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Sources of Light Absorbing Aerosols over Snow:

Spatial, Temporal & Chemical Variation in the Sierra Cascade Range, Western North America

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"Light Absorbing Aerosol" and "Black Carbon"

- "Black Carbon" (BC), "Light Absorbing Carbon" (LAC), "Elemental Carbon" (EC) - Chemical shorthand for refractory materials with high carbon number and low organic fraction. Usually dominated by sub-micron sizes and <u>assumed</u> to be combustion–derived "soot."

- "Light Absorbing Aerosol" (LAA) – Airborne material with significant optical absorption cross-section. No inference of chemical nature. Includes "soot", but also some organic matter (OM), coarse black material such as tire dust and asphalt fragments, and non-white minerals such as ferrite, limonite, biotite, clays, etc.

The Problem of “Soot on Snow”

- Pure snow has an albedo near 1; small changes in albedo can alter climate (Flanner *et al*. 2007).

- Small additions of black material (“BC”) increase solar heating and accelerate melting (Hansen & Nazarenko, 2004).

- “BC” has been linked to accelerated melt in Himalayas, Arctic, and elsewhere (Jacobson, 2004).

- Modeling suggests a significant BC effect in the western U.S. (Qian *et al*., 2009).

Snow Optics – A Very Brief History

−Dust layers are well known in ice cores and in snow fields worldwide.
−Grenfell and others (1970s) reported “excess” albedo in snow in the Arctic and alpine regions.
−Warren and Wiscombe (1980a,b) provided a theoretical explanation.

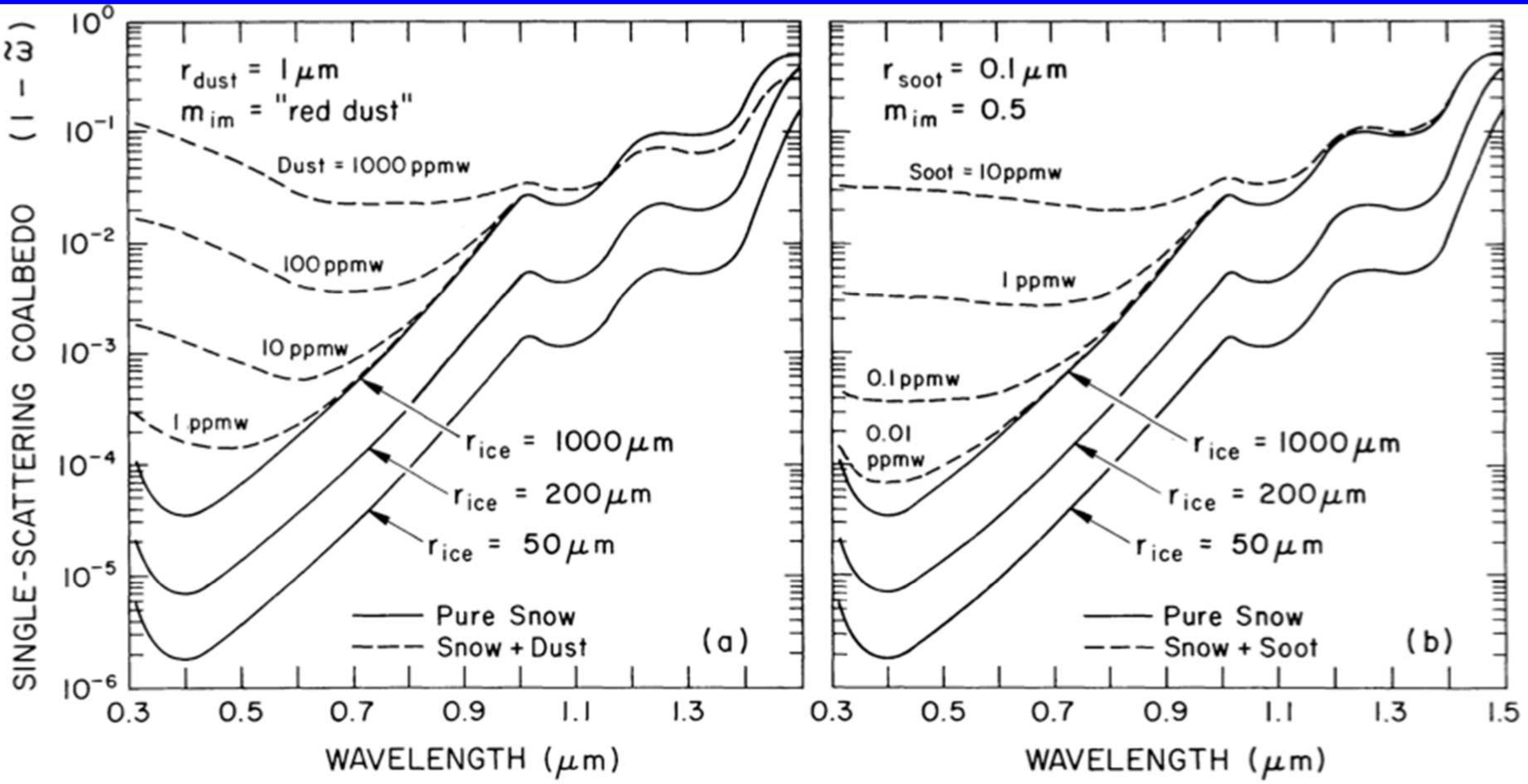


FIG. 3. Effect of solid impurities on single-scattering coalbedo (1 − $\tilde{\omega}$). Solid lines are taken from Fig. 3a of Part I. Dashed lines show the effect of adding (a) dust or (b) soot in various concentrations to ice spheres of radius 1000 μm.

Warren & Wiscombe (1980b)

Recent Model Results

Flanner *et al*. (2009)

- Globally, BC+OM exert 6-fold greater positive surface forcing from darkening snow than negative surface forcing by atmospheric dimming (reduced insolation).
- Fossil fuel and biofuel emissions of BC+OM induce 95% as much springtime snow cover loss over Eurasia as anthropogenic carbon dioxide.
- 21 of 22 climate models contributing to the IPCC Fourth Assessment underpredict the rapid warming (0.64° C decade^{-1}) observed over springtime Eurasia since 1979.
- Darkening from natural and anthropogenic sources of BC and mineral dust exerts 3-fold greater forcing on springtime snow over Eurasia (3.9 W m^{-2}) than North America (1.2 W m^{-2}).

Modest agreement at best between global models and snow measurements

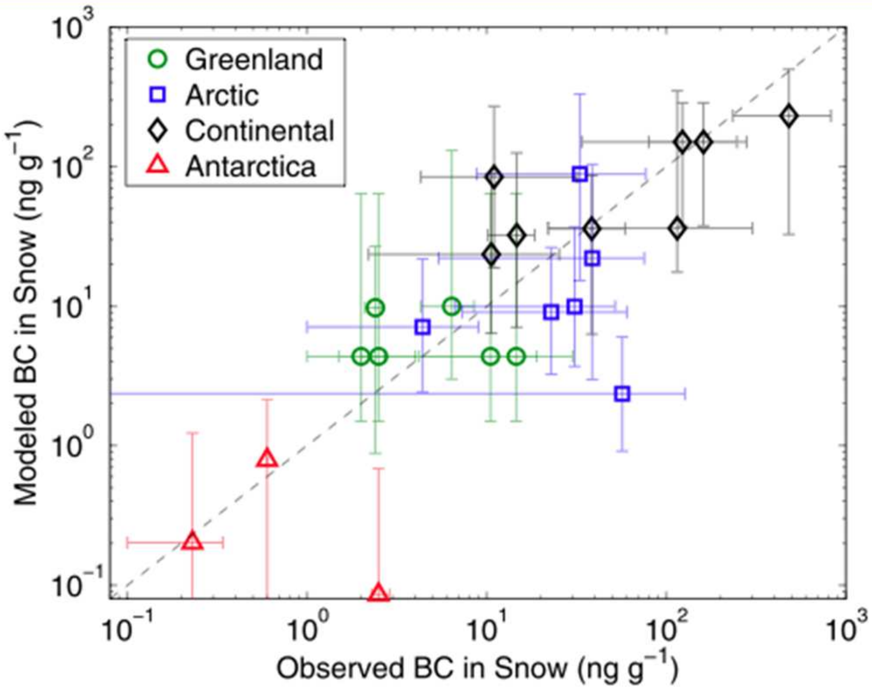


Figure 4. Model versus observed BC concentrations in near-surface snow for data from Table 2, grouped by region (precipitation measurements excluded). Model data are from the top 2 cm of snowpack. The center model point on this plot is the mean of 1998 and 2001 central experiments. The upper extent of the model error bar represents the maximum of 1998 and 2001 high experiments, whereas the lower extent is the minimum of both low experiments. The correlation coefficient of the log of these data is 0.78.

