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Sequential Maps Illustrating PM2.5 Sources and Transport Using MAIAC and RAP:
Detailed Quantitative Daily Maps of Aerosol in the Problematic California Valley

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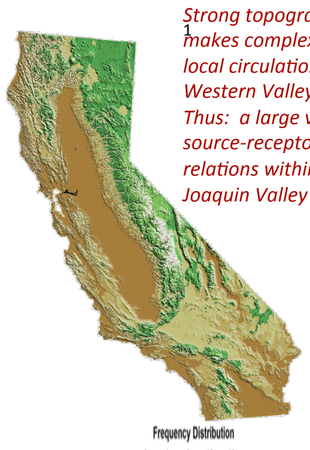
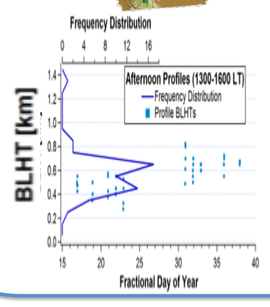
The Western US Poses Large Problems for Aerosol Mapping



Strong topography makes complex local circulations in Western Valleys
Thus: a large variety of source-receptor relations within this San Joaquin Valley

Bright surfaces make scattering difficult to quantify

Also, strongly variegated surfaces at <~ 1 km scales



Shallow, variable PBL depths 250–800 m give low AOT, but high PM2.5

Aims and Outline

The San Joaquin (SJq) Valley suffers from severe episodes of respirable aerosol (PM2.5) in wintertime. Both high pollution and retrieval difficulties tend to occur in many Mediterranean agricultural regions like the San Joaquin.

Difficulties of quantifying PM2.5 from space are described above.

The multi-angle MAIAC retrieval of Aerosol Optical Depth (AOT) provides the most data of all remote sensing methods and at a ca. 1 km resolution. Empirical regression methods (Lee et al., 2015, Sorek-Hamer et al, 2015, Strawa et al 2015 among others] have found that this AOT does provide good regression relationships for PM2.5, especially when random effects *a.k.a.* mixed effects models are used.

We attempt to rationalize and extend these methods by seeking a firmer physical understanding and methodology. To that end, we attempt to fit the MAIAC AOT to a single aerosol parameter, scattering coefficient, using the standard definition of AOT,

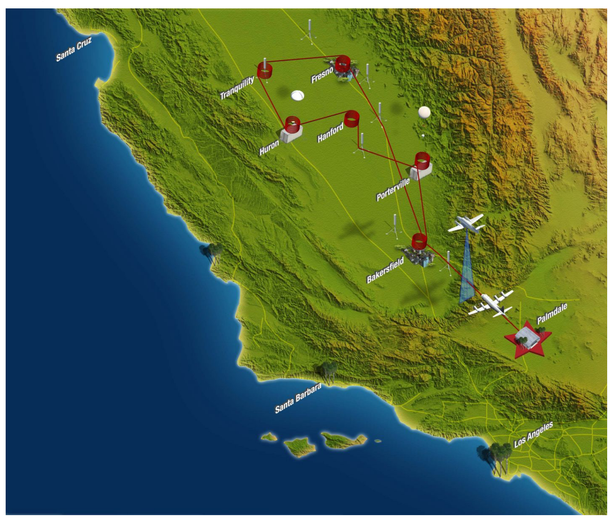
$$\tau_{Scat} = [\rho_{aer} k_{Scat}](RH) C_{StdCond} \Delta z_{Mixed\ Layer} PM2.5$$

