Research Final Report

A Characterization of California Ozone Baseline using Ozonesonde Measurements at Two Coastal Sites

Contract #15RD007

Principal Investigator:

Sen Chiao
Professor

Department of Meteorology and Climate Science

San José State University

San Jose, CA

Email: sen.chiao@sjsu.edu

Phone: 408-924-5204

Prepared for:

State of California Air Resources Board and the

California Environmental Protection Agency

PO Box 2815

Sacramento CA 95812

April 7, 2019

Disclaimer

The statements and conclusions in this Report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Acknowledgement

We acknowledge the suppliers of datasets utilized in this research. We appreciate Drs. Irina Petropavlovskikh and Bryan Johnson and Mr. Patrick Cullis at NOAA GMD for providing ozonesonde training. This Report was submitted in fulfillment of ARB Contract #15RD007, Improved Understanding of the Magnitude of Trans-Pacific Long Range Transported Ozone Aloft at California's Coast, by San Jose State University under the sponsorship of the California Air Resources Board. Work was completed as of December 2018.

Table of Contents

List of Figures

Figure 14. (a) North San Francisco Bay Area domain on the left and Sacramento Valley domain on the right. Modeled averages over these domains were used for comparison. The elevation and location of the sites are shown in (b). The unnamed stations in (a) along with Placerville are shown in (b) as well.

Figure 15. Potential vorticity of the 21 UTC MERRA-2 reanalysis data over the northeastern Pacific Ocean for (a) July 26th, 2016 at 11 km, (b) July 27th ,2016 at 11 km, (c) July 26th, 2016 at 8 km, and (d) July 27th, 2016 at 8 km. The black line represents a potential vorticity of 1.5 PVU.

Figure 16. Potential vorticity of the 21 UTC MERRA-2 reanalysis data over the northeastern Pacific Ocean for (a) August 4th, 2016 at 11 km, (b) August 5th, 2016 at 11 km, (c) August 4th, 2016 at 8 km, and (d) August 5th, 2016 at 8 km. The black line represents a potential vorticity of 1.5 PVU.

Figure 17. Potential vorticity of the 21 UTC MERRA-2 reanalysis data over the northeastern Pacific Ocean for (a) August 8th, 2016 at 11 km, (b) August 9th, 2016 at 11 km, (c) August 8th, 2016 at 8 km, and (d) August 9th, 2016 at 8 km. The black line represents a potential vorticity of 1.5 PVU.

Figure 18. GFS analysis of 250 hPa winds valid (a) 00 UTC 28 July, (b) 18UTC 5 August, and (c) 18UTC 9 August 2016 over the northeastern Pacific Ocean.

Figure 19. July 25th through August 13th averaged MERRA-2 relative humidity (%) for (a) BBY and (b) SAC and averaged MERRA-2 specific humidity (g/kg) for (c) BBY (d) SAC. The black contour lines in (a-b) represent 10% relative humidity. The black contour line in (c-d) represents a specific humidity of 0.15 g/kg.

Figure 20. July 25th through August 13th, 2016 averaged MERRA-2 potential vorticity for (a) BBY and (b) SAC and averaged MERRA-2 ozone mixing ratio for (c) BBY (d) SAC. The black contour lines in (a-b) represent 1.0 and 1.5 PVU respectively. The black contour line in (c-d) represents 70 ppb.

Figure 21. Calculated percentage change in observed daily ozone along the BBY ozonesonde vertical profile from one day to the next from July 26th to August 14th 2016.

Figure 22. Box plot for the calculated Maximum daily 8-hour Average ozone at BBY at the 12 m a.s.l. near the surface from July 25th to Aug 17th 2016. The local hours are from 0 through 23. The orange bar is the daily mean.

Figure 23a. Calculated surface maximum of all daily 8-hr average (MDA8) O3 concentration box plots from July 25th to Aug 17th 2016 for the SAC low elevation surface sites. The orange bar is the mean value.

Figure 23b. Calculated surface MDA8 O_3 concentration box plots from July 25th to August 17th 2016 for the SAC mid elevation surface sites. The orange bar is the mean value.

List of Tables

LIST OF ABBREVIATIONS

BAAQMD	Bay Area Air Quality Management District
BBY	Bodega Bay
CABOTS	California Baseline Ozone Transport Study
ECC	electrochemical concentration cell
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
ESRL	Earth System Research Laboratory
GFS	Global Forecast System
GHG	Greenhouse Gases
HMB	Half Moon Bay, California
HTAP	Hemispheric Transport of Air Pollution
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
LT	Low Tropopause
MDA8	Maximum Daily 8-hour Average
MERRA-2	Modern-Era Retrospective analysis for Research and Applications version 2
MOZART-4	Model for O_3 and Related Chemical Tracers, Version 4
NAAQS	National Ambient Air Quality Standard
NASA	National Aeronautics and Space Administration
NSV	Northern Sacramento Valley
NOAA	National Oceanic and Atmospheric Administration
NCAR	National Center for Atmospheric Research
PacNW	Pacific North West
PV	Potential Vorticity
QBO	Quasi-Biennial Oscillation
SAC	Greater Sacramento Area, California
SI	Stratospheric intrusions
RH	Relative Humidity
SH	Specific Humidity
SJSU	San Jose State University
SJV	San Joaquin Valley
THD	Trinidad Head, California
TOPAZ	Tunable Optical Profiler for Aerosol and oZone
UTLS	Upper Troposphere Lower Stratosphere

Abstract

San José State University launched near-daily ozonesondes from May through August 2016 at two coastal California sites as part of the 2016 California Baseline Ozone Transport Study (CABOTS). Data collected from these ozonesondes provide a fine-scale vertical distribution of ozone (O_3) concentrations in the troposphere. In this report, we summarize these measurements and use them with reanalysis data from Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), to identify stratospheric intrusion (SI) events and understand how these affected ozone concentrations in the troposphere and at surface sites in the Sacramento Valley and foothills of the Sierra Nevada. Results from this project show that the median of mid-tropospheric ozone concentration during CABOTS was 62 ppb. Our analyses indicate that SI events occurred as late as August 9th and that there was a positive correlation between increased ozone concentrations in the Bodega Bay ozone profile and ground level concentrations in the foothills of the Sierra Nevada. Analyses for Bodega Bay and Half Moon Bay also suggest that California baseline ozone toward the end of CABOTS was possibly influenced by wildfire emissions from the Soberanes Fire and Cold Fires.

Executive Summary

The goal of this research was to collect vertical profiles of tropospheric ozone concentrations during the 2016 California Baseline Ozone Transport Study (CABOTS) from late May through August at two coastal California sites - a main site in Bodega Bay, California (BBY) and the other in Half Moon Bay, California (HMB) - for the purpose of improving the characterization of baseline ozone. This data will also provide constraints for global chemistry models that calculate background ozone concentrations for California. Data analysis involved studying the evolution of ozone profiles and comparing them with global ozone models and with NOAA's Trinidad Head (THD) ozonesonde measurements. The analyses also included diagnosing stratospheric intrusion events from BBY ozone profiles and characterizing the impact of these on surface ozone sites in the Sacramento Valley and higher elevation sites in the Sierra Nevada Foothills.

The ozonesondes from BBY show a very complex pattern of tropospheric ozone profiles during late Spring and Summer for coastal California. Approximately 20% of the BBY ozonesondes included some form of SI within the profile, with most of the 19 SI events occurring during May and June. In particular, BBY was about 15 ppb higher than THD's average at 3-km level in June. BBY measured 10 ppb above THD's average in the lower troposphere in August. It is noteworthy that the MOZART-4 global chemistry model's 21-h forecasts for BBY underestimated tropospheric ozone throughout the background troposphere but overestimated ozone within the marine boundary layer.

Backward trajectories from NOAA's HYSPLIT model suggest that the very high ozone observations on July 27^{th} in the HMB ozonesonde (136 ppb) and the BBY ozonesonde (121 ppb) near 2 km were influenced by the 2016 Soberanes Fire in Monterey County. Also, BBY data with MERRA-2 reanalysis showed that from July 25^{th} – August 13^{th} three SI events occurred. The SI event that occurred on August 9^{th} caused some high elevation Sierra Nevada surface stations' MDA8 values to be about 10-20 ppb higher than normal. During this event, ozone concentrations at BBY at 0.6-1 km and at the high elevation site of Placerville, CA were positively correlated (0.61), which indicates ground level influence of the SI event.

The 2016 CABOTS ozonesonde measurements show evidence of a very complex and varying tropospheric profile. Median ozone concentration in the mid-troposphere during CABOTS was 62 ppb, which is close to the NAAQS of 70 ppb for 8-h ozone. The daily ozone profiles will give air quality modelers more confidence in the baseline ozone values to help improve ozone forecast models and update estimates of background ozone. SI events coming in from the Pacific Ocean occurred well into August and the SI events in August have shown evidence to affect surface ozone at the high elevation sites. The lower elevation sites showed little-to-no discernable increase in ozone during the late SI events in August. This study also captured the impact of the Soberanes and Cold Fires on BBY and HMB ozone profiles and would make an important case year for the study of the effects of wildfire smoke emissions on ozone production in California.

1. Introduction

Baseline ozone (O_3) is defined by the Task Force on Hemispheric Transport of Air Pollution (HTAP) as O_3 that is produced in the troposphere and is uninfluenced by local anthropogenic activity (Task Force on Hemispheric Transport of Air Pollution 2010). In 2015, the Environmental Protection Agency (EPA) lowered the 8-hour National Ambient Air Quality Standard (NAAQS) for O_3 from 75 ppb to 70 ppb (EPA 2015). As a result, measuring and understanding baseline O_3 concentrations is important for policy development and future planning.

Studies have shown increases in O_3 concentrations at western sites in North America may be influenced by the transport of air masses off of the Pacific Ocean (Parrish et. al. 2009; Cooper et. al. 2010; Cooper et. al. 2011). Long-term NOAA ozonesonde measurements have been collected at Trinidad Head, CA (THD) beginning in 1997 (Jaffe and Ray, 2007) and have been used to study baseline O_3. These datasets also helped identify the source of higher O_3 concentrations as likely originating from transport across the Pacific Ocean (Goldstein et. al., 2004). Ozonesonde data have also allowed the study of stratospheric intrusion events and their impacts on tropospheric O_3 concentrations, as well as the meteorological characteristics associated with them (Lin et. al. 2012).

Stratospheric intrusions (SI), or events when stratospheric air is transported down into the troposphere, transport O_3-rich stratospheric air to the lower troposphere, intermittently enhancing O_3 concentrations in the lower troposphere (e.g., Cooper et al., 2001; Stohl et al., 2003; Lin et al., 2012; Lin et al. 2015). Stratospheric intrusions are a common occurrence in California and the Western U.S. and have been shown to enhance surface ozone and account for about 13% of surface ozone variability (Lin et al., 2012). The deep descent of stratospheric air in an SI has been defined as that which crosses the dynamical tropopause and travels to 700 hPa pressure level within 5 days (Bourqui and Trépanier, 2010). Because the photochemical lifetime of O_3 is about 22 days in the free-troposphere and the non-conservative processes known to transport stratospheric air to the troposphere are on the order of a few days, stratospheric O_3 can significantly influence the background O_3 and the surface O_3 concentration. Nevertheless, the challenge is to identify and quantify the influence of stratospheric O_3 and to what extent it intrudes into the troposphere to influence surface O_3 pollution above the NAAQS for O_3 (e.g., Ding and Wang, 2006; Hsu and Prather, 2009; Langford et al., 2009).

From an air quality regulation and health perspective, it is necessary to understand to what extent SIs affect baseline O_3 across the Western U.S. before entering California as well as understanding long-term climate trends in baseline O_3. In regard to assessing the baseline O_3 trends an increased temporal scale for ozonesondes is necessary to deduce any significant trends in O_3 (Cooper et. al. 2010). Therefore, the California Baseline Ozone Transport Study (CABOTS) was conducted between May and August 2016 in California, consisting of measurements from coastal ozonesondes, ground-based O_3 lidar, aircraft, and high-elevation ground stations.

CABOTS was truly a ground-breaking air-quality field campaign for California. San José State University (SJSU) launched near-daily ozonesondes, the National Oceanic Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) deployed an O_3 lidar in the San Joaquin Valley for two intensive operating periods, aircraft measurements across the Central Valley were collected with CARB's Aircraft Pilot Observation Program, University of California Davis also collected airborne O_3 across the Central Valley and maintained a high-elevation coastal air quality monitoring laboratory , and NASA Ames flew a greenhouse gas (GHG) collection research aircraft during multiple days. The goal of CABOTS was to investigate how

O_3 gets transported and produced from the troposphere and the specific physical, chemical, and dynamical ways through which it affects inland surface sites across the state, especially the San Joaquin Valley, which is consistently in non-attainment for the 8-hr O_3 NAAQS.

SJSU's role during CABOTS was to release near-daily (approximately 6 per week) ozonesondes at the coastal location of Bodega Bay, California (BBY), as shown in Fig. 1, to measure vertical profiles of tropospheric baseline O_3 during the high surface O_3 season for California for the entire duration of CABOTS. BBY was chosen, instead of THD, as the main ozonesonde location for CABOTS because of three main reasons. First, it has an onshore northwesterly prevailing wind pattern upwind and away from the very urban San Francisco Bay Area. Second, it is located close to the San Francisco Bay area and captures 'clean' marine air uninfluenced by anthropogenic sources before it flows inland into the Central Valley via the San Francisco Bay and the Carquinez Strait. Lastly, it is in a location that has onshore upper level winds aloft during the peak O_3 seasons of spring and summer, thus providing the best 'clean' air source for baseline O_3 measurements before the air is transported over the coastal range and into the Central Valley. Additional funding from the BAAQMD and the EPA toward the middle of the campaign allowed for a second ozonesonde release location in Half Moon Bay, CA (HMB) (Fig. 1). Half Moon Bay is also in the coastal marine environment west of the San Francisco Bay Area and approximately 60 miles south-southeast of BBY and is separated from the Bay Area geographically by the Coastal Range and the mountainous Santa Cruz Mountains and San Francisco Peninsula. This second site provided information about finer scale spatial variation of ozone layers.

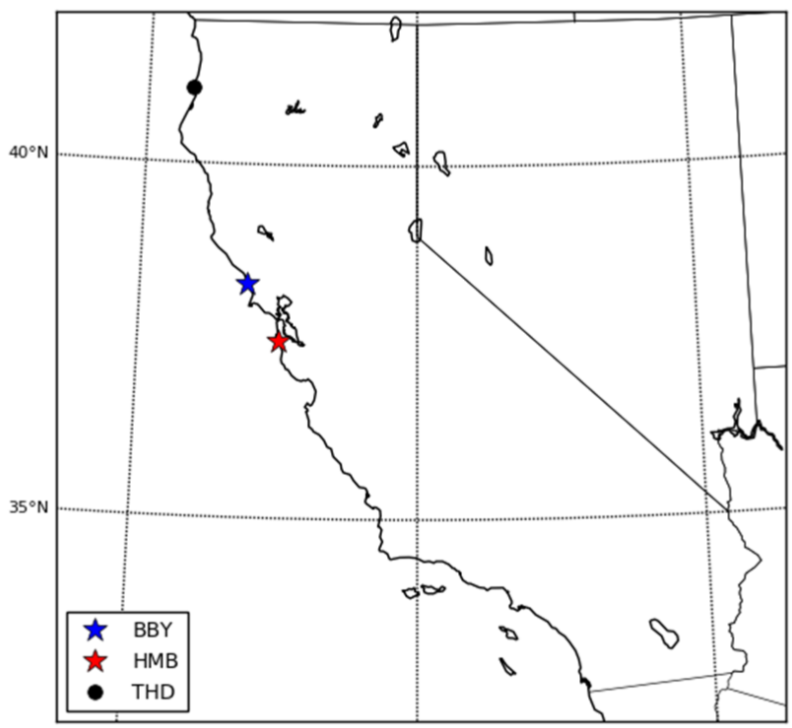

Figure 1. Map of the ozonesonde release locations Bodega Bay, CA (BBY) and Half Moon Bay, CA (HMB) during CABOTS. Trinidad Head, CA (THD) is the routine NOAA ozonesonde release location.

2. Materials and Methods

This project utilized the model 2ZV7 O_3 Sounding System from Droplet Measurement Technologies. An Inter-Met radiosonde of Model iMet-1-RSB and Model 2ZV7 electrochemical concentration cell (ECC) ozonesonde were launched with a 403 MHz Yagi antenna on the ground connected to a 403 MHz receiver to retrieve the incoming data. GRAW DFM-09 radiosondes with electrochemical concentration cell (ECC) were utilized for this project. ECC-Ozonesondes typically have an O_3 uncertainty of ± 10%. 300-g Totex radiosonde balloons were used to reach a target balloon popping height of 20-25 km within the Stratosphere to ensure a full coverage of the troposphere.

Preparation of the ozonesonde was completed with an EN-SCI Corporation Model KTU-2 ozonizer. Initial preparation of the ozonesonde typically occurred 5-7 days in advance. A typical day-of ozonesonde release preparation was also conducted the morning of the launch to ensure the ozonesonde was functioning properly and up to scientific standards.

Data from the ozonesondes was collected using SkySonde, which is a meteorological sonde release software package developed by Allen Jordan from NOAA. SkySonde tracks the balloon in real time and provides a map of the flight path during and after the experiment. A field laptop is connected to the radiosonde receiver through a modem and allows data collection on the SkySonde server.

The specific coordinate locations of BBY and HMB were (38.32, -123.07) and (37.5052 -122.48306), respectively. The target release time for the ozonesondes at each location were 2:00 local time or 2100 UTC. This time was decided as the best ozonesonde release time to capture as much photochemically produced O_3 above the marine boundary layer and in the troposphere as possible. An ozonesonde ascent rate of 3-5 m/s was our goal to obtain a higher vertical resolution of the measurements. Most ozonesondes were within this ascent rate range. A total of 86 ozonesondes were released at BBY, and a total of 24 ozonesondes were released at HMB.

3. Results

A. Ozonesonde Observations

The upper air O_3 measurements from the near-daily BBY ozonesondes show very complex spatial and temporal tropospheric O_3 variability from the surface to the upper troposphere and lower stratosphere (UTLS) throughout the entire CABOTS time period (Fig. 2). During the first half of the study, in late spring and early summer, there were two general time periods of strong upper level influence on the observations. The time periods of May 16th to May 24th and from June 9th to June 18th show much higher O_3 mixing ratio layers reaching down from the UTLS into the middle troposphere near 3 km. From May 27th to June 2nd, O_3 mixing ratios just above the surface in BBY were on some days 15 to 20 ppb higher than normal with respect to the rest of the summer season at that level.

The second half of CABOTS also experienced many other interesting features based on the curtain plots in Figs. 2 and 3. The middle-troposphere (4-7 km) experienced a period of higher O_3 from June 30th to July 10th without very high UTLS O_3 values present above 8 km. From July 23rd to August 9th, the mid-to-upper troposphere observed higher O_3 anomalies with elevated O_3 mixing ratio values between 80 and 120 ppb extending down near 5 km. Figure 3b shows a lowered troposphere near 300 hPa above this layer, suggesting strong upper level influence but only after August 2nd. Two other notable periods during the second half of CABOTS were the high O_3 layers in the low troposphere on July 27th and August. 3rd. Results show possible influence from the California's 2016 Soberanes Fire and 2016 Cold Fire, and wild fire smoke emissions are a probable cause to seeing enhanced O_3 mixing ratios at BBY and HMB during these dates.

This near-daily ozonesonde data provides an opportunity to compare how atmospheric chemistry forecast models may be able to simulate tropospheric O_3. Global atmospheric chemistry forecast transport models often have very coarse resolutions, and they may not be able to describe all the fine details of local emission sources. One example is NCAR's Model for O_3 and Related Chemical Tracers (MOZART), which has a horizontal resolution of approximately 2.8 x 2.8 degrees (Emmons et al. 2010).

