Experimental findings from Aircraft Measurements in the Residual Layer

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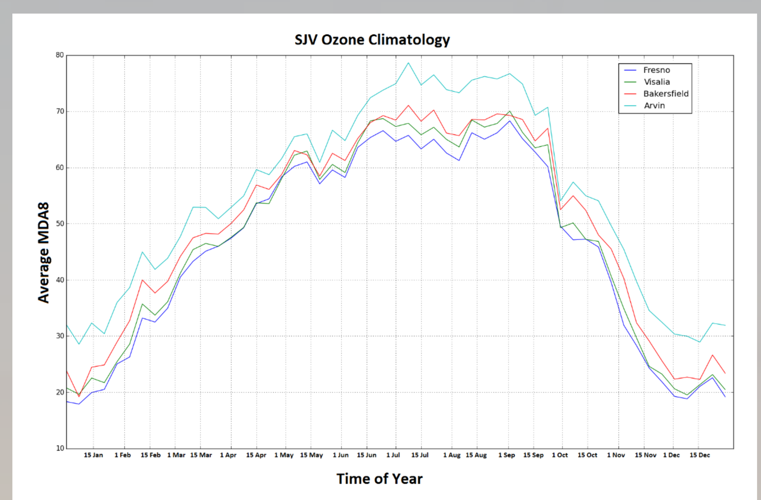
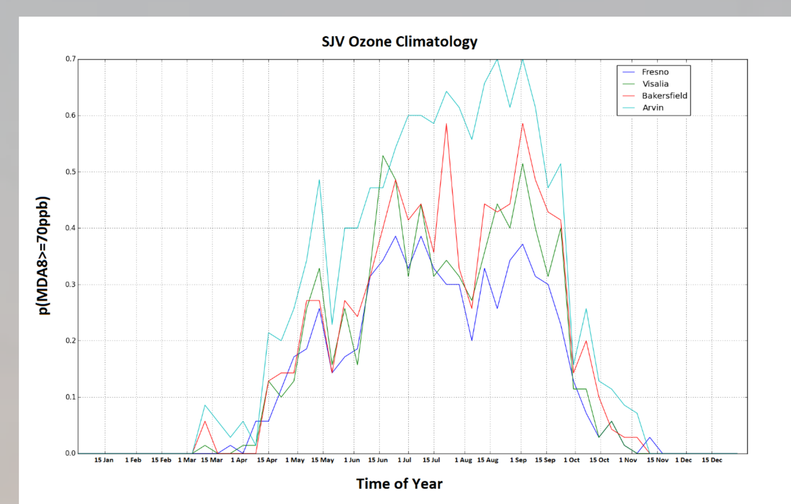
Background

The Southern San Joaquin Valley of California is home to some of the highest ozone pollution in the United States. A 10 year climatology of ozone (2006-2015) is shown in the figures below. The most ozone occurs from June through September. It is of noted interest that when looking at exceedance frequencies of a maximum daily 8-hour average (MDA8) of 70 ppb, a local minimum occurs around early August.



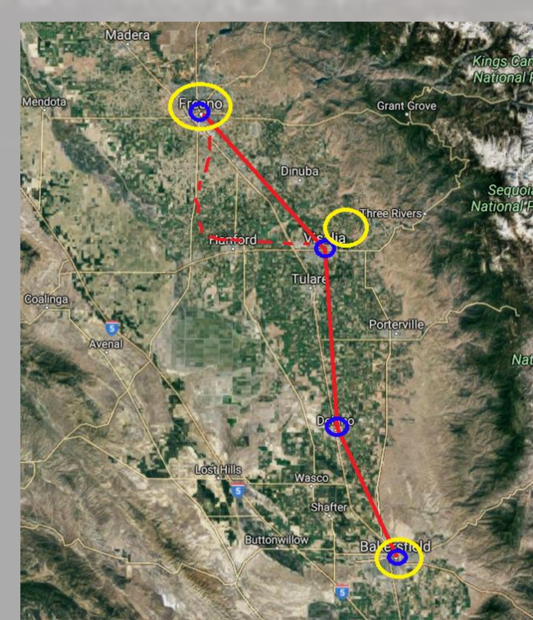
Annual variation of Maximum Daily 8-hour Average Ozone (MDA8) at several locations in the San Joaquin Valley.



Annual variation of MDA8 legal exceedances at several locations in the San Joaquin Valley.

Targeting high ozone episode events, a Mooney aircraft operated by Scientific Aviation, inc. was deployed to take measurements of Ozone, NOx, Water Vapor, Carbon Dioxide, Methane, Temperature, and Wind.