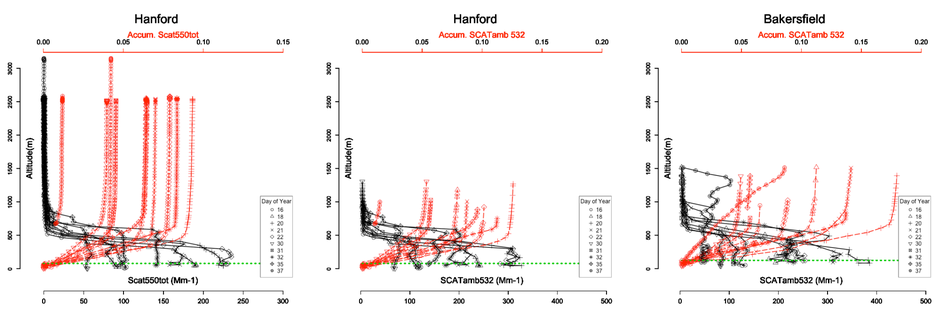
We will assume that the quantity reported by MAIAC, based on much more complex optical paths and radiation theory can fit this simple relationship. Similarly, PM2.5 is the the dry mass of aerosol per standard cubic meter, and we assume that the EPA reference method PM2.5 reflects this appropriately.

Clearly, understanding the Mixed Layer Depth ML or Δz is an important first step. However, another term in the relationship $[\rho_{aer} k_{Scat}](RH)$ can also vary: we write the term so as to emphasize that the aerosol-material mass and also its specific scattering are both intertwined properties of the relative humidity, RH. This term may be very different for the SJq and even regions in the SJq, since the DISCOVER-AQ measurements (partially described below) indicate that the aerosol mass is dominated by ammonium nitrate and domestic-heating smoke, with lesser roles played by dust, sea-salt, and even some sulfate. (The Qi Zhang publications from UC Davis confirm this). Globally useful large scale models like GEOS and MERRA re-analyses do not capture either composition effects and do not represent ML depth accurately.

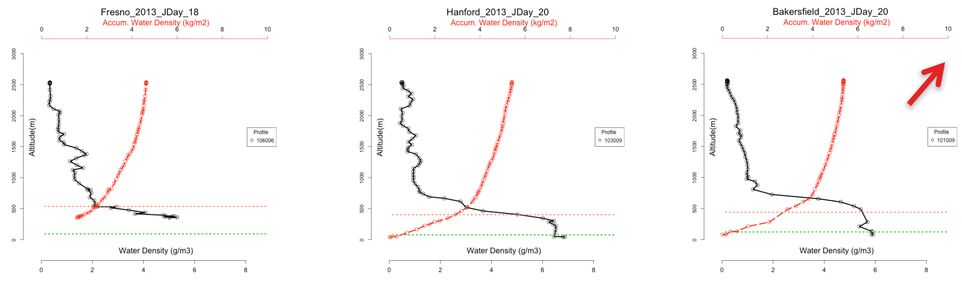
The use of the NOAA RAP (Rapid Refresh Product) constrains its ML depths to observed humidity and temperature and so captures ML well. This allows us to make a useful sequence of maps for two major air pollution episodes and some minor buildups. These provided the authors with unexpected *initial* insights into aerosol source-receptor relationships in the SJq, and suggest directions for chemical and microphysical research to characterize $[\rho_{aer} k_{Scat}](RH)$ and achieve an optical mass closure for atypical aerosol compositions. RAP has 14 km resolution so that features near the valley sides may not be captured well.

NASA's DISCOVER-AQ California (Jan 5 – Feb 15 2013) provided a thorough understanding of the aerosol-polluted mixed layer in wintertime conditions. There is considerable information on aerosol sizing and composition that may be exploited to provide an optical mass closure linking AOT to PM2.5 (and more detailed optical measures). At the north end of the SJq, UC Davis made extensive surface measurements.



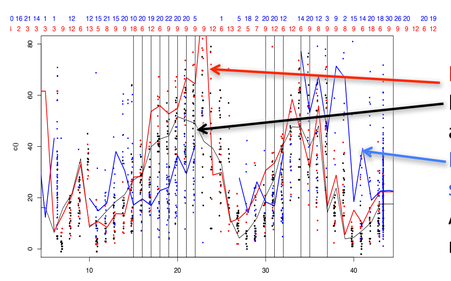


The P-3 aircraft made repeated profiles of b_{scat} under standard-RH and ambient conditions. These indicated that light-affecting aerosol was nearly always confined to the ML and typically rather well-mixed. (Anderson group). R Ferare has reported that the the lidar data from the King Air supports these ML depths and that their data gives good estimates related to PM2.5 under certain conditions.