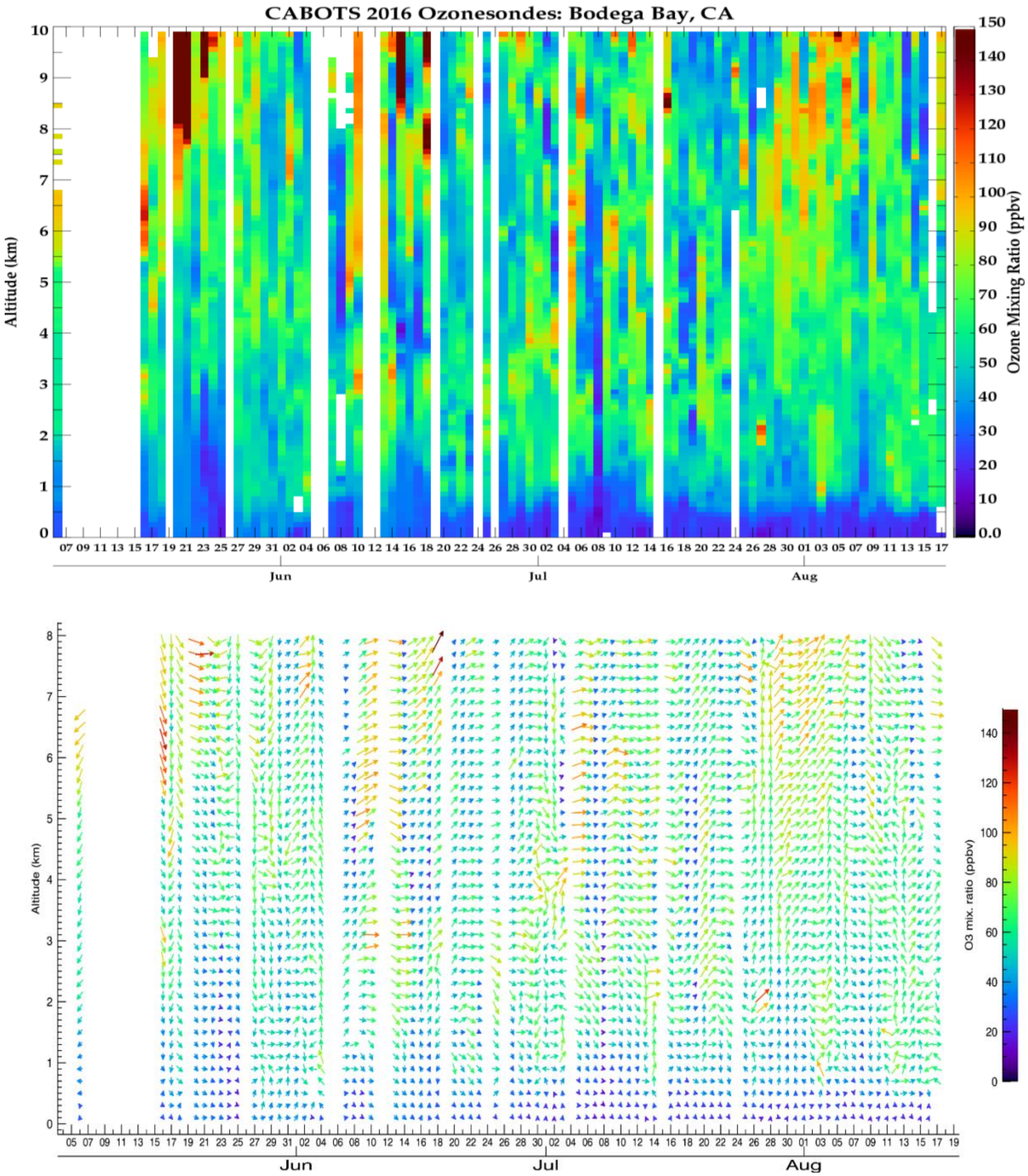

Figure 2. (a) Vertical ozone measurement curtain plot in mixing ratio (ppb) from Bodega Bay, California from May 6th through August 17th. (b) Ozone wind vectors during CABOTS from the Bodega Bay ozonesondes. The color of the wind vector represents the observed ozone mixing ratio (ppb) and the length of the vector indicated the relative strength of the winds in ms^{-1} . The altitude unit is kilometers above sea level.

As shown in Figure 3, the MOZART-4's 24-h O_3 forecast product was analyzed during CABOTS from June through August. The data for May was unavailable. The MOZART forecast was interpolated in time and space to BBY during the time of each launch, making most profiles roughly a 21-h forecast. The MOZART model is not able to capture most small details and features effectively, and on some days overestimates the O_3 values in the lowest model levels near the surface in the boundary layer.

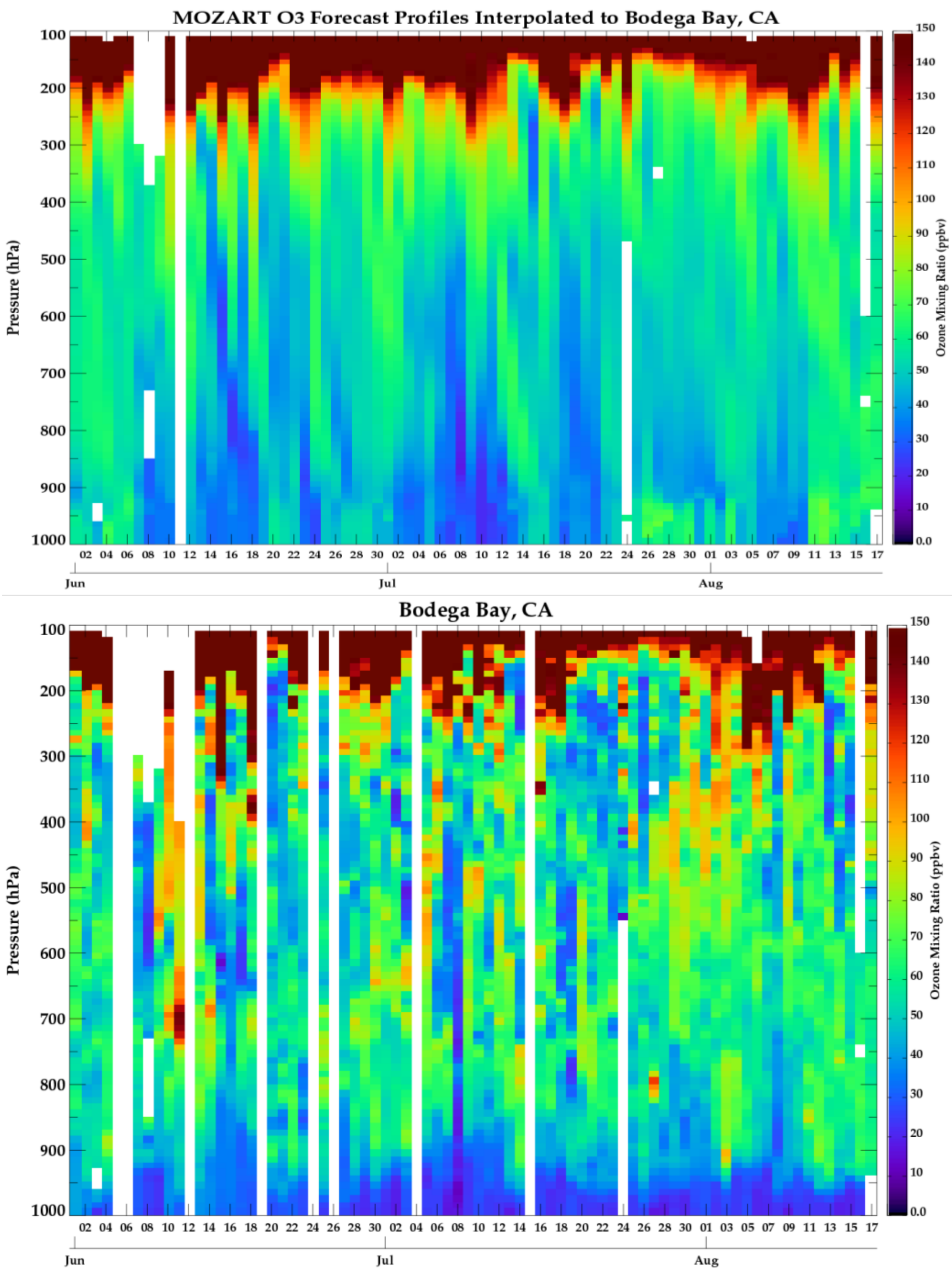

Figure 3. 1-day ozone forecast analysis profiles from the MOZART-4 chemistry model (a) compared with (b) the Bodega Bay ozone profiles during CABOTS**.**

The near-weekly ozonesondes in THD (Fig. 4) show a similar pattern from the BBY ozonesondes with the high O_3 values and the height of the UTLS. However, THD shows a period of higher O_3 during the latter half of June, which is missing in the BBY measurements. This may be a result of weaker springtime upper level troughs not extending farther south toward BBY during this time.

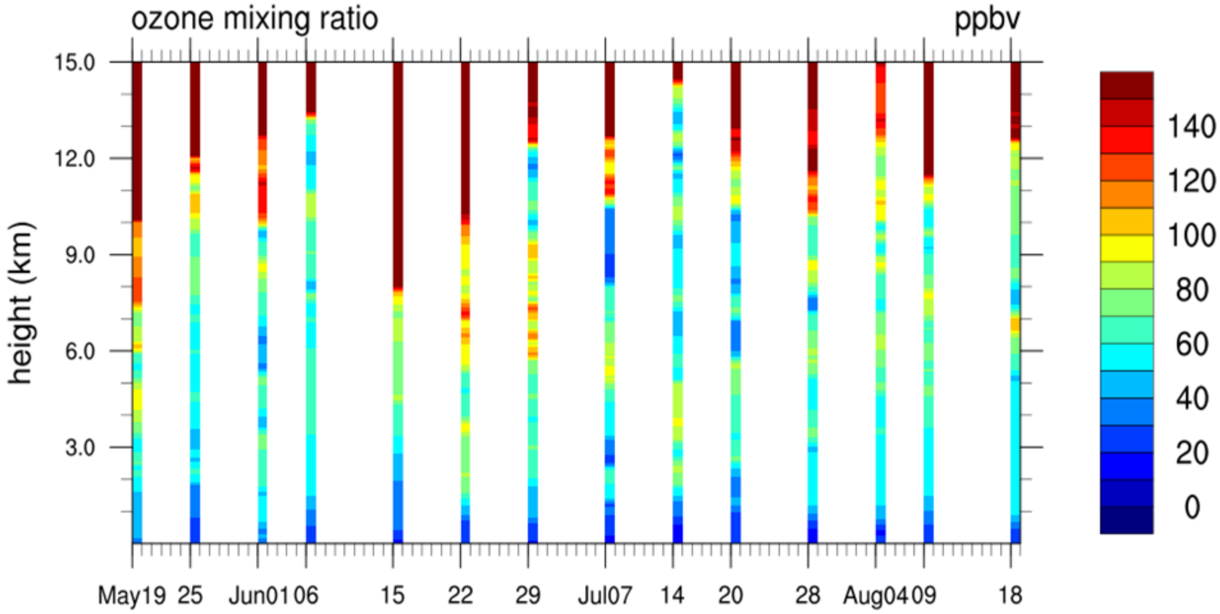

Figure 4. Verical ozone profiles from Trinidad Head, CA during CABOTS 2016.

In addition to ozonesonde measurements at BBY, additional EPA and BAAQMD funding came through toward the end of July and allowed for ozonesondes to be released from HMB (Figs. 1, 5b) for extra coastal O_3 vertical measurements closer to the San Francisco Bay Area. Another coastal measurement site will provide more confidence in BBY's data as well as extra data points for state and local air quality modelers. Figure 5 shows a comparison of BBY and HMB curtain plots of the tropospheric O_3 measurements, and being that they are within 60 mi. of each other, it is no surprise they show generally good agreement with one another. The HMB ozonesonde also picks up on the very high O_3 layer near 2 km on July 27th.

B. Trinidad Head Climatological Comparison

Comparisons were made between the 2016 BBY and HMB tropospheric O_3 data from the CABOTS ozonesondes and with the climatology dataset of tropospheric O_3 along coastal California from THD during the summer time. The tropospheric O_3 percentile distributions of the summer time (JJA) O_3 for both BBY and HMB were plotted against the long-term THD O_3 trend since 1997 in Figure 6. Emphasis was placed on the mid troposphere layer (3-8 km) and above the marine boundary layer, similar to Cooper et al. 2010. Also, the summer measurements in Fig. 6 is shown because most of CABOTS took place during the summer. Results show the interannual variability in tropospheric O_3 since 1997. The average median O_3 values from 1997 to 2016 were approximately 58.4 ppb.

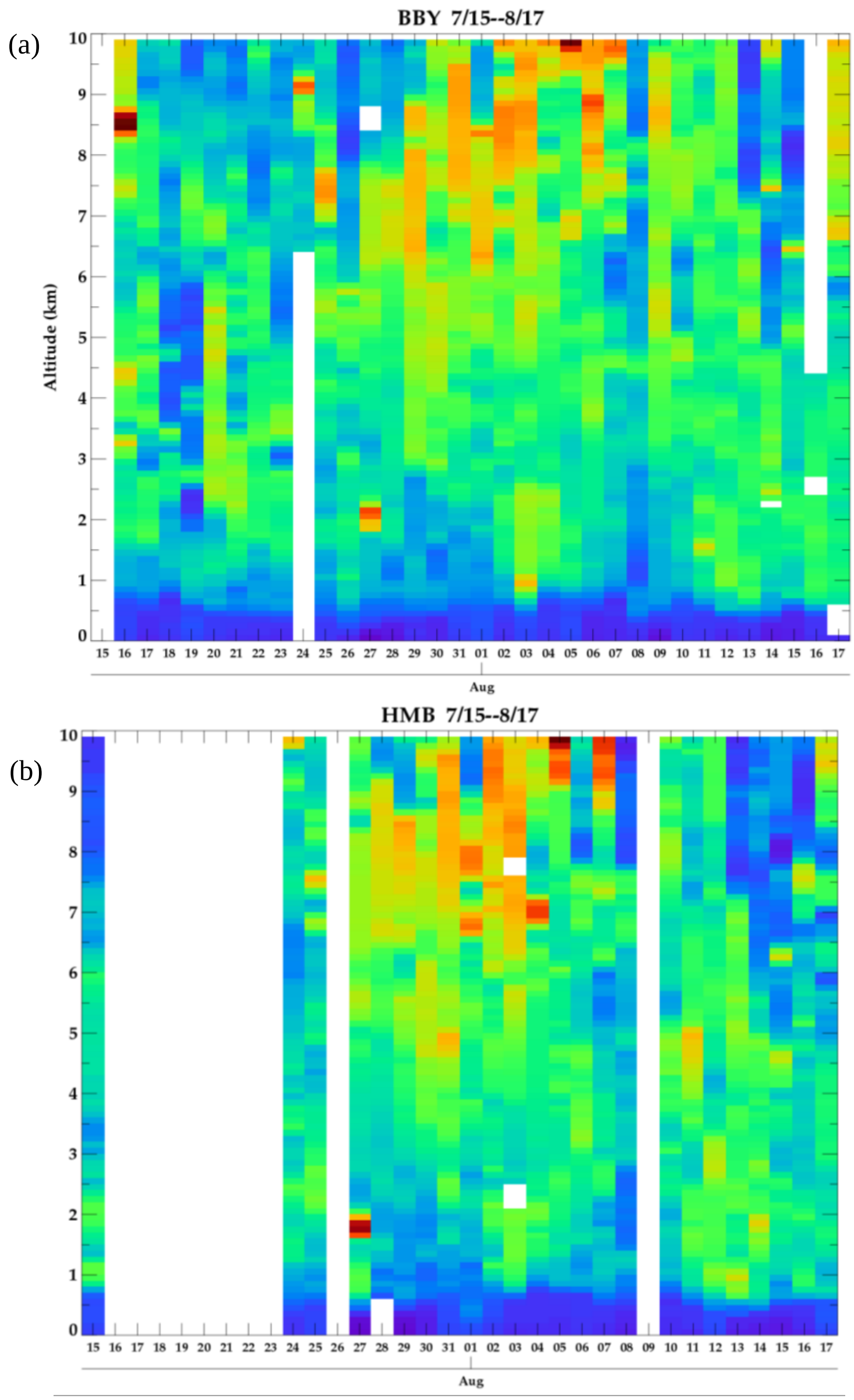

Figure 5. (a) Bodega Bay, CA (BBY) and (b) Half Moon Bay, CA (HMB) vertical ozone measurements (ppb) from the ozonesondes during CABOTS from July 15th to August 17th. The altitude unit is kilometers above sea level.

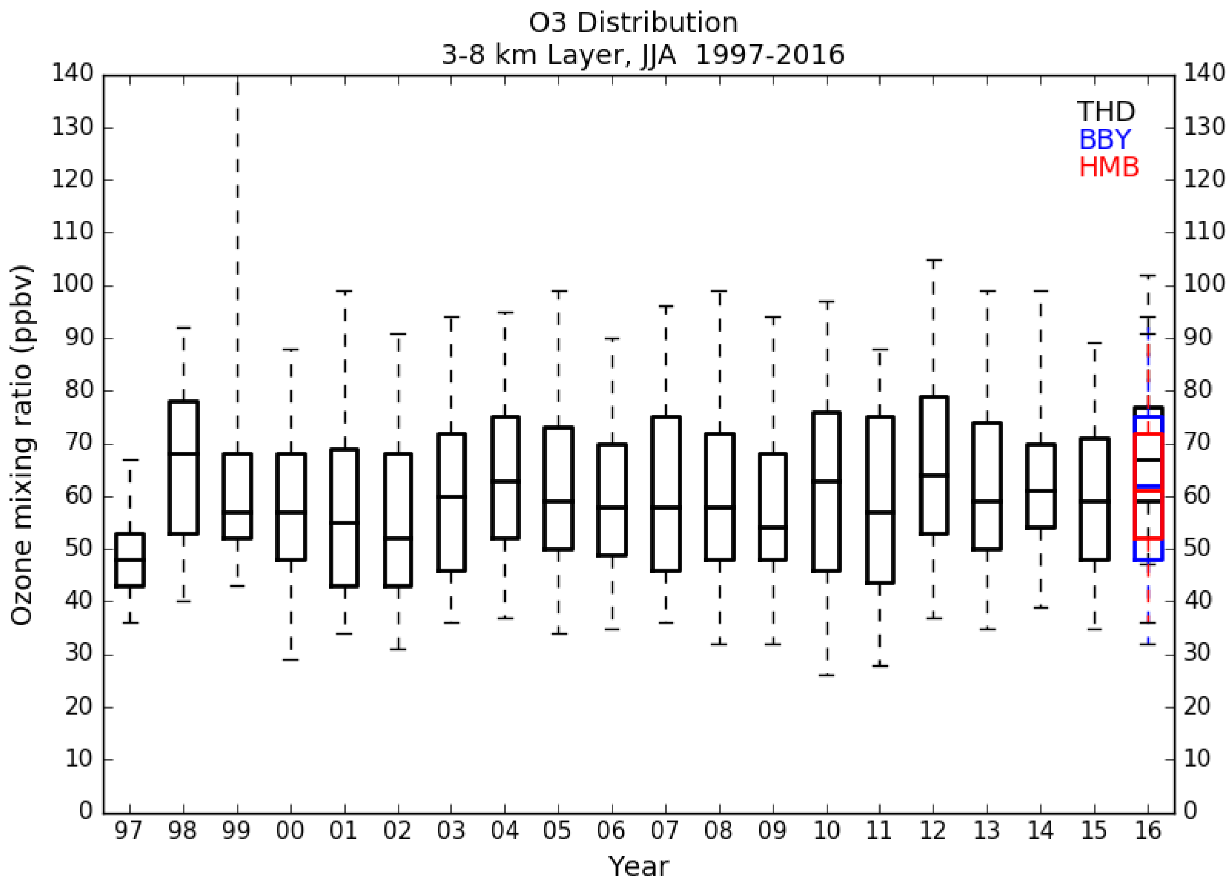

Figure 6. Summer (JJA) ozone mixing ratio percentile distributions (black) from the NOAA Trinidad Head, CA ozonesondes from 1996 to 2016 compared to Bodega Bay, CA (blue) and Half Moon Bay, CA (red) during CABOTS 2016. The bottom and top whiskers represent the 5th and 95th percentiles, respectively; the bottom and top of the box represents the 25th and 75th percentiles, respectively. The line inside the box is the 50th percentile.

In 2016 during CABOTS, THD's 3-8 km median O_3 was approximately 67 ppb (about 9 ppb higher than average). BBY and HMB's 3-8 km median O_3 were approximately 5 ppb lower than THD, and this lower value is expected due to HMB and BBY being further south in latitude. Also, BBY's median was 1 ppb higher than HMB.

CABOTS ozonesonde data also provides data about the latitudinal variation of vertical O_3 during the warm season. Figure 7 shows monthly summer mean O_3 profiles from the surface to 10 km of BBY compared to monthly means from THD. HMB was left out due to lack of data from most of the CABOTS time period. In May, BBY was well below average in the lower troposphere compared to the THD mean. BBY observed above average O_3 mixing ratios in most of the lower troposphere with BBY during August seeing about 10 ppb higher than THD's average near 1 km. BBY in June saw about 15 ppb higher than THD's June average at 3 km, most likely as a result of the high O_3 experienced near 3 km during June 10th-14th.

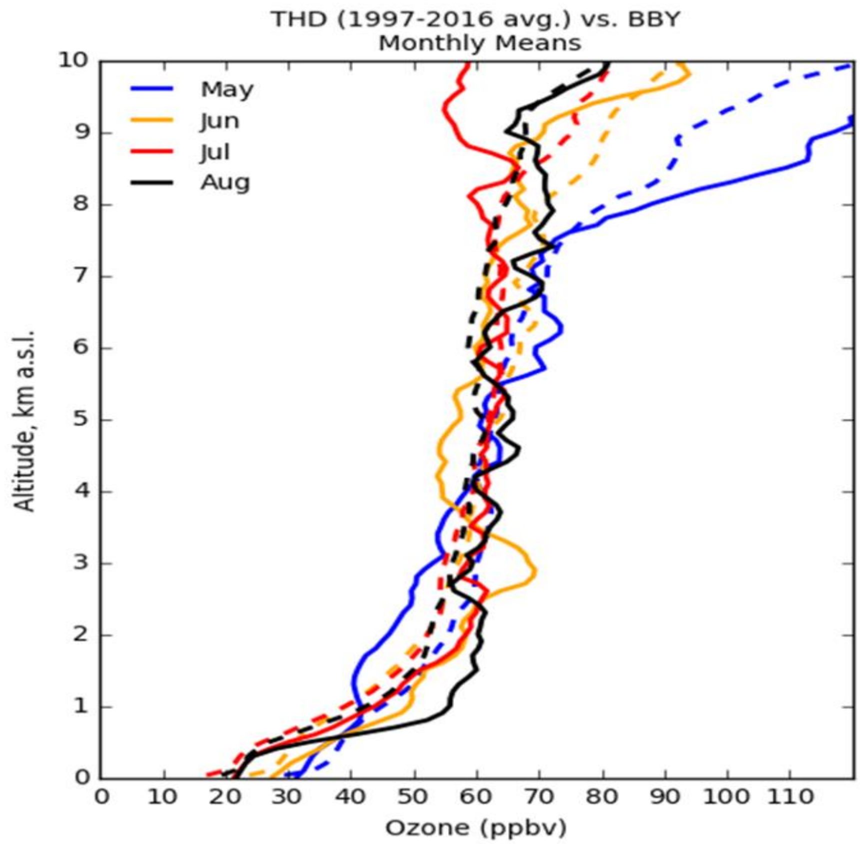

Figure 7. Monthly mean ozone vertical profiles from ozonesonde measurements at Trinidad Head (dashed lines) from 1997-2016 compared against Bodega Bay's (blue) from CABOTS. The ozone profiles are averaged at 100-m height levels.

