TECHNICAL PROPOSAL

Improved Understanding Of The Magnitude Of Trans-Pacific Long Range Transported Ozone Aloft At California's Coast

Principal Investigator:
Ian Faloona

Prepared for:
State of California
Air Resources Board
Research Division
PO Box 2815
Sacramento CA 95812

Prepared by:
University of California, Davis
One Shields Avenue
Davis, CA 95616
(530) 752-7782

February 27, 2015

ABSTRACT

This research contract proposes to routinely sample the lower 8000 m of the troposphere, six days a week throughout the ozone season (June-Sept), measuring ozone (O_3), nitrogen dioxide (NO_2), temperature, relative humidity, and horizontal winds with the use of a well-instrumented scientific research aircraft operated by Scientific Aviation, Inc. The daily sampling will start from UC Davis, climbing to 8km while ferrying to the site of the first of two deep helical profiles: offshore near Half Moon Bay. The profile will go as low as possible given the likely stratocumulus cover of the marine layer during this time of year, which typically lies below 400 m altitude. Then ferrying offshore to the Bodega Marine Laboratory, the second deep profile will be followed by a transit back to Davis. The sampling circuit will take approximately four hours of each sampling day, and will yield not just two deep offshore profiles with which to monitor the inflow of extra-continental ozone into California, but will also crucially provide vertical O_3, NO_2, and wind structure over the coast range to help track the transport patterns to surface sites inland. This unique data set will provide unprecedented observational constraints to support modeling of the impacts of long-range transport of ozone, and ozone precursors, throughout California. Furthermore, there are two important points of potential synergy with contemporaneous work in our group. The first is semimonthly profiles taken for NOAA GMD's greenhouse gas monitoring project, can also carry the O_3/NO_2 payload, thereby providing in-kind supplemental profile data at Trinidad Head to the north. The second, assuming the continuance of support for our monitoring site at Chews Ridge, which we have been conducting for the past three years, will provide the addition of continuous ozone and NO_x data slightly farther south at 1.5 km elevation. An alternative research plan is also proposed that would extend the sampling period to span the spring and summer seasons and more carefully investigate the vertical mixing of ozone from aloft to surface sites inland. ARB and the broader scientific community will benefit from this unprecedentedly thorough characterization of background ozone that provides the baseline for California's ozone air quality. This detailed knowledge of the baseline ozone is necessary for the design of effective State Implementation Plans (SIP) to attain the current and future national ambient air quality standards (NAAQS) for ozone.

INTRODUCTION

Because health effects research has consistently led to more stringent ambient air quality standards for ozone, California must continue to achieve significant new reductions in ozone precursor emissions. The SIP planning process must demonstrate how ground-level ambient ozone will be reduced over time to levels below the health-based standards. At the same time, baseline ozone concentrations have been increasing. Intermittent field studies have documented instances of elevated ozone concentrations aloft (associated with global, regional, and local sources) that could potentially be relevant to ground level exceedances. There have been limited, episodic campaigns of instrumented aircraft flights sponsored by federal, state, and regional groups (e.g., the National Oceanic and Atmospheric Administration [NOAA], the National Aeronautics and Space Administration [NASA], the San Joaquin Valley Air Pollution Control District, the ARB) as well as weekly ozonesonde launches on the north coast of the State (sponsored by NOAA) to investigate ozone events and processes. But these isolated efforts do not provide sufficient information to fully understand the spatial and temporal variations in baseline ozone concentrations entering California. Modeling exercises focused on the contributions of long-range transport and the stratosphere to ozone in the western United States (including California) have been conducted. However, these photochemical models rely on atmospheric boundary conditions specified by coarse resolution global models that have not performed well historically in California due to its complex terrain and meteorology. To better understand the contributions of the external pollution sources and atmospheric processes to high surface ozone concentrations in the State, a routine monitoring program is needed to document incoming layers of ozone aloft from the Pacific Ocean. The data and information collected in this project will help to validate and improve the atmospheric boundary conditions used in the ozone SIP modeling. This research project is a necessary first step toward understanding the difficult policy relevant question of what is the contribution of Pacific long-range transported ozone to surface sites in the state. Additional surface and upper air ozone measurements in specific locations of interest will be needed to estimate the contribution of long-range transported ozone aloft to surface ozone at a surface site.

Along with our ever expanding understanding of the causes of air quality degradation, the detrimental effects of ozone are becoming more clearly understood to include human and ecosystem health, as well as to have impacts on the climate system as a direct greenhouse gas, and to influence the global carbon and water cycles [Lombardozzi et al., 2015]. Because of such findings, there is a continual push towards lowering air quality standard thresholds. Meanwhile our understanding of the transport of air pollutants from outside of U.S. environmental jurisdiction is also developing to the point where incidents of elevated ozone influx (50-60 ppbv) have been modeled that seriously compromise the ability of local regulatory action to comply with the current, let alone future reductions in, air quality standards [Emery et al., 2012; Fiore et al., 2014; Lin et al., 2012]. These background intrusions of ozone have a multitude of extracontinental sources including boreal fires, lightning, stratosphere-troposphere exchange [Zhang et al., 1014], and the long-range transport of anthropogenic pollution from overseas [Parrish et al., 1992; Jacob et al., 1999; Liang et al., 2004; Hudman et al., 2004; etc.].

Several modeling studies have shown that the fidelity of simulated surface ozone is improved when constrained by actual lateral boundary conditions [Tang et al., 2009; Huang et al., 2010;

Lin et al., 2012], whether it be from ozonesondes or aircraft or satellite measurements. Additional modeling efforts point toward the connection between transported ozone and surface concentrations being a function of specific mesoscale flow patterns characteristic of the complex mountainous terrain of the Western US, implying that the impacts may be underestimated by the current coarse models used to estimate the background influence.

Recent work with the NOAA GMD ozonesonde data from Trinidad Head on the coast of Humboldt County has provocatively demonstrated correlations between the ozone measured by sonde between 1-2 km above the coast with surface ozone levels [Parrish et al., 2010; Huang et al., 2010] in the Northern Sacramento Valley. These correlations appeared particularly significant at elevated sites such as Lassen National Park (1760 m, r=0.61), Yreka (800 m, r=0.70), and Tuscan Butte (570 m, r=0.50). More recently, monitoring ozone from a mountainous coastal site in Monterey County, our group has found similar correlations with surface MDA8 ozone in Stockton, Fresno, and Arvin. The correlations appear to change systematically with season, consistent with differing dominant flow patterns that transport air flowing over the coast range into the San Joaquin Valley.

Thus a multitude of evidence now suggests that ozone carried in from exogenous sources overseas can significantly influence surface ozone throughout California. Evidence has been presented indicating that the northern hemisphere background ozone may be decreasing in the past decade [Parrish et al., 2012; Logan et al., 2012], but this is especially pronounced in areas near and downwind of North America and Europe, and does not appear to be the case in the eastern Pacific basin. On the contrary, rising background O_3 entering North American shores appears to be the case, particularly in the spring [Cooper et al., 2010; Lin et al., 2012].

Jonson et al. [2010] studied 12 different global chemical transport models and their efficacy at depicting ozone profiles from four sites including Trinidad Head. They found that in the spring of 2001, the models' ozone correlated fairly well in the upper and mid troposphere ($0.3 < r < 0.7$), but predicted O_3 very poorly in the lower troposphere (700-900 hPa), the region where Parrish et al. [2010] found the best relationship to surface levels in the Northern Sacramento Valley. The correlation coefficients for the models and observations in this level of the atmosphere ranged from -0.4 to 0.4, with an multi-model average near ~ 0.10. Therefore, it seems that the North American inflow of ozone that is most important to surface levels in California is not being accurately reproduced in global models. Improved understanding of the linkage between exogenous ozone and surface air quality in California is thus reliant on detailed, continuous observations.

Based on modeling estimates of East Asian carbon monoxide emissions, Liang et al. [2004] suggested that incursions of long-range pollution typically occur every 10 days throughout the year in the upper troposphere, every 15 days in the mid-troposphere, and every 30 days in the lower troposphere. The only continuous monitoring of ozone in California has been conducted by NOAA's baseline station at Trinidad Head. Oltmans et al. [2008] compiled data from 10 years of semi-monthly ozonesondes launched from the site shown here in Figure 1. The data clearly show the spring peak in free tropospheric ozone, which is generally considered to be the combined result of increased fluxes from the stratosphere and the hemispheric rise in photochemical activity [Monks, 2000], with the proportion most likely dependent on exact location. Also apparent in Fig. 1 is the summertime O_3 minimum in the marine boundary layer due to peak photochemical destruction, and the somewhat reduced amounts present in the lower free troposphere when inland surface ozone exceedances are most common.