Compared to aircraft profiles of water vapor and other constituents, NOAA's Rapid Update Model (RAP) gave excellent estimates of afternoon ML height, except on Jan 20th near Bakersfield, as we discuss for the map for that day shown on the right. We expect that RAP's success depends on its short forecast time, emphasizing, T and RH, i.e. observed heat and water vapor flux.

Data availability During the 2+ episodes, 2013, DISCOVER-AQ+DRAGON-NET



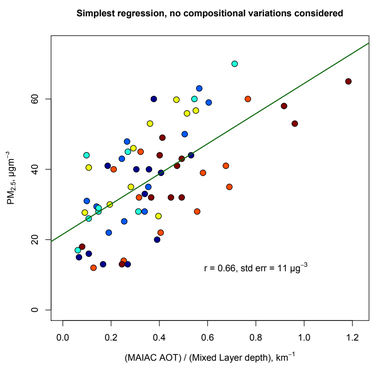
PM10
PM2.5,
and
MAIAC at PM site, scaled
All data and daily means (lines)

Day in 2013 –>

| | | Vertical lines: Sufficient data

Simple Regression using ML depth

$$PM2.5_{is} = a \cdot \frac{(\tau_{Scat})_{is}}{(\Delta z_{Mixed\ Layer})_{is}} + c + \varepsilon_{is} \quad i\text{nstance, Station}$$



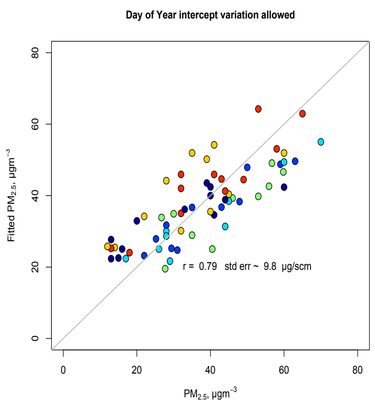
Simple multiple regression of PM2.5 vs the ratio (MAIAC aerosol optical depth) / (Mixed layer depth from RAP) Gives a useful if scattered relationship.

A "Mixed Effects" Regression allowing variation from day to day helps greatly

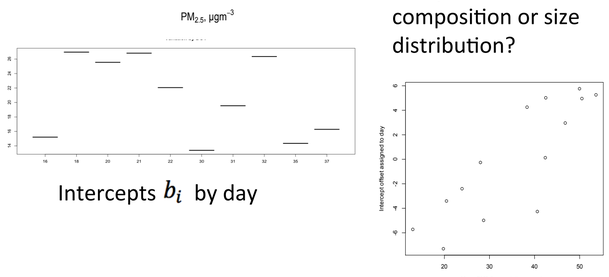
$$PM2.5_{is} = a \cdot \frac{(\tau_{Scat})_{is}}{(\Delta z_{Mixed\ Layer})} + b_i + c + \varepsilon_{is} \quad \ldots (+ d_s) \qquad i\text{nstance, Station}$$

i.e. ...

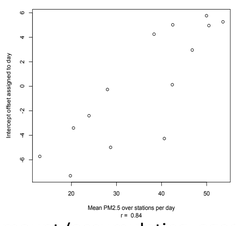
$$(\tau_{Scat})_{is} \approx \frac{PM2.5_{is} - b_i - c}{a} (\Delta z_{Mixed\ Layer})_{is}$$



Mixed-effects (*a.k.a.* random effects) regression allowing intercepts to vary with day, *i*, (instance) improves variance-explained and standard error of PM2.5 estimate greatly.
These are used for the maps shown on the right.
What does this mean?
- RH? ✗
- MAIAC difficulties? ✗?
- Dependence of relation on composition or size distribution?