C. Potential Influence from the 2016 Soberanes Fire and 2016 Cold Fire

The latter half of CABOTS coincided with the Soberanes Fire (July 22nd – October 12th) in Monterey County, California, and the Cold Fire (August 2nd – August 12th) east of BBY in Yolo County. Wildfire smoke emissions can produce O_3 precursors and may enhance O_3 downwind (Jaffe et al. 2012). The Soberanes was one of the largest and costliest fires of the 2016 California wildfire season. The two days during CABOTS that BBY and HMB observed the highest values of O_3 mixing ratio in the lower troposphere were July 27th and August 3rd.

On July 27th, a thin O_3 layer with a maximum mixing ratio of 122 ppb was observed just above 2 km (Fig. 8). The HMB ozonesonde profile data (Fig. 9) shows an even higher O_3 mixing ratio just below 2 km near 136 ppb. Above and below the high O_3 layer from BBY, the background O_3 was between 45 and 50 ppb, and the background O_3 above the high layer in the HMB profile was similar, between 40 and 50 ppb. The air on that day was very warm and dry due to the presence of an upper level ridge in the Desert Southwest. The air was coming from a south-southwesterly direction, and the top of the marine inversion layer was very shallow at 500 m. Backward trajectories from the NOAA HYSPLIT model shows evidence that a portion of the air at the 2 km layer that above HMB and BBY originated from the Monterey County and the Central Coast about 36 hrs prior to arriving. HMB was closer to the Soberanes fire than BBY, and more trajectories from the HMB location seemed to have originated from the Soberanes Fire area on the Central Coast before recurving back toward the San Francisco Bay Area. This may explain why HMB saw higher O_3 mixing ratios than BBY. On August 3rd, BBY observed 102 ppb near 1 km (Fig. 10a). That layer was also extremely dry with very low relative humidity. Some of the Cold Fire smoke may have originated from the east in the vicinity of the Cold Fire based on the NOAA HYSPLIT trajectory models for that day (Fig. 10b).

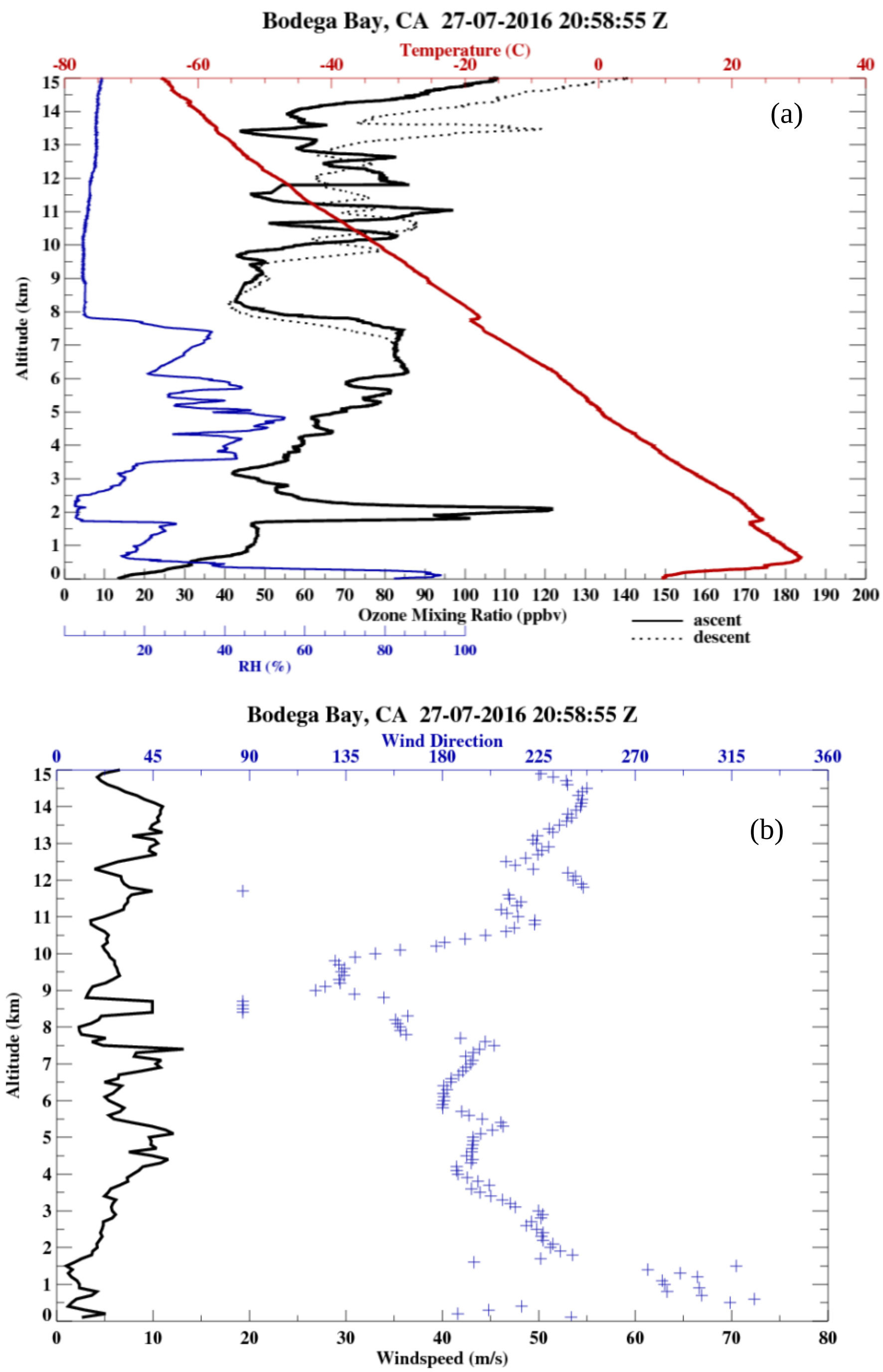

Figure 8. Bodega Bay, CA (a) vertical ozone profile and (b) vertical wind profile from the ozonesondes released on July 27th, 2016.

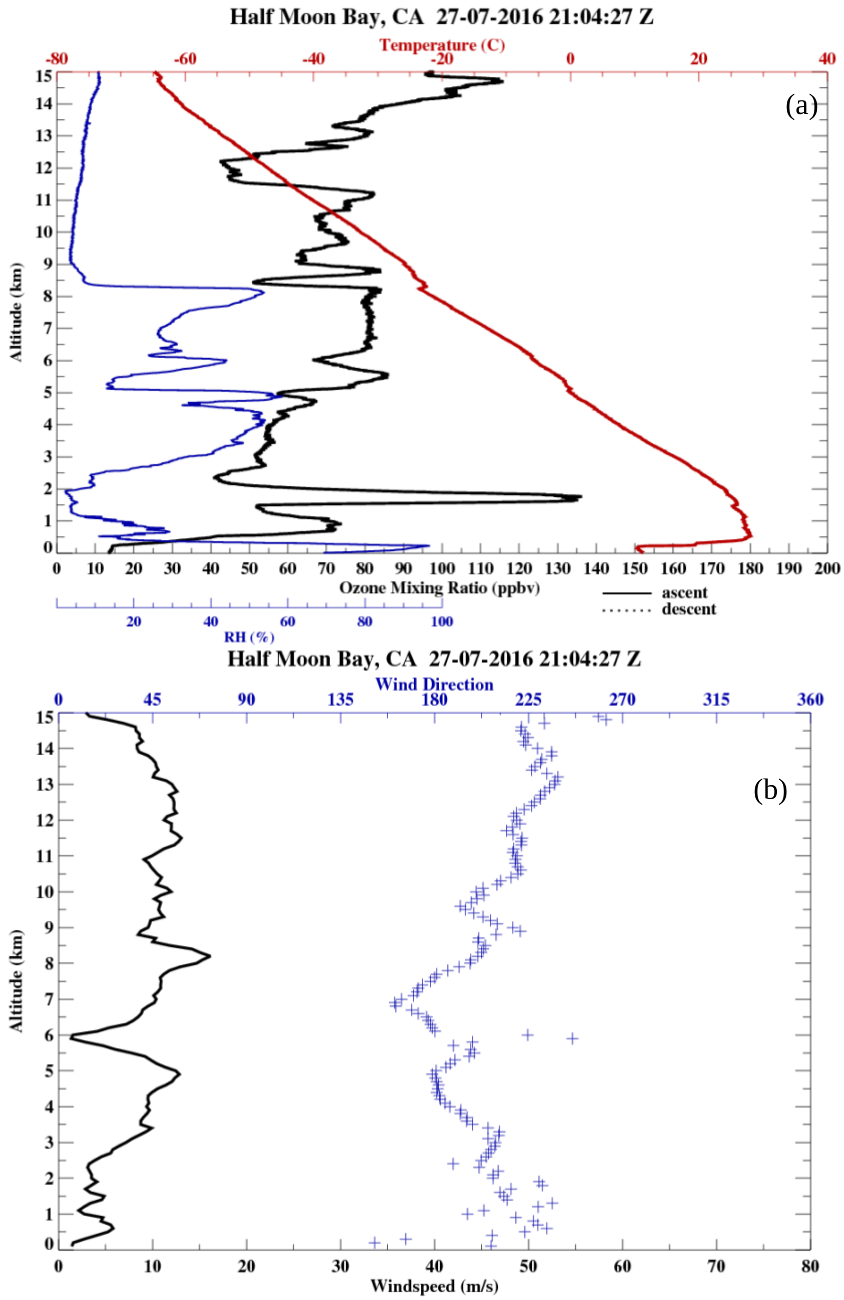

Figure 9. Half Moon Bay, CA (a) vertical ozone profile and (b) vertical wind profile from the ozonesondes released on July 27th, 2016.

D. Cases on Stratospheric Intrusion and Low Tropopause Events

For decades, potential vorticity (PV) and layered structures in O3 profiles, have been used to identify stratospheric air masses (e.g., Danielson et al. 1987; Oltmans et al. 1996; Roelofs et al. 2003; Škerlak et al. 2014). When defining the height of the tropopause, it is well established that the sharp rise in O3 corresponds well with the strong rise in PV (Trickl et al. 2014). Bourqui and Trépanier (2010) further categorized three distinct phases of the intrusion as: the transport of stratospheric air across the tropopause; the free descent with minimal tropospheric mixing; and the quasi-horizontal dispersion into the lower troposphere. Therefore, values of high PV within the troposphere indicate air which is stratospheric in nature, rich in O3, and exhibits very low water vapor content. In this part of research, we analyze O_3 and PV data from the MERRA-2 reanalysis dataset. MERRA-2 model is comprised of 3-hourly 72 hybrid sigma/pressure levels with a resolution of 0.5° latitude x 0.625° longitude. Other supporting variables used from this model include O3, relative humidity (RH), and specific humidity (SH). The utilized data were within the timeframe of July 25 through Aug 13, 2016.

(a)

(b)

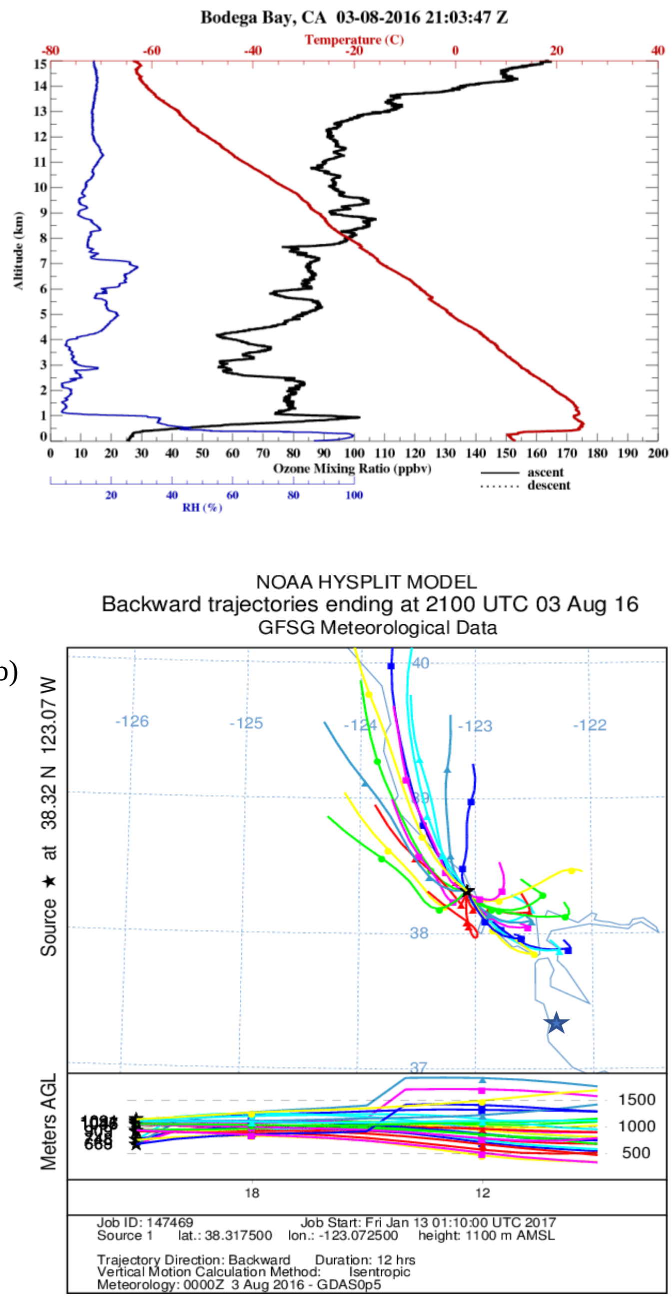

Figure 10. (a) The ozonesonde profile for August 3rd, 2016. (b) NOAA HYSPLIT Model 48-h backward trajectories ending on July 27th, 2016 for Bodega Bay; The blue star indicates the location of the Soberanes Fire.

Part of this analysis investigates the occurrences of SIs into the low-to-mid troposphere and a lowered O_3 tropopause (low tropopause; LT) events specifically at BBY during CABOTS. Bethan et al. 1996 classifies an O_3 tropopause as the lowest altitude to satisfy the following 3 conditions: a vertical O_3 mixing ratio gradient greater than 60 ppb/km., the O_3 mixing ratio has to be greater than 80 ppb, and the O_3 mixing ratio exceeds 110 ppb between 500 and 2000 m above the tropopause altitude. Though the accepted values to define the tropopause range from 1 – 5 PVU, the dynamical tropopause is typically defined where PV = 2 PVU and commonly defined as 1.5 PVU (Lin et al., 2012). This study utilizes a value of 1.5 PVU to define the tropopause, and a value of 1.0 PVU to define a deep intrusion of stratospheric air. Cox et al. (1997) specify the use of 1.0 PVU when tracing deep intrusions into the mid-latitude lower troposphere as the streamer associated with the tropopause fold can be recognized.

Tables 1 and 2 show all the defined SI and LT cases during CABOTS, respectively, along with their synoptic conditions. Most of the SI cases, not surprisingly, associate with deep long-wave upper level troughs or cut-off upper level lows present nearby or directly above. The presence of a deep long-wave trough provides favorable synoptic conditions for the formation of tropopause folds along the jet stream axis injecting stratospheric air into the troposphere, and the dry airstream of a midlatitude cyclone allows for the decent of stratospheric O3 (Lin et al., 2012, 2015). The lowest elevation of an SI intrusion was 3 km on June 18, 2016. There were 19 SI days present (22.10% of the total number of ozonesondes at BBY). There were only 6 LT days (7.14%) (Table 3). Most of the LT events occurred under strong cut-off low pressure areas. Further dissection of two individual days (cases) of an LT and SI were performed: Case 1 is the LT day on May 20th, 2016, and Case 2 is the SI day on June 18th, 2016.

1. *Case 1: Low Tropopause of May 20th 2016*

The BBY vertical O_3 profile on May 20th (Fig. 11a) shows a tropopause height of 8 km. The upper level synoptic pattern at the 300 and 500 hPa levels indicate a deep and broad positively tilted long-wave trough off the entire U.S. West Coast (cf. Figs. 11 b, c). A large swath of the dynamical tropopause is above the west coast at the 300 hPa layer, and there is one pocket of 2PVU and greater just northeast and west of BBY. MERRA-2 W-E cross-section analysis over BBY at 1700 UTC, about 3 hours prior to the ozonesonde release, shows one stronger extension of O_3 mixing ratios (>70 ppb) offshore and one smaller extension of O_3 extending inland (Fig. 11d). The larger tongue of O_3 mixing ratio extending downward and out into the ocean seems to be wrapping down and around the building ridge to the west. MERRA-2 analysis seems to agree reasonably well with the O_3 profile from the BBY ozonesonde. The MERRA-2 cross-sections reveal a pocket of dry air near 700 hPa above BBY that can also be seen in the O_3 profile near the 3-4 km layer. Specific humidity and PV also support the evidence of lower troposphere ozone layer around 3-4 km (figure not shown).

2. *Case 2: Stratospheric Intrusion of June 18th, 2016*

The O_3 profile on June 18th from BBY (Fig. 12) has a tropopause around 12 km and higher layers throughout the troposphere down to the 3 km. The high layer of O_3 of 90 ppb at 3 km has lower relative humidity values (< 3%) than any other layer. On this day at the 300 hPa level a very broad upper level trough, extending quite farther south almost to 20 °N with its axis is in the northeastern Pacific Ocean (Figs. 13a, b). California is dominated by southwesterly flow aloft downstream of the trough axis and to the northwest of an upper level ridge over the Southwest U.S. BBY sits under an area of 2 PVU on the 350 hPa level. There are multiple layers of SI noticeable on BBY's profile: one at 7.5 km, one at 6.5 km, and another at 3 km. For this case, a large area of higher O_3 mixing ratios (>90 ppb) descending past 500 hPa with a tongue of higher PV in the shape of a tropopause fold, also reaching down to 500 hPa in the same areas as the high O_3 (Figs. 13c, d).

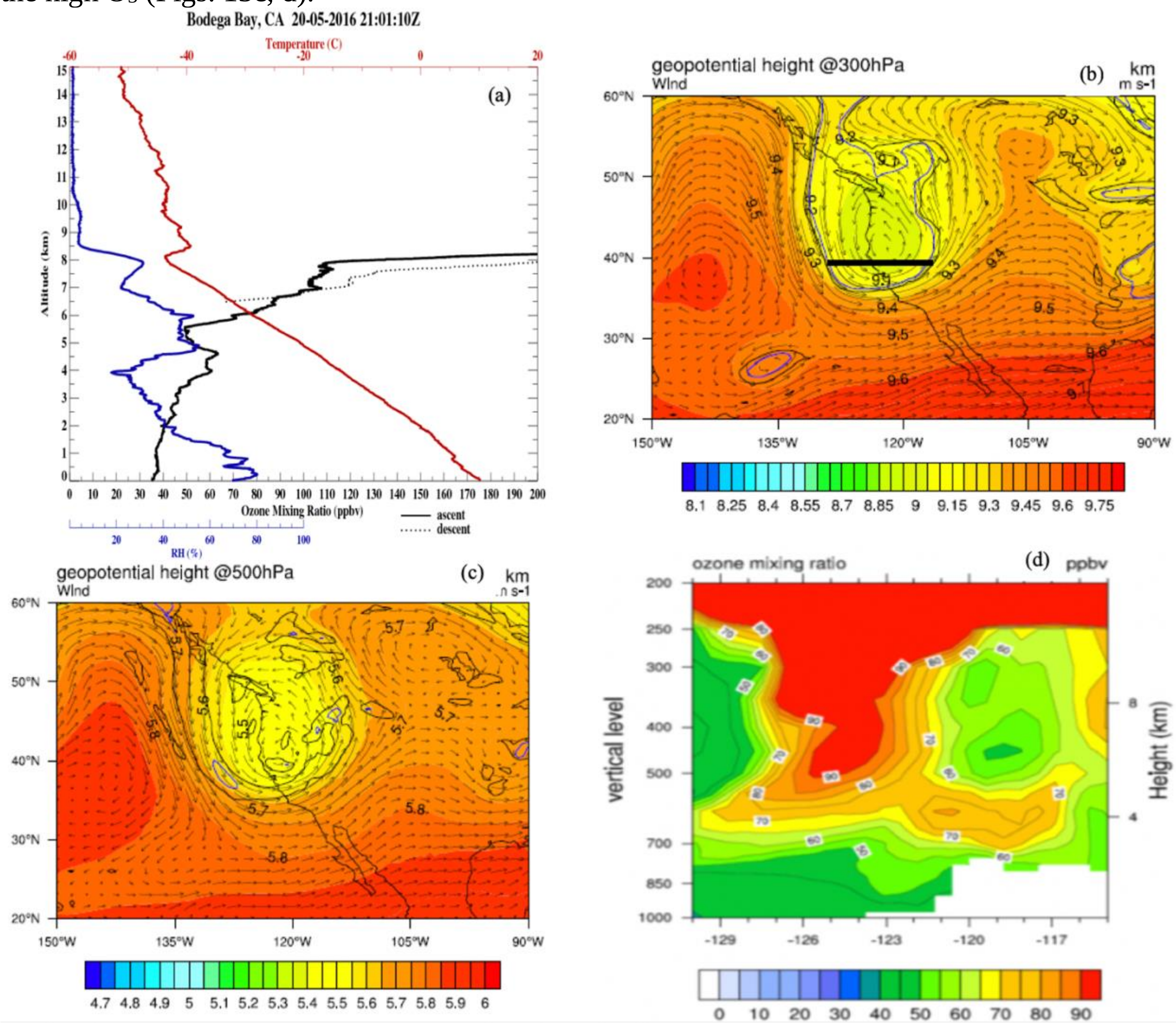

Figure 11. (a) Vertical ozone profile (black) at BBY, MERRA-2 analysis at (b) 300 hPa and (c) 500 hPa, and (d) E-W cross-section of ozone mixing ration for the Low Tropopause case (i.e., Case 1) on May 20th, 2016. The blue line in (b) and (c) represents the PV = 2PVU.