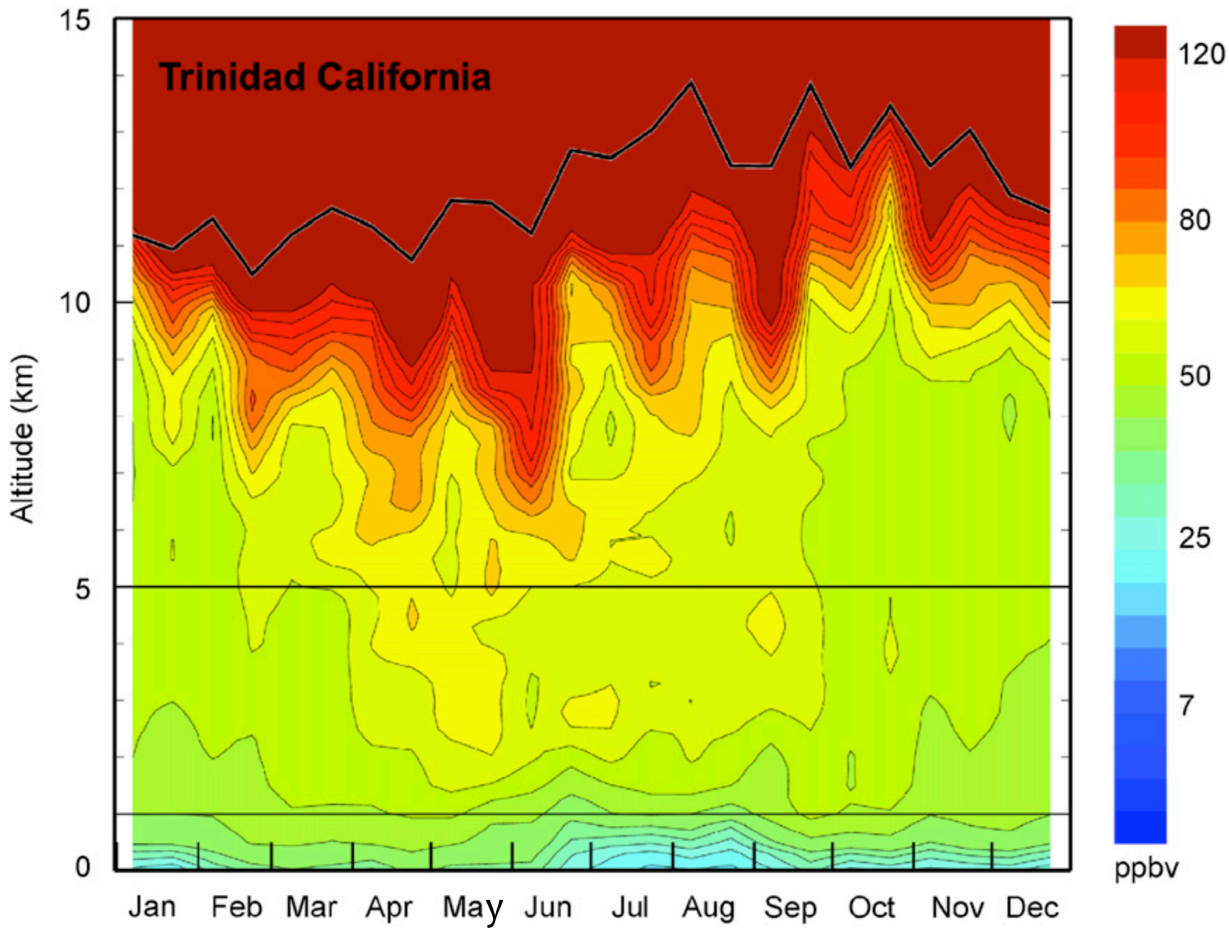


Figure 1. Cross section of annual cycle of ozone mixing ratio observed by sonde over Trinidad Head, California based on 10 years of semi-monthly measurements made by NOAA [Oltmans et al., 2008]. The black curve at the top represents the average thermal tropopause height.

Despite this invaluable depiction of the climatology of ozone entering the state, the sampling rate of twice a month is insufficient to resolve the episodic plumes that enter California in the lower troposphere from distant sources at the rate of once per month estimated by Liang et al. [2004].

On the other hand, total tropospheric ozone across the expanse of the transport region is available approximately daily by the Tropospheric Emission Spectrometer (TES) and Ozone Monitoring Instrument (OMI) satellite instruments. Figure 2 shows the monthly averages for June to August from 2005 of the OMI tropospheric ozone data product, which clearly indicates elevated ozone downwind of Asian sources. However, such data cannot discern at what altitude the ozone resides, and this, as demonstrated by Parrish et al. [2010], is crucial to predicting where the surface impacts will be realized. Clearly the observational network of ozone entering North American shores needs to be enhanced, and the proposed project suggests some ways that this might be accomplished in order to improve our ability to quantify the impacts of foreign ozone on California's air quality.

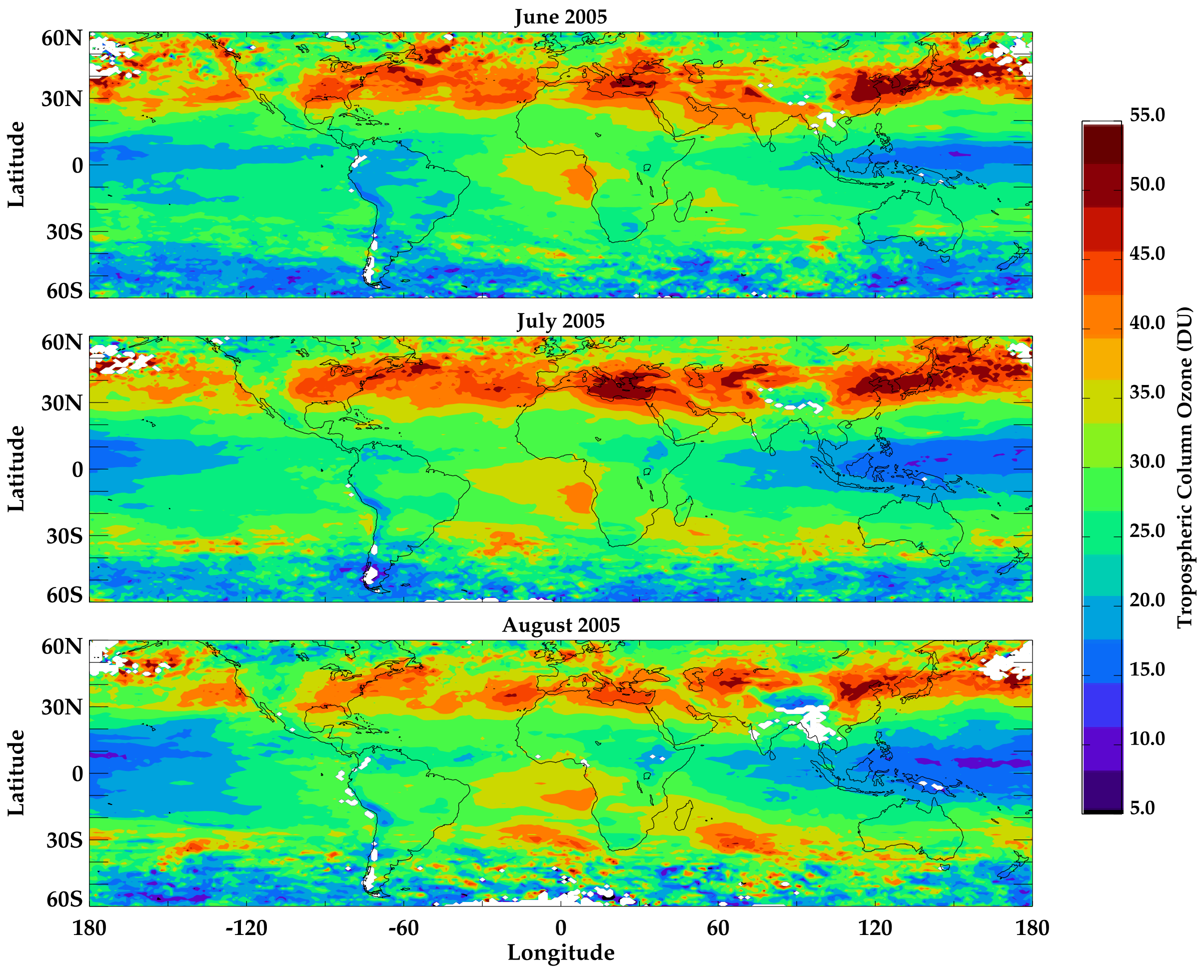


Figure 2. Monthly averaged tropospheric column ozone (in Dobson units) from the OMI instrument for the summer of 2005 [Ziemke et al., 2006].

