Improving Estimates of Entrainment Mixing, Subsidence, and Photochemical Ozone Production using Aircraft and Ozone lidar during the California Baseline Ozone Transport Study (CABOTS)

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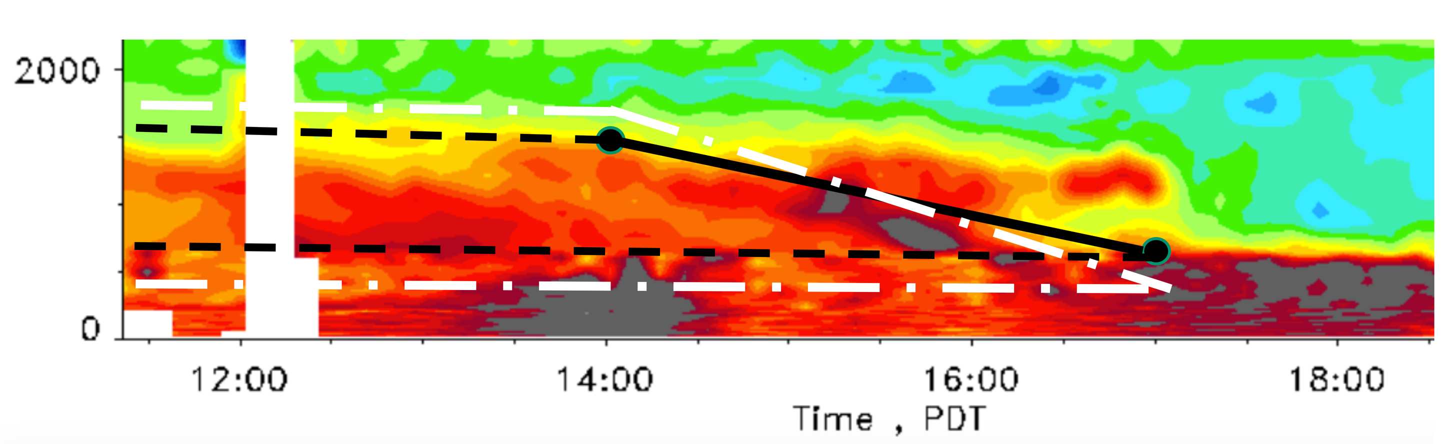
Introduction

Data collected from an instrumented aircraft of Scientific Aviation, owned by Stephen Conley, categorizing both dynamical and chemical structures of the Atmospheric Boundary Layer (ABL) is used to measure the entrainment process in a simple mixed layer model framework. Strategic flight patterns are used to determine the ABL's growth rate during the early to late afternoon when the ABL has a well developed mixed layer. The flights are conducted to accurately determine the horizontal and vertical patterns of key scalars including water vapor, methane, ozone, etc. so as to utilize this data meaningfully in ABL mixed-layer budget equations. The obtained entrainment velocities are then employed in closing the scalar budgets allowing the estimation of regional ozone photochemical production rates and methane emissions. The flights are from late July and early August 2016 during the California Baseline Ozone Transport Study (CABOTS). The flights take place across the San Joaquin Valley (SJV) around Fresno and Visalia. Concurrently in Visalia NOAA and CIRES scientists have set up a Tunable optical Profiler for Aerosol and oZone (TOPAZ) Lidar, with the hopes of better understanding higher baseline ozone coming into California from the west.

Subsidence

Subsidence is an essential parameter for determining the entrainment velocity at the top of the boundary layer. So far the airplanes of Scientific Aviation do not measure vertical wind so we are left to find another method. Previously we used omega (pressure velocity, ω) obtained from North American Regional Reanalysis Dataset (NARR) with ~35 km horizontal resolution and surface pressure data from stations in the region (see equation below). This method can be seen in a forthright publication Trousdell et al. 2016 also see Albrecht et al. 2016 for a similar usage of reanalysis data. Currently due to the absence of NARR data for our current flights we have attempted to use WRF model runs to acquire this data. Some have insisted that subsidence can be seen from the CABOTS TOPAZ ozone lidar data gleaned form what appear to be subsiding "layers" of ozone. Using a graphical technique we estimated subsidence from the lidar data and compared it to what WRF has predicted above Visalia(See figures below).