E. An Investigation of Stratospheric Ozone Transport to the Northern San Francisco Bay Area and Sacramento Valley

1. Data analysis

For this section of study, two sets of reanalysis data were used to show the occurrence of an SI during this study. The Global Forecast System (GFS-Analysis) is made up of 31 isobaric levels with a horizontal resolution of 1.0° x 1.0°. Data from July 28th through August 14th, 2016 were used to analyze the 250 hPa windspeed and direction over the Pacific Northwest (PacNW) to study the synoptic conditions during SI events during this time period. The PacNW's domain covers 30.0°N to 60.0°N and 170.0°W to 115.0°W. Within the same PacNW domain, PV data from MERRA-2 were analyzed for a proxy for stratospheric air influence. The MERRA-2 model is comprised of 3-hourly 72 hybrid sigma pressure levels with a horizontal grid resolution of 0.5° latitude x 0.625° longitude. Other supporting variables used from this model include O_3, relative humidity (RH), and specific humidity (SH). The MERRA-2 data was used within the time frame of July 25th through August 13th, 2016.

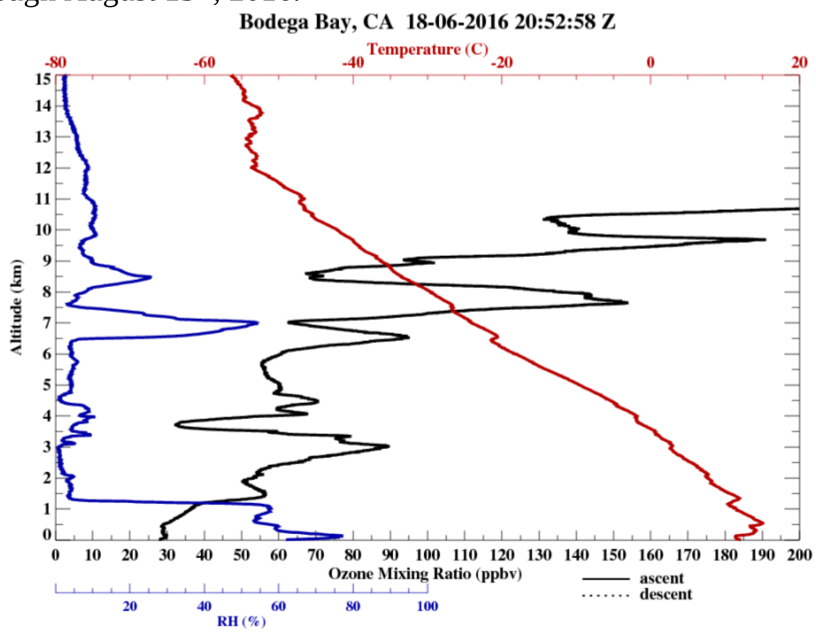

Figure 12. Vertical ozone profile (black) at Bodega Bay, CA for the Stratospheric Intrusion case (Case 2) on June 18th, 2016.

Data from 14 surface O_3 monitoring stations were used for analysis of the unhealthy air conditions in the Sacramento non-attainment zone (Table 1). Surface O_3 data were provided by CARB. This dataset included the hourly average surface O_3 values observed during the period of the CABOTS project. Figure 14a includes the location of the BBY monitoring site to show the distance inland of the Sacramento sites. Observations from 14 surface sites were used within this part of the study (Fig. 14b). The surface O_3 data for BBY were provided by the BAAQMD. This dataset included surface O_3 values recorded every minute, which were then averaged to hourly O_3 data. The BBY surface station data were analyzed for July 25th through August 17th, 2016

2. *Defining Three SI Cases*

Multiple SI events were noted during CABOTS, but this section focuses on three main events of interest during the case study period. The events chosen included the deepest penetration of stratospheric air into the middle troposphere and the placement of the jet stream across the PacNW was unique from the others. In choosing the cases, days with high PV was used. In general, the dynamic tropopause is defined when PV is equal to 1.5 PVU (1 PVU = 10^{-6}

$m^2 s^{-1} K kg^{-1}$) or 2 PVU, so large PV values at high altitudes are regarded to be linked to the stratosphere. Therefore, a value of 1.5 PVU is used as an indication of the dynamic tropopause in this study. Values greater than 1.5 PVU with low SH (or water vapor mixing ratio) indicate a stratospheric air mass (Figs. 15-17). Therefore, values of high PV within the troposphere indicate air which is stratospheric in nature, rich in O_3, and exhibits very low water vapor content. Hoskins et al. (1985) showed that the air mass with PV larger than 1.5 PVU should not be always regarded as a stratospheric origin because the diabatic heating through the mixing processes of stratospheric and tropospheric air can generate high PV values. The diabatic heating effect could be a dominant factor to produce high PV if air is moist in the low-levels (< 3 km). Therefore, this study defines the intrusion events to have PV = 1.5 PVU in the high altitude at least above 4 km (Figs. 15-17).

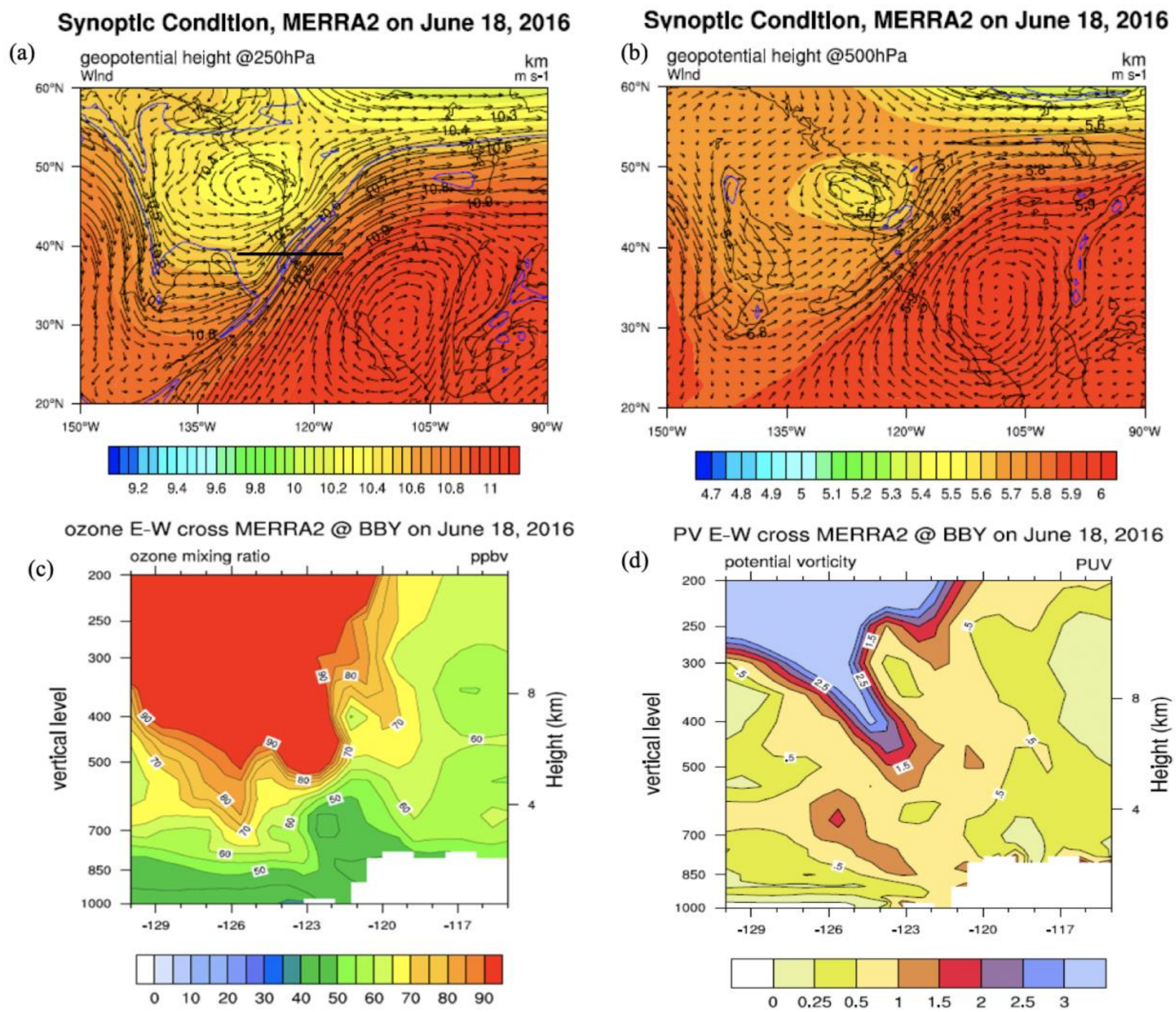

Figure 13. Case 2 (Stratospheric Intrusion). MERRA-2 analysis for (a) 250 hPa, (b) 500 hPa, and E-W cross-section of (c) ozone mixing ratio and (d) potential vorticity valid at 1700UTC June 18, 2016.

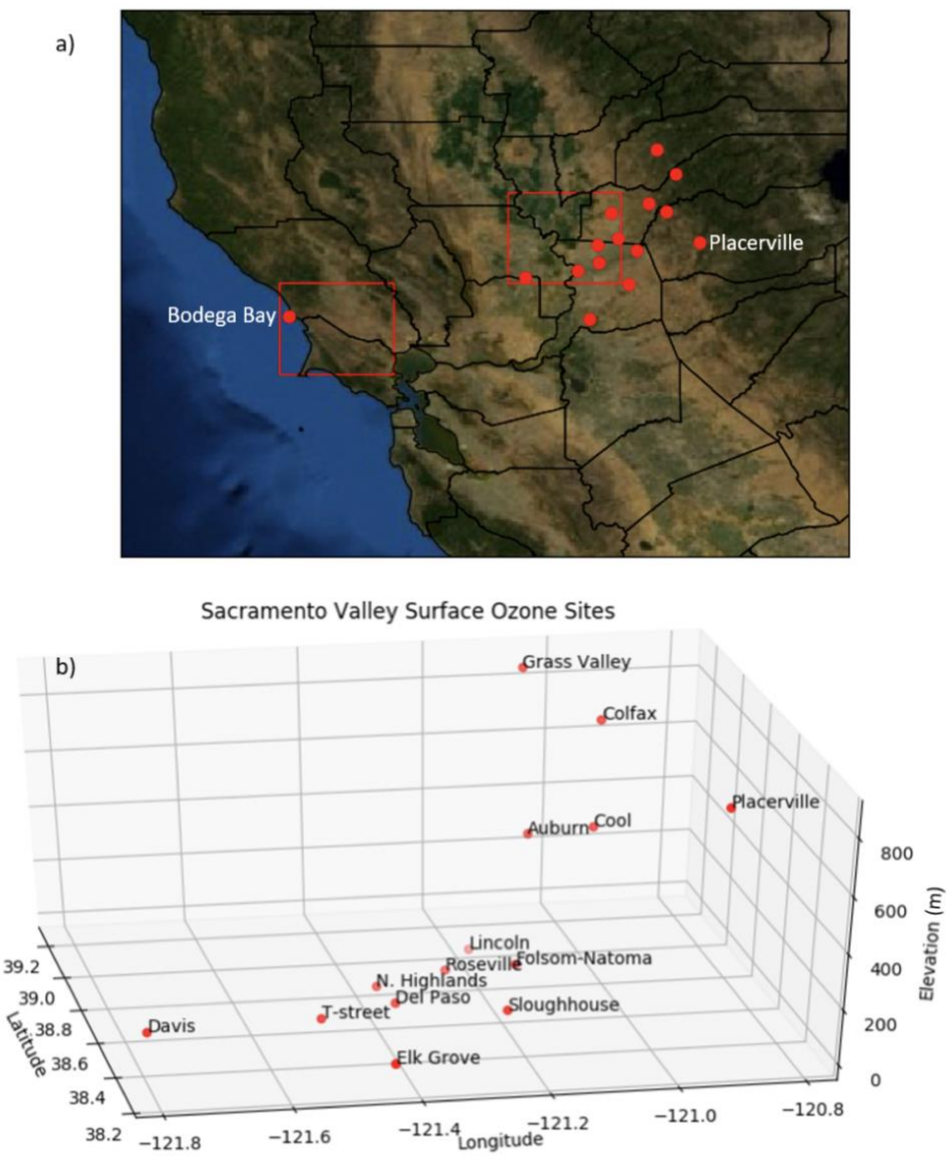

Figure 14. (a) North San Francisco Bay Area domain on the left and Sacramento Valley domain on the right. Modeled averages over these domains were used for comparison. The elevation and location of the sites are shown in (b). The unnamed stations in (a) along with Placerville are shown in (b) as well.

The top panels of Figures 15 (July 26-27, 2016), 16 (Aug 4-5, 2016), 17 (Aug 8-9, 2016) illustrate the MERRA-2 PV values at a height of 11 km for the 2100 UTC timestamp of the date prior to the intrusion and the date of the intrusion. Low tropopause heights were recognizable above Northern California on the dates of interest in the regions of high PV. The bottom panels of Figs. 15-17, illustrate the deeper penetration of a stratospheric air mass over Northern California. High PV was observed near 8 km on July 27th (Fig. 15), near 5 km on August 5th (Fig. 16), and near 9 km on August 9th (Fig. 17). Figure 18 links the regions of higher PV with the placement of the 250 hPa jet stream, and the synoptic scale features of upper-level fronts, known signatures of tropopause folding, and low-pressure systems across the PacNW. The vertical progression of the SI shows the deeper penetration of stratospheric air into the middle troposphere and the downward progression of travel with time.

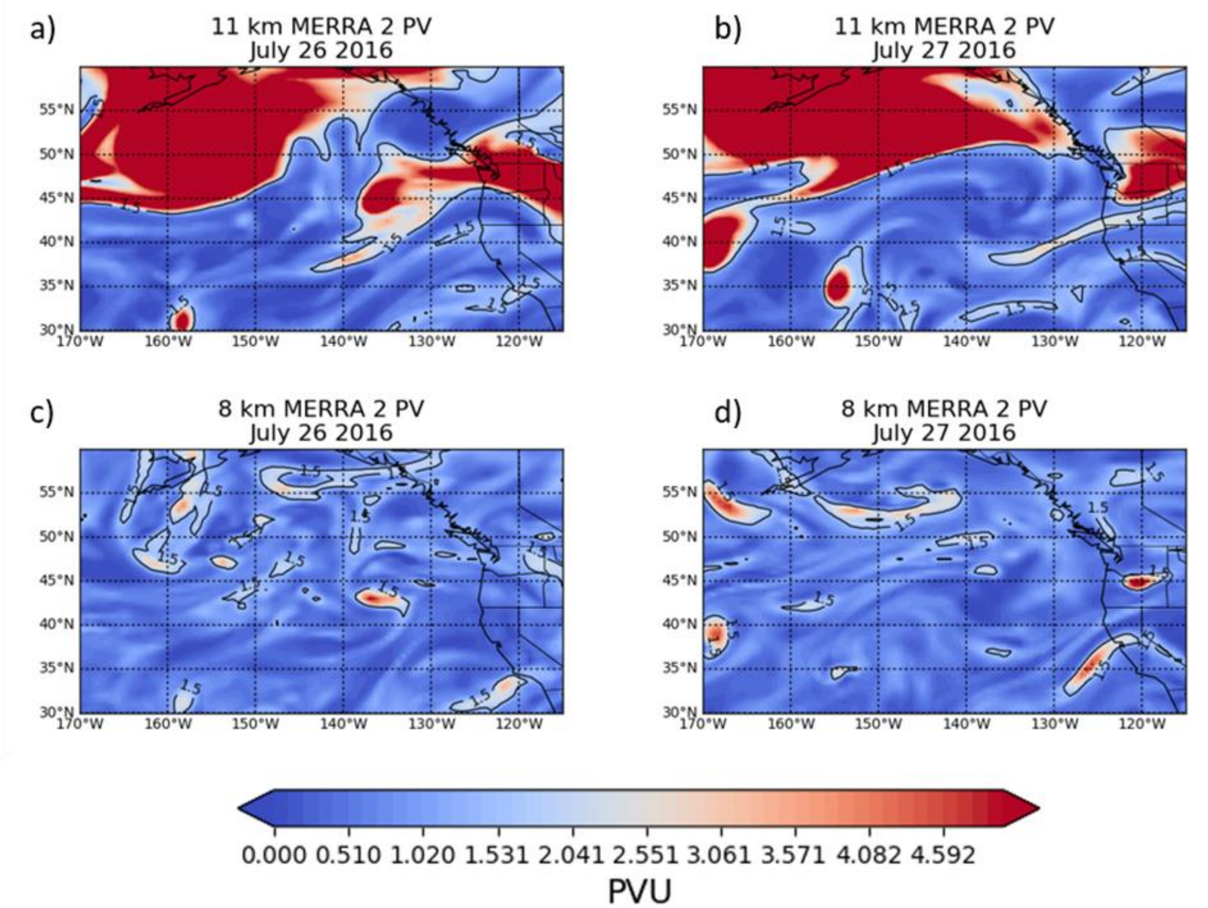

Figure 15. Potential vorticity of the 21 UTC MERRA-2 reanalysis data over the northeastern Pacific Ocean for (a) July 26th, 2016 at 11 km, (b) July 27th ,2016 at 11 km, (c) July 26th, 2016 at 8 km, and (d) July 27th, 2016 at 8 km. The black line represents a potential vorticity of 1.5 PVU.

The first SI began on July 27th into the elevated air above Northern California and remained present into July 28th, 2016. During this event the jet stream was slightly north of center across the PacNW. Starting at the west of the domain, two embedded shortwave lows were pulling the jet stream southward (Fig 18a). A weak high-pressure system off the coast of Oregon and Northern California was driving the jet stream towards the north. The main jet streak lies in the northern central half of the domain, with wind speeds approaching 60 m/s. The tropopause remains at a higher altitude over most of California. The deeper penetration of the stratospheric air mass at 8 km observed above a narrow strip of Northern California as it progressed up from the south to influence the region by July 27th, 2016 (Figs. 15c, d).

The importance of this first SI was the building of higher pressure over the Four Corners region of the desert southwest (c.f., SJSU CABOTS, 2016). The building of this higher pressure resulted in the northwest transport of moisture in the 3 – 8 km vertical column above Southern California. Along with this came the northwesterly advection of the dry stratospheric air mass over Southern California to influence the air mass above the North San Francisco Bay Area, Sacramento, and the Lake Tahoe region simultaneously.

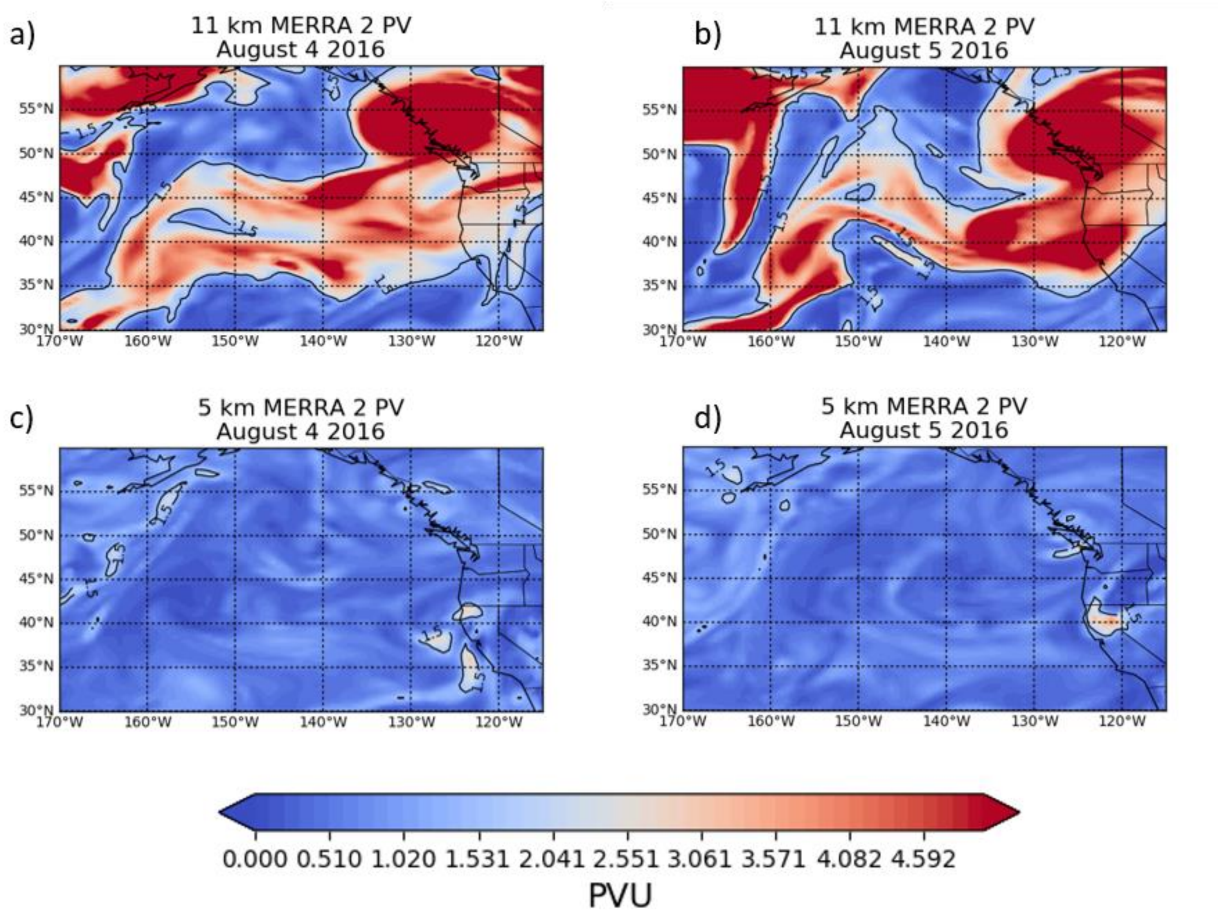

Figure 16. Potential vorticity of the 21 UTC MERRA-2 reanalysis data over the northeastern Pacific Ocean for (a) August 4th, 2016 at 11 km, (b) August 5th, 2016 at 11 km, (c) August 4th, 2016 at 8 km, and (d) August 5th, 2016 at 8 km. The black line represents a potential vorticity of 1.5 PVU.

