8 on the afternoon of May 4 when the local winds
20 rotated to the southeast bringing both aged fire and urban emissions to the site. The
21 concentrations finally returned to normal on May 5 and 6 when cloudy skies, cooler
22 temperatures, and widespread rain moved ashore to help extinguish the fire.

1 The measured RH and O₃ in **Figure 3A** are consistent with the RAQMS transect in Figure
2 2B, supporting the conclusion that the air sampled on May 2 had a significant influence from the
3 lower stratosphere. The large (20 ppbv) increase in the MDA8 O₃ on the following day when the
4 fire plume recirculated inland reflects the combined influence of the fire and regional urban
5 emissions. Although NO_x in fire plumes often becomes sequestered in more stable forms (e.g.
6 peroxyacetyl nitrates or PAN [*Alvarado et al.*, 2010]) that decompose slowly and limit O₃
7 production, significant local production can occur if the plume mixes with NO_x-rich air from
8 urban areas such as Los Angeles [*Singh et al.*, 2012]. May 3 was one of only two O₃ exceedance
9 days in all of 2013 at Ojai and Piru (cf. **Figure 1**) and the only exceedance day at Thousand
10 Oaks, Compton, Lompoc, and Los Angeles International Airport. Altogether, the NAAQS was
11 exceeded at 24 monitoring sites across southern California on May 3 and 4, and at 6 monitoring
12 sites 400 km downwind in Clark County, Nevada, on May 4. The unusual nature of the
13 exceedances in Ventura and western Los Angeles counties argues against a strictly local or
14 regional anthropogenic influence and suggests that the high O₃ observed there was at least partly
15 due to the combined effects of the stratospheric intrusion and Springs fire.

16

17 **3. Discussion and Conclusions**

18 Stratospheric intrusions have previously been implicated in the explosive development of
19 wildland fires in New Jersey [*Charney et al.*, 2003] and Michigan [*Zimet et al.*, 2007], but have
20 not previously been connected to fires in southern California or to the Santa Ana winds. The
21 frequent occurrence of stratospheric intrusions above the west coast during the winter and spring
22 suggests that similar circumstances may have played a role in other major southern California
23 fires. This hypothesis is supported by **Figure 4**, which compares the 500-hPa geopotential

1 heights and total column ozone measured at the onset of the Springs Fire with those from
2 October 22, 2007 near the start of the most destructive fire episode in southern California
3 history. The October 2007 outbreak consisted of at least 30 fires, which burned nearly 1 million
4 acres between October 20 and November 9, destroying more than 1500 homes with 14 deaths.
5 The estimated total cost was about \$1.4 billion [*California Department of Forestry and Fire*
6 *Protection*, 2008]. These fires also led to exceedances of the PM_{2.5} and O₃ NAAQS at multiple
7 monitoring sites in Santa Barbara, Ventura, and San Diego counties [*Pfister et al.*, 2008]. **Figure**
8 4 shows that the synoptic conditions on October 22, 2007 were even more favorable (i.e. deeper
9 trough, larger Great Basin High, and stronger upper level winds) for tropopause folding and
10 synoptic forcing of the Santa Ana winds. Radiosonde profiles (not shown) from San Diego, CA
11 acquired on that day exhibit stable, dry layers consistent with stratospheric intrusions in the
12 lower troposphere [*Langford et al.*, 2009]. Similar synoptic conditions also occurred at the
13 beginning of the Cedar Fire, the single largest fire in southern California history, which started
14 on October 25, 2003 and led to widespread O₃ and PM_{2.5} exceedances on the 26th and 27th of
15 October. (http://www.arb.ca.gov/research/chs/fire/report_revised_Sept2010.pdf).

16 Our findings suggest that modern forecast models with the capacity to predict stratospheric
17 intrusions such as RAQMS (<http://raqms-ops.ssec.wisc.edu>) or the NOAA Rapid Refresh Air
18 Quality Model (http://ruc.noaa.gov/wrf/WG11_RT/Welcome.cgi) [*Grell et al.*, 2005] may
19 provide valuable lead time for agencies to issue air quality alerts and Fire Weather Warnings,
20 and to reallocate fire fighting resources before these extreme events occur. All three of the fires
21 mentioned above occurred during La Niña periods when the polar front jet was shifted relatively
22 far southward leading to more frequent deep STT events above the southwestern U.S. [*Lin et al.*,
23 2015]. These events may become more numerous in future as wildland fires are expected to