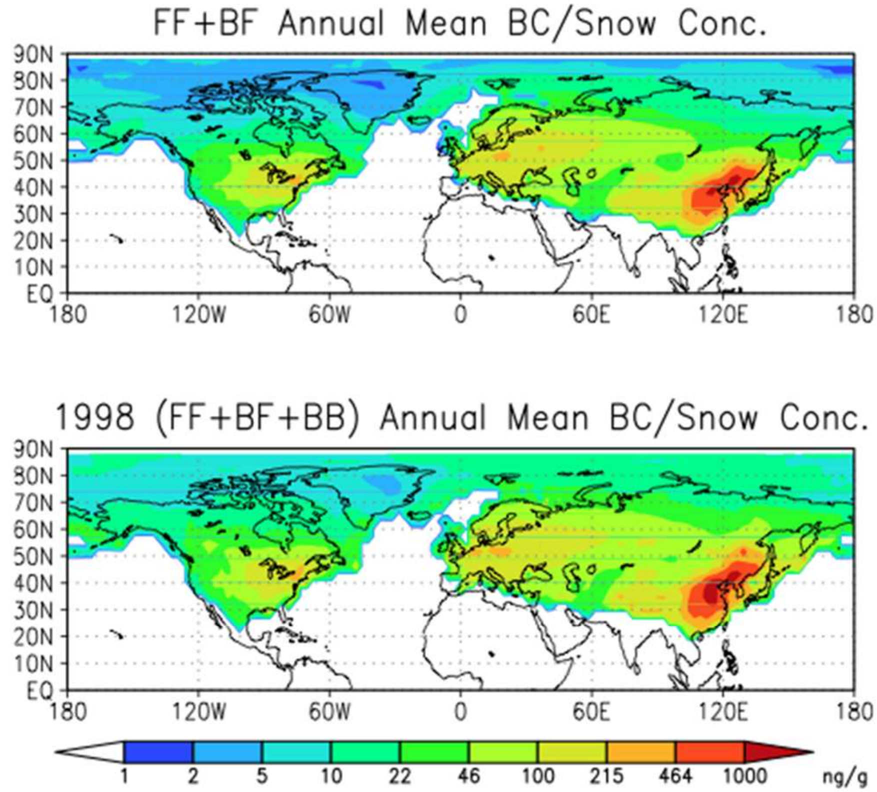


Figure 5. Annual mean predicted BC concentrations in snow (ng BC per g of ice) using central estimate (top) fossil fuel and biofuel sources only, and (bottom) fossil fuel, biofuel, and 1998 biomass burning emission sources.

Flanner et al. (2007)

It’s Not Just “Black Carbon”…

Dust on Snow, San Juan Mts., Colorado

Dust accelerates melt and early runoff in the Rocky Mtns.

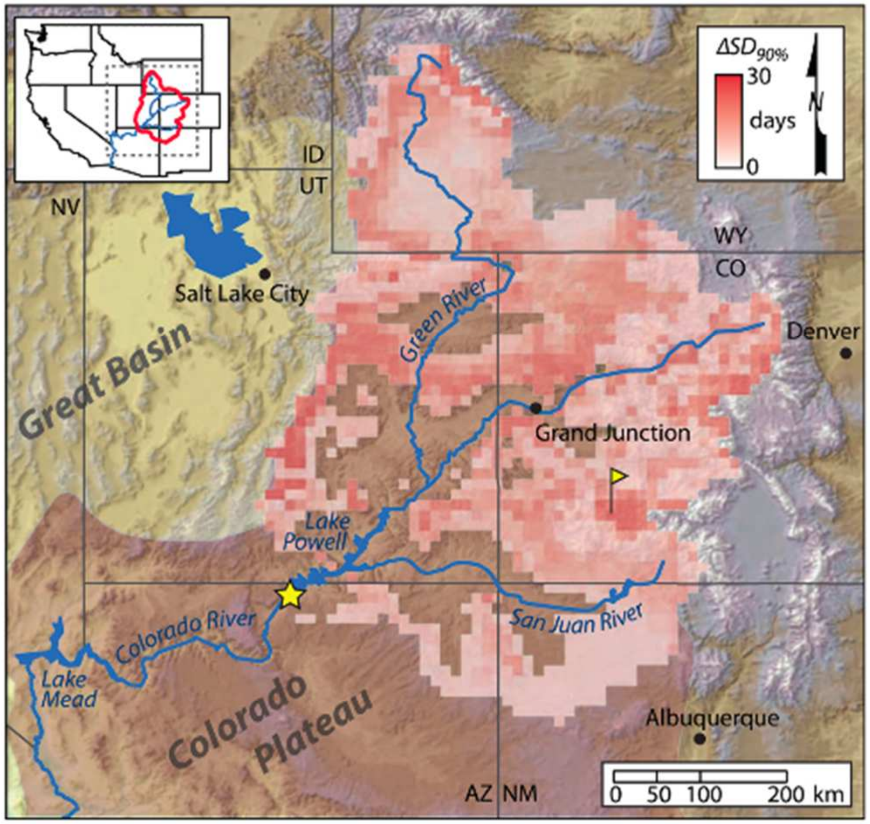


Fig. 1. Overview of Upper Colorado River Basin, and the Colorado Plateau and Great Basin physiographic provinces, overlain with change in date of $\Delta SD_{90\%}$ for elevations above 1,800 m. Star indicates Lees Ferry, AZ and flag indicates SBBSA.

Results

Fig. 2*A* shows modeled hydrographs of full natural flow (effects of water management removed from observations) at Lees Ferry averaged over 1916–2003 for ADL and BDL. The ADL mean

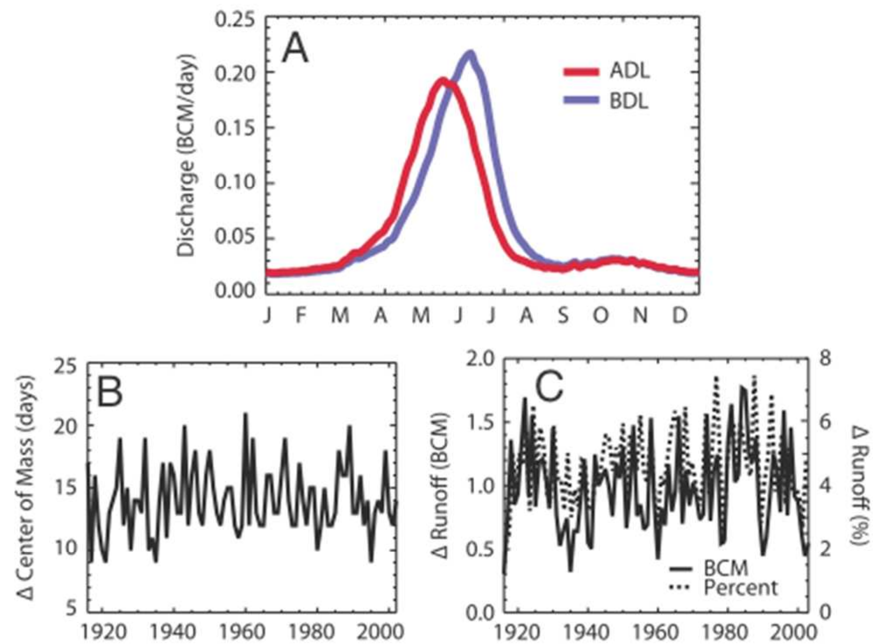


Fig. 2. Differences in runoff timing and volume between ADL and BDL dust scenarios. (*A*) Mean discharge at Lees Ferry, AZ on the Colorado River for ADL and BDL scenarios across the period 1916–2003. (*B*) Time series of BDL versus ADL Δ runoff in billion cubic meters across 1916–2003. (*C*) Time series of BDL versus ADL Δ runoff in percent of ADL runoff.