The second SI began early on August 5th, 2016 above Northern California and remained present through the early hours of August 6th, 2016. The jet stream across the PacNW was weak in this event, with maximum windspeeds near 40 m/s (Fig 18b). At the northwest corner, the jet stream diverges southward pulled by a region of low-pressure in the southwest corner of the domain. A high-pressure system in the Gulf of Alaska, a low-pressure system centered over British Colombia, and an embedded shortwave located about 10° off the west coast of Northern California and Oregon assists in keeping the placement of the jet stream southward. The jet stream traverses across the middle of California in a northeasterly direction, creating low tropopause heights visible by a wider spread of higher PV (Fig 16). This included the North San Francisco Bay Area, Sacramento, and Lake Tahoe. Figures 16c, d illustrate the deeper penetration of the stratospheric air mass at a height of 5 km over Northern California as it progresses eastward from the California coast to influence the region above most of Northern California by August 5th, 2016. The intrusion into the low-to-mid troposphere moved into Northern California from the west with the upper-level trough.

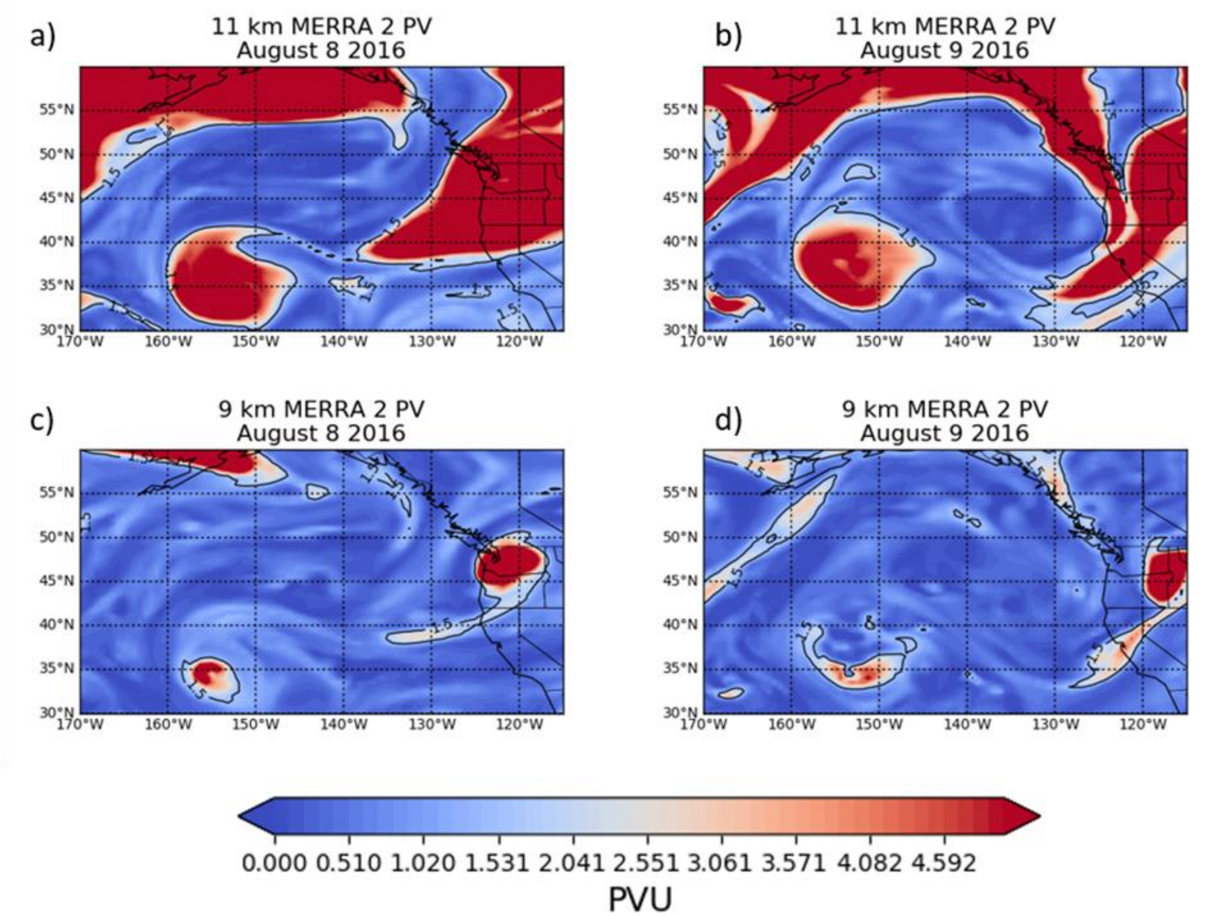

Figure 17. Potential vorticity of the 21 UTC MERRA-2 reanalysis data over the northeastern Pacific Ocean for (a) August 8th, 2016 at 11 km, (b) August 9th, 2016 at 11 km, (c) August 8th, 2016 at 8 km, and (d) August 9th, 2016 at 8 km. The black line represents a potential vorticity of 1.5 PVU.

The third SI occurred early on August 9th, 2016 within Northern California and remained present through just that date. The jet-stream was high across the PacNW, hugging the Gulf of Alaska (Fig. 18c). A large center of low-pressure occurred in the Southwest central region of the domain, with high-pressure to the northwest creating the large ridge of high pressure. The jet streaks were near 50 m/s and were located just upstream from the positive tilted shortwave troughs, the one of interest located over Northern California. The embedded shortwave elongated the trough off the West Coast of the San Francisco Bay Area, giving a positive tilt to the trough axis, and a large upper level-frontal region, perfect for tropopause folding. Figures 17c, d depict the deeper penetration of the stratospheric air mass at a height of 9 km over Northern California, and how it progressed southeasterly to influence the region above the greater San Francisco Bay Area, Sacramento, and Lake Tahoe by around 2100 UTC on August 9th, 2016. During the defined time periods, the three SI cross over and influence both the North San Francisco Bay Area and the Sacramento Valley. Furthermore, Figure 19 confirms that there are low RH and low SH (< 10 %, <0.15 g/kg) during the intrusion cases in our study. Thus, we can still assume air mass with PV=1.5 PVU encircled on Fig. 20 as of a stratospheric origin. These regions were further analyzed to show the similarity of the two regions, defining them as comparable.

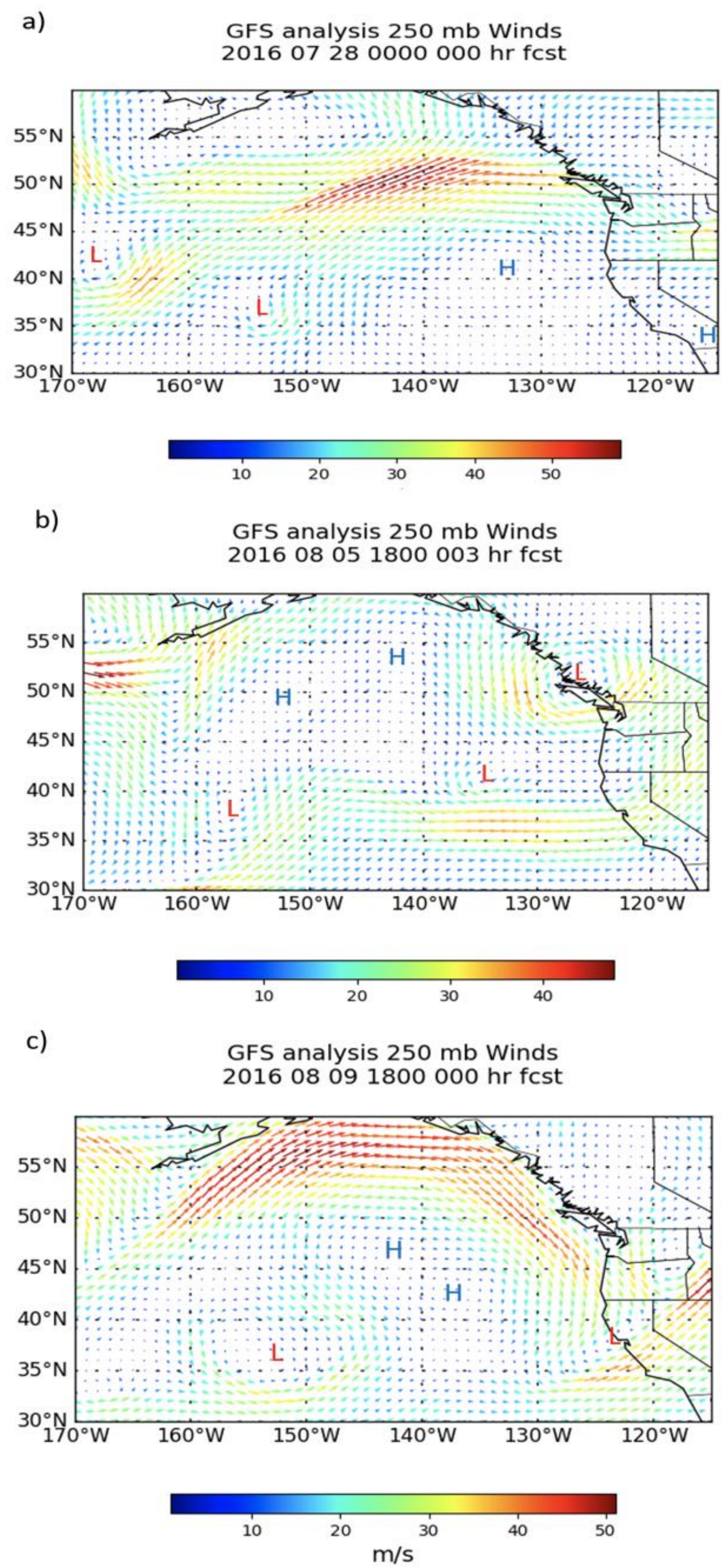

Figure 18. GFS analysis of 250 hPa winds valid (a) 00 UTC 28 July, (b) 18UTC 5 August, and (c) 18UTC 9 August 2016 over the northeastern Pacific Ocean.

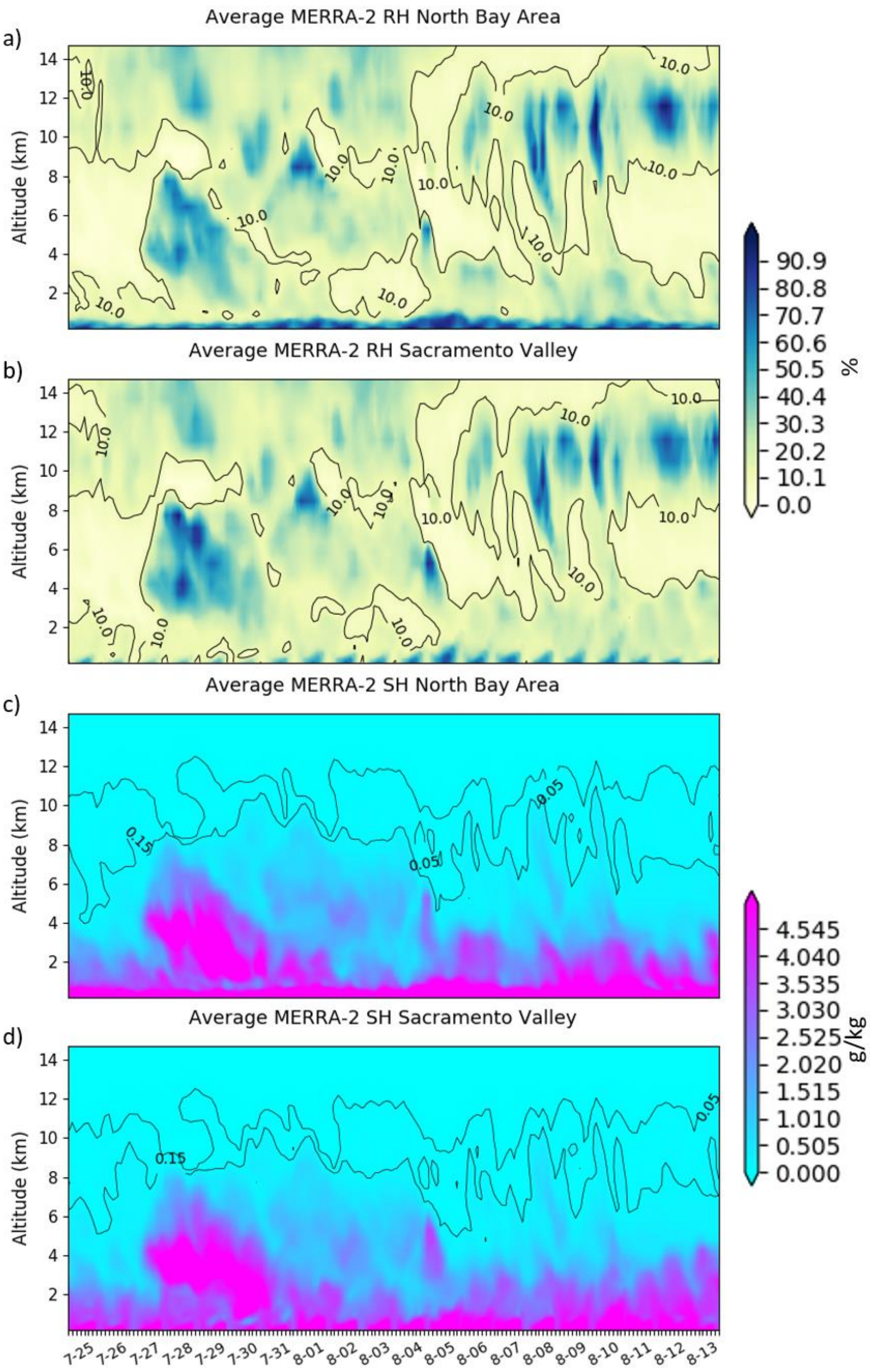

Figure 19. July 25th through August 13th averaged MERRA-2 relative humidity (%) for (a) BBY and (b) SAC and averaged MERRA-2 specific humidity (g/kg) for (c) BBY (d) SAC. The black contour lines in (a-b) represent 10% relative humidity. The black contour line in (c-d) represents a specific humidity of 0.15 g/kg.

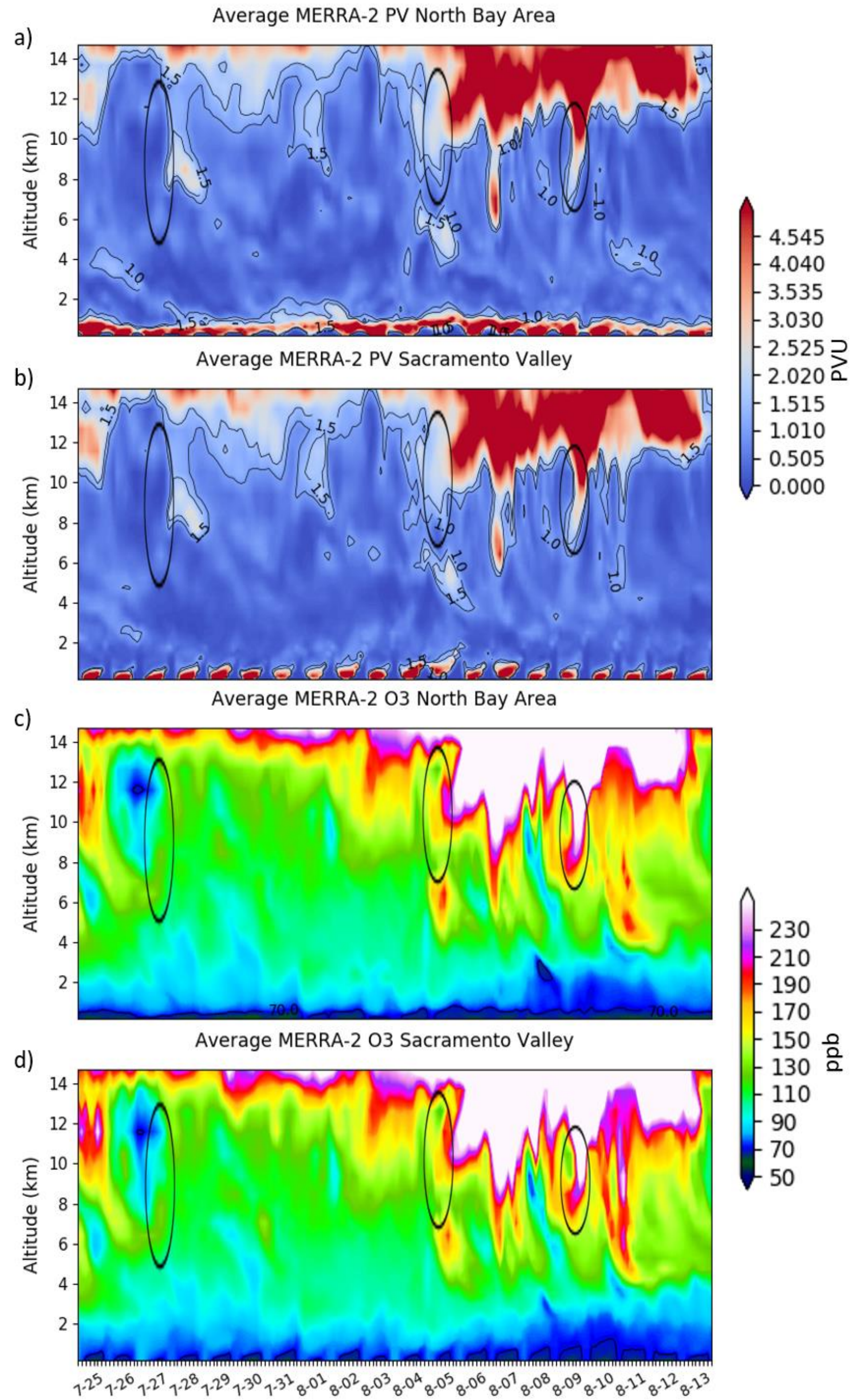

Figure 20. July 25th through August 13th, 2016 averaged MERRA-2 potential vorticity for (a) BBY and (b) SAC and averaged MERRA-2 ozone mixing ratio for (c) BBY (d) SAC. The black contour lines in (a-b) represent 1.0 and 1.5 PVU respectively. The black contour line in (c-d) represents 70 ppb.

3. *Method and Analysis*

i. Regions of Comparison

Two regions of comparison were defined as follows, one for the Northern San Francisco Bay Area which includes BBY and the second for the Sacramento Valley (SAC). Figure 18a highlights the two regions under comparison, defined by the resolution of MERRA-2 analysis data, a 0.5° latitude x 0.625° longitude box. The upper right corner of the SAC domain was set at 39.0 °N, -121.25 °W; the bottom left corner of the BBY domain was set at 38.0 °N, -123.125 °W. All the ozonesonde observations were within the defined BBY region. For both domains, the average value of PV, O_3, RH, and SH, were calculated and analyzed for the 15 km vertical column from the surface up for the period of July 25th through August 13th (Figs. 19-20). Similar patterns with time emerge for each variable, especially above 2 km. The three SIs of interest will be discussed further on a regional scale.

The MERRA-2 reanalysis RH data exhibited patterns differing the first half of the period to the second half (Fig. 19). During the first few days, the 2 – 8 km vertical column of air remained quite dry, under 10 % RH. As the surge of moist air in the 3 – 8 km vertical column begins on July 27th, the drier air dispersed to lower altitudes, with dry air pockets below 2 km. These were most pronounced at both locations during July 29th through July 31st. A dry air mass of less than 10 % was influential above both regions in the 1 – 5 km vertical column from August 1st through August 5th. Following August 5th, the moisture in the lower 2 km remained greater than 10% RH, with the exception at BBY on August 7th (Figs.19a, b). The drier air masses remain elevated within the 3 – 8 km, and at the top of the vertical column within the 12 – 15 km. It is important to note the extent of dry air throughout most of the vertical column on August 5th, 2016.

A visual is given to the SH from MERRA-2 reanalysis data in Figs. 19c, d. Similar to Cox et al. (1997), a value of 0.05 g/kg is given to the SH-defined tropopause, and a value of 0.15 g/kg indicates the deeper penetration of stratospheric air (Figs. 20a, b). The surge of moisture into the 3 – 8 km vertical column above both regions on July 27, 2016 is clear (Figs. 19c, d). This gave the rising push of the 0.15 g/kg line from the 4 – 6 km vertical column to above 8 km. Yet also a lowering of the 0.05 g/kg line from near 11 km to near 8 km occurred simultaneously. Pockets of generally low SH values were influential in the lower 1 km vertical column above both regions on July 29 through July 31, 2016. Stratospheric air began to penetrate lower into the atmosphere beginning on August 4th, reaching near 5 km on August 5th. For the rest of the case study period there are multiple oscillations to the height of the SH-defined tropopause, including the lowering near 6 km on August 9th, 2016.