$$W = \left(-\frac{830m}{3\,hr}\right) = \frac{-276m}{hr} = -7.68\ cm\ s^{-1}$$
*std dev is 4.6 $cm\ s^{-1}$

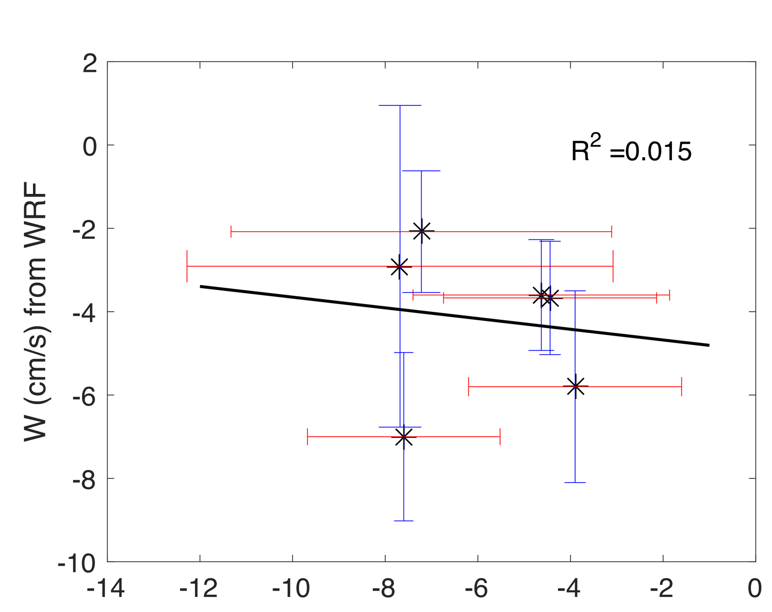


Fig. (Above) Here is an example of estimated subsidence from TOPAZ ozone layers on 08/04/2016. The black line is the estimated height change while the white line is an estimated error in that measurement.

Fig. (left) Shows the poor correlation we have found between the WRF predicted subsidence and that which was determined from what appear to be subsiding ozone layers in the TOPAZ data. WRF data is selected right above Visalia in the range of 800 to 1500m and then averaged. Clearly we need some way to account for advection of ozone at height to really determine what the ozone at height is doing. Presumably these layers are not simply laminar and have some structure or tilt.

Entrainment Velocity

The entrainment velocity is parameterized as the difference between the Lagrangian growth in the boundary layer height and the subsidence at the ABL top. The entrainment velocity is the rate at which the boundary layer is growing by incorporating free tropospheric air, which in fair weather is subsiding. See more info about determining about determining vertical velocity or subsidence at the top of the boundary layer in the subsidence section. During the winter in the SJV near Fresno we found entrainment average at 1.5 cm/s and max out at 2.4 cm/s. In the summer near the southern end of the SJV we found an average of 3 cm/s and a max of 6.5 cm/s (Trousdell et al. 2016). Similar values have been reported in the Sierra Foothills, the Netherlands, and the Ozark Mountains(see Karl et al. 2013, Vila-Guerau de Arellano et al. 2004 and Wolfe et al. 2015 respectively).

For our current study between Fresno and Visalia, Ca in the valley we have found entrainment values ranging from about 3 to 6 cm/s with an average of 4.3 cm/s. These flights took place in late July and early August 2016.

$$w_e = \frac{dh}{dt} - W$$

To be precise we include the advection of ABL height, *h*, when calculating the local time rate of change of *h*;

$$\frac{dh}{dt} = \frac{\partial h}{\partial t} + U_i \frac{\partial h}{\partial x_i}$$

The advection of boundar layer height has been shown to be significant (Trousdell et al. 2016) on order of 1 cm/s in the very southern end of the San Joaquin Valley.