It’s Not Just in the Rocky Mtns…

Dark Layers in Himalayan Firn

Recent global modeling indicates dust is also a significant factor in Asia

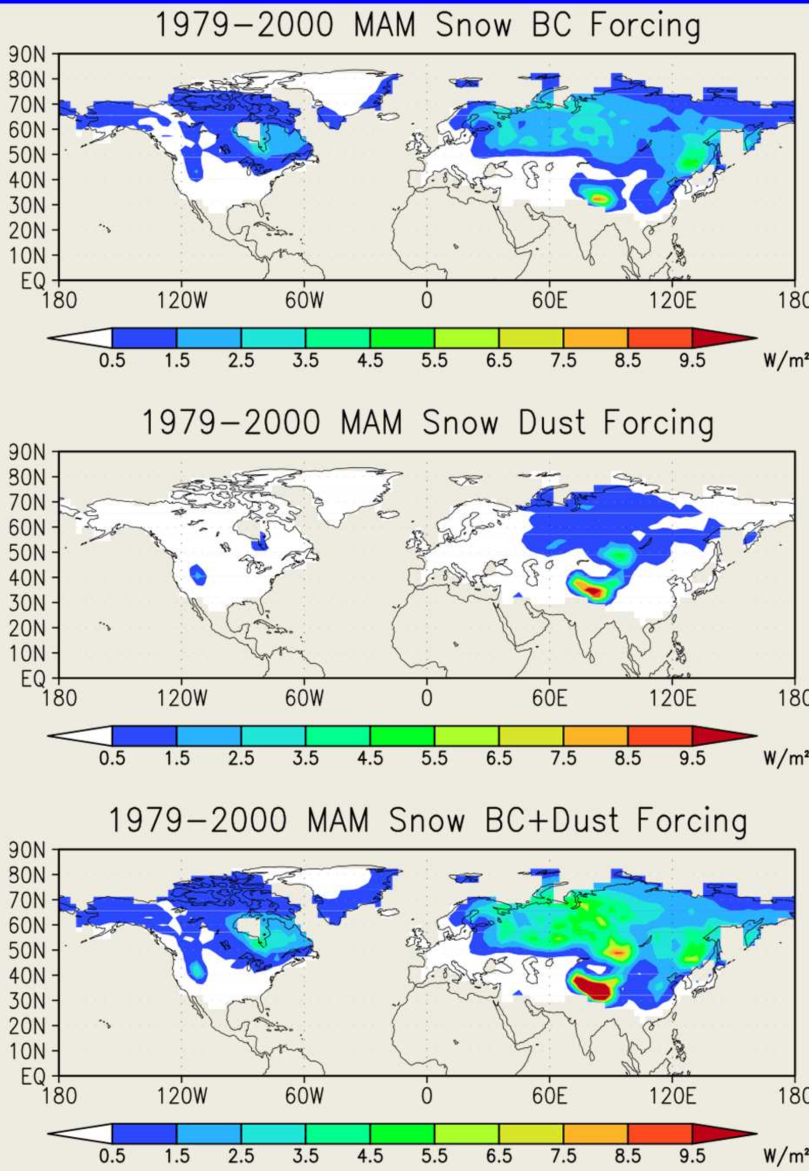


Fig. 7. March–May surface radiative forcing, averaged spatially and temporally only over snow, caused by (top) black carbon in snow, (middle) mineral dust in snow, and (bottom) both agents. Data are 1979–2000 ensemble means from experiment T2 (Table 1).

Flanner et al. (2009)

What’s Missing?

- Models indicate that aerosols are strongly altering snowpack albedo and melt rates.
- Snow pits, firn and ice cores show episodic strong deposition to snow.
- Precipitation sampling shows LAA incorporated in snow.

- **There is very little in-situ data on dry deposition to snow, and**
- **There is very little chemical and mass validation of transport models to snow-covered regions.**

Why the Sierra-Cascade?

- Western U.S. snowpack is reported to be declining (Mote *et al*. 2005).
- Sierra-Cascade is exposed to hemispheric pollution from Asia and is downwind of significant population along U.S. west coast (VanCuren & Cahill, 2002).
- Models suggest BC promotes earlier melt in Sierra – Cascade cordillera (Qian *et al*., 2009).
- Accelerated melt exacerbates spring flooding and reduces summer water supplies in downstream regions.
- There is limited data on BC in precipitation and snow and no recent data on winter BC dry deposition in Sierra Cascade snowsheds.

Background – the SUPRECIP Project

- CEC – Supported project with Daniel Rosenthal for aircraft – based cloud physics to assess aerosol impacts on clouds and precipitation over California.
- Supplemental projects:

  Ramanathan & Hadley - sample BC in precipitation

  (Hadley *et al*., Measured black carbon deposition on the Sierra Nevada snow pack and implication for snow pack retreat**,** *Atmos. Chem. Phys. Discuss*., 10, 10463–10485, 2010.)

  Hudson (DRI) - measure CNC properties below clouds

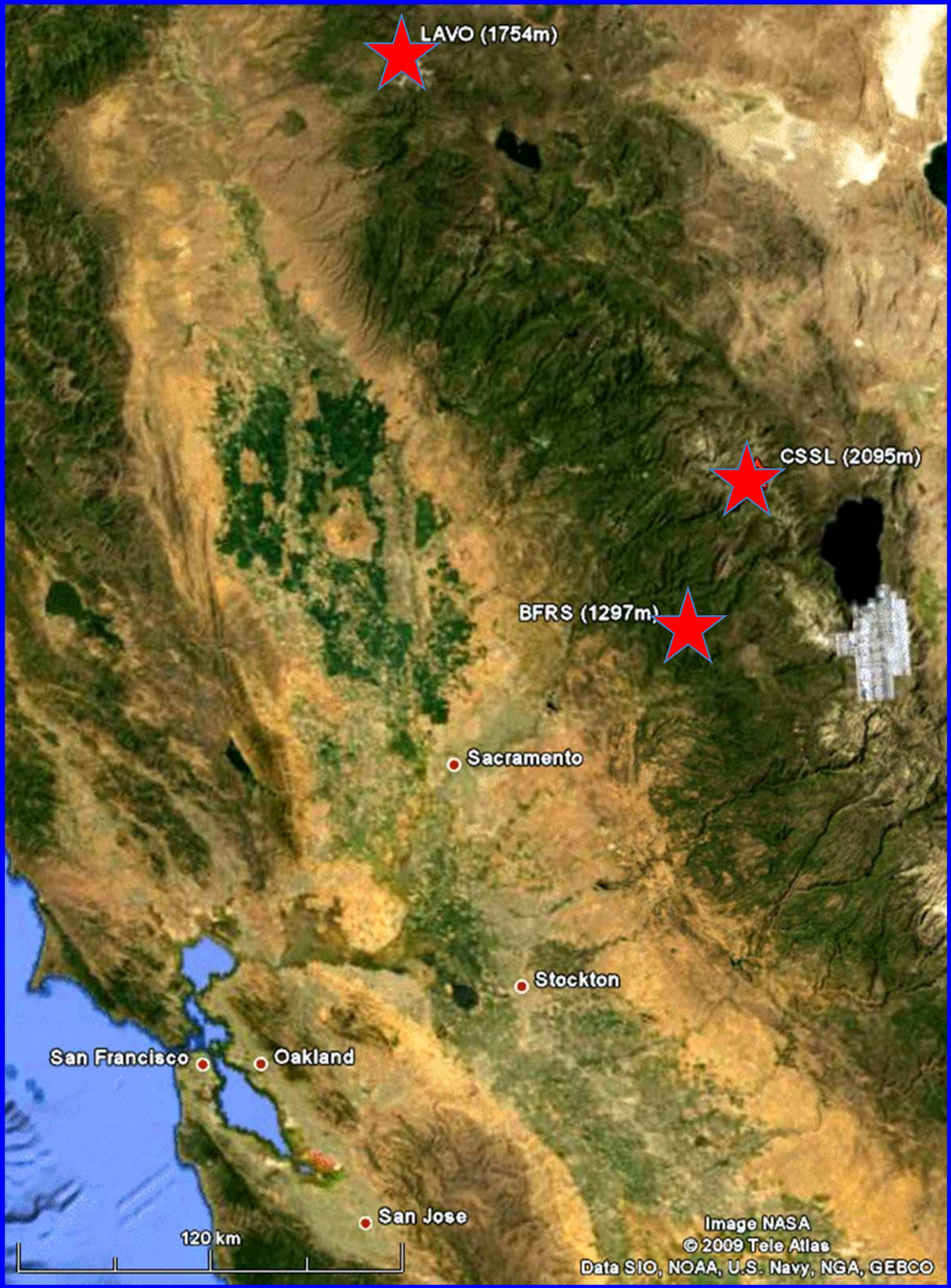
  Cliff group - (UCD) characterize aerosols below clouds.