- 67 flights, ~ 2.5 hours each
- Deployments:
  - 10-12 Sep 2015
  - 2-4 Jun 2016
  - 28-29 Jun 2016
  - 24-26 Jul 2016
  - 12-18 Aug 2016
- Flights at 6, 12, 17, 22 PST



Typical flight track (red), low approaches (blue), typical profile locations (yellow).

Nocturnal Budget Equation

$$O_3 + NO_2 \rightarrow O_2 + NO_3$$

h = nocturnal boundary layer height
Vd = 0.2 cm/s

$$\frac{d[O_x]}{dt} = 2k[O_3][NO_2] + \bar{u}\frac{\overline{\Delta[O_x]}}{\Delta x} + \bar{v}\frac{\overline{\Delta[O_x]}}{\Delta y} + \frac{-[O_3]_{SFC}*v_d}{h} + \frac{k_z\frac{\Delta[O_x]}{\Delta z}}{h}$$

The **storage** term is measured by fitting a linear regression through the time series of the species

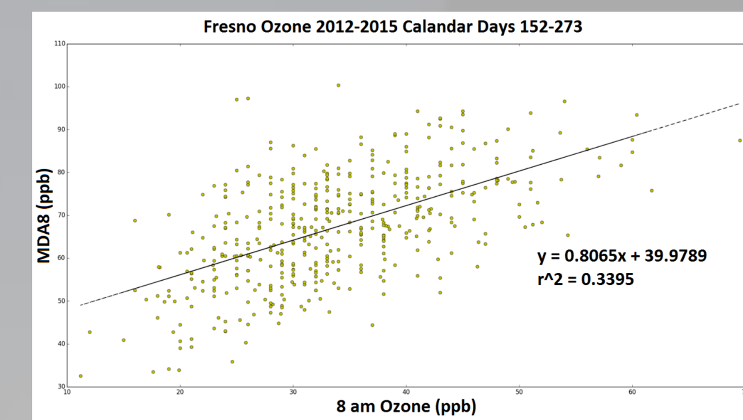
The **chemistry** term is modeled with observed concentrations and obtaining an average k value from airplane temperature measurements

The **advection** terms are computed by dotting the average wind measured in the area of interest with the ozone gradients, taken by a linear regression.

The **mixing** term is taken by first estimating a gradient between the nocturnal boundary and residual layer. Then, the eddy diffusivity becomes the one unknown in this budget equation, and can be solved for.

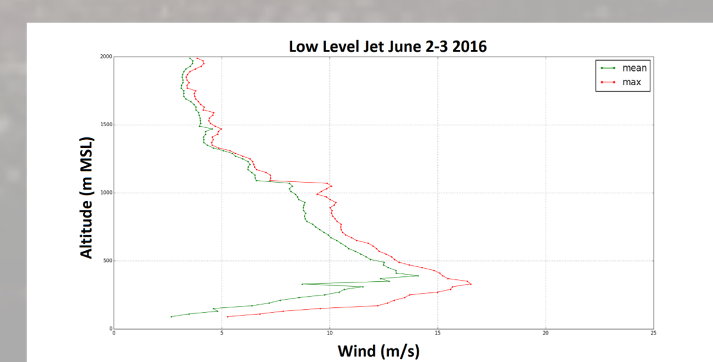
The **deposition** term is taken with airplane surface measurements of the species and estimating a deposition velocity from literature.

Given the importance of understanding the causes of these high ozone episodes, one of many questions that can be asked is on the role that the advection, chemical processes, and mixing dynamics at night have on the ozone observed the following day. First, it is noted that a weak but significant correlation is observed between ozone around sunrise and MDA8. This signifies a possible significance of overnight mixing in the total budget analysis.

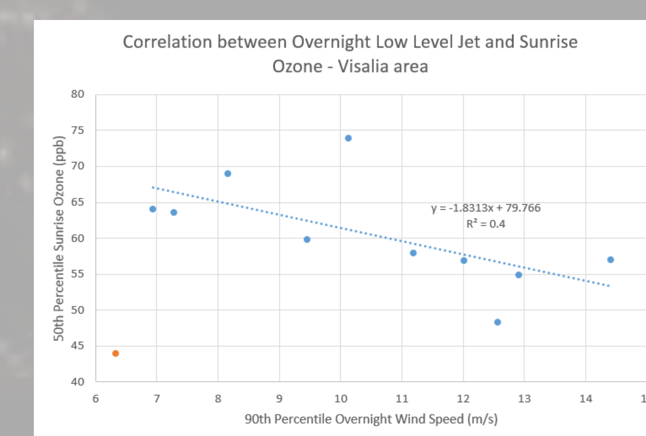


Correlation between morning ozone and MDA8 for summer months in Fresno, CA.