OBJECTIVES

This research contract will deploy a wide array of airborne instrumentation to characterize the physical and chemical conditions of the troposphere at two inflow locations: one offshore of Half Moon Bay to capture flow that comes onshore near the San Jose valley and/or Monterey Bay, and the other near Bodega Bay to sample the flow that enters the state through the Petaluma gap and the San Francisco Bay Area. The airplane will be stationed at the UC Davis airport and will perform a four hour sortie at the same time each day (suggested 11:00-15:00 PST) six days a week for the entire months of June, July, August, and September. Transit legs will require constant ascent/descent out/in of UCD. At an ascent rate of 500'/min, it will take approximately 50 minutes to reach 26,000 ft (8.1 km), the ceiling of the Mooney TLS. The horizontal transit time from UCD to Half Moon Bay and from Bodega Bay to UCD is roughly comparable. At each location a spiral pattern approximately 5 km in diameter will be flown from 8 km to just above the marine boundary layer inversion, which is likely to cap the low stratocumulus so prevalent throughout the region in the summer. The stratus deck will preclude flying to the ocean surface because of instrument flight rules; however, the height of the cloud tops are typically below 500 m [Dorman et al., 2000]. The ozone in the marine boundary layer is very low in the summer (see Fig. 1), and is likely not an important contributor to trans-Pacific ozone entering California. The total daily flight time is estimated to be 4 hours and will measure winds, relative humidity, temperature, ozone, and NO_2 from about 0.5 to 8 km at two offshore locations. Additionally, slant profiles of these measurements will be made during the transit legs, which may be instructive in mapping the onshore wind and ozone flux patterns above the continental boundary layer. Figure 3 shows the geography of the approximate flight plan.

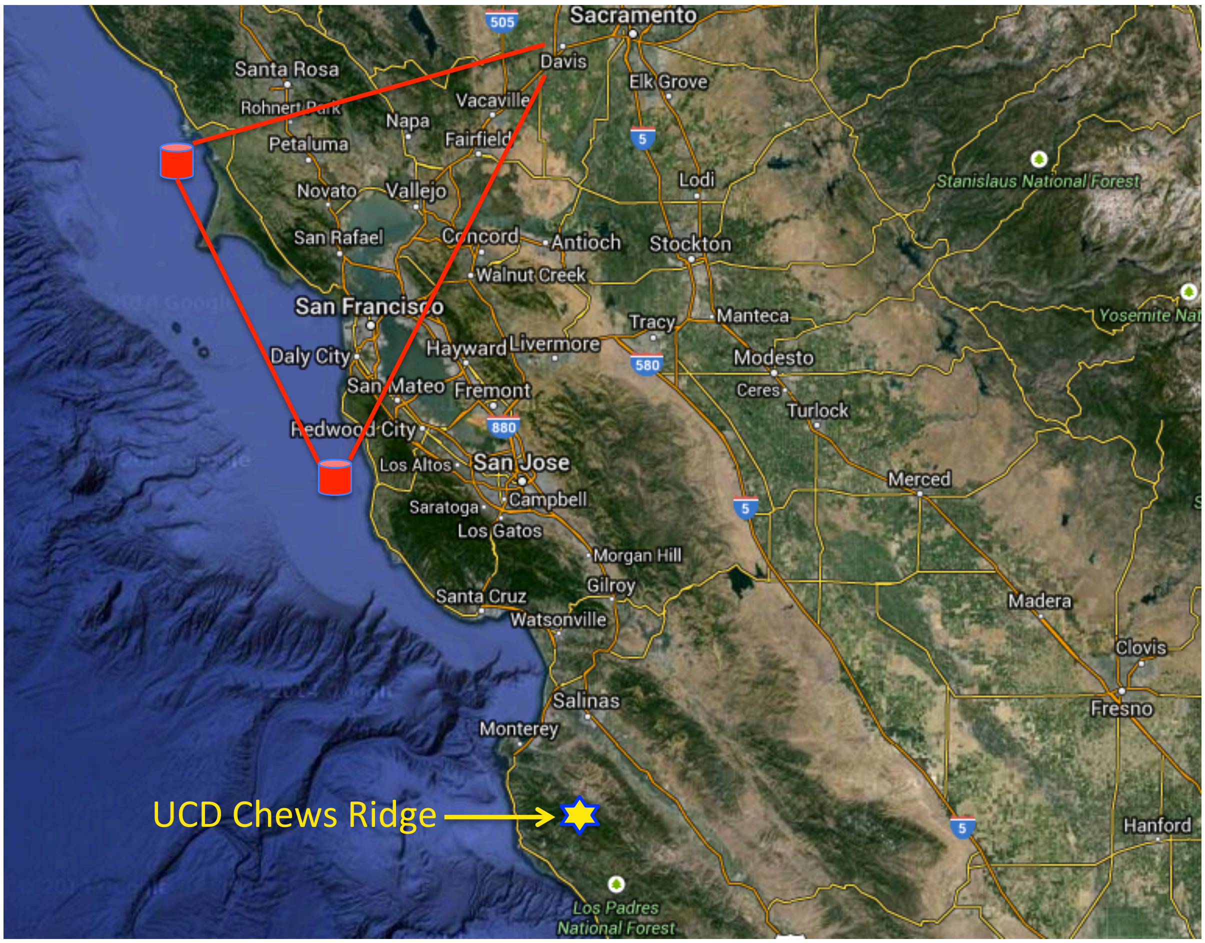


Figure 3. Google map of study region depicting the flight paths as red lines, deep profiles (from 0.5 – 8.0 km) as red cylinders, and the location of UCD's high altitude (1.5 km) climate sentinel site at Chews Ridge as a gold star.

The measurements will be used as vital, high-resolution lateral boundary conditions to ARB's modeling efforts to quantify the impacts of trans-Pacific ozone to California's surface air quality. Furthermore the thermodynamic and wind measurements (four distinct samplings from the near surface to 8km each day) can offer a rare opportunity to check the fidelity of the model's meteorology.

In addition, there are two projects that may have direct bearing on the proposed work, and will serve as value-added support to this research. The first is the ongoing contract of Scientific

Aviation with NOAA to perform their twice-monthly deep profiles (same altitude range as proposed here) at Trinidad Head. From the motivation of the proposed project, Scientific Aviation will perform those flights with the additional payload of the ozone and NO_2 instruments. In such a case there would be supplemental aircraft profiles available twice each month at the Trinidad Head site, the locus of a wealth of long term measurements. This added benchmark will prove invaluable in determining the representative nature of the 2016 ozone season to be sampled. And with this overlap, the proposed high-resolution study can be more readily extended to longer time scales and greater generality.

Secondly, if the proposed project is awarded, there is a high likelihood that our ongoing continuous ozone monitoring underway on Chews Ridge will be extended beyond its current end date of the winter of 2015 to include the period of this study. Chews Ridge is situated at 1500 m elevation in the Santa Lucia mountain range ~30 km east of Pt. Sur in Monterey County, and has provided many insights into the transport of ozone over the coast range and into the San Joaquin Valley. Analysis of these data indicate a substantial correlation between the mountain observations and ozone levels found near the top of the daytime maximum boundary layer over Fresno, and even surface ozone measured at Arvin, albeit to a smaller degree. It appears that continuous monitoring at the high elevation site can provide crucial boundary conditions to ozone modeling for the SSJV. Thus with these two ancillary data sources, the project can span a much greater extent of the California coast (from Trinidad Head to Pt. Sur), and be contextualized into the much longer data set collected by NOAA's Global Monitoring Division at their baseline station at Trinidad Head (approximately 25 years of O_3 sondes).