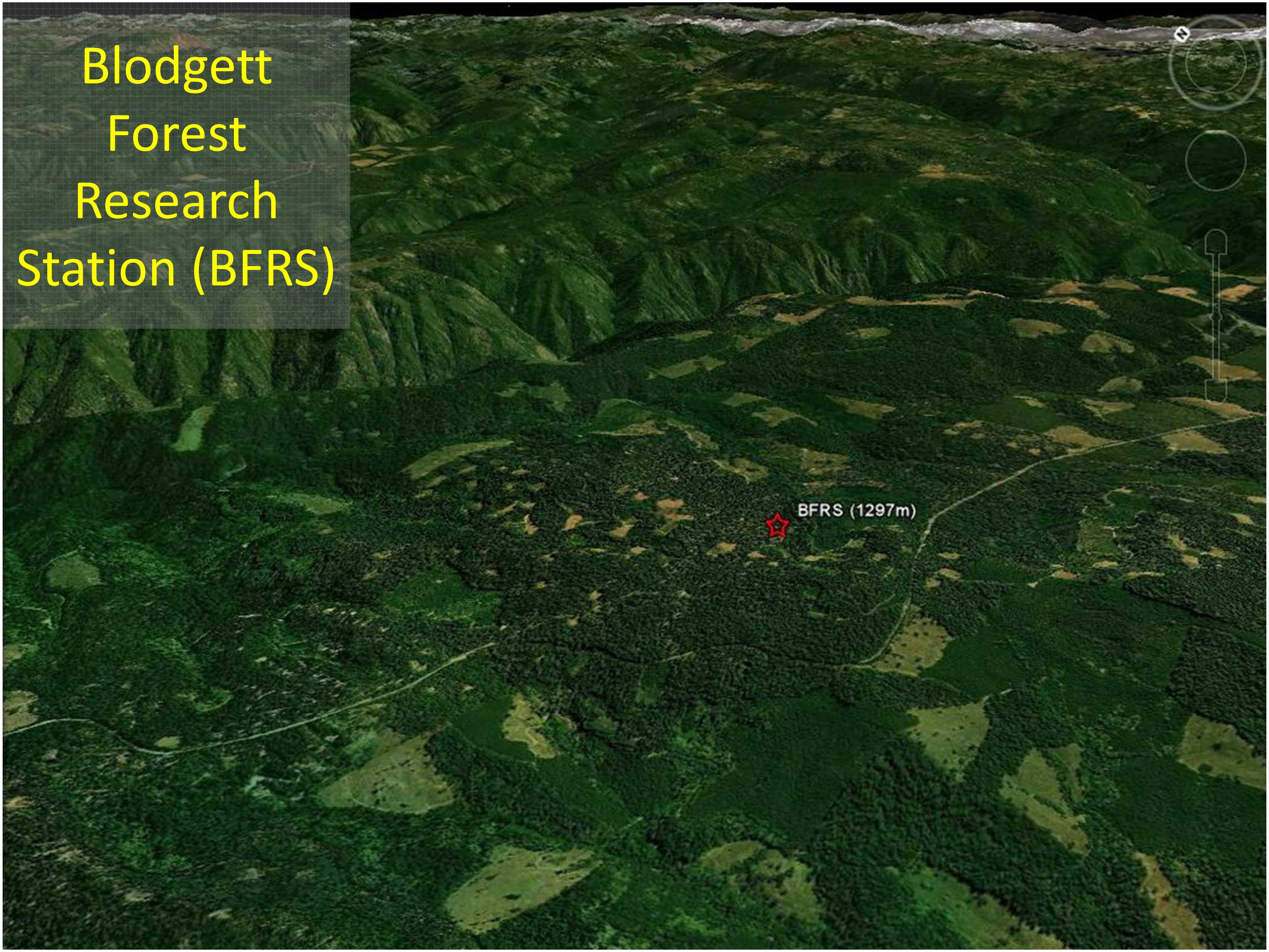
“Found Experiment” – LAA Dry Deposition from SUPRECIP aerosol samples.

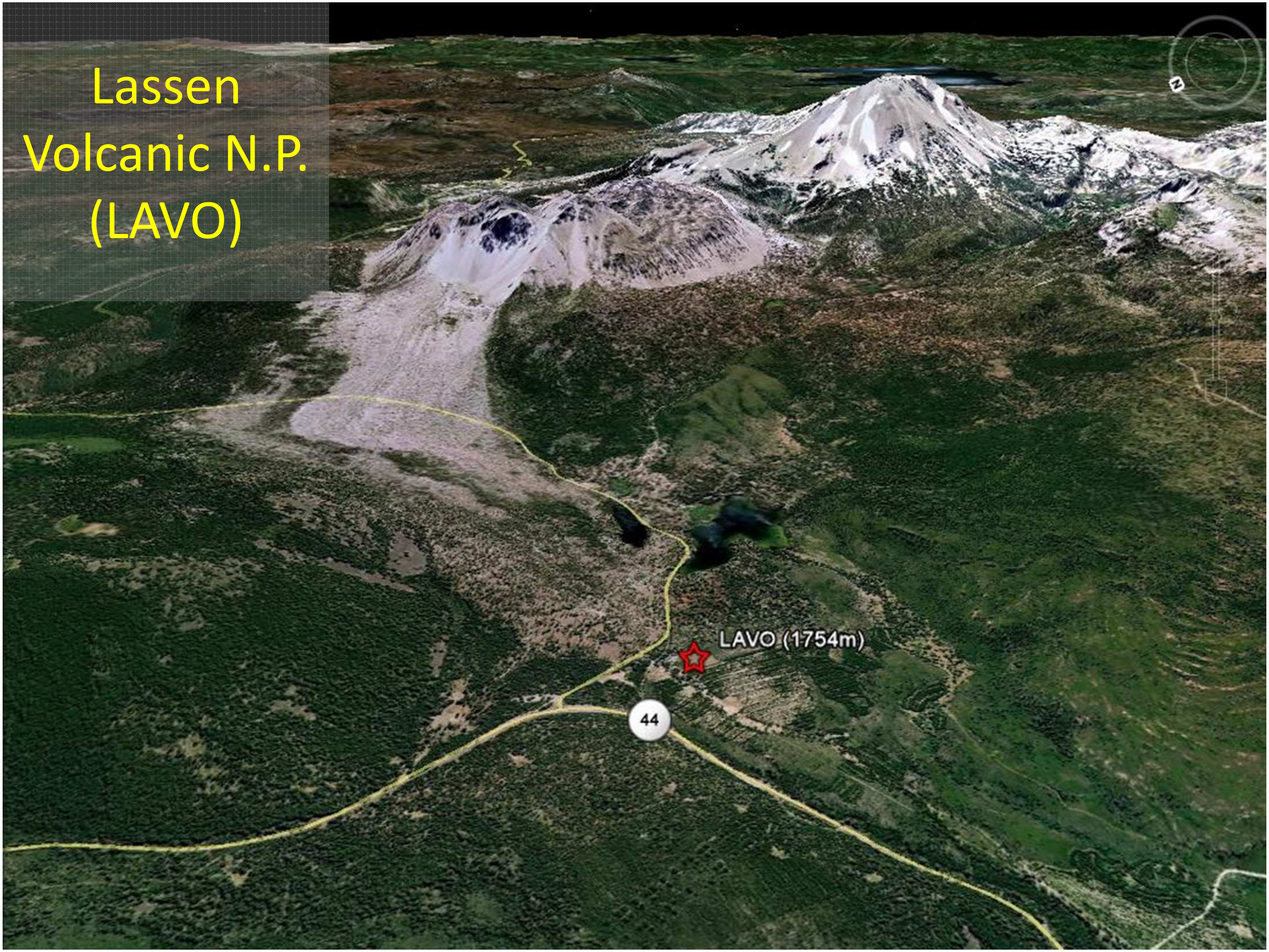
- Collect time- and size- resolved aerosol samples at multiple mountain sites in late winter
- Derive “black” component from optical analysis
- Relate “black” material to metallic source signatures in aerosols by Positive Matrix Factorization (PMF)
- Compare multiple sites to distinguish local and regional source signatures
- Compute “black” aerosol deposition to snowpack
- Combine with Hadley’s BC in precipitation to model snow albedo
- Compare with WRF-Chem model estimate by Yun Qian (Qian *et al*., 2009)

Sampling Program

- LAVO: Lassen Volcanic National Park – IMPROVE 1754 m.
- CSSL: Central Sierra Snow Lab – UCB “Donner Summit” 2095 m.
- BFRS: Blodgett Forest Research Station – UCB 1297 m.