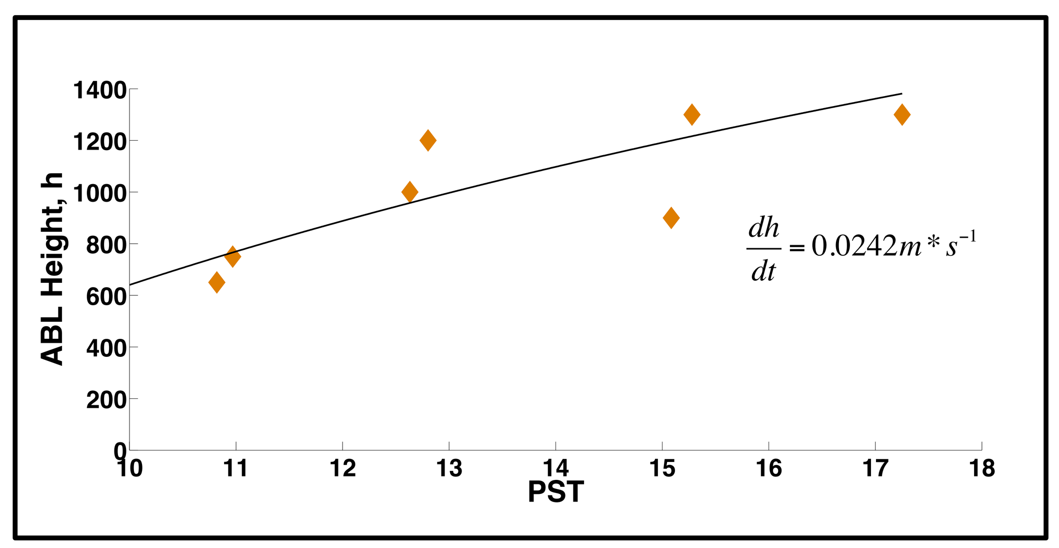
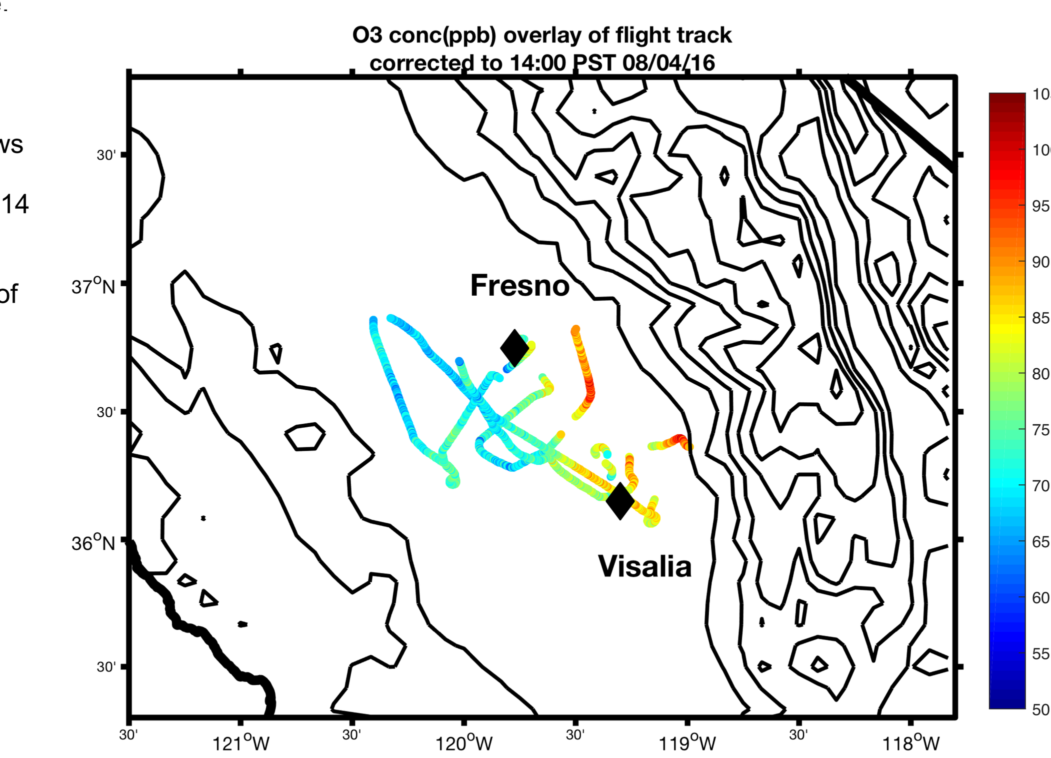


Fig.(At left) Each point is generated from looking at vertical profiles of θ, RH, and methane. Data from 8/14/1

Fig. (at right) Shows O3 concentration (ppb) corrected to 14 PST using a calculated, linear, regional time rate of change overlaying flight track.