POSSIBLE ALTERNATIVE RESEARCH PLANS

The decision to fly one of the two deep profiles proposed here at Bodega Bay was born from practical considerations to minimize the transit time from UC Davis airport, but also from model results presented by Cooper et al., [2011]. In that work, the authors used forward trajectories calculated by FLEXPART (a state of the art Lagrangian particle dispersion model driven by 0.5 degree resolution winds from the National Centers for Environmental Prediction's Global Forecast System) to estimate the quantity of ozone in each 200 m layer that is transported to within 300 m of the ground throughout California. The trajectories were calculated from the ozonesonde profiles measured during their IONS-2010 (Intercontinental Chemical Transport Experiment Ozonesonde Network Study) campaign at four sites along the California coast (Trinidad Head, Pt. Reyes, Pt. Sur, and San Nicolas Island). The surface receptor sites were grouped into 7 regions throughout the state. Figure 4 is a reproduction of their results, which indicate that the sonde site with the greatest statewide influence by far is Pt. Reyes. The effect is particularly dramatic for air below 2 km altitude that winds up in the San Joaquin Valley, but not solely confined to the marine boundary layer, which tends to be capped at around 0.5 km. This would point towards significant transport of lower free troposphere air, flowing above the capping inversion from Pt. Reyes into the Southern Central Valley, where it is then entrained into the valley boundary layer.

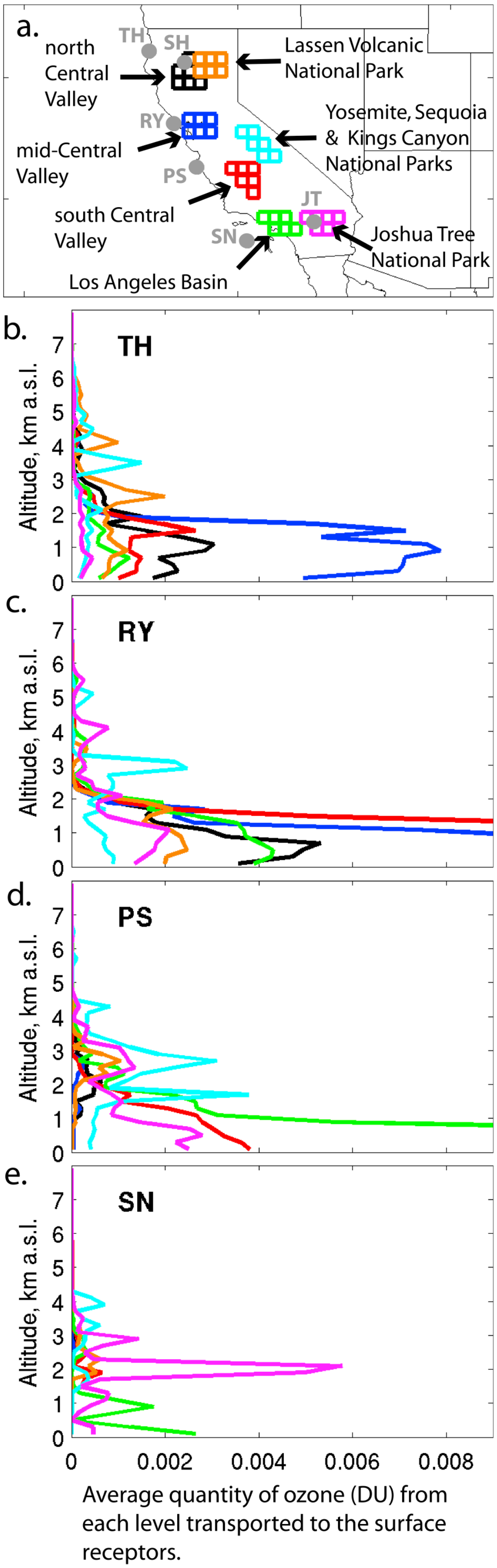


Figure 4. Average quantity of O_3 (in Dobson units) transported to the surface from each of the four IONS-2010 ozonesonde sites: TH – Trinidad Head; RY – Pt. Reyes; PS – Pt. Sur; SN – San Nicolas. The receptor regions are color coded in the top map. From Cooper et al., [2011].

Cooper's results in Figure 4 are also noteworthy because of the influence that the air column at Pt. Reyes has on the Los Angeles basin and the northern Sacramento Valley. However, the in the latter case it does seem to be confined to the traditional surface inflow through the Sacramento Delta at low elevations within the boundary layer, and consequently is less susceptible to long-range transport. Thus it is expected that the proposed profiling locations will be able to capture a broad range of inland impacts.

Nevertheless, there are a few interesting complications on further consideration. The data in Figure 4 was only run for the duration of the IONS-2010, which coincided with the CalNex program from May to June. In general, studies of the long-range transport of pollutants to North America have emphasized the springtime as the most important season for this effect to be observed. Indeed all of the recent targeted field campaigns, such as CalNex, ITCT, INTEX-B, and even ARCTAS-CARB, were all conducted between the months of April and June. Although this is when the effect has been most pronounced, it is out of phase with the peak in ozone exceedance events, which tend to take place consistently across June, July, August, and September. Figure 5 shows three consecutive years of weekly averaged MDA8 O_3 data from three stations in the ARB air monitoring network across the San Joaquin Valley: Fresno – Sierra Skypark, Arvin – DiGiorgio, and Lower Kaweah. The dashed vertical gridlines demarcate the beginning of each month from June to October. It is clear that peak values of this ozone metric take place nearly equally throughout June to September. In the course of research our group is currently conducting on Chews Ridge, we have found that the transport patterns are very distinct between the spring and summer months. Figure 6 illustrates the

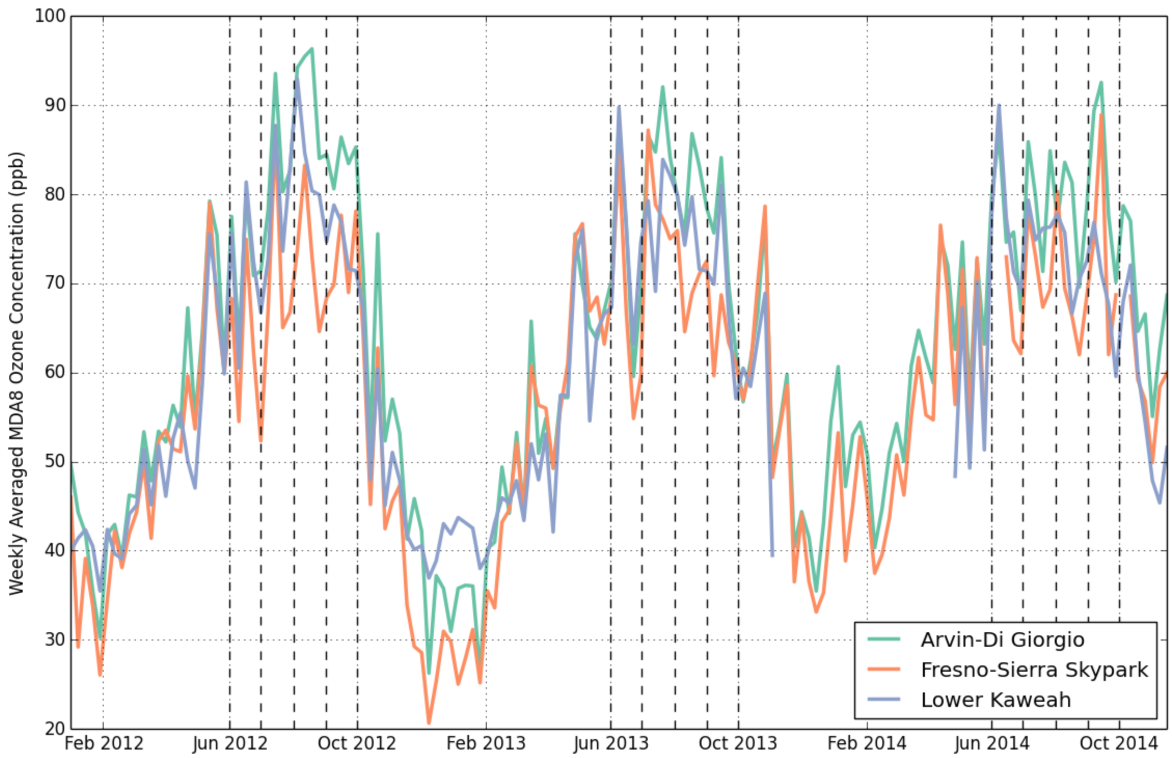
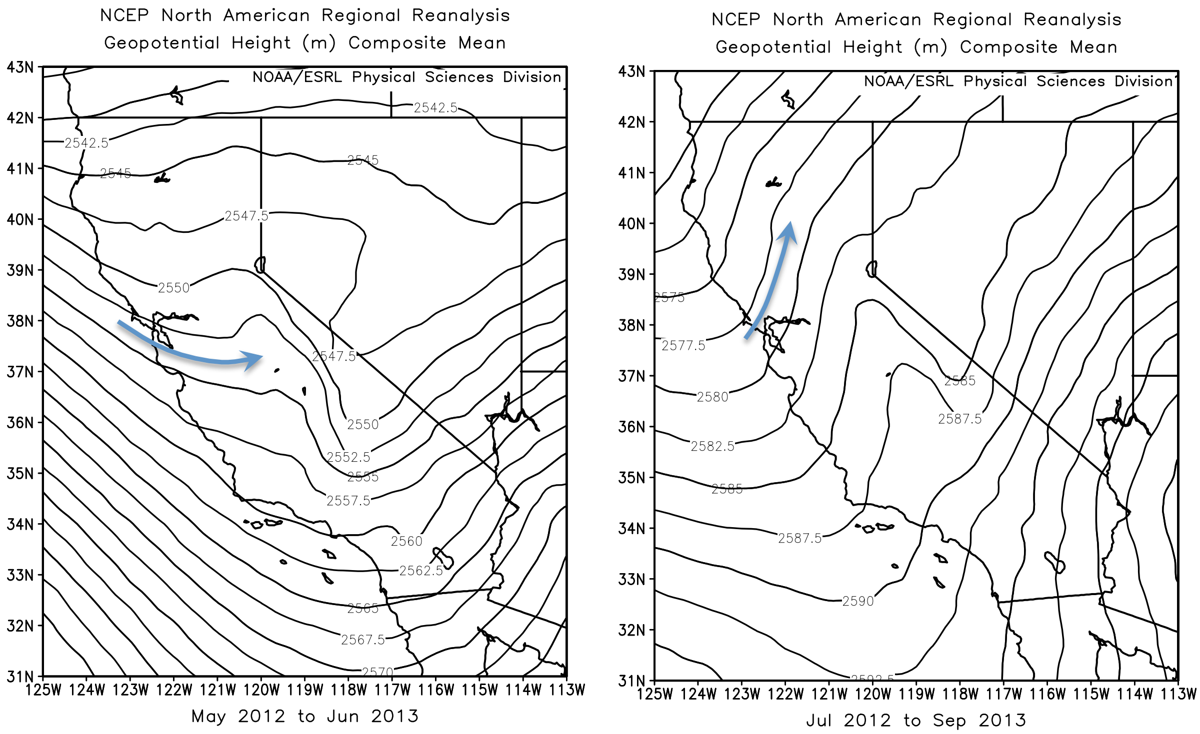