Blodgett Forest Research Station (BFRS)
BFRS (1297m)


Lassen
Volcanic N.P.
(LAVO)
LAVO (1754m)
44
N


Central Sierra Snow Lab (CSSL)
Norden
Soda Springs

RDI Sampling System

- Proprietary design Rotating Drum Impactor particle collector.
- Autonomous operation for up to 6-weeks
- 8 Size bins 10 – 0.09 μm
- Continuous aerosol sample is analyzed in 3-hour time steps.

Sampler Installations

CSSL Summer

CSSL Winter→

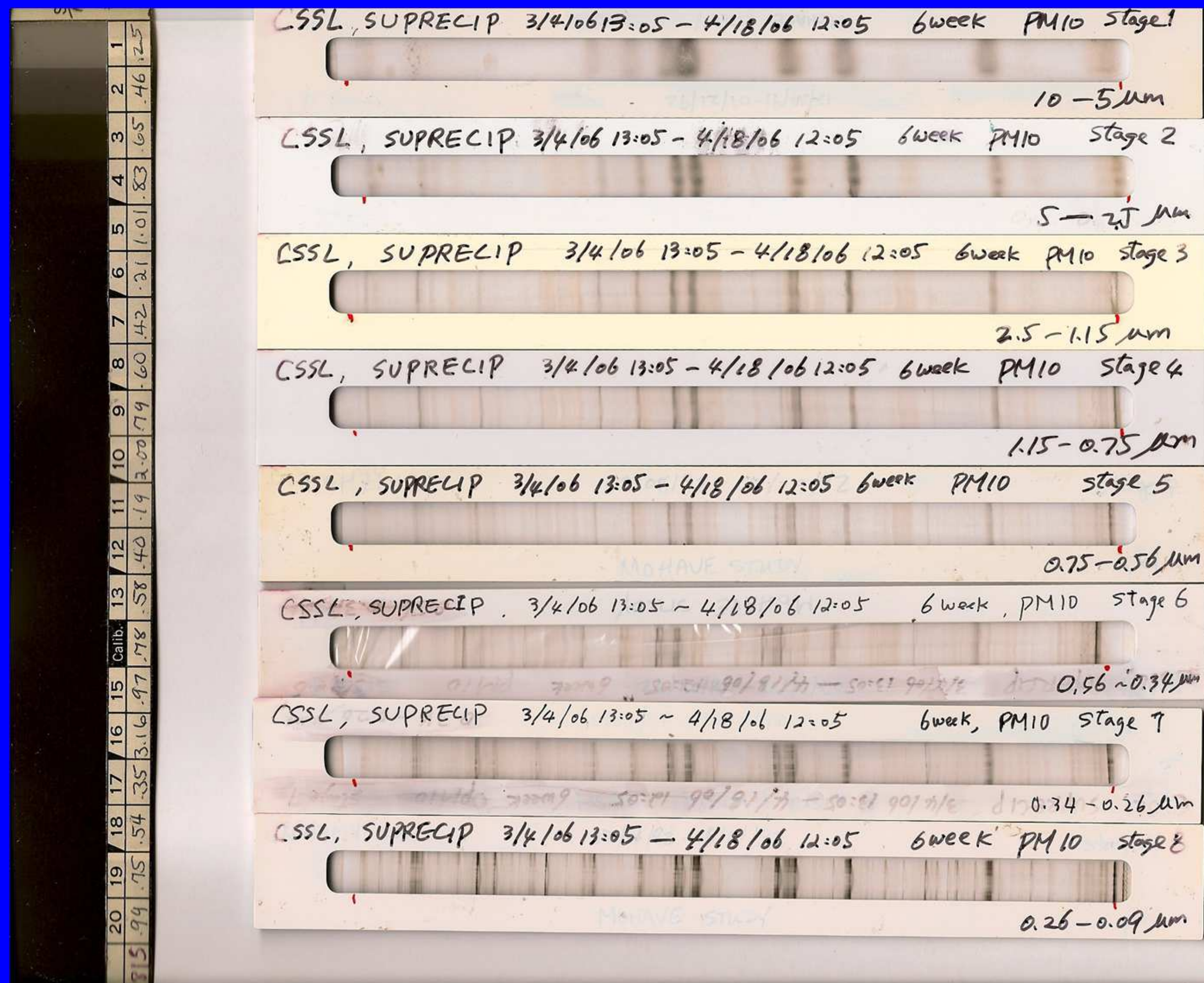
LAVO Winter→

Sample Analysis

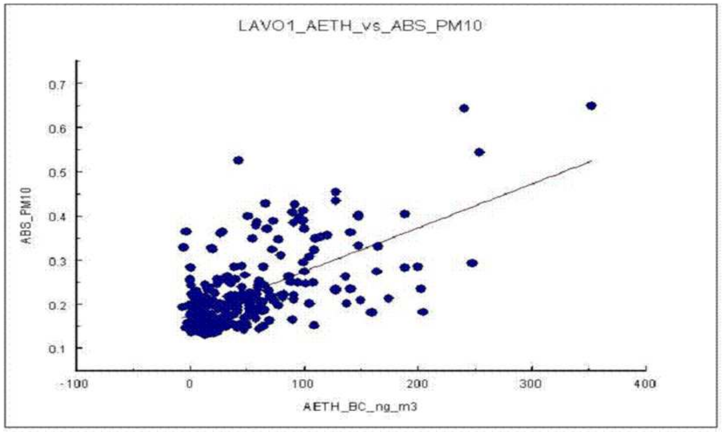