The vertical velocity values seen across the SJV vary significantly even becoming positive in places (see Figure below). We are still unsure as the what leads to all of the variation.

$$W \cong \frac{1}{\rho g}\left(\omega - \frac{\partial p}{\partial t}\right)$$

Fig. (Below) Here we show WRF vertical velocity for 08/04/16 averaged over 13-17 PST. The values were obtained from 800 to 1200 meters, right above the boundary layer. It is important to note the variation in the SJV.

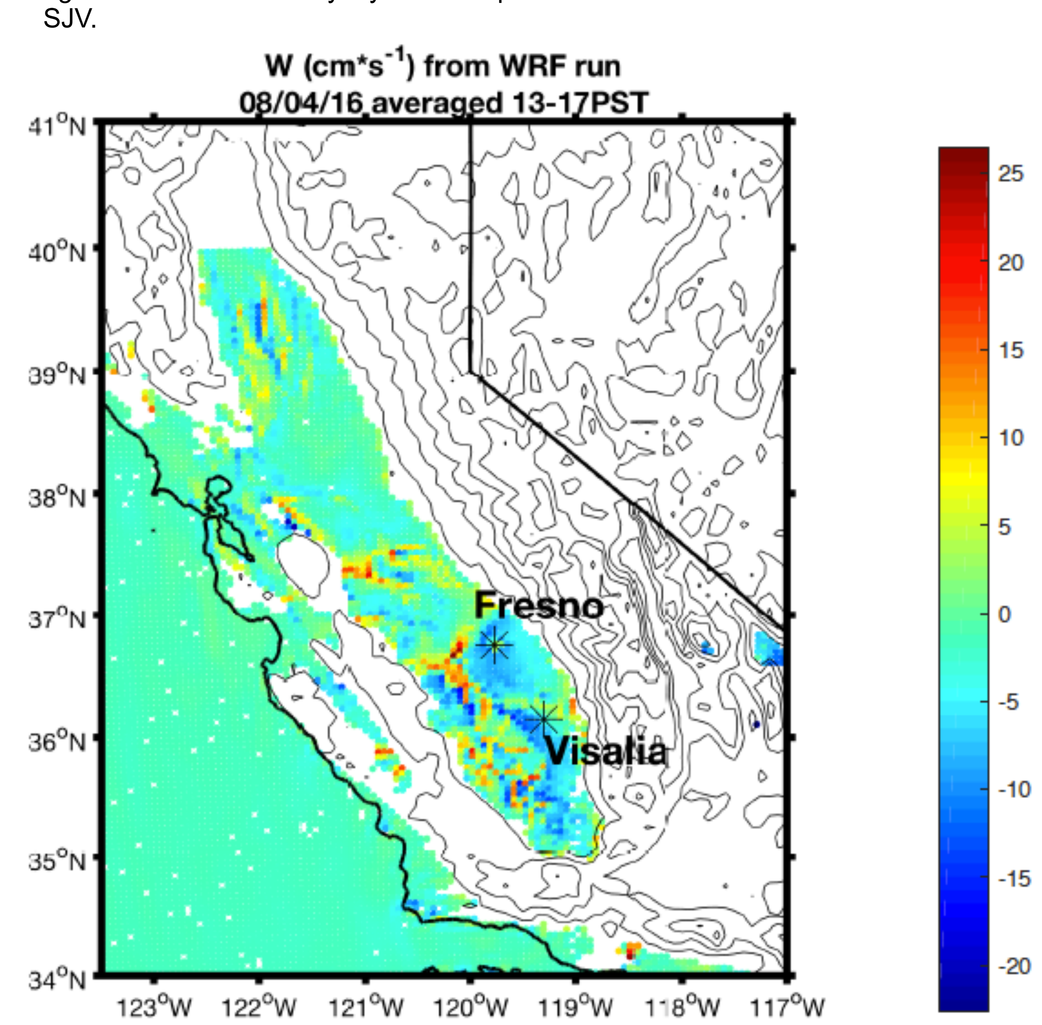
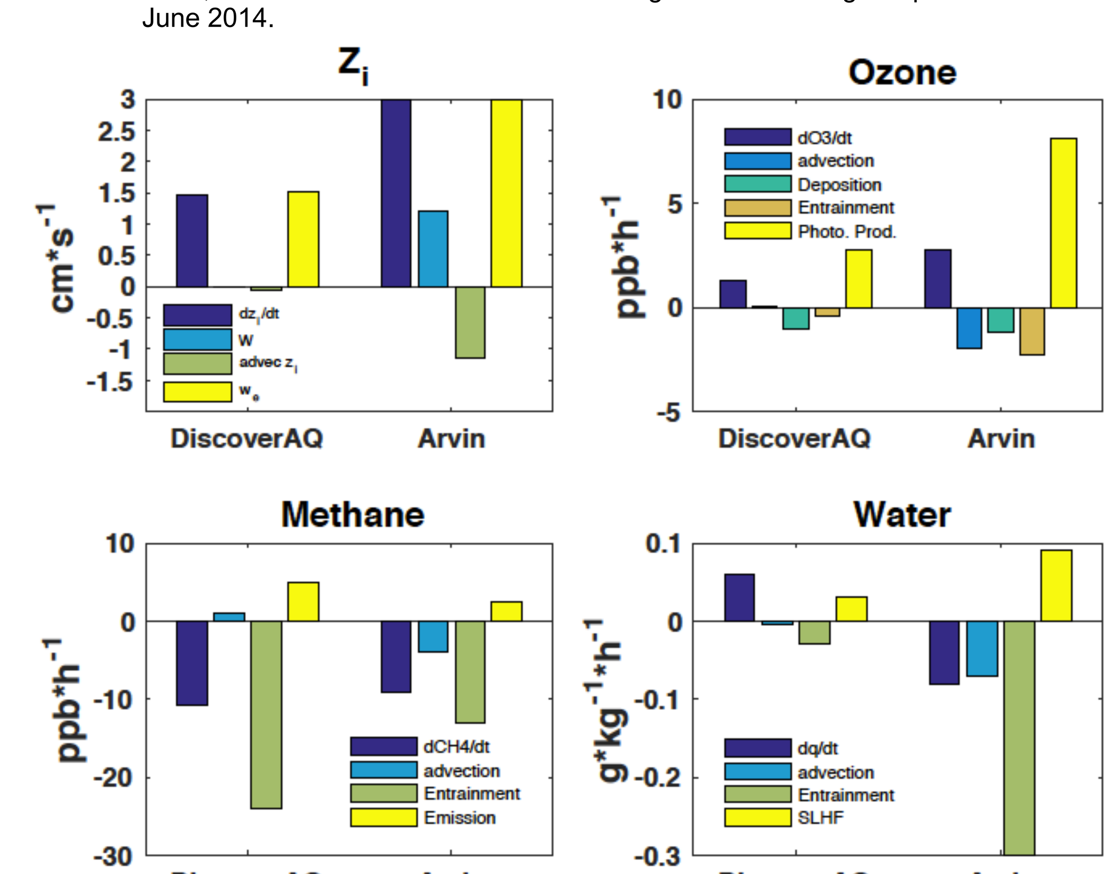