Figure 5. Weekly averaged MDA8 ozone data from 2012 – 2014 from three sites in the Southern San Joaquin Valley. The data is averaged weekly and the vertical dashed lines show the four months of the typical ozone season from June to September. Data courtesy of the CARB AQMIS [http://www.arb.ca.gov/aqmis2/aqmis2.php].

mean geopotential heights of the 750 hPa pressure surface across California from the NCEP North American Regional Reanalysis data set with a resolution of ~ 32 km in the horizontal. At this altitude, we believe that the complex topography of the California should not distort the mean flow patterns evinced in the pressure field. Away from the surface the consequent flow should be nearly geostrophic, and so Figure 6 shows that the prevailing winds aloft (near 2.5 km asl) at Pt. Reyes shift from spring (May/June) when they mostly flow directly over the San Joaquin Valley, to a summertime pattern dominated by a stationary trough aligned with the coastline that would direct flow northward into the Sacramento Valley. Evidence supporting this seasonal shift in flow aloft was found in our Chews Ridge ozone data set, where, for example, the correlation between surface ozone at Fresno changes from its highest values in spring, where the geostrophic flow at 750 hPa nearly directly connects the two points, to summertime when the correlation significantly degrades and the flow pattern seems to shift to the north end of the SJV.

In order to address such differing surface impacts, not only on a seasonal scale, but also on a synoptic scale, we propose an alternative sampling strategy to the first one proposed above which focused solely on the June – September time frame. If deemed more important to prolong the near-daily sampling of ozone in the troposphere, we could perform sorties from April or May to October to encompass the secondary ozone peaks visible in Figure 5. To keep the flight hours comparable, we would then fly only one single deep profile (at Bodega Bay), but would pay more attention to characterizing the onshore flow at the level just above the northern coast range and delta region. Transits back to UCD could follow the observed in-situ winds and could

Figure 6. NCEP North American Regional Reanalysis geopotential heights of the 750 hPa pressure surface for May/June (left) and July-Sept (right) 2012 and 2013. Blue arrows indicate the expected geostrophic flow



direction from Pt. Reyes onshore.

porpoise to different altitudes to measure the lower tropospheric static stability and wind shear and boundary layer progression of the flow feeding the Central Valley. These types of in-situ measurements would be highly valuable in verifying the entrainment rates of ozone aloft into the boundary layer of the interior of California. They are also very rare. Comparisons with wind profilers in the SJV by Bao et al., [2008], for example, show root mean square errors in the WRF simulated winds above the boundary layer routinely greater than 5 m/s.

A study by Emery et al. [2011] using the Comprehensive Air quality Model with extensions (CAMx) and the Community Multiscale Air Quality (CMAQ) model showed how excessive vertical mixing in these models lead to biases in springtime surface ozone simulations across the western US of 20 ppbv or more. The authors found that this problem was particularly troublesome over complex terrain where exaggerated vertical velocities were produced in the models resulting in upper level ozone, imposed by the large scale global model boundary conditions, being brought down rapidly to the surface. This work indicates that in order to improve SIP modeling efforts to account for trans-Pacific ozone it is not sufficient to measure the inflow, but further requires detailed study of the vertical exchange of the transported ozone with the boundary layer. Flight data collected in transit to and from UCD to the offshore site, focused on the lower 2-3 km of the atmosphere, could provide important validation of the Richardson numbers throughout this critical mixing zone.

One other reason to consider this alternative sampling strategy comes from our analysis of the ozonesonde data from IONS-2010. In attempting to ascertain the representative nature of our measurements at Chews Ridge, we performed a correlation analysis with the two central California sonde sites from IONS-2010 – Pt. Reyes and Pt. Sur – because the latter was located within 20 km from our Chews Ridge site. Figure 7 depicts the correlation between the two sonde data sets separated by 200 km for the coincident launches (approximately 35 in total) during May/June 2010. As Parrish et al. [2010] point out, and Figure 7 demonstrates, autocorrelations of free tropospheric ozone tend to fall off with an e-folding distance of 500-1000 km in the horizontal [Liu et al., 2009]. Furthermore, at altitudes of maximal impact to surface sites within California (1 – 2.2 km in the Parrish et al. [2010] study), which happens to include the altitude of our Chews Ridge monitoring site, approximately 70% of the ozone variance measured at Pt. Sur is explained by measurements at that altitude above Pt. Reyes.