1 become more frequent in a warmer, dryer climate [Yue *et al.*, 2014] and global circulation
2 models (GCMs) suggest that STT will also increase due to a stronger Brewer-Dobson circulation
3 [Hegglin and Shepherd, 2009].
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10 National Oceanic and Atmospheric Administration or U.S. Government position, policy, or
11 decision.
12

13 **References**

14 Alvarado, M. J., et al. (2010), Nitrogen oxides and PAN in plumes from boreal fires during
15 ARCTAS-B and their impact on ozone: an integrated analysis of aircraft and satellite
16 observations, *Atmospheric Chemistry and Physics*, 10(20), 9739-9760, doi: 10.5194/Acp-
17 10-9739-2010.

18 Bourqui, M. S., and P. Y. Trepanier (2010), Descent of deep stratospheric intrusions during the
19 IONS August 2006 campaign, *J. Geophys. Res.*, 115, doi:10.1029/2009JD013183.

20 Bytnerowicz, A., D. Cayan, P. Riggan, S. Schilling, P. Dawson, M. Tyree, L. Wolden, R. Tissell,
21 and H. Preisler (2010), Analysis of the effects of combustion emissions and Santa Ana

1 winds on ambient ozone during the October 2007 southern California wildfires,
2 *Atmospheric Environment*, 44(5), 678-687, doi: 10.1016/J.Atmosenv.2009.11.014.

3 California Department of Forestry and Fire Protection (2008), California fire siege 2007: An
4 overview, edited, California Department of Forestry and Fire Protection.

5 California Department of Forestry and Fire Protection (2013), Springs Fire Incident Information,
6 edited.

7 Charney, J. J., X. Bian, B. E. Potter, and W. E. Heilman (2003), The role of a stratospheric
8 intrusion in the evolution of the Double Trouble State Park Wildfire, paper presented at
9 Proceedings of the 5th Symposium on Fire and Forest Meteorology, American
10 Meteorological Society, Orlando, FL.

11 Conil, S., and A. Hall (2006), Local regimes of atmospheric variability: A case study of southern
12 California, *Journal of Climate*, 19(17), 4308-4325, doi: 10.1175/Jcli3837.1.

13 Corbett, S. W. (1996), Asthma exacerbations during Santa Ana winds in southern California,
14 *Wild Environ Med*, 7(4), 304-311, doi: 10.1580/1080-
15 6032(1996)007[0304:Aedsaw]2.3.Co;2.

16 Danielsen, E. F., and V. A. Mohnen (1977), Project Dustorm report: ozone transport, in situ
17 measurements, and meteorological analysis of tropopause folding, *Journal of*
18 *Geophysical Research*, 82, 5867-5877.

19 Grell, G. A., S. E. Peckham, R. Schmitz, S. A. McKeen, G. J. Frost, W. C. Skamarock, and B.
20 Eder (2005), Fully coupled 'online' chemistry in the WRF model, *Atmospheric*
21 *Environment*, 39, 6957-6976.

- 1 Hegglin, M. I., and T. G. Shepherd (2009), Large climate-induced changes in ultraviolet index
2 and stratosphere-to-troposphere ozone flux, *Nature Geoscience*, 2(10), 687-691.
- 3 Hughes, M., and A. Hall (2010), Local and synoptic mechanisms causing Southern California's
4 Santa Ana winds, *Climate Dynamics*, 34(6), 847-857, doi: 10.1007/S00382-009-0650-4.
- 5 Jaffe, D. A., and N. L. Wigder (2012), Ozone production from wildfires: A critical review,
6 *Atmospheric Environment*, 51, 1-10, doi: 10.1016/J.Atmosenv.2011.11.063.
- 7 Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*,
8 77, 437-471.
- 9 Langford, A. O., K. C. Aikin, C. S. Eubank, and E. J. Williams (2009), Stratospheric
10 contribution to high surface ozone in Colorado during springtime, *Geophys. Res. Lett.*,
11 36, doi:10.1029/2009GL038367.
- 12 Langford, A. O., J. Brioude, O. R. Cooper, C. J. Senff, R. J. Alvarez, R. M. Hardesty, B. J.
13 Johnson, and S. J. Oltmans (2012), Stratospheric influence on surface ozone in the Los
14 Angeles area during late spring and early summer of 2010, *J. Geophys. Res.-Atmos.*, 117,
15 doi:Artn D00v06li.
- 16 Langford, A. O., et al. (2015), An overview of the 2013 Las Vegas Ozone Study (LVOS): Impact
17 of stratospheric intrusions and long-range transport on surface air quality, *Atmospheric*
18 *Environment*, 109, 305-322, doi: 10.1016/J.Atmosenv.2014.08.040.
- 19 Lin, M. Y., A. M. Fiore, O. R. Cooper, L. W. Horowitz, A. O. Langford, H. Levy, B. J. Johnson,
20 V. Naik, S. J. Oltmans, and C. J. Senff (2012), Springtime high surface ozone events over
21 the western United States: Quantifying the role of stratospheric intrusions, *J. Geophys.*
22 *Res.-Atmos.*, 117, doi:10.1029/2012jd018151.