From the comparison of MERRA-2 PV, the same SI of interest are noted above BBY and SAC (Figs. 20a, b). When evaluating the MERRA-2 average O_3, both BBY and SAC were similar in structure to the placements of the higher and lower O_3 concentrations (Fig 20c, d). The moisture observed throughout the vertical column above both the BBY and SAC region follow similar large pattern structure (Figs. 19 a, b). The injection of stratospheric air traced by the 0.15 g/kg SH value shows very similar depths above both the BBY and SAC regions (Figs. 19c, d). These similarities to the elevated air masses define the regions as comparable, especially particularly above 2 km. Therefore, BBY ozonesonde measurements would give an indication of the vertical O_3 structure elevated above SAC as measurements from ozonesondes are representative of large horizontal areas (Liu et al., 2009).

A comparison of BBY average PV values (Fig. 20a) to that averaged over the SAC region (Fig. 20b) shows many similarities, including the height of the PV-defined tropopause.

During the case study period, the 1.5 PVU defined tropopause varies from 10 to 14 km. It was observably higher during the first half of the case study period, lower during the second half, and experienced quite a bit of day to day variability (Figs. 20a, b). Cox et al. (1997) found that 1.0 PVU is best suited for the investigation of deep SI to recognize the streamers associated with the fold. The 1.0 PVU outline marked the deep penetration of stratospheric air into the troposphere, including into the lower troposphere below 5 km. The three SI are recognizable in both vertical columns concurrently, along with signs of other events (Figs. 20a, b).

The first SI under investigation began mid-day on July 27th, 2016 and remained present over both regions throughout the day of July 28th (Figs. 20 a, b). This stratospheric air mass was injected from a relatively high tropopause height of near 14 km and injects downward to near 7 km. The intrusion has passed through by the early hours of July 29th, 2016.

The second SI for examination happened on August 5th, 2016. Beginning on August 4th, the tropopause heights lowered to near 8 km (Figs. 20a, b). The strongest indication of stratospheric influence occurred during the latter hours of August 5th, within the 10 – 12 km as PV values increased with a much stronger gradient. Engulfed in the 4 – 7 km region of the tropopause is a cut-off of higher PV, a sign of stratospheric air mass injection. This air mass noticeably progresses downward with time, beginning near 7 km on August 4th, and stretches downward with time, influencing air near 4 km during the early hours of August 6th, 2016.

The third SI of interest occurred on August 9th, 2016 and was quick moving driven by the upper-level front. As with the second intrusion event, the height of the tropopause was relatively low, being near 11 km (Figs. 20a, b). This stratospheric air mass penetrated deeper into the troposphere in the earlier hours of the date, approaching as low as 6 km. By the afternoon hours, much of the intrusion remained above 8 km. The upper-level front passed through quickly and tropopause heights restored to near 10 km.

The modeled average O_3 concentrations for the case study period within the 15 km vertical column above BBY and SAC are visible from Figures 20c, d. Near the tropopause, O_3 concentrations were lower or higher in association with the higher or lower PV-defined tropopause heights. Similar features are noticeable in the modeled MERRA-2 reanalysis O_3 data, yet the range of values is quite different (Figs. 2b, 20c). The values observed at BBY were collected during the peak concentration hour of high surface O_3. The differences between the BBY ozonesonde data and the modeled reanalysis MERRA-2 data shows the importance of obtaining stronger boundary conditions in our modeling systems for coastal regions.

ii. CABOTS Data Analysis

The daily variation of O_3 by height was evaluated to visualize the downward progression of the dry, rich in O_3 stratospheric air masses with time. Utilizing BBY ozonesonde observations, the daily percent changes in O_3 were calculated and analyzed for the 15 km vertical air column. Figure 21shows the daily percent changes in measured BBY O_3 for the period. Multiple scales are required to distinguish both the largest and smallest of changes. Therefore, the vertical column was divided into three sections: the upper troposphere (Fig. 21a), the middle troposphere (Fig. 21b), and the lower troposphere (Fig. 21c).

At the location of the defined SI, daily changes in O_3 were further analyzed to give insight into the downward progression of increasing O_3 with time. Figure 21a is used in the investigation of O_3 variability throughout the 10 – 15 km vertical column, including the tropopause. The substantial changes in O_3 associated with the variable tropopause heights are noticeable with the broad scale range of -150 – 450 % change in O_3. Daily variations in ozonesonde data for the three stratospheric intrusion dates of interest are further discussed.

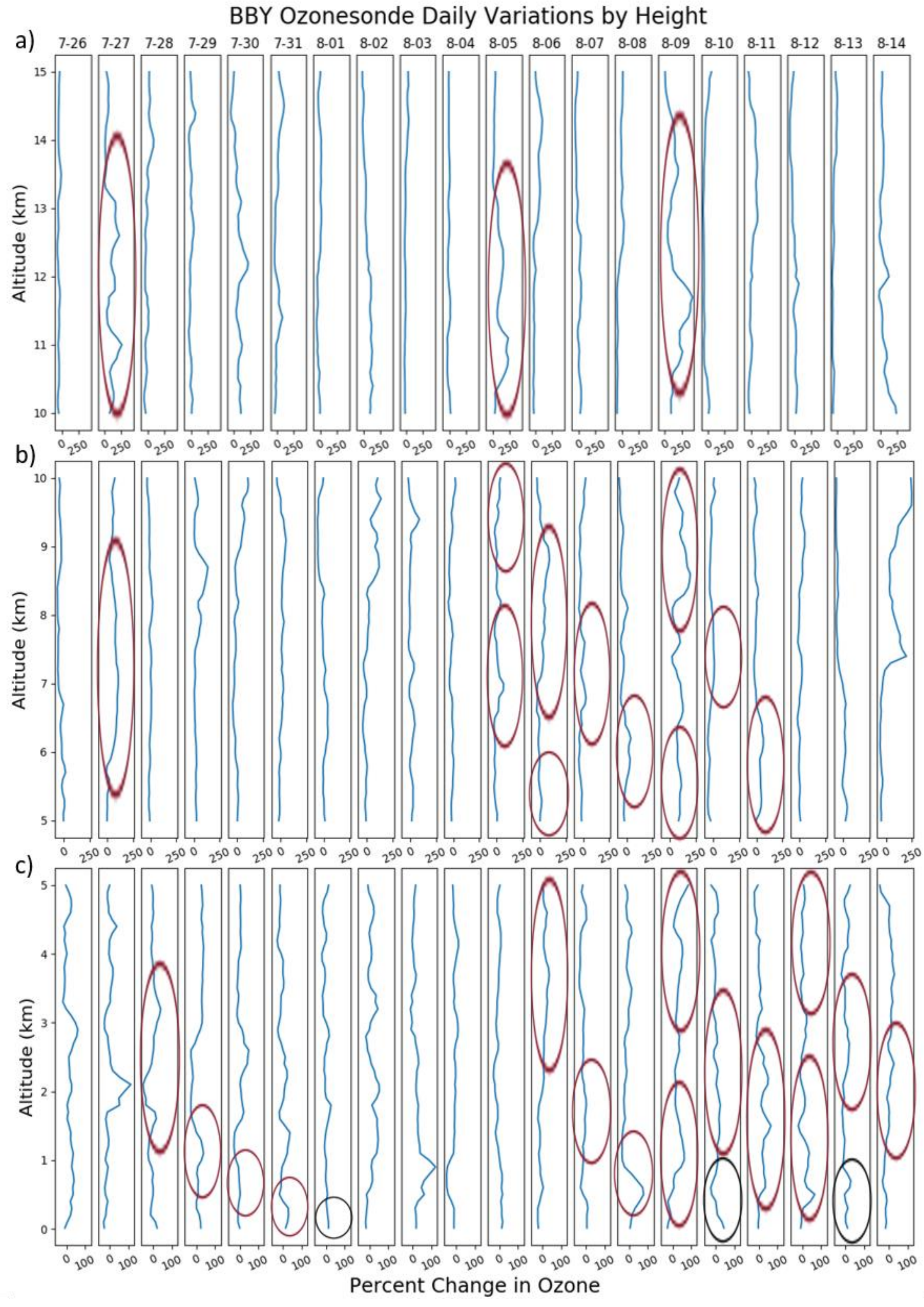

Figure 21. Calculated percentage change in observed daily ozone along the BBY ozonesonde vertical profile from one day to the next from July 26th to August 14th 2016.

From July 26th to July 27th an increase of O_3 was observed through a long vertical column between 6 – 14 km above sea level, and captured O_3 measurements at the beginning of the first SI of interest (Fig. 21a). The altitude with the greatest O_3 fluctuation from the first intrusion was near 11 km, which saw an increase of 258%. From August 4th to August 5th an increase of O_3 was observed through the 7 – 14 km vertical column during the second SI of interest (Fig. 21a). The greatest daily change in O_3 observed between the 4th and the 5th was at 11.0 km, which experienced a 236% increase. From August 8th to August 9th an observed increase in O_3 occurred throughout most of the vertical column, excluding the upper and the lower one kilometer. The greatest of all the daily percent changes in O_3 was observed from August 8th to August 9th. An increase of O_3 by 415% from the day prior was observed at a height of 11.1 km, with an ozonesonde measurement of 169 ppb on August 9th. The positive daily change in O_3 was tracked to the lower levels of the troposphere, including the surface.

During the first SI, the tropopause was relatively high. The interest was in the 6 – 8 km of the vertical column. At this height, the MERRA-2 reanalysis data showed a cut-off of high PV beginning on July 27th, 2016 (Fig. 20a, b). The BBY ozonesondes captured data for this intrusion. At this height, daily increases in O_3 ranged from 90 – 110 % (Fig 21b). The concentration changed from about 40 ppb to nearly 80 ppb. Progressing with time, on July 28th, and downward near 1.5 – 4 km, ozonesonde measurements captured an increase around 50% from the day prior (Fig. 21c). Over the next 2 days the downward progression of the stratospheric air became slower. By July 31st, this air mass with stratospheric O_3 influence impacted concentrations below 2 km and reached the lower 1 km by August 1st, 2016 (Fig. 21c).

The second half of the case study began with a similar downward progression of increasing O_3 with time, marking the second SI. The MERRA-2 PV defined intrusion penetrates from a relatively low tropopause deep into the middle troposphere (Figs. 20a, b). This feature is recognizable for August 4th to August 5th as an increase in the O_3 daily percent changes, down to the 7 km region where the observed increase was near 100% (Figs. 21a, b). Both the upper and lower portions of the intrusion are tracked downward, impacting the surface O_3 concentration on two separate dates. Daily O_3 increases were recognizable from August 5th to August 6th in the 7 – 9 km region, and smaller increases occurred within the 3 – 5 km region (Figs. 21b, c). Following the upper air mass steadily downward, by August 8th the observed daily O_3 increases had progressed downward, impacting concentrations near 5 – 7 km. The stratospheric O_3 which originated near 7 km, influenced the O_3 concentrations in the lower 1 km by August 8th. By August 10th, 2016 an O_3 increase near 50% occurred at the lowest levels of the vertical column.

On August 9th, 2016 the third SI began as stratospheric air was injected into the middle troposphere (Figs. 20a, b). Along with this event came a heavier push to the downward progression of the previous stratospheric air mass tracked, along with further stratospheric O_3 influence in the upper column of air (Fig. 21). By now, the stratospheric air which influenced upper-level O_3 initially on August 5th, has progressed down with time to influence the O_3 levels in the 3 – 6 km vertical column. By August 10th, 2016 this stratospheric air began to influence the O_3 levels in the 1 – 3.5 km vertical column. A steady downward trend of increasing O_3 can be followed toward the marine boundary layer and impacted the surface O_3 by August 13th, 2016 (Fig. 21c). At this time, stratospheric O_3 associated with the upper-level intrusion into the middle troposphere on August 9th, had progressed downward and influenced the O_3 concentrations within the 1 – 3 km region by August 13th, 2016.

Both the first and second SI cases exhibit a 6-day downward progression of O_3 transportation from the commencement of the intrusion into the middle troposphere, to impacting the BBY surface O_3 concentrations (Fig. 21c). The BBY surface O_3 monitoring data provided by

BAAQMD reflects these same increases (Fig. 22). To reduce the effects of local pollution on the surface monitoring values (Parrish et al. 2010), the maximum daily 8 hour average (MDA8) O_3 surface values were calculated and investigated.

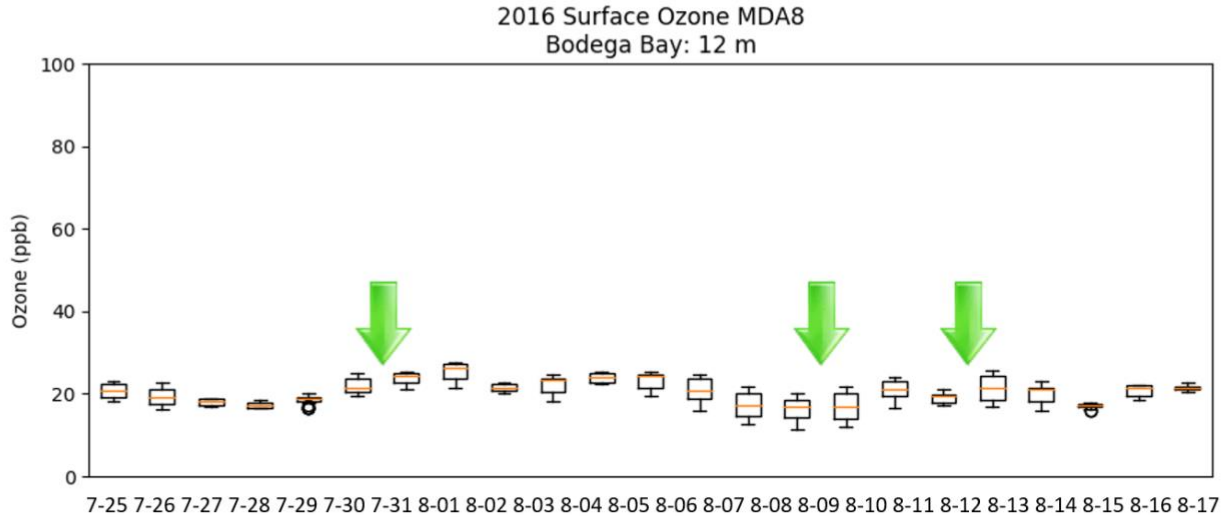

Figure 22. Box plot for the calculated Maximum daily 8-hour Average ozone at BBY at the 12 m a.s.l. near the surface from July 25th to Aug 17th 2016. The local hours are from 0 through 23. The orange bar is the daily mean.

The observed O_3 increases in the lowest levels of the vertical profile captured by BBY ozonesonde measurements match up nicely with the observed increases in surface O_3 concentrations at BBY. The green arrows indicate dates which the stratospheric O_3 influenced the surface O_3 concentrations (Fig. 22). From July 30th through August 1st, a clear increase in the mean surface MDA8 O_3 values were observed (Fig. 22). A secondary increase in surface MDA8 O_3 values occurred from August 9th through August 11th. A third distinguishable increase in surface O_3 occurred from August 12th to August 13th, as both an increase to the mean observation and the daily range of concentrations. These increases in surface O_3 concur with the stratospheric air influence at the surface observed through BBY ozonesonde data and MERRA-2 PV reanalysis data. The observed MDA8 O_3 concentrations at BBY illustrate a small daily range of less than 10 ppb. The mean MDA8 O_3 value observed at BBY during the case study was near 20 ppb (Fig. 22).

iii. Surface Maximum Daily 8-hr Average Ozone

This study calculates the surface MDA8 O_3 for 14 different surface monitoring stations located in the southern Sacramento Valley and the local lower Sierra Nevada Foothills. The monitoring sites in the Sacramento Valley were subcategorized into three groups based on elevation; high, mid, and low. These were defined by the elevation of the chosen sites accordingly: surface stations located i) above 108 m, - ii) between 108 m and 47 m, and - iii) below 47 m. This conveniently groups the surface O_3 monitoring sites similarly by longitude. The high elevation sites are located furthest east while the low elevation sites are located farthest west (Fig. 18b).

The mean MDA8 O_3 observations were compared among all the surface monitoring sites. A mean MDA8 O_3 of near 70 ppb was observed during the case study period at Grass Valley. The mean MDA8 O_3 concentrations were greatest at the highest elevation sites and decrease with a corresponding decrease in height (Fig. 23). This same general pattern is noticeable throughout the data observed at both the mid and the low elevation category sites. The low monitoring sites observed mean MDA8 O_3 concentrations ranging from 30 – 40 ppb (Fig. 23a). The mid-elevation monitoring sites observed mean MDA8 O_3 concentrations for the period ranging from 40 – 50 ppb (Fig. 23b). Similarly, mean MDA8 O_3 concentrations observed at the Colfax and Placerville sites were around 70 ppb (Fig. 23c). This observation alone creates a clear picture for the non-attainment and unhealthy surface air conditions during the period of interest.

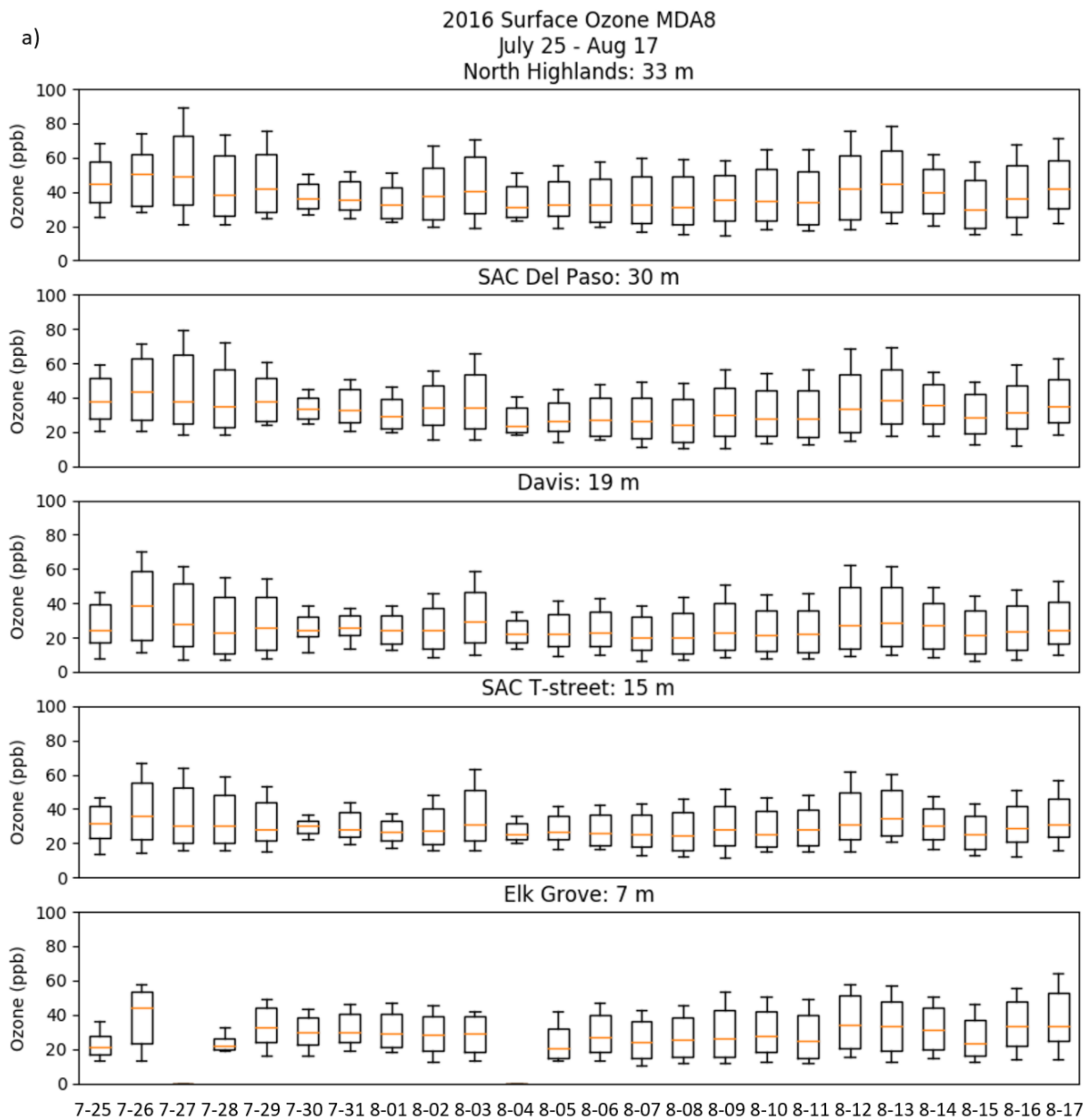

Figure 23a. Calculated surface maximum of all daily 8-hr average (MDA8) O3 concentration box plots from July 25th to Aug 17th 2016 for the SAC low elevation surface sites. The orange bar is the mean value.

The mean MDA8 O_3 values among the low category sites were closest to the BBY surface data (Figs. 22, 23a). Interestingly, the minimum values in the daily range though can be substantially less than that observed at BBY. Minimum MDA8 O_3 values at the low elevation sites remain under 20 ppb, and as low as 5 ppb at Davis. The low elevation sites exhibited the lowest observed O_3 concentrations among all the sites.