At night, a wind maximum known as the "Fresno Eddy" is often observed at about 300 meters above the valley floor. Speeds up to 21 m/s (47 mph) have been observed on this field campaign. This is viewed as a possible agent in overnight mixing of ozone from the residual boundary layer into the nocturnal boundary layer. Eliminating one outlier, a correlation is observed between the strength of the low level jet at night and ozone observed on the following sunrise flight.



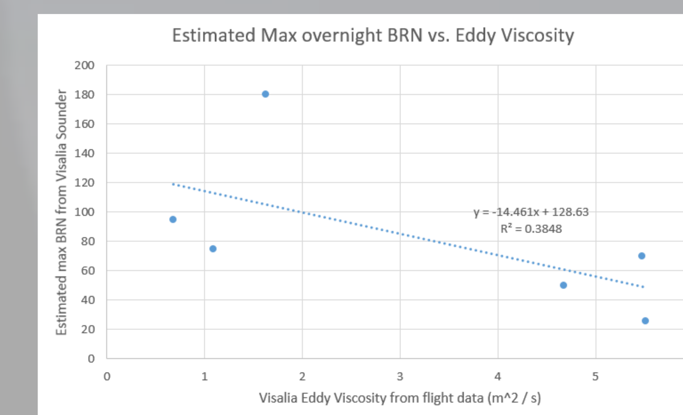
Example of a strong low level jet ("Fresno Eddy") observed with flight data. Winds to 17 m/s, near tropical storm force, were observed.



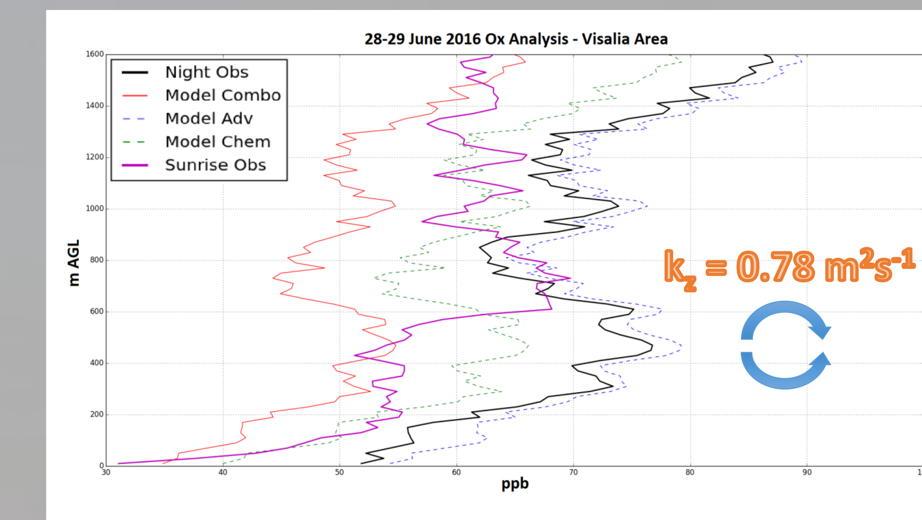
Correlation between nighttime wind and sunrise ozone from flight data, for areas between 36.11 and 36.54 degrees North, within an altitude bin of 0-500 meters for wind and 300-600 meters for ozone.