Fig. (below) Four budgets calculated from the flight data of two previous campaigns one during DiscoverAQ during January and February 2013, and the other around Arvin, Ca a town in the southern SJV during the June through September 2013 and June 2014.



ABL Height

To obtain information about the boundary layer heights and the change in any particular scalar quantity across the entrainment zone we look at aircraft profiles. On average for each flight deployment 4 profiles are performed in the plane by flying up and down across the top of the boundary layer.

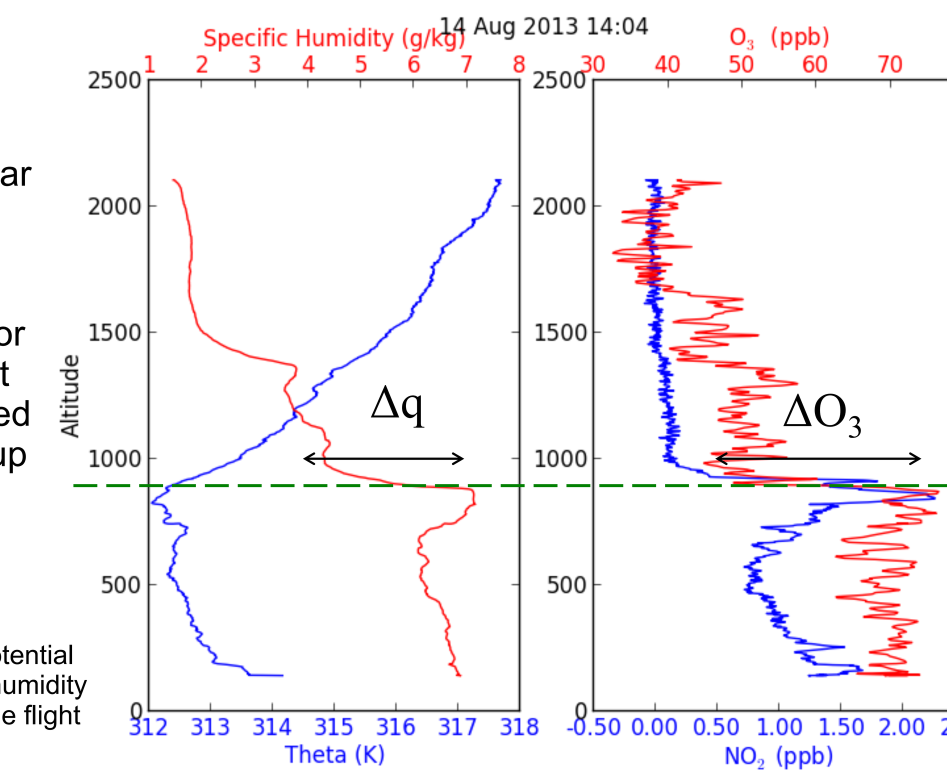


Fig. Vertical profiles of potential temperature (θ), specific humidity (q), ozone (O_3), and on one flight NO_2 .

Example Budget: Ozone

$$\frac{\partial O_3}{\partial t} = -U_i \frac{\partial O_3}{\partial x_i} + \frac{w_e \Delta O_3}{h} + \frac{v_d [O_3]}{h} + P_{net}$$

•This ozone budget equation consists of, starting from the left;

- Local time rate of change
- Horizontal mean advection
- Entrainment flux − parameterized as entrainment velocity multiplied delta O_3 (difference across entrainment zone) and divided by the ABL height.
- Dry deposition of ozone − parameterized by a deposition velocity (-0.005 m/s for summer and -0.0035 in winter; Padro, 1996; Pio et al., 2000) multiplied by an average O_3 concentration and divided by boundary layer height
- Net photochemical production.

•Using the flight data we calculate the horizontal wind vector, ozone concentrations and gradients, the boundary layer height, and the delta O_3 across the entrainment zone directly. To close out the equation and get at the net photochemical production we use an estimated deposition velocity and the entrainment velocity derived using the ABL depth budget described above.

Method Benefits

- The budget equation method allows us to ascertain the relative importance between different processes like advection, entrainment, emission or photochemical production of ozone for example(see figure to left of section).
- So far we have calculated Ozone Photochemical production, emission of methane, surface latent heat flux, and surface heat flux as residual terms from the budget equations. Others have demonstrated this technique with non-conserved species (Kawa and Pearson, 1989b; Bandy et al., 2011; Conley et al., 2009; Faloona et al., 2010; Wolfe et al., 2015).

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Future Work

- Estimate NOx emissions in the region and compare with Emissions Database for Atmospheric Research (EDGAR), etc.
- Use the CLASS model with paramters derived from our flight data including surface heat flux to see if we can mimic the same observed boundary layer growth.
- Calculate ozone budget terms in a layered fashion from flight data in the SJV near Visalia in hopes of finding someway to understand what is observed by the CABOTS TOPAZ lidar.

Recognition

I would like to thank Ian Faloona my advisor at UC Davis for all his help, Stephen Conley who operates and maintains the airplanes for the flight research, Dani Caputi from UC Davis for additional data analysis, Andrew O' Neil Langford and Christoph Senff for the CABOTS TOPAZ data.