Synchrotron- XRF:
28 Elements Na – U

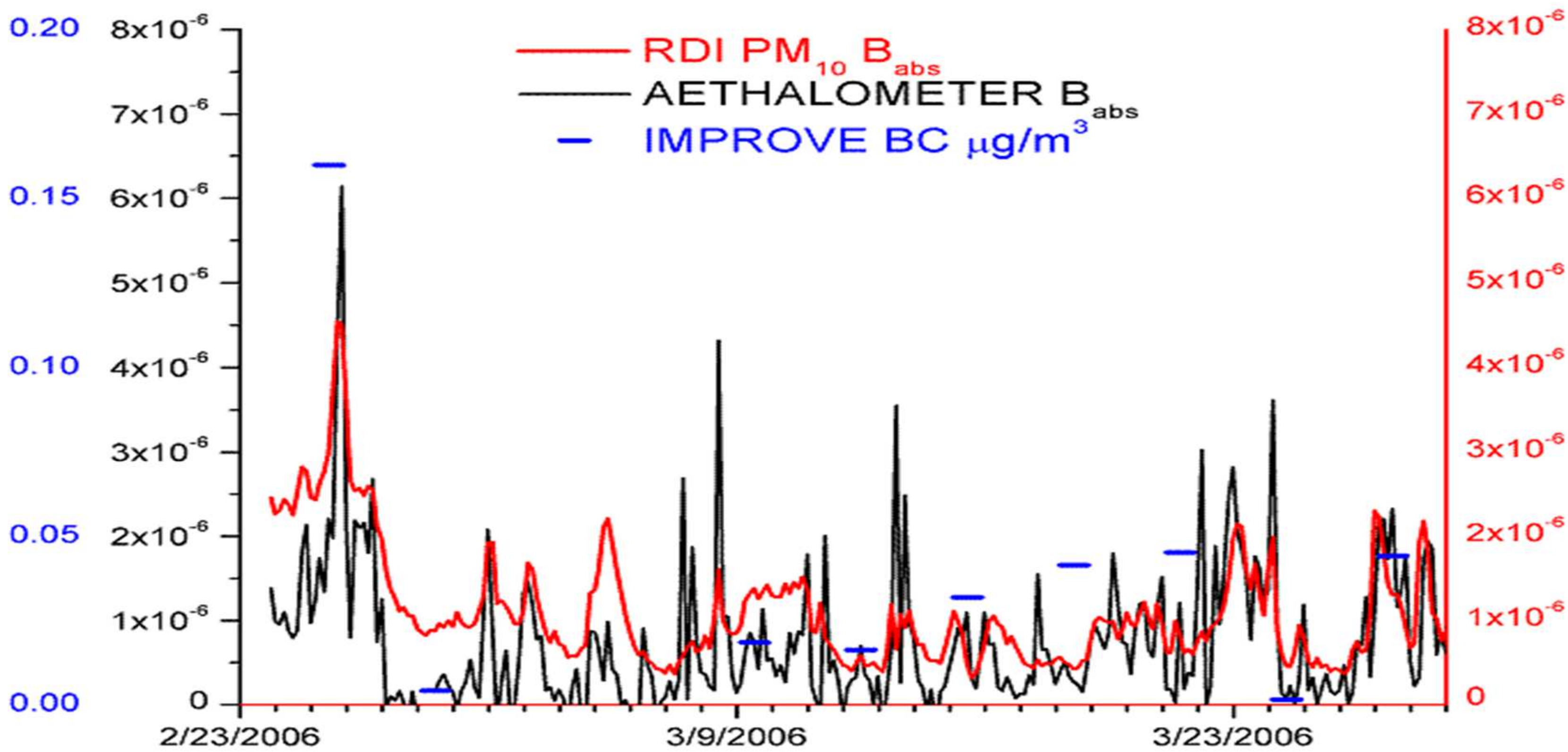
Soft Beta Gauge:
Aerosol Mass

Optical Scan:
Light absorption



Measuring Absorption
LAVO CASTNET Intercomparison






WINTER AEROSOL SOURCES

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PMF Analysis – *alá* Hopke & Paatero

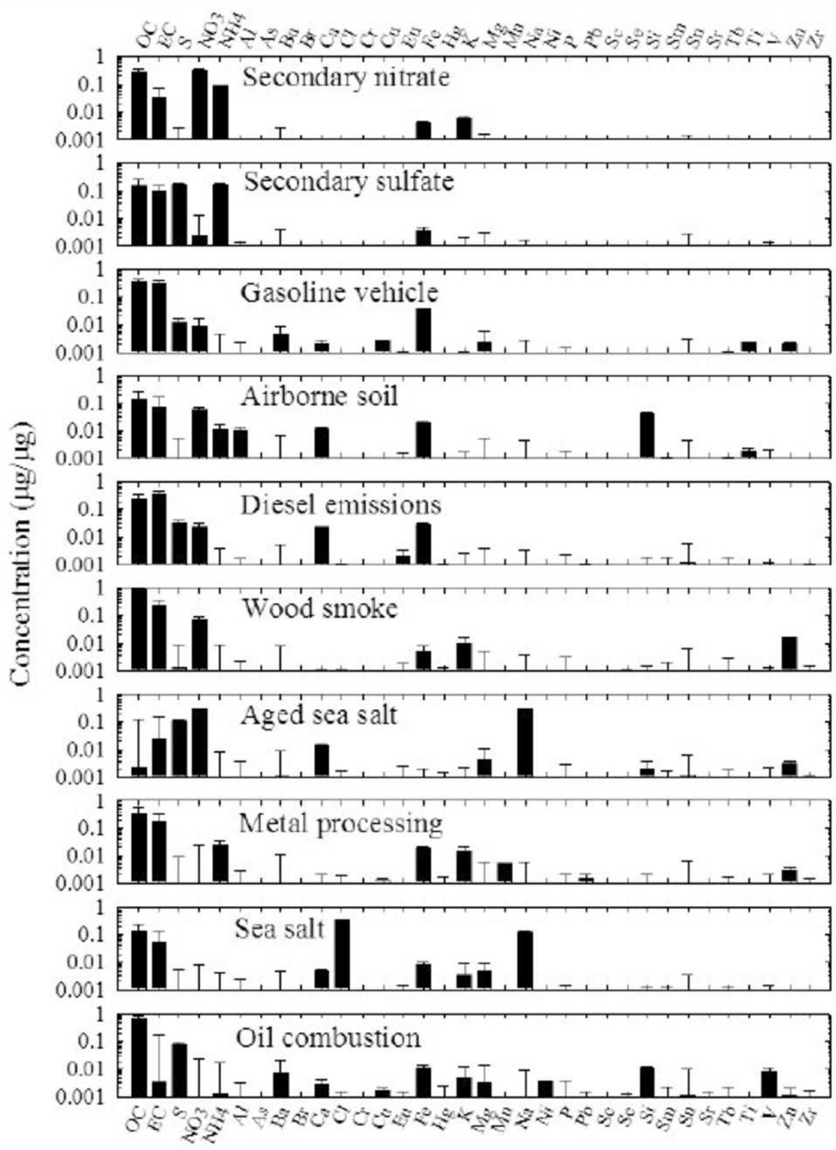


Figure 77. Source profiles deduced from $PM_{2.5}$ samples measured at Olive St. (prediction ± standard deviation).

(Hopke et al., 2006)