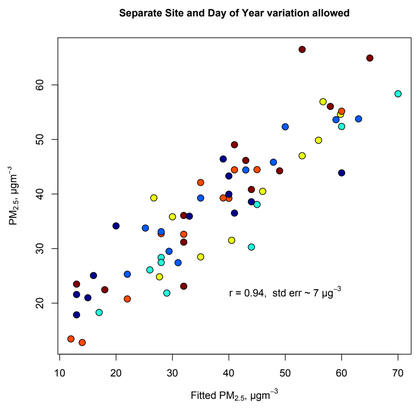


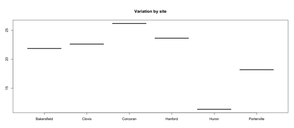
Intercepts b_i by day

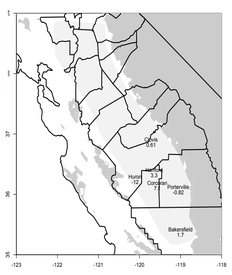


A hint: Intercepts correlate with PM2.5 amount (accumulating, aged, aerosol?) but not scaled optical depth. Evidence for aging may appear in the differences (PM10–PM2.5) in top graph of the two episodes.

Note that intercepts also appear different for the different stations in the figure above. In fact, allowing a term $+ d_s$ improves the fit and lowers the standard error significantly although differences in intercepts are smaller among stations than among days.







Intercepts $+ d_s$ arranged S to N and on a map. They are restricted in geo-graphic range.

How to use this information for maps??

Maybe not a puzzle: The use of AOT $(\tau_{Scat})_{is}$ alone in this regression gives essentially the same correlation and standard error (very slightly better). However, the use of additional station information $+ d_s$ is not strongly helpful with this approach.

$$PM2.5_{is} = a \cdot + b_i (\tau_{Scat})_{is} + c + \varepsilon_{is} \quad \ldots (+ d_s), \qquad no\ (\Delta z_{Mixed\ Layer})_{is}$$

Apparently, the intercepts are able to supply some of the ML-depth information, and they may can be more exact than RAP ML depths. However, extrapolation requires caution. Addtionally, ANOVA strongly prefers the use of the ML depth.

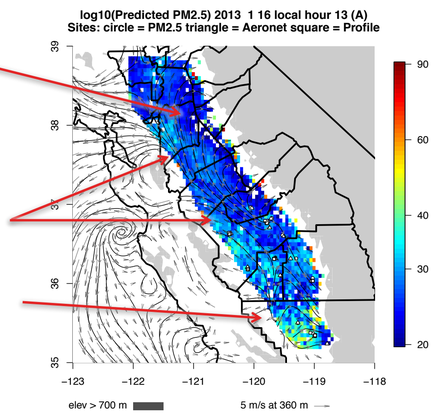
An Air Pollution / Meteorological Narrative of the First SJq PM2.5 Episode, 2013 !

Selected Days, Others are Available

Prior to Episode:
Generally low PM2.5 through SJq Valley; air evacuated through Delta and Bay

I-5 aerosol accentuated by flow to NNW, parallel to freeway

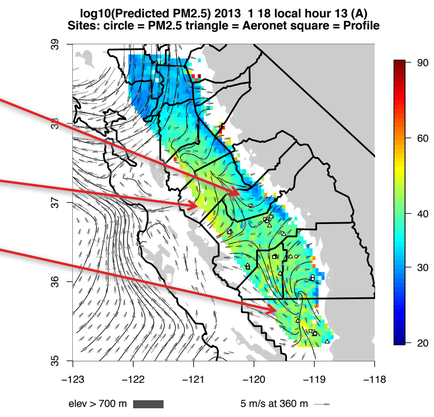
Bakersfield: NNW flow weak; air recirculates