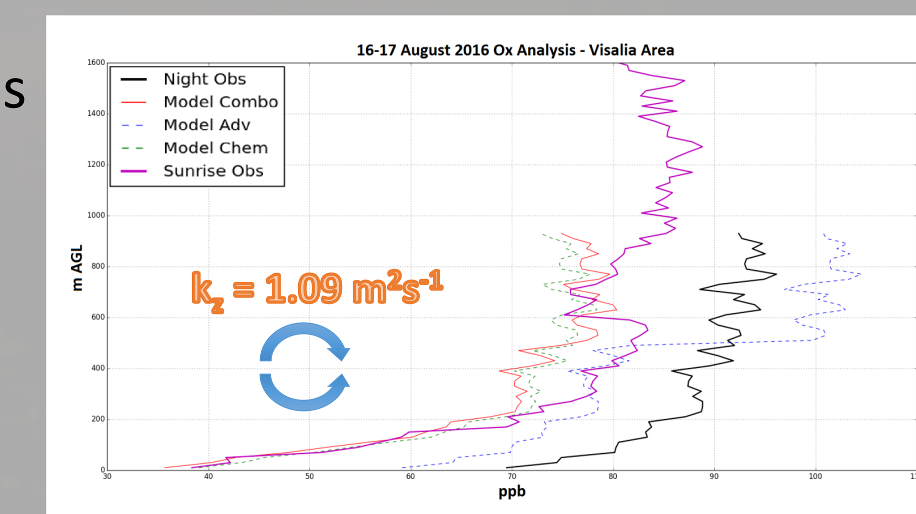
Budget Analysis

Using measurements taken on the late night flight, we attempted to predict morning ozone measurements using the chemistry and advection terms. In some cases, the projected profiles of the sunrise flights were reasonably close to the observed profiles. Adding in estimates of the remaining terms of the budget, it was possible to estimate the eddy viscosity, or turbulent mixing efficiency, from this analysis.



Estimated Bulk Richardson Number from Visalia Sounder, correlated with Eddy Viscosity estimates from flight data.



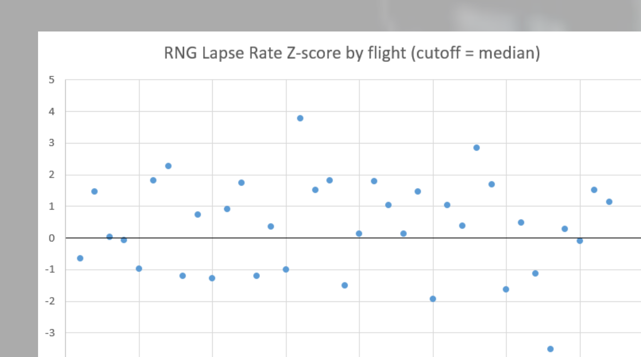


Examples of modeled sunrise ozone profile predictions, with estimated eddy viscosities.

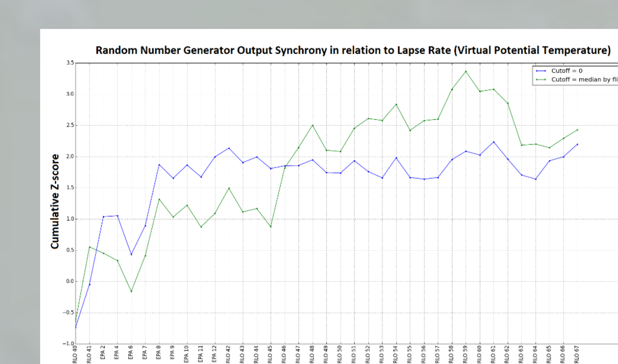
From the nights where values of nocturnal eddy viscosity were obtained that passed quality control, an attempt was made to estimate the maximum Bulk Richardson Number from the Viasalia Radio Acoustic Sounding System, and a weak correlation is observed. The Bulk Richardson Number was estimated from the sounders overnight wind and temperature data up to 1000 meters.

Anomalous Observations

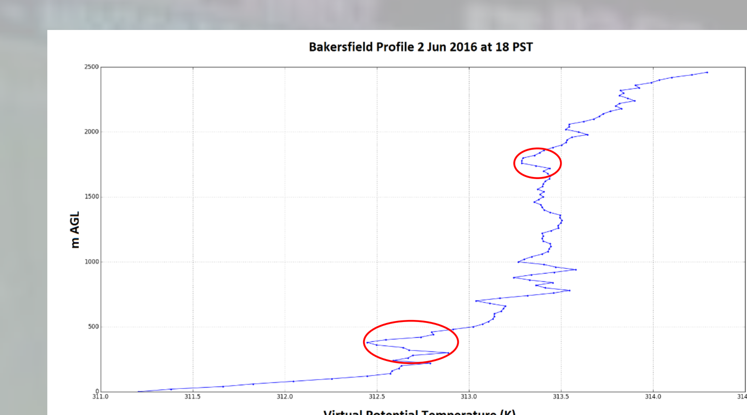
- Several elevated mixed layers ($d\theta_v/dz < 0$) were observed at night, which is fairly unexpected by conventional boundary layer theory. It is speculated that this may result from complex katabatic flow dynamics.
- A Quantum Random Number Generator on board the aircraft produced significantly more ordered output when flying through regions of lower $d\theta_v/dz$ (z=2.43, p=.015, two-tailed). If future flights replicate this finding, this may raise deeper questions about the nature of turbulence.



Z-scores of random number generator lapse rate analysis for each individual flight.



Cumulative Z-score of random number generator lapse rate analysis.



Example of localized nocturnal instabilities seen from the potential temperature profile.