1 Lin, M. Y., A. M. Fiore, L. W. Horowitz, A. O. Langford, S. J. Oltmans, D. Tarasick, and H. E.
2 Rieder (2015), Climate variability modulates western U.S. ozone air quality in spring via
3 deep stratospheric intrusions, *Nat. Comm.*, 6, 7105, doi:10.1038/ncomms8105
4 <http://www.nature.com/naturecommunications>.

5 Mensing, S. A., J. Michaelson, and R. Byrne (1999), A 560-year record of Santa Ana fires
6 reconstructed from charcoal deposited in the Santa Barbara Basin, California, *Quaternary*
7 *Res*, 51(3), 295-305, doi: 10.1006/Qres.1999.2035.

8 NOAA National Climatic Data Center (2014), Daily Weather Records, edited.

9 Pfister, G. G., C. Wiedinmyer, and L. K. Emmons (2008), Impacts of the fall 2007 California
10 wildfires on surface ozone: Integrating local observations with global model simulations,
11 *Geophysical Research Letters*, 35(19), doi:10.1029/2008gl034747.

12 Pierce, R. B., et al. (2003), Regional Air Quality Modeling System (RAQMS) predictions of the
13 tropospheric ozone budget over east Asia, *J. Geophys. Res.-Atmos.*, 108(D21), doi:Artn
14 8825, doi 10.1029/2002jd003176.

15 Raphael, M. N. (2003), The Santa Ana Winds of California, *Earth Interact*, 7.

16 Singh, H. B., C. Cai, A. Kaduwela, A. Weinheimer, and A. Wisthaler (2012), Interactions of fire
17 emissions and urban pollution over California: Ozone formation and air quality
18 simulations, *Atmospheric Environment*, 56, 45-51, doi: 10.1016/J.Atmosenv.2012.03.046.

19 Skerlak, B., M. Sprenger, and H. Wernli (2014), A global climatology of stratosphere-
20 troposphere exchange using the ERA-Interim data set from 1979 to 2011, *Atmospheric*
21 *Chemistry and Physics*, 14(2), 913-937, doi:10.5194/Acp-14-913-2014.

1 Sommers, W. T. (1978), LFM Forecast Variables Related to Santa-Ana Wind Occurrences,
2 *Monthly Weather Review*, 106(9), 1307-1316.

3 Sprenger, M., and H. Wernli (2003), A northern hemisphere climatology of cross-tropopause
4 exchange for the ERA15 time period (1979-1993), *J. Geophys. Res.*, 108,
5 doi:10.1029/2002JD002636.

6 Ventura County (2014), Final report: Firefighting air assets: the Camarillo Springs fire, edited,
7 Ventura County Grand Jury.

8 Weir, J. R. (2007), Using relative humidity to predict spotfire probability on prescribed burns,
9 *Proceedings: Shrubland dynamics-fire and water*, P(47), 69-72.

10 Westerling, A. L., D. R. Cayan, T. J. Brown, B. L. Hall, and L. G. Riddle (2004), Climate, Santa
11 Ana winds and autumn wildfires in Southern California, *Eos Trans. AGU*, 85(31), 289-
12 300.

13 Yue, X., L. J. Mickley, and J. A. Logan (2014), Projection of wildfire activity in southern
14 California in the mid-twenty-first century, *Climate Dynamics*, 43(7-8), 1973-1991, doi:
15 10.1007/S00382-013-2022-3.