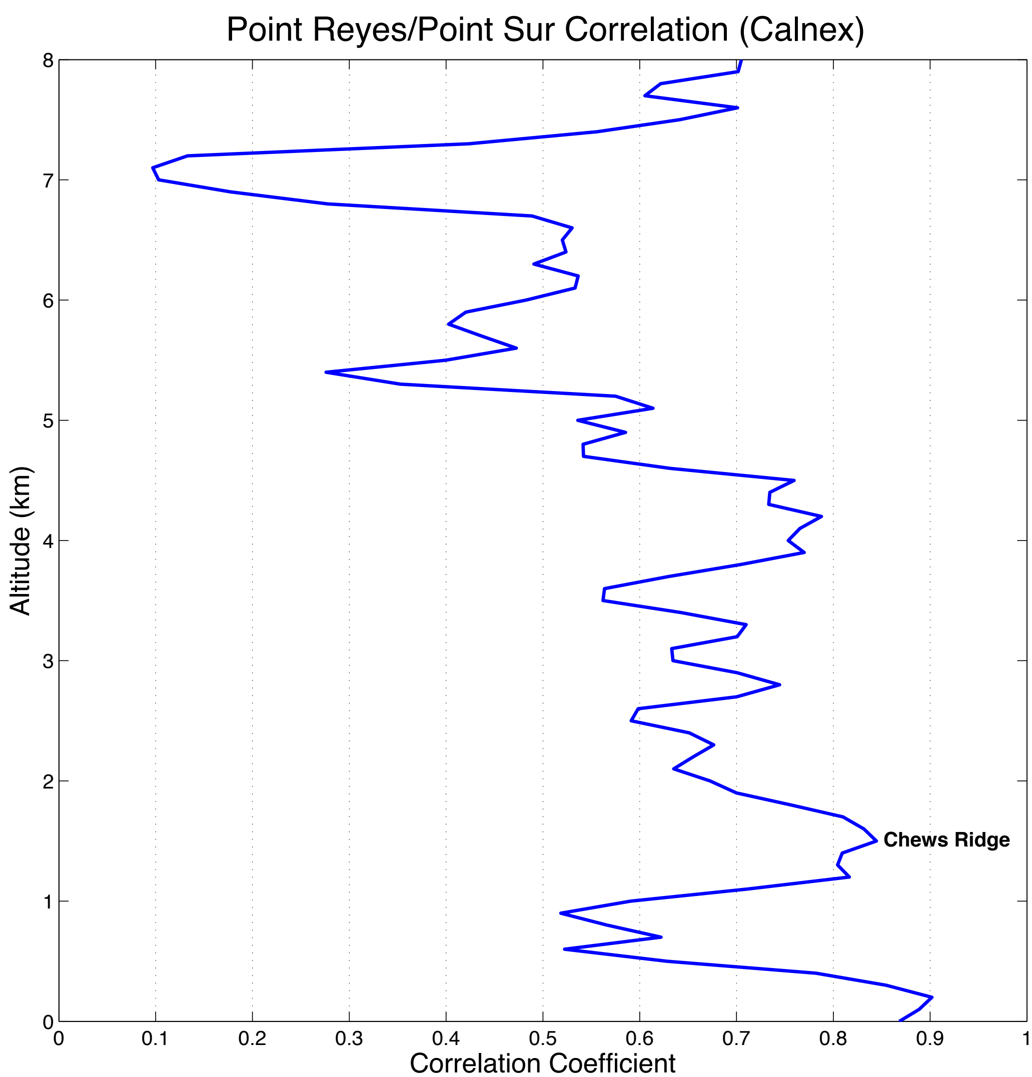


Figure 7. Correlation coefficient of ozone measurements made during coincident sonde launches from Pt. Reyes and Pt. Sur during CalNex (IONS-2010) in 100 m altitude bins throughout May and half of June, 2010.

This evidence suggests that measuring profiles at two locations offshore within a reasonable transit time of one another (about 30 minutes or ~100 km) will be, at least in part, redundant. In combination with the fact that the springtime peak in background tropospheric ozone is showing evidence of occurring earlier in the year [Parrish et al., 2013], and some surface exceedances may be observed in the April/May time frame in the San Joaquin Valley (Fig. 5), it may be more prudent to extend the monitoring period but reduce each sortie's flight time. This would have the added benefit of enabling a more targeted investigation of the onshore flow patterns and vertical mixing unique to each sampling day. In the event that this alternative research tack were taken, we would work closely with ARB's research division to derive a revised aircraft sampling plan with a total budget similar to what is proposed herein.

TECHNICAL DETAILS

I. Aircraft instrumentation

The instrumented aircraft, operated by Scientific Aviation, Inc. will make seven measurements that are central to air quality meteorology at the cost of ~$680 per flight hour (this includes the additional cost for an augmented insurance policy of $5M liability required by the California Department of General Services.) The measurements and their time resolution, vendor, and method include:

T, RH:	Temperature and relative humidity (1-2s response, Vaisala probe on wing)
U, V:	Horizontal wind speed and direction (~1s, dual GPS developed in-house)
O_3:	Ozone (~2s, 2B Technologies UV absorbance)
NO_2:	Nitrogen dioxide (~1s, Los Gatos Research cavity enhanced spectroscopy)

The temperature and relative humidity measurements are crucial for determining the thermodynamic structure and layering of the atmosphere, which strongly controls vertical motions. Moreover, the high-precision measurement of the horizontal winds is critical for tracking the strength of advection (horizontal O_3 and NO_2 fluxes) and any changes of this term with height. Several past studies of long-range transport have identified the thermal dissociation of PAN to NO_2 in the subsidence behind the Pacific High as an important component to ozone import from overseas [Parrish et al., 2004; Hudman et al., 2004]. NO_2 is a trace gas that is intimately tied to ozone production, as it is photolysis of its labile N-O bond that provides the atomic oxygen to form ozone from molecular oxygen in the lower troposphere. Any import of NO_2 via long-range transport by this mechanism could have a substantial ozone production potential once flowing onto the heavily forested coast range with its ample biogenic VOC emissions. Therefore the additional profiles of NO_2 will make a significant contribution to the overall project. But beyond that, because of its relatively short lifetime (~1-2 days), NO_2 also serves as a very distinct marker of continental boundary layer air due to relatively large local sources. It can therefore be used to identify boundary layer air, and possibly air that has been lofted in the complex terrain of the region [Fast et al., 2012], to distinguish indigenous ozone from trans-Pacific sources.

II. Major Tasks

1. Project Planning – Work with the Federal Aviation Administration, ARB, and other appropriate advisory groups to refine the project plans, flight plans, and quality assurance efforts. Also work with ARB's modeling division to identify optimal sampling of inland transects to validate the models' vertical exchange rates.

2. Flights – A total of 385 flight hours over the course of one summer season (or spring and summer as per alternative plan described above.)

3. Data Collection and Validation – All data collected during flights will be quality checked and transmitted electronically to ARB. In addition to ozone, the aircraft, subcontracted from Scientific Aviation, Inc. will collect methane NO_2, temperature, humidity, and wind speed and direction.

3. Post Flight Analysis – In flight data will be combined with other sources (e.g. ARB's air quality surface network throughout California, RASS wind and temperature profiler at Bodega Marine Lab, Trinidad Head profiles, and Chews Ridge meteorology and ozone) to get the bigger picture of onshore ozone flux and its impacts on surface measurements.

4. Provide Project Deliverables – Approved QA/QC Plan, Detailed Flight Plan based on discussions with ARB staff, Draft Final Report (describing objectives, equipment, operations, results, etc.), Final Report (responding to comments from staff and the Research Screening Committee), Final Data Set(s), and Documentation of Data Set(s).

III. Data Management Plan

The aircraft will monitor accurate horizontal winds (Conley et al., 2014), temperature, humidity, ozone (O_3), and nitrogen dioxide (NO_2). A data management system is currently in use that collects measurements from all of the onboard instruments, applies a common time stamp, displays key values in real-time and stores all measurements for post- flight analysis. The files are stored in comma delimited ASCII format, and in addition to the system time, the official UTC time provided by the GPS is included for synchronization with other data systems.

IV. Data Quality Assurance/Quality Control Plan

Instrument Calibration - Ozone (2B Technologies Model 205) analyzer will be calibrated directly against a 2B Model 306 Ozone calibration source prior to and after each experimental deployment to track any changes in instrument performance. Similar calibration schedules will be maintained for NO_2 with a NIST traceable gas blend provided commercially (e.g., Scott-Marin). These calibrations are performed through the inlet lines along the wing and include leak checks of all the inlet lines. Line power is provided in the hangar at the UC Davis airport, and therefore all instruments can be warmed up at least 30 minutes prior to taxi and take off. Because the airplane is equipped with two batteries, there is no need to power down the instruments after the ground warm-up period and taxi and take off. This greatly reduces potential problems.

Within one month of contract execution, a detailed description of the various project quality assurance efforts, as well as detailed data quality control procedures, will be provided to ARB for review and approval. The QA/QC plan will at the very least contain these components:

- Instrument audits (e.g., aircraft instrument responses tested with a through-the-probe audit of multiple known concentrations from a certified source)
- Instrument comparisons (e.g., flight legs dedicated to flying adjacent to a known audited ozone monitor such as those stationed in the ARB air quality network in the SJV)
- Instrument calibrations against certified standards
- Documentation of data validation protocols and criteria

V. Project Deliverables

Specific project deliverables include the following:

- Quarterly Progress Reports
- Draft and Final Reports
- Peer-reviewed journal article(s), as appropriate
- All data and analyses generated through the course of this project (the final data from this project will be publicly available for use by modelers and the air quality community); preliminary data will be available for download from the Scientific Aviation server within one week of each field deployment.
- A public seminar at the California EPA building in Sacramento

REFERENCES

Bao, J.-W., S.A. Michelson, P.O.G. Persson, I.V. Djalalova, and J.M. Wilczak, Observed and WRF-Simulated Low-Level Winds in a High-Ozone Episode during the Central California Ozone Study, *J. of Appl. Met. and Climat.*, 47, 2372-2394, 2008.