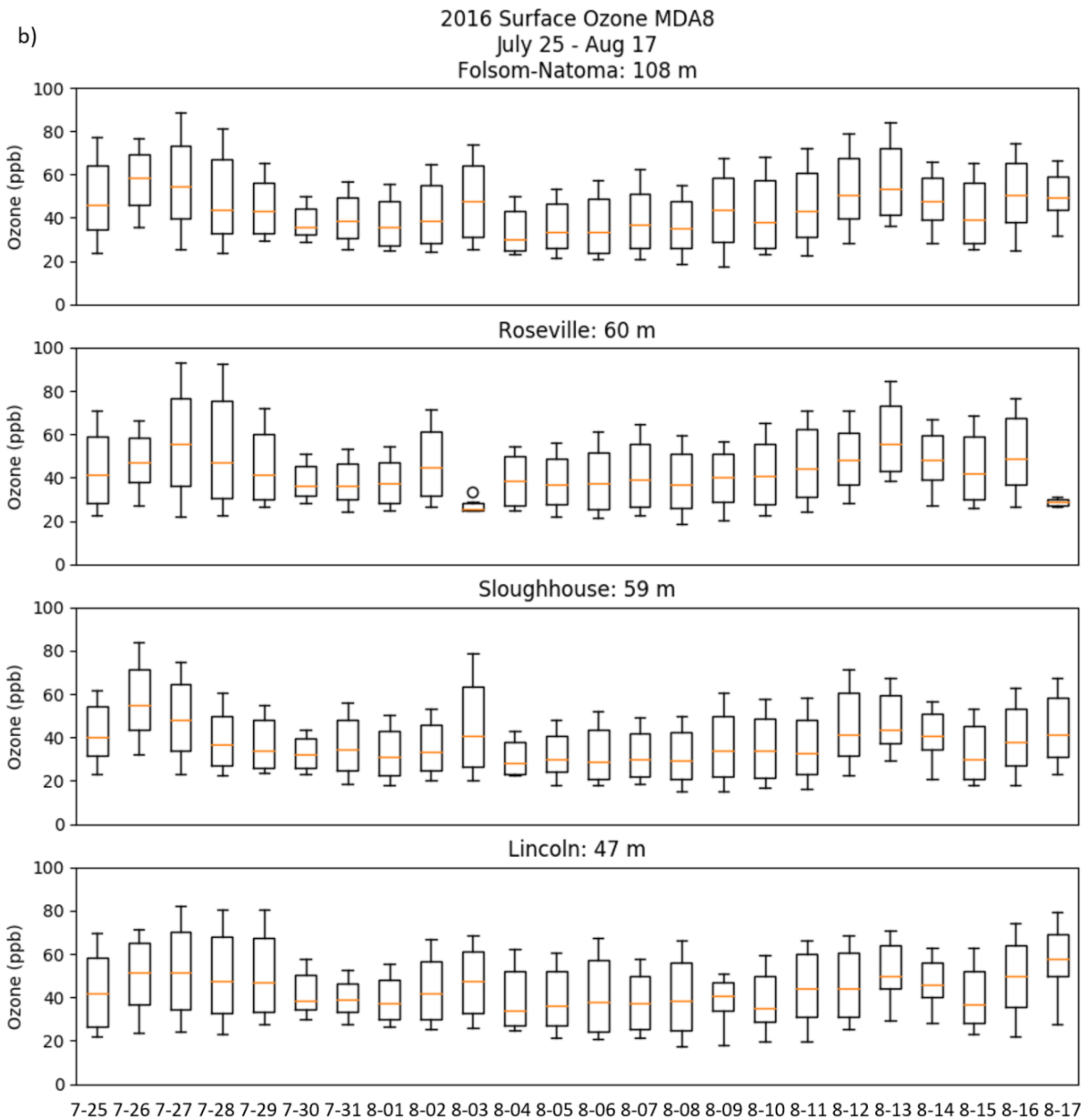

Figure 23b. Calculated surface MDA8 O3 concentration box plots from July 25th to Aug 17th 2016 for the SAC mid elevation surface sites. The orange bar is the mean value.

In general, sites located in the mid-elevation region had the greatest daily range of MDA8 O_3 values. Figure 23 suggests that the daily range of MDA8 O_3 at the mid-elevation sites exhibit a wider spread when the high elevation sites exhibit a mean MDA8 O_3 daily value that was above average for the case study period. The opposite appears to hold true. If the high elevation sites exhibited a mean MDA8 O_3 daily value below the mean concentration for the selected case study period, then the daily range observed at the mid elevation sites were generally less. Similarly, the minimum MDA8 O_3 concentration within the mid category sites were greater or less based on the mean concentrations observed at BBY (Fig. 22) and other lower elevation SAC surface sites. This gives an indication of how this mid-elevation layer is mixed and influenced with the air masses above and below.

An analysis of the lowest elevation surface monitoring site O_3 concentrations gives insight into the differences between coastal and inland sites of similar elevation and latitude. Elk Grove, the lowest elevation among all the sites (7 m), still exhibits a substantially greater daily range of MDA8 O_3 than that of BBY. The maximum values captured at Elk Grove approach that of 70 ppb, the current NAAQS for 8-hr O_3, on a few days including August 12th, and August 17th, 2016 (Fig. 23a). This gives an indication of the marine influence on O_3 concentrations at BBY, as well as the impacts of local emissions at inland sites. The correlations among all the 15 surface O_3 monitoring stations are in Table 6.

iv. Correlations Among Surface Sites

A correlation analysis was performed utilizing the calculated surface MDA8 O_3 values. The calculated correlation coefficients for the 15 surface O_3 monitoring stations are recorded in Table 6. Correlations for the MDA8 O_3 concentrations between two surface sites were calculated based on exact date and hour comparison. The strongest correlations between individual surface monitoring stations O_3 concentrations were found to be within the sub-region height category: low, mid, or high. It is important to note that the correlations among the mid and low sites are all strong correlations (> 0.8). This shows the importance of latitude and longitude among the O_3 concentration correlations in the lower 110 m of the SAC air basin. The correlations among the high elevation surface sites exhibited a wide array of correlation strength ranging from a moderately weak correlation near 0.4 to a very strong correlation near 0.9 due to larger spatial variation.

Generally, as the distance between the two surface monitoring stations under comparison increases in the vertical and horizontal directions, the correlation becomes weaker. The Davis station and the lowest in elevation, Elk Grove station generally exhibited weaker correlations, along with the highest in elevation, Grass Valley station. These and are located furthest west, furthest south and furthest north (cf. Fig. 18). Weak to little correlation are found between the BBY and the SAC surface MDA8 O_3.

The high elevation surface sites display both positive and negative correlations with the BBY surface MDA8 O_3 data (Table 6). The Colfax and the Cool sites exhibited very weak positive correlations with the BBY surface data and had stronger correlations with the SAC monitoring sites than did the other three high elevations sites. These stronger correlations are likely due to the sites being downwind of SAC. Summertime thermally-driven upslope flows are known to transport pollutants from SAC to the north-east Sierra Nevada foothills (Fast 2012). Therefore, these sites would not be strong candidates to further understand stratospheric O_3 transport. The three sites of Auburn, Placerville, and Grass Valley each displayed a very weak, negative correlation with BBY surface data, indicating a height dependency on the O_3 correlation. For completion, all five high-elevation sites were then correlated and analyzed against elevated BBY ozonesonde measurements of similar elevation.

The correlation analysis was performed first between the BBY ozonesonde concentrations at 100-m increments between 400 m and 1000 m and at 2000 m against the observed 2100 UTC surface O_3 values at each of the high-elevation surface monitoring locations. The highest values represent the observations that were closest to the ozonesonde measurements obtained near 2100 UTC ± a quarter of an hour to observe the well-known daily maximum surface O_3 concentration. The correlation coefficients are recorded in Table 7.

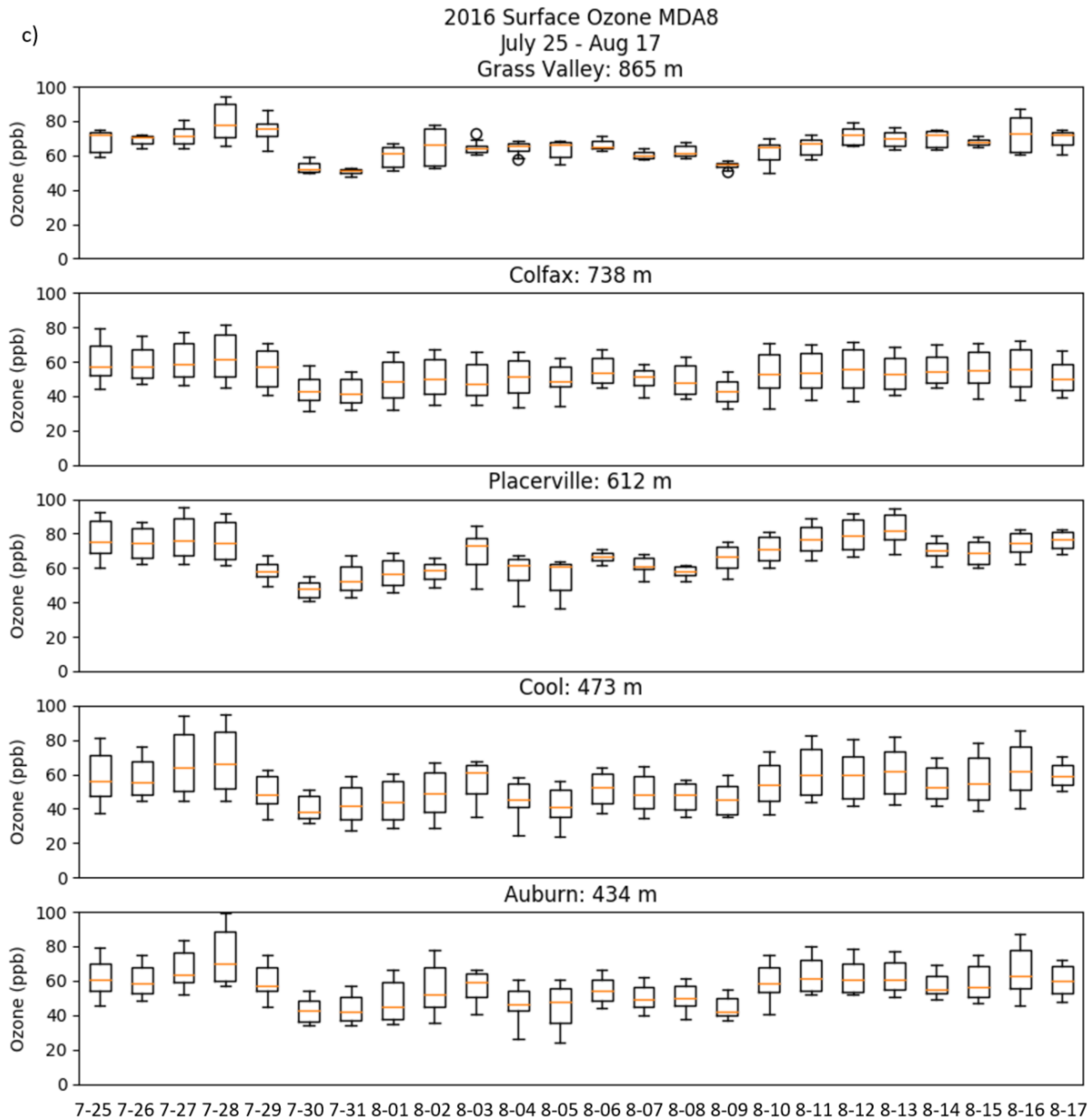

Figure 23c. Calculated surface MDA8 O3 concentration box plots from July 25th to Aug 17th 2016 for the SAC high elevation surface sites. The orange bar is the mean value.

The largest O_3 correlation coefficients are with elevated BBY ozonesonde measurements (bold type in Table 7); and sites which previously exhibited a negative correlation now display a positive correlation (Table 7). Notice that these correlation studies are for single times and the same day (i.e. discrete same day correlations). An ozone layer from BBY however needs to be transported to a site inland; the time needed for this is likely on the order of 20 hrs, given a wind speed of 3 ms^{-1}. From this, a possibly better correlation may be obtained using a delayed time for sites inland (possibly the next day at 2100 UTC).

Of the five high-elevation sites, the Placerville station, located roughly 200 km from the BBY coast, exhibited the strongest correlations with the elevated BBY ozonesonde data. Therefore, the Placerville observations were picked to further analyze. An analysis of surface O_3 data at Placerville and elevated BBY ozonesonde data shows the similarities between the locations. A clear variance with height is noticeable in the correlation strength between the Placerville surface O_3 data and BBY ozonesonde measurements, especially at similar elevations (Table 7). Three elevations exhibited a moderately strong correlation of 0.6. A visual to these relationships are given with a linear regression plot (Fig. 24).

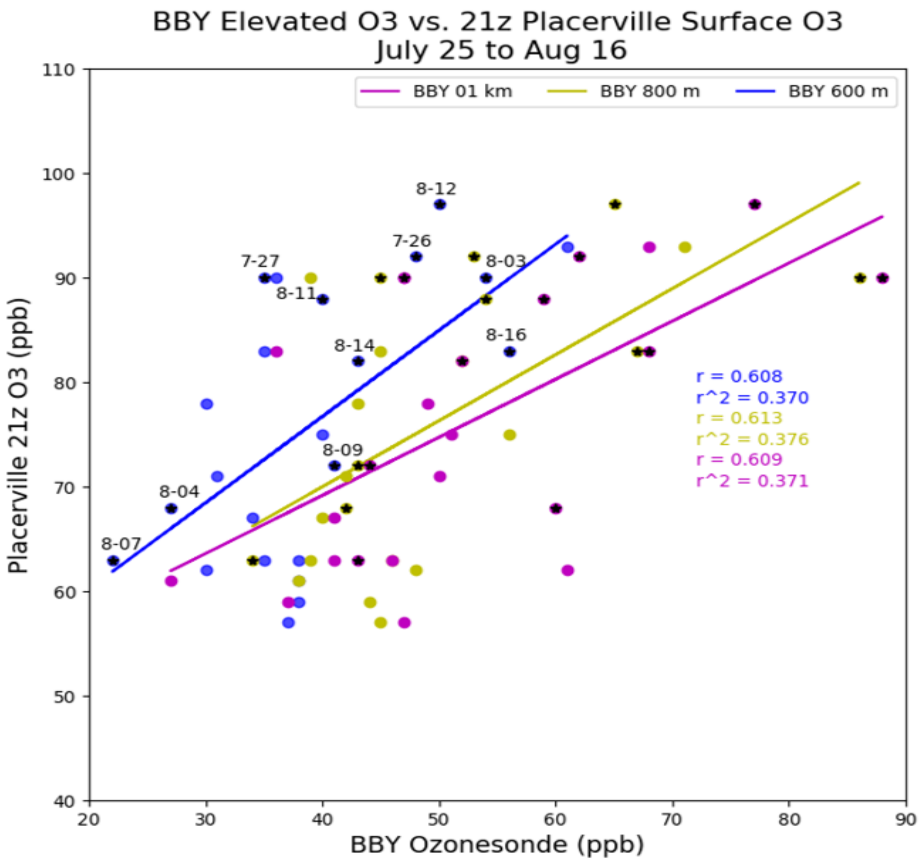

Figure 24. Linear Regression plot for elevated BBY observed O3 at 1 km (purple), 800m (yellow) and 600m (blue) during 21 UTC and the Placerville station observed surface station O3 at 21 UTC for the case study period July 25 – Aug 16, 2016.

It can be inferred that the O_3 at either location is often influenced by the same source region, yet the strength of the impact varies and appears more influential at the North San Francisco Bay Area coastal site than the Sierra Nevada Foothill surface site (Fig. 25). Three groups of interesting data emerged from these daily O_3 variations, listed in Table 8. The dates of interest are further discussed.

The first case was at the beginning of the case study period on July 26th and 27th. All sites exhibited an increase on July 26th, followed by a decrease on July 27th. The daily O_3 changes were similar in value, if not matching (Table 8). It can be inferred from Fig. 2a that the tropopause was low in the days prior. This could have resulted in stratospheric O_3 transport into the troposphere. Contributing to the case of stratospheric influence was high PV in the 0.5 to 1.0 km layer as shown in Figs. 20a, b. On July 27th, the observed BBY ozonesonde values approached 120 ppb at 2 km (Fig. 2b), as the Soberanes Fire in Monterey County had another outbreak.

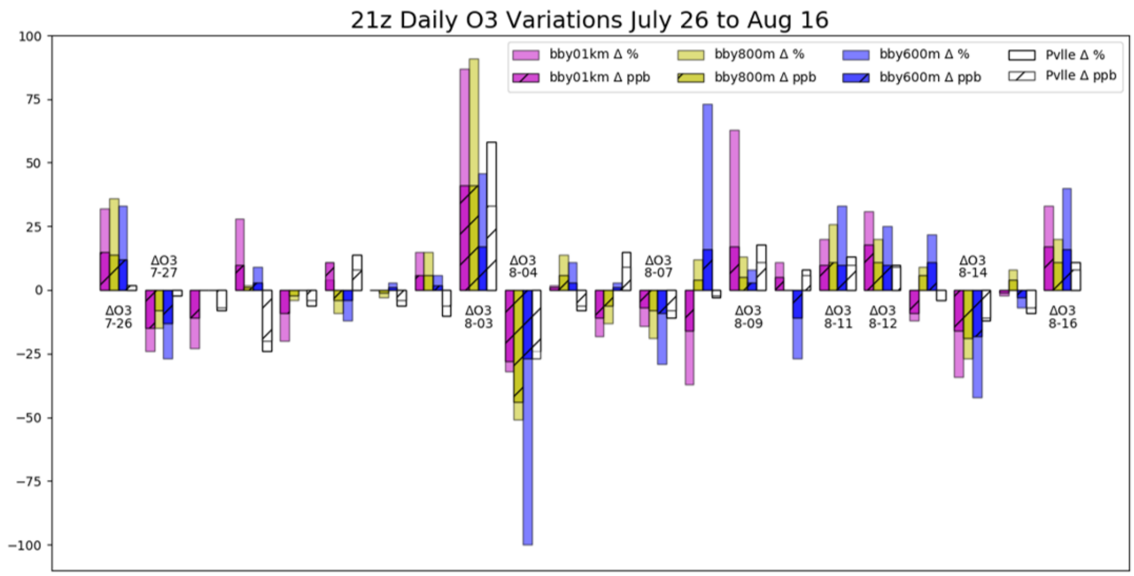

Figure 25. Daily observed ozone variations, in both changes in percentage (solid bar) and in concentration (hatched bar), for three elevated BBY locations ozonesonde observations (colors) and 2100 UTC Placerville surface ozone observations (white). The case study period July 25th through August 16th, 2016.

The second case of interest occurred on the August 3rd . The daily changes in O_3 are the greatest of the period (Fig. 25). The observations on August 2nd show an increase throughout most of the 1 – 5 km column, with a downward trend on August 3rd and a large spike at 1 km (Fig. 21c). On August 3rd, the observed concentrations at 1 km reached 100 ppb (Fig. 2b). The MERRA-2 humidity data indicate dry air in the region (Figs. 19a, b). Though there are signs of stratospheric influence, this data was also subject to fire influences. The Cold Fire in Yolo County was active and located between Placerville and the BBY coast (SJSU CABOTS, 2016).

The strongest case for stratospheric O_3 transport into the lower 1 km was the final case, Case 3. There were no fire outbreaks or growth and the Cold Fire had been extinguished. The O_3 variances at Placerville were very similar to that observed in the elevated BBY ozonesonde data. The downward progression of increasing O_3 that began near the tropopause on August 5th, reached 5 km by the August 9th, the lowest 1 km on August 13th, and left no trace by August 14th (Figs. 21a, c). Figure 25 shows an increase in O_3 at 1 km and Placerville, no change to 800-m O_3, and a decrease in 600-m O_3 on August 10th, followed by an increase in O_3 at BBY 0.6 – 1.0 km and Placerville on August 11th and 12th. Then, a decrease in O_3 at all levels on August 14th.

This increase followed by a decrease is a general trend at many sites (i.e., a peak in mid-August ozone concentrations). This analysis indicates that the 0.6 – 1.0 km elevated region was influenced by 10 – 20 ppb of stratospheric O_3 per day as it progressed downward on August 11th – 14th, 2016 above Northern California during the afternoon peak O_3 hour. Overall, the results suggested that either influence of the stratosphere was extremely widespread or further meteorological conditions complicate the interpretation. In other words, stratospheric influence can be detected in Placerville.

F. Tables

Table 1. Stratospheric Intrusion Cases During CABOTS

Stratospheric Intrusion Cases		
Date	**Extent of Intrusion (km)**	**Synoptic conditions**
May 18	5 km	Low pressure on north, omega flow over BBY
May 23	4 km	Long-wave trough
May 25	8 km	Similar as May 18
May 27-29	8.5 km	Trough to the north, building ridge over BBY
Jun. 10-11	5.5 km	long wave trough
Jun. 13, 15-16	5 km	upper level low, trough, onshore strong wind.
Jun. 18	3 km	Strong trough, jet stream
Jul. 6	6 km	Weak long-wave trough
Jul. 12	4.5 km	Weak upper level low, Jet stream
Aug. 2-3	8 km	Omega flow on the north, jet stream
Aug. 6	4 km	Cut-off upper level low
Aug. 9-10	5 km	Upper level trough

Table 2. Low Tropopause Cases During CABOTS 2016

Low Tropopause Cases		
Date	Altitude/ Vertical Depth	Synoptic Conditions Present
May 20-21*	Tropopause down to 8km	Upper level low, cut-off low, cold front, trough
May 23	9 km	Long-wave trough
Jun. 15	8 km	upper level low, trough, onshore strong wind.
Aug. 5	6 km	Cut-off upper level low
Aug. 7	6 km	Cut-off upper level low

Table 3. Number of Stratospheric Intrusion Days and Low Tropopause Days During CABOTS

Number of Stratospheric Intrusion days	%	Number of Low Tropopause Days	%
19	22.10 %	6	7.14 %

Table 4. Classification of Stratospheric Intrusion and Low Tropopause Events by Synoptic Condition.