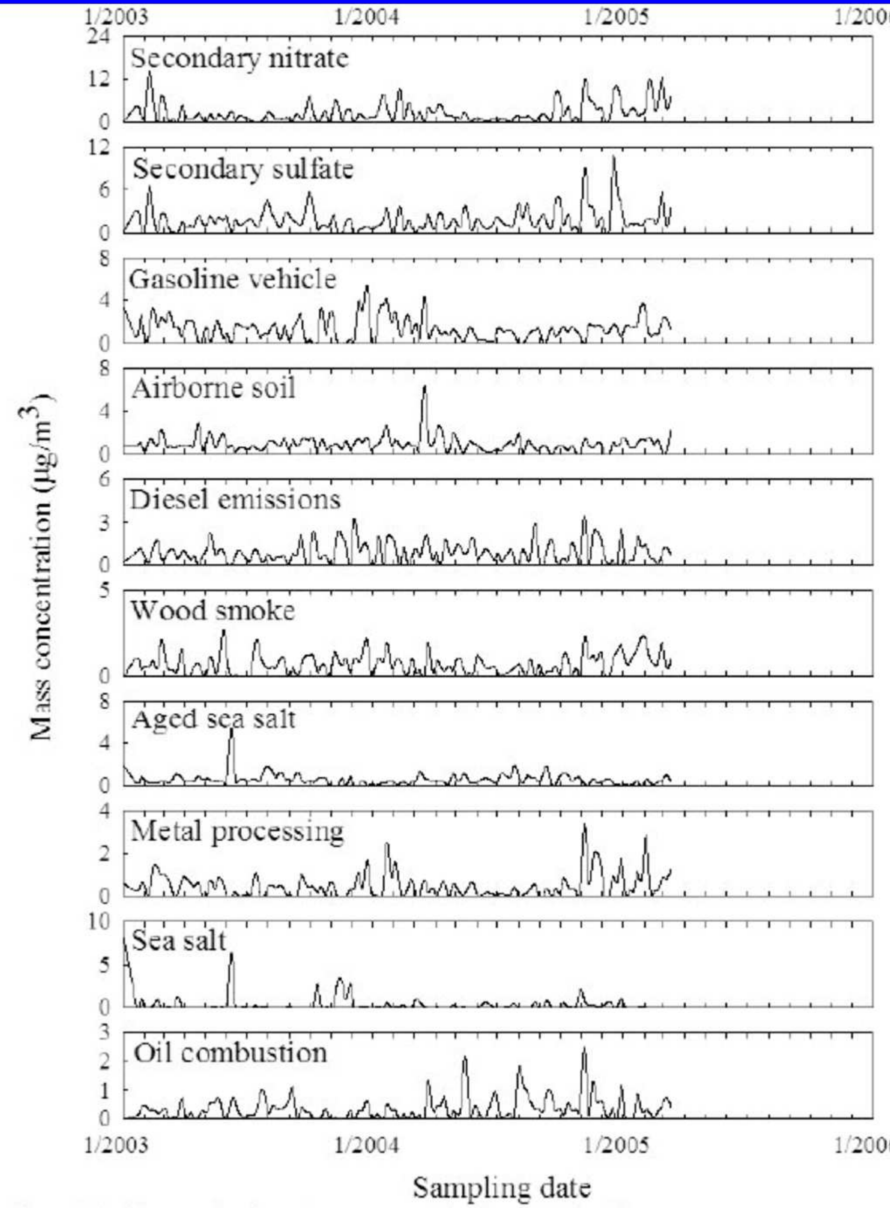
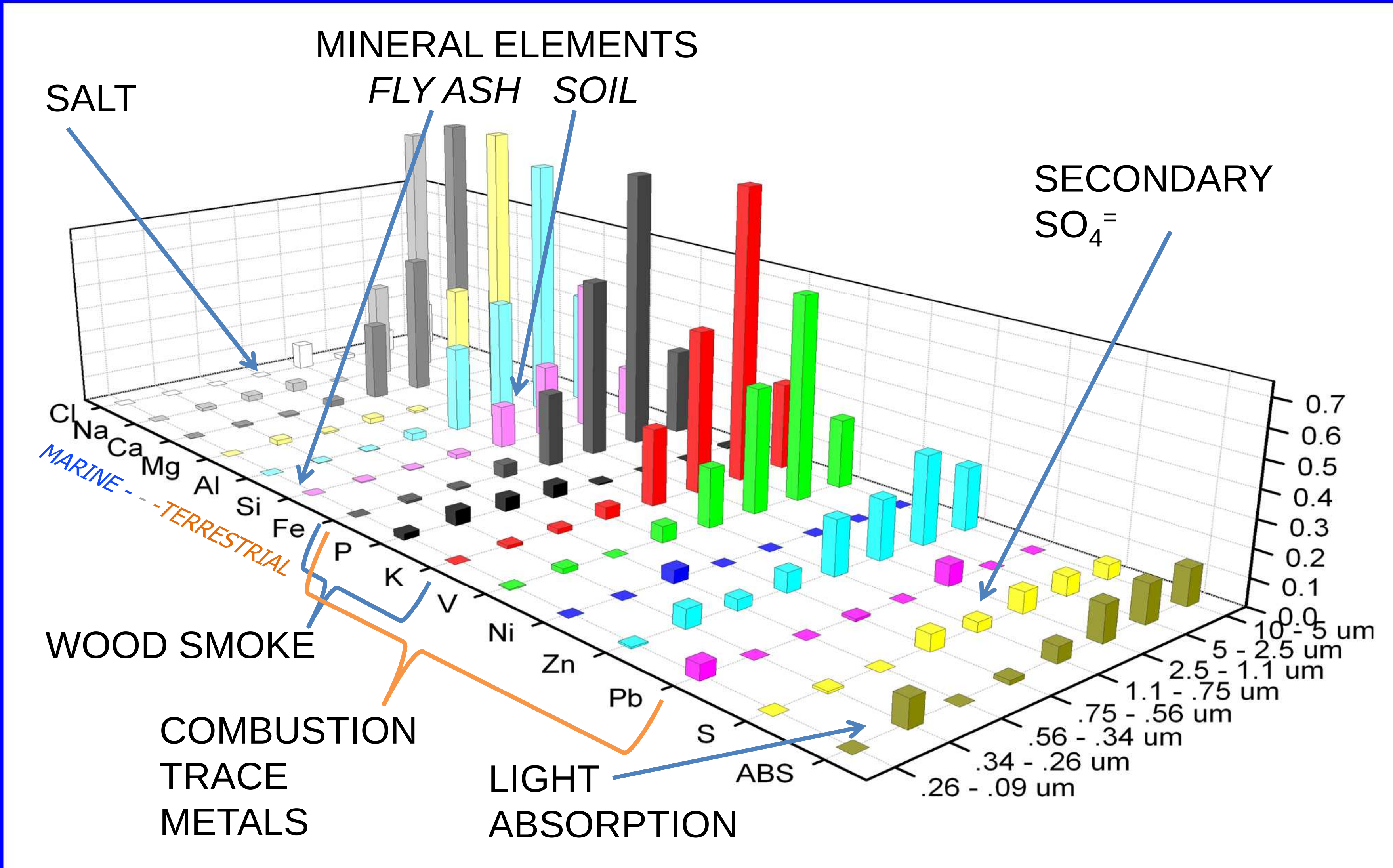


Figure 82. Time series plot of source contributions at Olive St.