Conley, S.A., Faloona, I.C., Lenschow, DH, Karion, A, and Sweeney, C. A Low- Cost System for Measuring Horizontal Winds from Single-Engine Aircraft, *J. Atm. and Ocean. Tech.*, 31(6): 1312-1320, 2014.

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

Cooper, O.R., *et al.*, Measurement of western U.S. baseline ozone from the surface to the tropopause and assessment of downwind impact regions, *J. Geophys. Res.,* 116, D00V03, doi:10.1029/2011JD016095, 2011.

Dorman, C.E., T. Holt, D.P. Rogers, and K. Edwards, Large-scale structure of the June-July 1996 marine boundary layer along California and Oregon, *Mon. Wea. Rev*., 128, 1632-1652, 2000.

Emery, C., Ed Tai, G. Yarwood, and R. Morris, Investigation into approaches to reduce excessive vertical transport over complex terrain in a regional photochemical grid model, *Atm. Environ.*, 45, 7341e7351, 2011.

Emery C., J. Jung, N. Downey, J. Johnson, M. Jimenez, G. Yarwood, and R. Morris, Regional and global modeling estimates of policy relevant background ozone over the United States, *Atm. Environ.*, 47, 206e217, 2012.

Fast J.D., WI Gustafson, Jr, LK Berg, WJ Shaw, MS Pekour, MKB Shrivastava, JC Barnard, R Ferrare, CA Hostetler, J Hair, MH Erickson, T Jobson, B Flowers, MK Dubey, PhD, SR Springston, BR Pirce, L Dolislager, JR Pederson, and RA Zaveri. Transport and Mixing Patterns over Central California during the Carbonaceous Aerosol and Radiative Effects Study (CARES), *Atmos. Chem. and Phys.*, 12(4):1759-1783. doi:10.5194/acp-12-1759-2012, 2012.

Fiore A.M., J.T. Oberman, M.Y. Lin, L. Zhang, O.E. Clifton, D.J. Jacob, V. Naik, L.W. Horowitz , J.P. Pinto, and G.P. Milly, Estimating North American background ozone in U.S. surface air with two independent global models: Variability, uncertainties, and recommendations, *Atm. Environ.*, 96, 284e300, 2014.

Huang, M., Carmichael, G. R., Adhikary, B., Spak, S. N., Kulkarni, S., Cheng, Y. F., Wei, C., Tang, Y., Parrish, D. D., Oltmans, S. J., D'Allura, A., Kaduwela, A., Cai, C., Weinheimer, A. J., Wong, M., Pierce, R. B., Al-Saadi, J. A., Streets, D. G., and Zhang, Q.: Impacts of transported background ozone on California air quality during the ARCTAS-CARB period - a multi-scale modeling study, *Atmos. Chem. Phys.*, 10, 6947–6968, doi:10.5194/acp-10- 6947-2010, 2010.

Hudman, R. C., Jacob, D. J., Cooper, O. C., et al.: Ozone production in transpacific Asian pollution plumes and implications for ozone air quality in California, *J. Geophys. Res.*, 109, D23S10, doi:10.1029/2004JD004974, 2004.

Jacob, D., J.A. Logan, and P.P. Murti, Effect of rising Asian emissions on surface ozone in the United States, *Geophys. Res. Lett*., v26, nD14, 2175-2178, 1999.

Jonson, J.E., A. Stohl, A. M. Fiore, P. Hess, *et al.*, A multi-model analysis of vertical ozone profiles, *Atmos. Chem. Phys*., 10, 5759–5783, 2010.

Liang, Q., L. Jaegle´, D.A. Jaffe, P. Weiss-Penzias, A. Heckman, and J.A. Snow, Long-range transport of Asian pollution to the northeast Pacific: Seasonal variations and transport pathways of carbon monoxide, *J. Geophys. Res.*, v109, D23S07, doi:10.1029/2003JD004402, 2004.

Lin M., et al., Transport of Asian ozone pollution into surface air over the western United States in spring, *J. Geophys. Res*., 117, D00V07, doi:10.1029/2011JD016961, 2012.

Liu, G., Tarasick, D.W., Fioletov, V.E., Sioris, C.E., and Rochon, Y.J., 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, 2009.

Logan, J. A., *et al.*, Changes in ozone over Europe: Analysis of ozone measurements from sondes, regular aircraft (MOZAIC) and alpine surface sites, *J. Geophys. Res.*, 117, D09301, doi:10.1029/2011JD016952, 2012.

Lombardozzi, D., Levis, S., Bonan, G., Hess, P.G., Sparks, J.P., The Influence of Chronic Ozone Exposure on Global Carbon and Water Cycles, *J. of Climate*, 28, 1, 292-305, DOI: 10.1175/JCLI-D-14-00223.1, 2015.

McKendry, I.G., D.G. Steyn, J. Lundgren, R.M. Hoff, W. Strapp, K. Anlauf, F. Froude, J.B. Martin, R.M. Banta, and L.D. Olivier, Elevated ozone layers and vertical down-mixing over the lower Fraser Valley, BC, *Atmospheric Environment* **31**, 2135-2146, 1997.

McKendry, I.G., and J. Lundgren, Tropospheric layering of ozone in regions of urbanized complex and/or coastal terrain: a review, *Progress in Physical Geography* **24**, 329–354, 2000.

Morris, G.A., and B. Ford , B. Rappengluck, A.M. Thompson, A. Mefferd, F.g Ngan, B. Lefer, An evaluation of the interaction of morning residual layer and afternoon mixed layer ozone in Houston using ozonesonde data, *Atm. Environ.,* **44**, 4024-4034, 2010.

Monks, P.S., A review of the observations and origins of the spring ozone maximum, *Atmos. Env.*, 34, 3545-3561, 2000.

Oltmans, S.J., Lefohn, A.S., Harris, J.M., and Shadwick, D.S., Background ozone levels of air entering the west coast of the U.S. and assessment of longer-term changes, *Atmos. Environ.*, 42, 6020–6038, 2008.

Parrish et al., Indications of photochemical histories of Pacific air masses from measurements of atmospheric trace species at Point Arena, California, *J. Geophys. Res.*, v97, nD14, 15,883-15,901, 1992.

Parrish, D.D., K.C. Aikin, S.J. Oltmans, B.J. Johnson, M. Ives, and C. Sweeny, Impact of transported background ozone inflow on summertime air quality in a California ozone exceedance area, *Atmos. Chem. Phys*., 10, 10093–10109, 2010.

Parrish, D.D., *et al.*, Long-term changes in lower tropospheric base- line ozone concentrations at northern mid-latitudes, *Atmos. Chem. Phys*., 12, 11485–11504, 2012.

Parrish, D.D, K.S. Law, J. Staehelin, R. Derwent, O.R. Cooper, H. Tanimoto, A. Volz-Thomas, S. Gilge, H.-E. Scheel, M. Steinbacher, and E. Chan, Lower tropospheric ozone at northern midlatitudes: Changing seasonal cycle, *Geophys. Res. Lett*., 40, 1631–1636, doi:10.1002/grl.50303, 2013.

Tang, Y., P. Lee, M. Tsidulko, H.-C. Huang, J.T. McQueen, G.J. DiMego, L.K. Emmons, R.B. Pierce, A.M. Thompson, H.-M. Lin, D. Kang, D. Tong, S. Yu, R. Mathur, J.E. Pleim, T.L. Otte, G. Pouliot, The impact of chemical lateral boundary conditions on CMAQ predictions of tropospheric ozone over the continental United States, *Environ Fluid Mech.*, 9:43–58 DOI 10.1007/s10652-008-9092-5, 2009.

Zhang, L., D.J. Jacob, X. Yue, N.V. Downey, D.A. Wood, and D. Blewitt, Sources contributing to background surface ozone in the US Intermountain West, *Atmos. Chem. Phys.*, 14, 5295–5309, 2014.

Zhong, S., C.D. Whiteman, and X. Bian, Diurnal Evolution of Three-Dimensional Wind and Temperature Structure in California's Central Valley, *Journal of Applied Meteorology*, 1679-1699, 2004.

Ziemke, J.R., S. Chandra, B.N. Duncan, L. Froidevaux, P.K. Bhartia, P.F. Levelt, and J.W. Waters, Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Transport Model, *J. Geophys. Res.*, 111, D19303, doi:10.1029/2006JD007089, 2006.