16 Zimet, T., J. E. Martin, and B. E. Potter (2007), The influence of an upper-level frontal zone on
17 the Mack Lake Wildfire environment, *Meteorological Applications*, 14(2), 131-147, doi:
18 10.1002/Met.14.

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1 **List of Figures**

2

3 **Figure 1.** (A) Topographic map of Ventura County and surrounding areas showing the mean
4 hourly winds and RH measured by California Air Resources Board monitors between 0600 and
5 0700 PST on May 2. Simi Valley (SV) lies near the center of the map. (B) Same as (A), but with
6 the corresponding hourly O₃ concentrations. Panels (C) and (D), same as (A) and (B), but with
7 the 0600 to 0700 PST April-May 2013 mean RH and O₃ values. The “x” in all four panels marks
8 the origin of the Springs Fire and the red outlines show the final footprint of the burned area on
9 May 6, 2013.

10

11 **Figure 2.** (A) RAQMS ozone distribution (colors) and mean winds (arrows) on the 310K
12 isentropic surface (~2 to 4 km ASL) at 1200 UT on May 2, 2013. The white contours show the
13 Montgomery stream functions ($\times 10^3 \text{ m}^2 \text{ s}^{-2}$) for the geostrophic wind. The filled circle marks the
14 location of the San Diego (NKX) radiosonde station. The vertical dashed line corresponds to (B),
15 Latitude-height transect of the RAQMS O₃ (colors) and T_d (black contours) through Simi Valley,
16 CA at 119°W. The white contours show the isentropes with the dashed curve extending across
17 (B) indicating the 310K surface. The dashed circle encloses an area of dry, ozone-rich air above
18 Ventura County, CA and the vertical dashed line shows the location of the 1200 UT NKX
19 sounding plotted in panel (C).

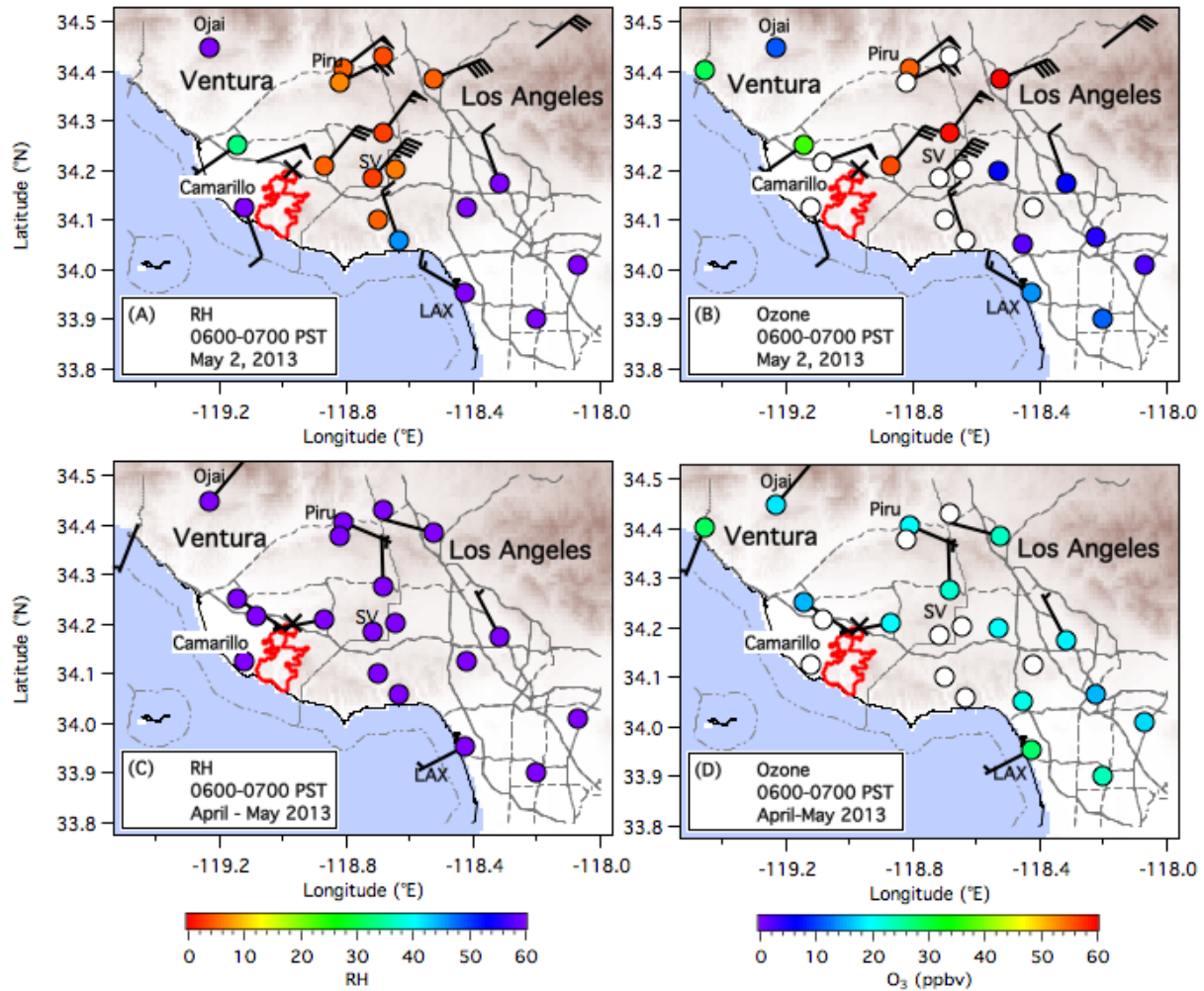
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1 **Figure 3.** Time series of (A) relative humidity (RH) and O₃, (B) NO_x and PM_{2.5}, and (C) wind
2 speed and direction measured at the Simi Valley-Cochran Street monitoring station (34.28°N, -
3 118.68°E, 316 m ASL) before and during the Springs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