Upper Level Trough to the North	7	Upper level low, trough	5
Subtropical Jet stream	2	Cut-off low pressure system	4
Omega pattern	6	Long-wave upper level trough	1
Long-wave trough	4		

Table 5. Surface Ozone Monitoring Sites Used for Stratospheric Ozone Transport Analysis.

Name	Latitude (°N)	Longitude (°W)	Elevation a.s.l. (m)
Grass Valley (GV)	39.23352	121.05567	865
Colfax (Cfx)	39.09979	120.95391	738
Placerville (Pvle)	38.72528	120.82192	612
Cool (Cl)	38.89094	121.00337	473
Auburn (Ab)	38.93568	121.09959	434
Folsom - Natoma (FN)	38.68329	121.16444	108
Roseville (Rvle)	38.74643	121.26498	60
Sloughhouse (Sh)	38.49444	121.21115	59
Lincoln (Ln)	38.88559	121.30199	47
North Highlands (NH)	38.71209	121.38108	33
Del Paso (DP)	38.61374	121.36801	30
Davis (Dvs)	38.53455	121.77340	19
T - Street (TSt)	38.56844	121.49311	15
Bodega Bay (BBY)	38.31869	123.07197	12
Elk Grove (EG)	38.30256	121.42083	7

Table 6. Correlation coefficients for the calculated MDA8 O3 comparison of exact time and hour observations at two given stations. The SAC sites are listed in order of lowest elevation to highest elevation above sea level. The bold, italicized values highlight the strongest correlations for each surface monitoring station.

	BBY	EG	TSt	Dvs	DP	NH	Ln	Sh	Rvle	FN	Ab	Cl	Pvle	Cfx
EG	***0.38***	1.00												
TSt	0.26	0.94	1.00											
Dvs	0.24	0.94	***0.97***	1.00										
DP	0.24	***0.95***	***0.98***	0.95	1.00									
NH	0.23	0.91	0.96	0.94	***0.97***	1.00								
Ln	0.20	0.91	0.92	0.89	0.92	0.92	1.00							
Sh	0.22	0.92	0.96	0.92	0.96	0.94	0.90	1.00						
Rvle	0.14	0.90	0.92	0.88	0.93	0.93	***0.93***	0.91	1.00					
FN	0.18	0.91	0.94	0.89	0.95	0.94	0.93	***0.97***	***0.95***	1.00				
Ab	-0.02	0.69	0.71	0.66	0.74	0.75	0.80	0.75	0.82	0.82	1.00			
Cl	0.04	0.78	0.79	0.75	0.82	0.82	0.84	0.82	0.89	0.89	***0.94***	1.00		
Pvle	-0.06	0.48	0.58	0.49	0.59	0.57	0.62	0.68	0.67	0.74	0.81	***0.84***	1.00	
Cfx	0.10	0.79	0.81	0.80	0.83	0.84	0.84	0.81	0.85	0.84	0.89	***0.90***	0.67	1.00
GV	-0.16	0.07	0.12	0.02	0.16	0.15	0.26	0.22	0.23	0.28	***0.58***	0.44	0.43	0.43

Table 7. Correlation coefficients for high elevation surface O3 values observed for the 2100 UTC hour with elevated Bodega Bay 2100 UTC ozonesonde measurements. The bold values denote the strongest correlations observed for each inland surface station.

Correlation Coefficient	BBY 400m	BBY 500m	BBY 600m	BBY 700m	BBY 800m	BBY 900m	BBY 1km	BBY 2km
Auburn	0.129	0.171	0.313	0.317	0.304	0.207	0.193	**0.561**
Cool	0.277	0.346	0.434	0.421	0.408	0.307	0.299	**0.506**
Placerville	0.497	0.578	**0.608**	0.573	**0.613**	0.577	**0.609**	0.496
Colfax	0.294	0.245	0.285	0.285	0.287	0.221	0.294	**0.429**
Grass Valley	0.220	0.291	0.327	0. 364	**0.379**	0.292	0.322	0.378

Table 8. O3 observations and daily variations in O3 observed at the three elevated BBY points of interest and at the Placerville surface monitoring station for the dates of interest. Red values are all decreases.

	BBY 1 km			BBY 800 m			BBY 600 m			Placerville 612 m		
Date	ppb	Δ ppb	Δ O3%	ppb	Δ ppb	Δ O3%	ppb	Δ ppb	Δ O3%	ppb	Δ ppb	Δ O3%
26-Jul	62	15	32	53	14	36	48	12	33	92	2	2
27-Jul	47	-15	-24	45	-8	-15	35	-13	-27	90	-2	-2
3-Aug	88	41	87	62	41	91	54	17	46	90	33	58
4-Aug	60	-28	-32	47	-44	-51	27	-27	-100	68	-27	-24
11-Aug	59	10	20	54	11	26	40	10	33	88	10	13
12-Aug	77	18	31	65	11	20	50	10	25	97	9	10
13-Aug	68	-9	-12	71	6	9	61	11	22	93	-4	-4
14-Aug	52	-16	-34	52	-19	-27	43	-18	-42	82	-11	-12

4. Discussion

Our results show that stratospheric intrusion events occurred during the summer of 2016 and that these events can impact ozone concentrations at high elevation surface sites. Lin et al. (2012) notes that SI events can happen in the summer with the presence of deep upper level troughs in SI prone areas such as Western North America. Our results show that Placerville experienced about a 10-20 ppb increase just after August 9th, and the other high elevation sites around it experienced similar increases. Interestingly, the O_3 keeps increasing for a few days after the initial increase of a SI event. Placerville's MDA8 reached well above 80 ppb from August 10th – 12th, which is well above the NAAQS.

The high O_3 concentrations measured at HMB and BBY near 2 km above the coastal marine boundary layer is an occurrence worth exploring further, especially due to the fact that a possible source of the air came from the Soberanes Fire. Even though this observation was measured above the surface, Pfister et al. (2012) shows that wildfire emissions can cause MDA8 surface O3 to be increased by as much as 10-15 ppb. Also, they point out that a significant source of NO_2, a well-known O3 precursor group and PAN (peroxyacetyl nitrate) can come from cooler-burning boreal, extratropical forests. PAN may undergo thermal decomposition if the air descends dry adiabatically or warms. Thermal decomposition of PAN creates extra sources of NO2, which when reacting with other sources of non-methane organic gases from wildfire emissions and sunlight could produce more O_3, however, it is an extremely complex problem with numerous possibilities. Fig. 10b shows that many trajectories did descend as the air flowed around the high-pressure area to the east, so it is possible that PAN and NO_x may have been transported out over the ocean and experienced various photochemical reactions enhancing O_3 before reaching HMB. Another question worth exploring in the future is whether this high O_3 layer affected any surface air through vertical mixing of the afternoon boundary layer or whether it affected any high elevation sites.

5. Summary and Conclusions

SJSU released near-daily ozonesondes at Bodega Bay and Half Moon Bay, two coastal locations west and northwest of the San Francisco Bay Area during CABOTS 2016. The objective of this project was to measure tropospheric O_3 at a near-daily timescale from late May through mid-August during the height of late spring and summer O_3 season for California in order to study how baseline O_3 might affect surface stations across the state.

The first part of the ozonesonde analysis focuses on the observed ozone profiles during the entire time period and comparisons of these with values from THD. From May through August, the vertical O_3 profiles during CABOTS show a very complex vertical patterns of tropospheric O_3 during Spring and Summer for coastal California. There were two general periods of stratospheric O_3 influencing the mid-troposphere during the first half of CABOTS: May 16th – May 24th and June 9th – 18th. During the Summer, the two time periods of June 30th – July 10th and July 23rd – August 9th also show observed elevated tropospheric O_3, however the first summer period, there was no real UTLS O_3 influence, and the latter period shows higher O_3 almost a week prior to a lowered troposphere until August 2nd. Also, California's very active wildfire season of 2016 may have had some influence on the measurements, especially the high O_3 layer of 120 ppb and higher observed on July 27th at BBY and HMB ozonesondes. On, August 3rd BBY's O_3 measurements also may have been enhanced due to the presence of the 2016 Cold Fire in Yolo County.

Climatology comparisons with mid-tropospheric O_3 values a THD show that median mid-tropospheric O_3 values at BBY and HMB were approximately 5 ppb less than THD's median.

Monthly mean comparisons of THD and BBY ozonesonde profiles show that in May, BBY in the low-troposphere was about 10 ppb below THD. In June near the 3-km layer, BBY was above THD's June average by 15 ppb. BBY measured above average O_3 by 10 ppb in the low troposphere.

The second part of this analysis of the 2016 CABOTS ozonesonde measurements focused on analyzing SI and LT events. There was evidence from the BBY ozonesondes and analysis from MERRA-2 that there were 19 individual SI events, which accounted for almost 20% of the CABOTS days, and there were 5 LT events, which was about 7% of the days. Most SI and LT events were accompanied by late-season strong upper level troughs and cut-off low. This study documented a strong LT case on May 20th 2016 with a tropopause height as low as 8 km and a well-defined SI event on June 18th, 2016 with the SI extending down to 3 km.

Further analysis of BBY ozonesondes and MERRA-2 analysis shows evidence of SI events during the second half of CABOTS during the summer and causing increases to elevated surface O_3 sites in the Sierra Nevada Foothills, but not significant increases in surface O_3 to sites in the Central Valley. This last part of the CABOTS analysis focused on the period of July 25th – August 13th. During this time, the dynamic tropopause height fluctuates between 14 and 10 km, but with evidence of 3 SIs during the time period. The first SI case occurred on July 27th – 28th with a SI extending down to 7 km at BBY, which also experienced an approximate O_3 change of 250 % at 11 km. The 6 – 8 km layer experienced 100% change in O_3, and the lowest level experienced a 50% increase in O_3 as a result. The second SI case occurred on August 5th-6th and extended down to 4 km, the lowest extension of the three late season cases. Cases 1 and 2 noted a time frame of about 4 to 6 days for the SI to affect surface O_3 values at BBY. The third SI case occurred on August 9th with an SI extending down to 6 km. Although the extension was not as deep, this case saw almost a 400% change in O_3 near 11 km at BBY, and it was the strongest case for stratospheric intrusion affecting the high elevation site of Placerville, CA. Placerville's surface O_3 showed the highest correlation (0.61) with O_3 measured at BBY in the 0.6-1 km layer, and it observed a 10-20 ppb increase in O_3 because of the SI event.

Although the ozonesonde measurement frequency at THD, BBY and HMB were different during CABOTS, the results suggested that BBY ozone profile concentration was well below average in the lower troposphere compared to the THD mean in spring (i.e., May). In June, BBY was about 15 ppb higher than THD's June average at 3km. During August BBY was about 10 ppb higher than THD's average near 1 km above sea level. These spatial variations of ozone concentration at THD and BBY suggested the synoptic weather systems passing through THD and BBY at different time periods.

Although BBY and HMB had similar features for most of strong intrusion days due to the closed location, ozone profiles showed clear different feature in the middle troposphere when the northern CA is under high pressure. For instance, under intrusion favorable weather patterns (i.e., upper level low pressure), the ozone profiles in different locations show similar features. Nevertheless, if without strong intrusion features, high ozone in middle troposphere varied more significantly at two different locations. In such conditions, other ozone sources such as long-range transportation rather than subsidence may need to be considered.

6. Recommendations

A baseline ozone has been established due to decades of weekly ozonesonde data collected at Trinidad Head (THD) CA. Studies have shown connections between the elevated ozone (1 - 5 km) at THD and surface O_3 observed in the North Sacramento Valley. The 2016

California Baseline Ozone Transport Study (CABOTS) collected the near-daily upper air ozone which further demonstrated that baseline O_3 which enters California air basins through the San Francisco Bay, progresses generally eastward across the Delta, and diverges at the foothills to influence air basins to the north and south.

Overall, the current THD site cannot completely represent the baseline O_3 enters California. From CABOTS we have learned that the distance between THD to BBY and/or HMB does create temporal and spatial variations of upper air ozone differences in northern California. Therefore, to establish a long-term fixed location for measuring upper air O_3 entering the California Air Basins from the south opening of the mouth to the SF Bay is essential. It is invaluable to have a long-term measurement of the uncontaminated O_3 travel upstream and into the California Air Basins. The upper air O_3 entering from the coast, especially in the lower 3 - 7 km, are known to possess long-range emissions across the Pacific. With the impacts of local emissions reduced, the baseline ozone shall have a greater impact on the Regional Air Quality. This is thought to be shown as a reduction in observed concentrations, and an improvement in air quality. Yet with uncertainties from long-range transported O_3 under climate change conditions, the improvement of Regional Air Quality in CA would be affected significantly.

It is, therefore, recommended that in addition to THD, weekly ozonesonde launches from Half Moon Bay is imperative to advance our understanding of how the baseline O_3 that channels through the SF bay area and transported inland, with potential to mix toward the surface, and to influence other regions. With weekly ozonesondes releases at HMB, or periodic airborne measurements of upper air O_3 around south opening of the mouth to the SF Bay, the seasonal dependence of SI and LT events as well as the variability of long-range transported O_3 can be further explained.

References

Bethan, S., Vaughan, G., & Reid, S. J. (1996): A comparison of ozone and thermal tropopause heights and the impact of tropopause definition on quantifying the ozone content of the troposphere. *Quarterly Journal of the Royal Meteorological Society*, 122(532), 929-944.

Bourqui, M. S., and P.-Y. Trépanier, 2010: Descent of deep stratospheric intrusions during the ION August 2006 campaign, *J. Geophys. Res.*, **115**, D18301, doi:10.1029/2009JD013183.

Cooper, O. R., J. L. Moody, D. D. Parrish, M. Trainer, T. B. Ryerson, J. S. Holloway, G. Hubler, F. C. Fehsenfeld, S. J. Oltmans, and M. J. Evans, 2001: Trace gas signatures of the airstreams within the North Atlantic cyclones: Case studies from the NARE'97 aircraft intensive, *J. Geophys. Res.*, **106(D6)**, 5437-5456, doi:10.1029/2000JD900574.

Cooper, O. R., et al. (2010): Increasing springtime ozone mixing ratios in the free troposphere over western North America, *Nature*, *463* (7279), 344-348, doi:10.1038/nature08708.

Cooper, O. R., et. al. (2011): Measurement of western U.S. baseline ozone from the surface to the tropopause and assessment of downwind impact regions, *Journal of Geophysical Research*, 116, doi:10.1020/2011JD016095.

Cox, B. D., M. Bithell, L. J. Gray, 1997: Modelling of intrusions within a mid-latitude synoptic-scale disturbance, *Q. J. R. Meteorol. Soc.*, **123**, 1377-1403.

Danielson, E. F., R. S. Hipskind, S. E. Gaines, G. W. Sachse, G. L. Gregory, and G. G.Hill, 1987: Three-dimensional analysis of potential vorticity associated with tropopause folds and observed variations in ozone and carbon monoxide, J. Geophys. Res., 92(D2), 2103-2111, doi:10.1029/JD092iD02p02103.

Ding, A., and T. Wang, 2006: Influence of stratosphere-to-troposphere exchange in the seasonal cycle of surface ozone at Mount Wiliguan in western China, *Geophys. Res. Lett.*, **33**, L03803, doi:10.1029/2005GL024760.

Emmons, L. K., et. al., 2010: Description and evalutation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4), *Geosci. Model Dev.*, **3**, 43-67, https://doi.org/10.5194/gmd-3-43-2010.

Environmental Protection Agency (2015), National Ambient Air Quality Standards for Ozone. *Federal Register*, **80**, 65292-65468, available at https://www.gpo.gov/fdsys/pkg/FR-2015-10-26/pdf/2015-26594.pdf.

Fast, J. D., and Coauthors, 2012: Transport and mixing patterns over Central California during the carbonaceous aerosol and radiative effects study (CARES), Atmos. *Chem. Phys.*,**12**, 1759-1783, doi:10.5194/acp-12-1759-2012.

Fiore, A. M., et. al. (2008): Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality, *Journal of Geophysical Research*, 113, doi:10.1029/2007JD009162.

Goldstein, A. H., et. al. (2004): Impact of Asian emissions on observations at Trinidad Head, CAlifornia, during ITCT 2K2, *Journal of Geophysical Research*, 109, doi:10.1029/2003JD004406.

Hoskins, B. J., McIntyre, M. E., and Robertson, A. W., 1985: On the use and significance of isentropic potential vorticity maps, *Quart. J. R. Met. Soc.*, **111**, 877-946.

Hsu, J., and M. J. Prather, 2009: Stratospheric variability and tropospheric ozone, *J. Geophys. Res.*, **114**, D06102, doi:10.1029/2008JD010942.

Jaffe, D. and Ray, J. (2007): Increase in surface ozone at rural sites in the western US, *Atmos Environ*, 41 (26), 5452-5463, doi:https://doi.org/10.1016/j.atmosenv.2007.02.034.

Langford, A. O., K. C. Aikin, C. S. Eubank, and E. J. Williams, 2009: Stratospheric contribution to high surface ozone in Colorado during springtime, *Geophys. Res. Lett.*, **36**, L12801, doi:10.1029/2009GL0383367.

Lin, M., et al. (2012): Springtime high surface ozone events over the western United States: Quantifying the role of stratospheric intrusions, *Journal of Geophysical Research*, 117, doi:10.1029/2012JD018151.

Lin, M., A. M. Fiore, L. W. Horowitz, A. O. Langford, S. J. Oltmans, D. Tarasick, and H. E. Rieder, 2015: Climate variability modulates western US ozone air quality in spring via deep stratospheric intrusions, *Nature Communication*, **6**, 7105, doi:10.1038/ncomms8105.

Liu, G., D. W. Tarasick, V. E. Fioletov, C. E. Sioris, and Y. J. Rochon, 2009: Ozone correlation lengths and measurement uncertainties from analysis of historical ozonesonde data in North America and Europe, J. Geophys. Res., 114, D04112, doi:10.1029/2008JD010576.

Oltmans, S. J., et al. 1996: Summer and spring ozone profiles over the North Atlantic from ozonesonde measurements, J. Geophys. Res., 101(D22), 29179-29200, doi:10.1029/96JD01713.

Parrish, D. D. et al. (2009): Increasing ozone in marine boundary layer inflow at the west coasts of North America and Europe, *Atmos. Chem. Phys.*, 9 (4), 1303-1323.

Pfister, G. G., Wiedinmyer, C., & Emmons, L. K. (2008): Impacts of the fall 2007 California wildfires on surface ozone: Integrating local observations with global model simulations. *Geophysical Research Letters*, 35(19), doi.10.1029/2008GL034747

Roelofs, G. J., et al., 2003: Intercomparison of tropospheric ozone models: Ozone transport in a complex tropopause folding event, J. Geophys. Res., 108(D12), 8529, doi:10.1029/2003JD003462.

SJSU CABOTS, 2016: Bodega Bay Launch Blog, June 2018, sites.google.com/a/sjsu.edu/cabots-sjsu/daily-blog.

Srivastava, S. and Sheel, V. (2012): Study of troposheric CO and O3 enhancement episode over Indonesia during Autumn 2006 using the Model for Ozone and Related chemical Tracers (MOZART-4), *Atmos. Environ.*, 67, http://dx.doi.org/10.1016/j.atmosenv.2012.09.067.

Škerlak, B., M. Sprenger, and H. Wernli, 2014: A global climatology of stratosphere–troposphere exchange using the ERA-Interim data set from 1979 to 2011, Atmos. Chem. Phys., 14, 913-937, doi:10.5194/acp-14-913-2014.

Stohl, A., et al., 2003: Stratosphere-troposphere exchange: A review, and what we have learned from STACCATO, *J. Geophys. Res.*, **108(D12)**, 8516, doi:10.1029/2002JD002490.

Task Force on Hemispheric Transport of Air Pollution (2010), Hemispheric Transport of Air Pollution 2010 Part A: Ozone and Particulate Matter, available at http://pure.iiasa.ac.at/id/eprint/14571/1/HTAP%202010%20Part%20A%20110407.pdf.

Trickl, T., H. Vogelmann, H. Giehl, H.-E. Scheel, M. Sprenger, and A. Stohl, 2014: How stratospheric are deep stratospheric intrusions?, Atmos. Chem. Phys.,14, 9941-9961, doi:10.5194/acp-14-9941-2014.

Glossary of Terms, Abbreviations, and Symbols

Sign	Description	Unit
a.s.l	Above sea level	
BAAQMD	Bay Area Air Quality Management District	
BBY	Bodega Bay, CA	
CABOTS	California Baseline Ozone Transport Study	
ECC	Electrochemical Concentration Cell	
EPA	Environmental Protection Agency	
GFS	Global Forecast System	
HMB	Half Moon Bay, CA	
hPa	hectoPascal	
HTAP	Hemispheric Transport of Air Pollution	
LT	Low Tropopause	
MDA8	Maximum Daily 8-hr Average	
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2	
MOZART	Model for Ozone and Related Chemical Tracers	
NAAQS	National Ambient Air Quality Standard	--
NCAR	National Center for Atmospheric Research	
NOAA	National Oceanic Atmospheric Administration	--
NO_2	Nitrogen Dioxide	
NO_x	Nitric oxides	
O_3	Ozone	ppb
PacNW	Pacific Northwest	
PAN	Peroxyacetyl Nitrate	
ppb	parts per billion	
PV	Potential Vorticity	PVU
PVU	Potentinal Vorticity Unit	

RH	Relative Humidity	%
SAC	Sacramento	
SH	Specific Humidity	g/kg
SI	Stratospheric Intrusion	
SIP	State Implementation Plan	
SJSU	San José State University	--
UTC	Universal Time Coordinate	
UTLS	Upper Troposphere Lower Stratosphere	