PROJECT SCHEDULE

Task 1: Project planning (including development of Flight Plan and QA/QC Plan in consultation with ARB staff)
Task 2: Aircraft deployments/flights
Task 3: Instrument calibrations
Task 4: Data collection and validation
Task 5: Data analysis
Task 6: Draft final report
Task 7: Amend and submit final report along with data sets (including documentation files)

Task/ Quarter	JFM 2016	AMJ 2016	JAS 2016	OND 2016	JFM 2017	AMJ 2017	JAS 2017	OND 2017	Jan-Sep 2018	OND 2018
1	XXX	XXX								
2		X	XXX							
3		XX	XXX	X						
4		X	XXX	X						
5		X	XXX	XXX	XXX	XXX	XXX	XXX	XXX	
6								XXX	XXX	XXX
7									XXX	XXX
	m	p	m	p	m	p	m		d	f

m – meet with ARB staff
p – quarterly progress report
d – deliver draft final report
f – deliver final report and data

CURRICULUM VITAE OF KEY SCIENTIFIC PERSONNEL

IAN C. FALOONA
University of California Davis
Department of Land, Air, & Water Resources
Associate Professor/Bio-micrometeorologist
One Shields Ave.
Davis, CA 95616-5270
(530) 752-2044
icfaloona@ucdavis.edu
http://faloona.lawr.ucdavis.edu/index.htm

EDUCATION

Postdoctoral Fellow, Chemistry/Microscale Meteorology — 2003
The National Center for Atmospheric Research
Research Topics: *Airborne instrumentation development, eddy correlation measurements of chemical fluxes, turbulent dynamics of stratocumulus clouds*

Ph.D., Meteorology — 2000
The Pennsylvania State University
Thesis Topic: *Studies of Atmospheric Oxidation Using Measurements of OH and* HO_2 *Radicals*

B.A., Chemistry — 1991
University of California, Santa Cruz
Thesis Topic: *Energy Transfer in Molecular Collisions of He and DABCO*

EMPLOYMENT EXPERIENCE

Department of Land, Air, & Water Resources, University of California Davis
Job Description: Associate Professor/Bio-micrometeorologist — 2010-present
Job Description: Assistant Professor/Bio-micrometeorologist — 2004 - 2010

National Center for Atmospheric Research — 2000 - 2003
Job Description: Advanced Study Program Postdoctoral Fellow

The Pennsylvania State University — 1995 - 2000
Job Description: NASA Global Change Graduate Student Fellow

SECOR International, Fort Collins, CO — 1991 - 1994
Job Description: Data Analyst/Field Engineer

Los Alamos National Laboratory — 1988 - 1989
Job Description: Undergraduate Research Assistant

TEN RECENT REFEREED PUBLICATIONS

O'Brien, T.A., L.C. Sloan, P.Y. Chuang, I.C. Faloona, & J.A. Johnstone, Multidecadal simulation of coastal fog with a regional climate model, *Climate Dynamics*, *40, 2801-2812, 2013*.

Conley, S.A., I.C. Faloona, D.H. Lenschow, T. Campos, C. Heizer, A. Weinheimer, C.A. Cantrell, R.L. Mauldin, R.S. Hornbrook, I. Pollack, and A. Bandy, A Complete Dynamical Ozone Budget Measured in the Tropical Marine Boundary Layer during PASE. *J. Atm. Chem.*, 2011.

Choi, W.S.-, I. C. Faloona, M. McKay, A. H. Goldstein, and B. Baker, Estimating the atmospheric boundary layer height over sloped, forested terrain from surface spectral analysis during BEARPEX. *Atmos. Chem. & Phys.*, **11**, 6837-6853, 2011.

Turnbull, J., A. Karion, M. Fischer, I. Faloona, T. Guilderson, S. Lehman, B.R. Miller, J. Miller, S. Montzka, T. Sherwood, S. Saripalli, C. Sweeney, P. Tans. Measurement of fossil fuel derived carbon dioxide and other anthropogenic trace gases above Sacramento, California in Spring
2009, *Atm. Chem. & Phys.*, **11**, 705-721, 2011.

Faloona, I.C., S.A. Conley, B. Blomquist, A. Clarke, S. Howell, V. Kapustin, and A. Bandy, Sulfur dioxide in the tropical marine boundary layer: Dry deposition and heterogeneous oxidation observed during the Pacific Atmospheric Sulfur Experiment, *J. Atm. Chem.*, **63**(1), 13-32, 2010.

Choi, W., Faloona, I. C., Bouvier-Brown, N. C., McKay, M., Goldstein, A. H., Mao, J., Brune, W. H., LaFranchi, B. W., Cohen, R. C., Wolfe, G. M., Thornton, J. A., Sonnenfroh, D. M., and Millet, D. B.: Observations of elevated formaldehyde over a forest canopy suggest missing sources from rapid oxidation of arboreal hydrocarbons, *Atmos. Chem. & Phys.*, **10**, 8761-8781, 2010.

Conley, S.A., I. Faloona, G.H. Miller, B. Blomquist, D. Lenschow, A. Bandy, Closing the Dimethyl Sulfide Budget in the Tropical Marine Boundary Layer during the Pacific Atmospheric Sulfur Experiment, *Atm. Chem. & Phys.*, **9**, 8745-8756, 2009.

Faloona, I., Sulfur processing in the marine atmospheric boundary layer: A review, and critical assessment of modeling uncertainties, *Atmospheric Environment*, **43**, 2841–2854, 2009.

Day, D. A., and I. Faloona, Carbon monoxide and chromophoric dissolved organic matter cycles in the shelf waters of the northern California upwelling system, *J. Geophys. Res. - Oceans*, **114**, C01006, doi:10.1029/2007JC004590, 2009.

Petters, M. D., J. R. Snider, B. Stevens, G. Vali, I. Faloona, and L. Russell, Accumulation Mode Aerosol, Pockets of Open Cells, and Particle Nucleation in the Remote Subtropical Pacific Marine Boundary Layer, *J. Geophys. Res*., 111 (D2): Art. No. D02206, 2006.

BUDGET

CARB: Improved Understanding Of The Magnitude Of Trans-Pacific Long Range Transported Ozone Aloft At California's Coast	
Budget	
A. PERSONNEL	
1. PI, Full Professor (1 months)	$8,133
2. Graduate Student Researcher (100% x 2years)	$48,693
3. Undergraduate summer	$6,720
Total Wages & Salaries	$63,546
B. FRINGE BENEFITS	
A1 (@40.4%)	$3,286
A2 (@1.3%)	$633
A3 (@1.3%)	$87
Student Fees (in-state, 2 years)	$24,154
Total Fringe plus Fees	$28,160
C. TRAVEL	
1. Domestic	
Hotel +meals/incidentals (3 people Bakersfield) 4 days, 5 deployments	$0
2. Transport ($0.575/mi x 300 mi)	$0
Total Travel	$0
D. EQUIPMENT	
1. 2B Technologies O3 instrument	$6,000
Total Equipment	$6,000
E. OTHER DIRECT COSTS	
1. Materials & Supplies (lab expendables: cal gases, tubing, valves, fittings)	$2,500
2. SUBCONTRACT: Aircraft Investigations by Scientific Aviation	
(384 Flight Hours Total @ $650/hr + suppl. insurance)	$262,100
3. Conference Registration Fees	$1,200
3. Publication Costs	$2,500
Total Other Costs	$265,800
Total Other Direct Costs	$268,300
F. TOTAL DIRECT COSTS	$366,006
G. INDIRECT COSTS (State Rate)	
Total Indirect Costs (10%)	$33,585
H. TOTAL Project (=DIRECT AND INDIRECT) COSTS	$399,591

ESTIMATED COST BY TASK

Task	Task Name	Labor	Employee Fringe	Education /Tuition	Sub-contract	Equipment	Travel	Materials, Supplies	Misc. (conferences)	Overhead	Total
1	Planning	$6,355	$401	$2,415	$0	$0	$0	$500	$0	$3,359	$13,029
2	Deployment	$22,241	$1,402	$8,454	$262,100	$6,000	$0	$500	$0	$11,755	$312,452
3	Calibrations	$3,177	$200	$1,208	$0	$0	$0	$875	$0	$1,679	$7,140
4	Data QA	$4,448	$280	$1,691	$0	$0	$0	$0	$370	$2,351	$9,140
5	Data Analysis	$15,886	$1,002	$6,038	$0	$0	$0	$625	$3,330	$8,396	$35,278
6	Draft Report	$9,532	$601	$3,623	$0	$0	$0	$0	$0	$5,038	$18,794
7	Final Report	$1,906	$120	$725	$0	$0	$0	$0	$0	$1,008	$3,759
TOTALS:		$63,546	$4,006	$24,154	$262,100	$6,000	$0	$2,500	$3,700	$33,585	$399,591