5
6 **Figure 4.** National Centers for Environmental Prediction (NCEP) Reanalysis [*Kalnay et al.*,
7 1996] 500 hPa geopotential heights for 12UT on (a) May 2, 2013 and (b) October 22, 2007 from
8 the NOAA ESRL Physical Sciences Division. Daily mean total column O₃ for (c) May 2, 2013
9 and (d) October 22, 2007 from the NASA Ozone Monitoring Instrument (OMI) aboard the Aura
10 satellite showing stratospheric intrusions. The lower total column ozone in (d) compared to (c)
11 reflect normal fall-spring differences.

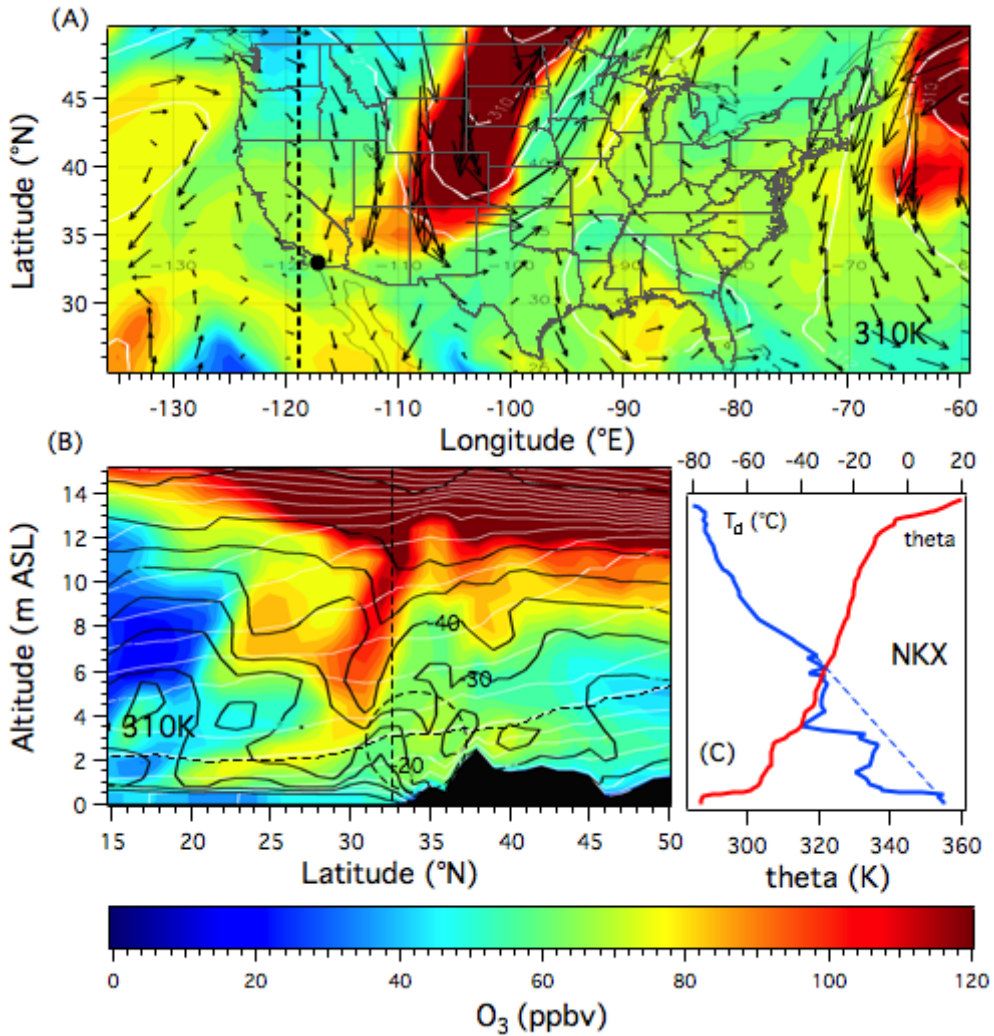
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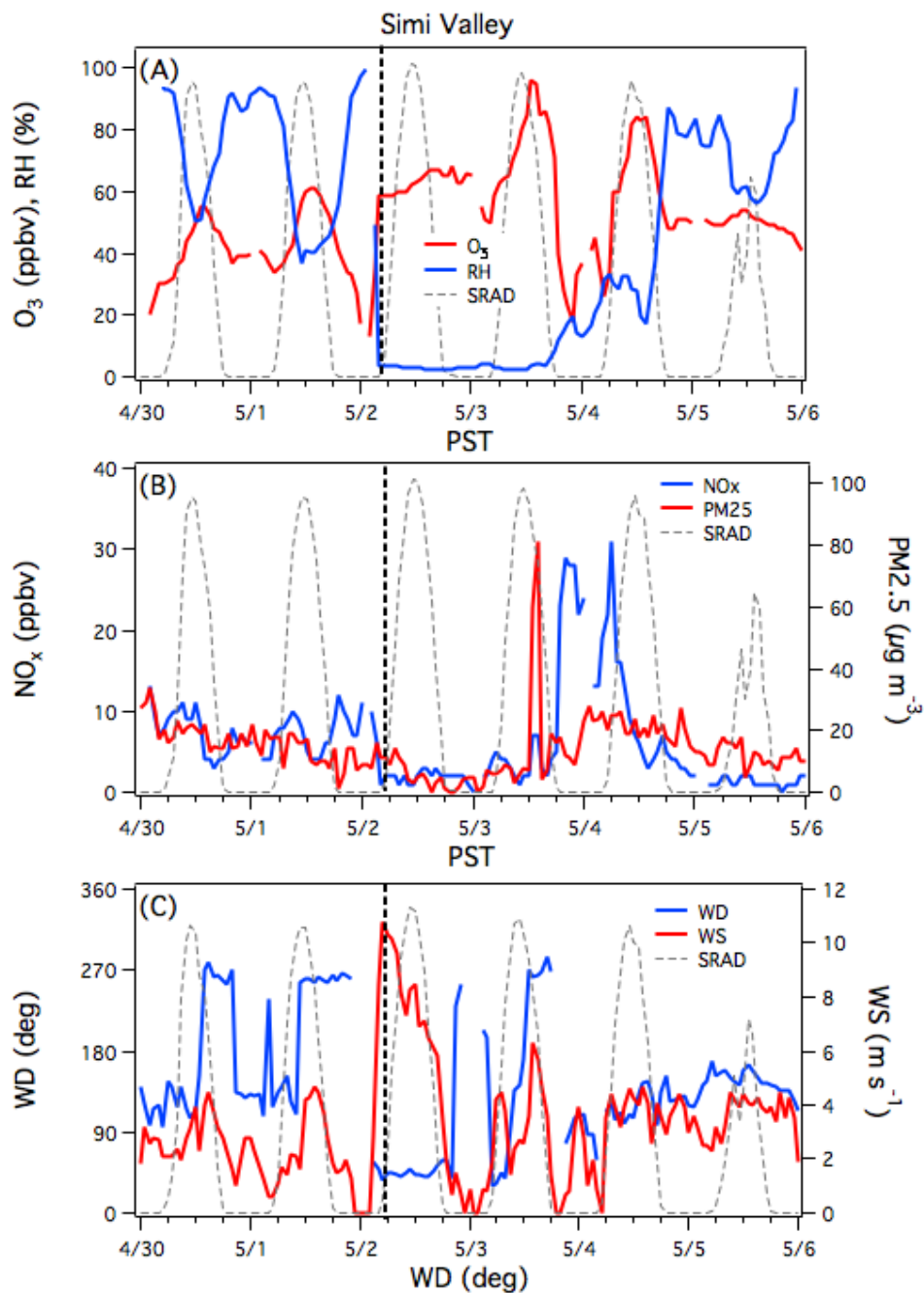
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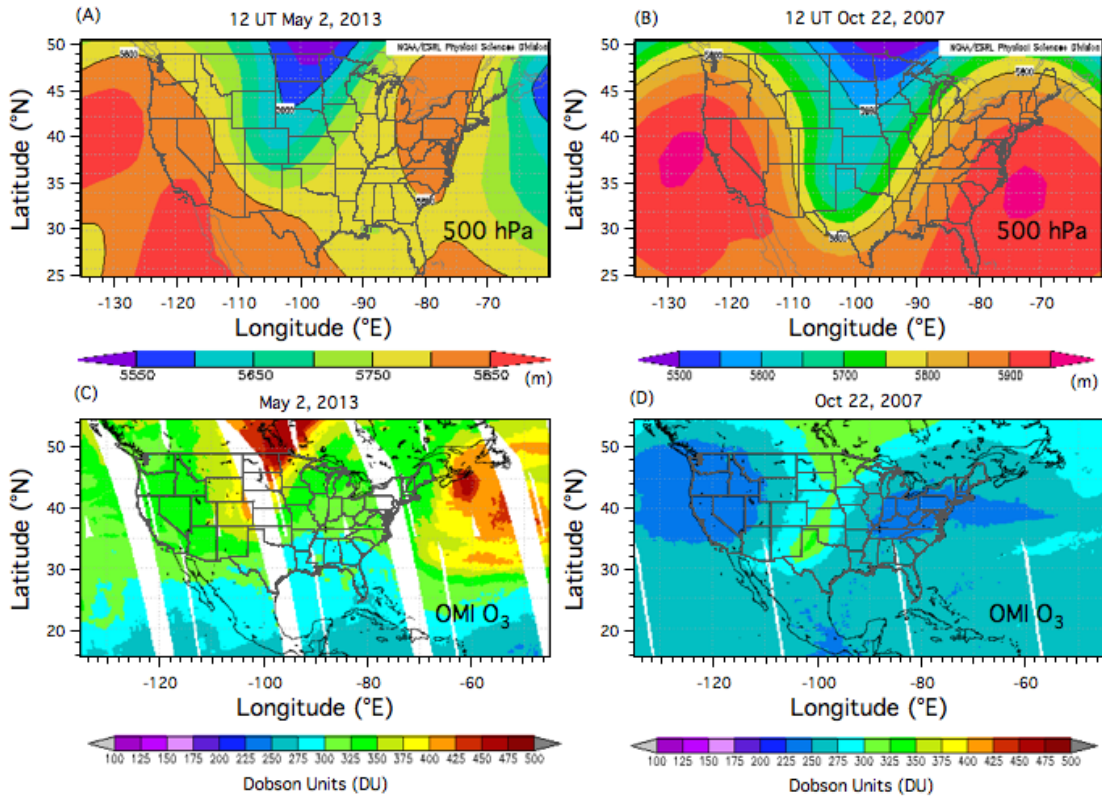


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 2 **Figure 2.** (A) RAQMS ozone distribution (colors) and mean winds (arrows) on the 310K
 3 isentropic surface (~2 to 4 km ASL) at 1200 UT on May 2, 2013. The white contours show the
 4 Montgomery stream functions ($\times 10^3 \text{ m}^2 \text{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



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 2 **Figure 3.** Time series of (A) relative humidity (RH) and O₃, (B) NO_x and PM_{2.5}, and (C) wind
 3 speed and direction measured at the Simi Valley-Cochran Street monitoring station (34.28°N, -
 4 118.68°E, 316 m ASL) before and during the Springs Fire. The dashed gray traces represent the
 5 normalized solar radiation. The vertical black dashed line shows the start of the Springs fire.

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