18th Episode builds:
Winds are light and variable

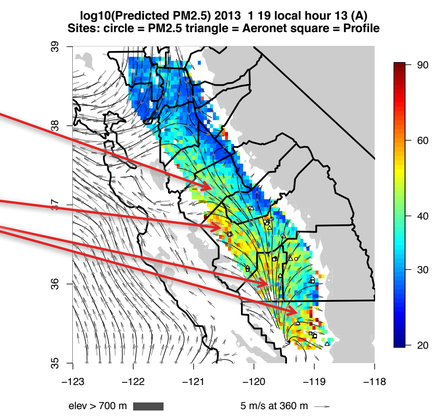
Transport of north-Valley pollution seen; winds cross I-5

Bakersfield flow divergent; relatively clean



19th Episode builds:
Weak flow towards NNW through SJq Valley,

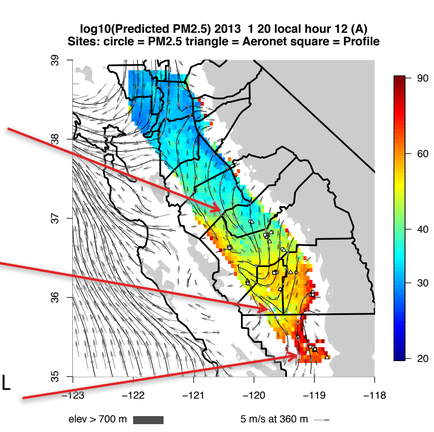
... accentuating I-5 and South-SJq PM2.5 sources



20th Episode nears peak:
Similar, weaker, flow towards NNW through N / Central SJq Valley,

South-SJq PM2.5 sources are trans-ported and converge towards SE Valley:

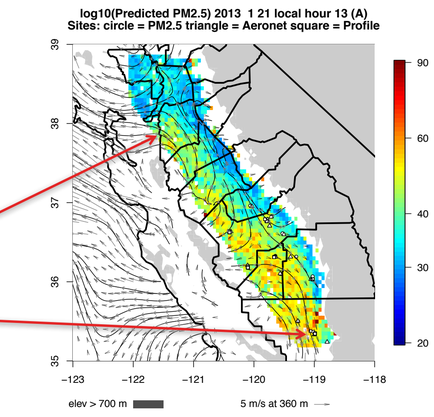
RAP underestimates ML depth on this day. Therefore surface PM2.5 overstated (red) here?



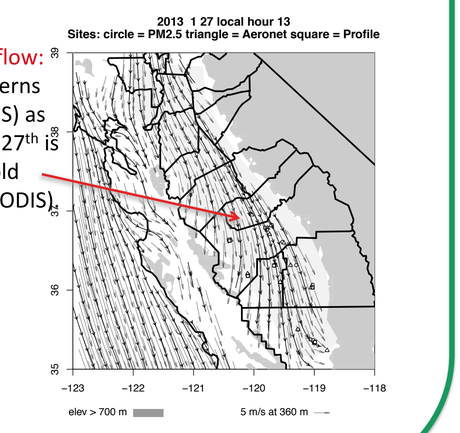
21st Episode peaks
Generally high PM2.5 through Western SJq Valley; low winds, slow spilling of PM2.5

towards Bay

and towards South



27th, Strong Final Outflow:
23rd –26th, mixed patterns with clouds (no MODIS) as episode ends. On the 27th is the effect of a final cold frontal airmass (no MODIS).



Conclusions:

- *The use of RAP mixed-layer heights along with MAIAC AOT provided detailed maps of the origins and transport of PM2.5 for two episodes in the SJq Valley, a region with specialized meteorology, aerosol composition, thin mixed layers, and severe aerosol-caused health effects. Earlier successes of mixed effects models without explicit ML depth information is understandable.*
- *The episodes range from 3 to 12 days with varied structure, and so these maps go far beyond other aerosol retrievals for the region in suggesting source-receptor relationships.*
- *Insights from DISCOVER-AQ allows remote sensing studies to connect the varying chemistry and microphysics of few-day events. Further, careful, analysis of the DISCOVER-AQ data and also the permanent state-wide permanent PM2.5 network are indicated.*
- *Although relative humidities below 70% seemed to have little effect on scattering coefficient, there are indications that composition and size-distribution changes affect the AOT-to-PM2.5 relationship strongly.*