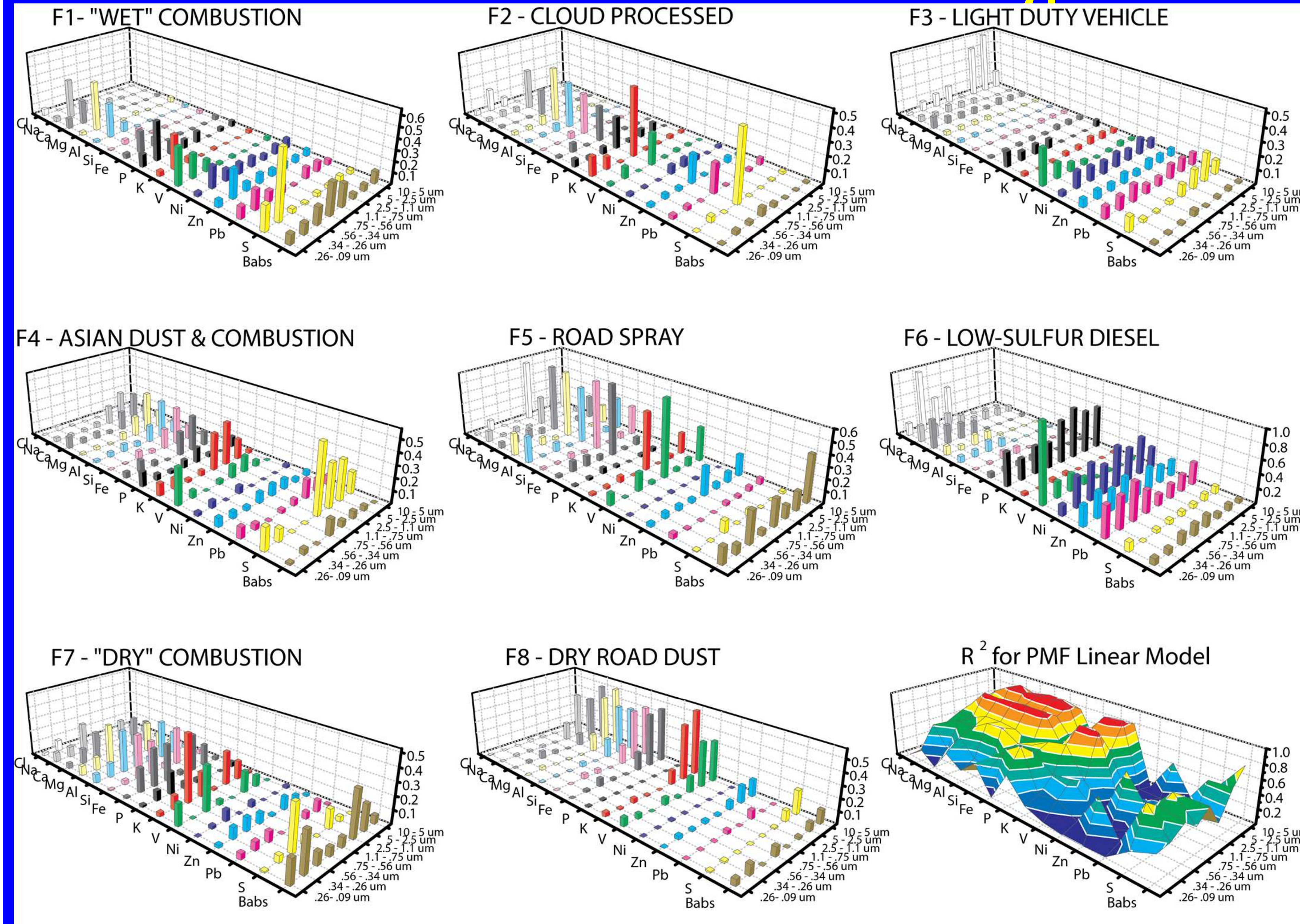
PMF *alá* RDI

Visualize aerosol composition by size and species

Concentrations normalized to stage-species z-values to emphasize correlations

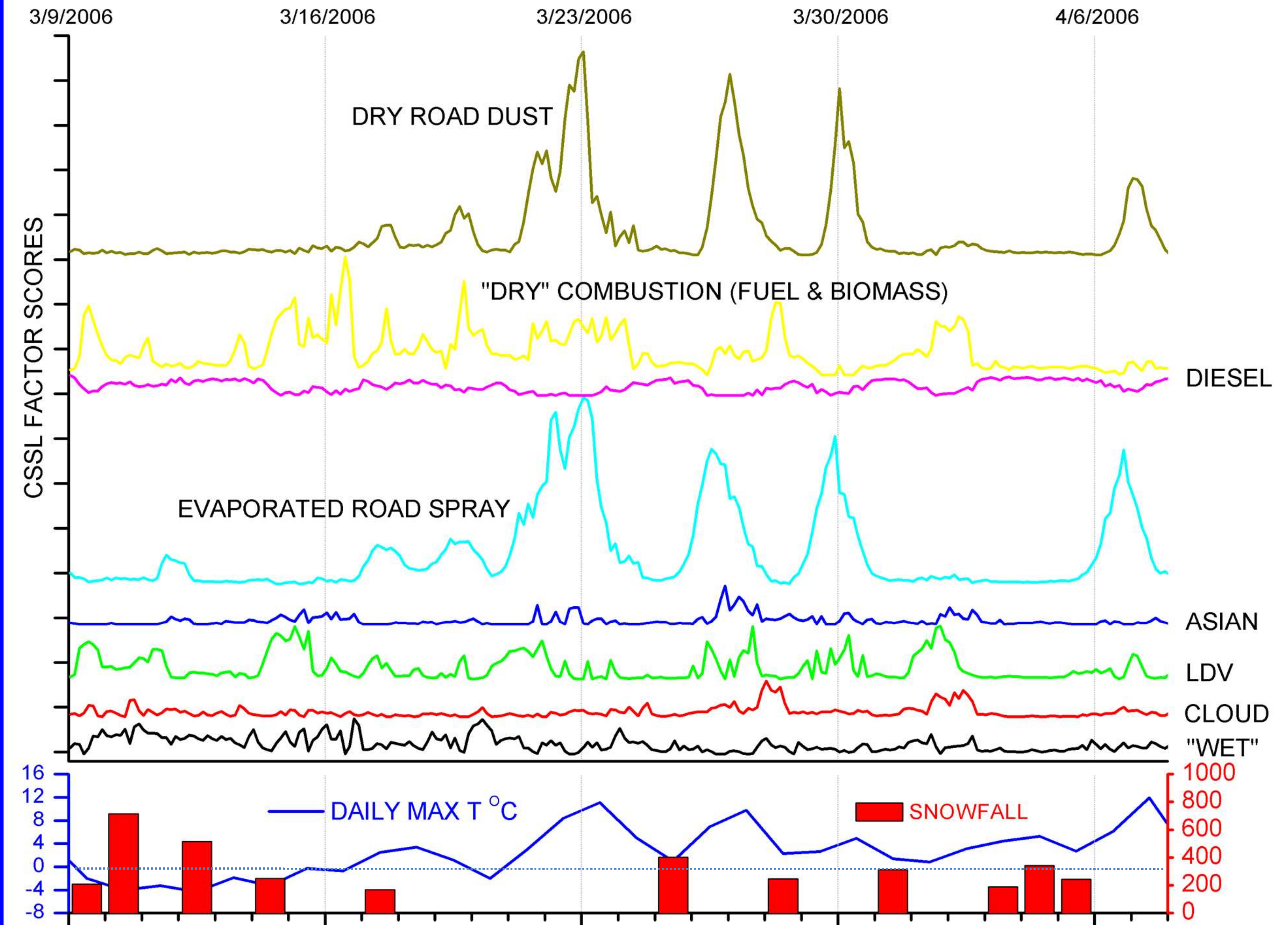


“Pooled” PMF Classified Aerosol Types

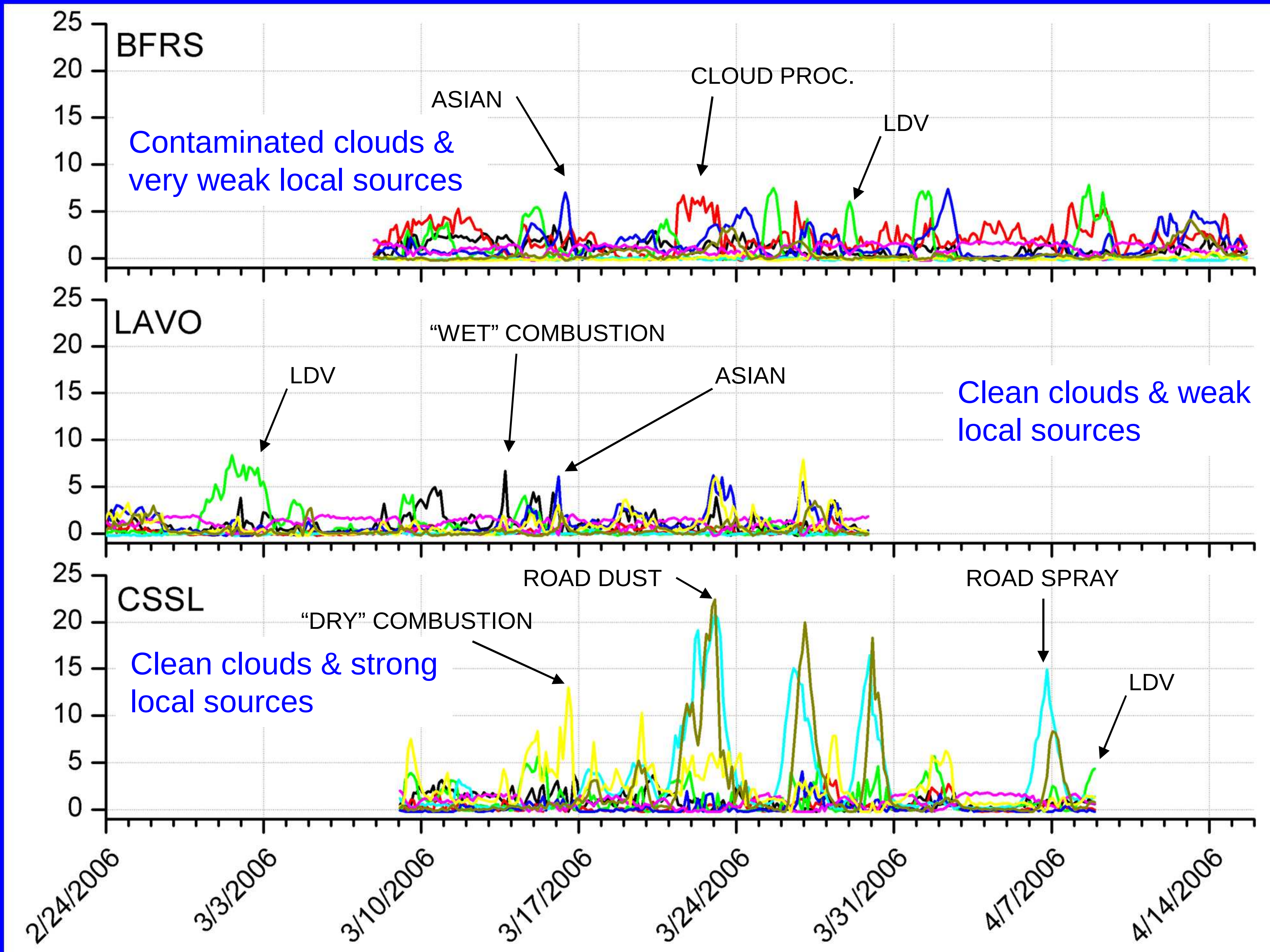


Analysis of Ambient Aerosols

Temporal Dynamics - CSSL

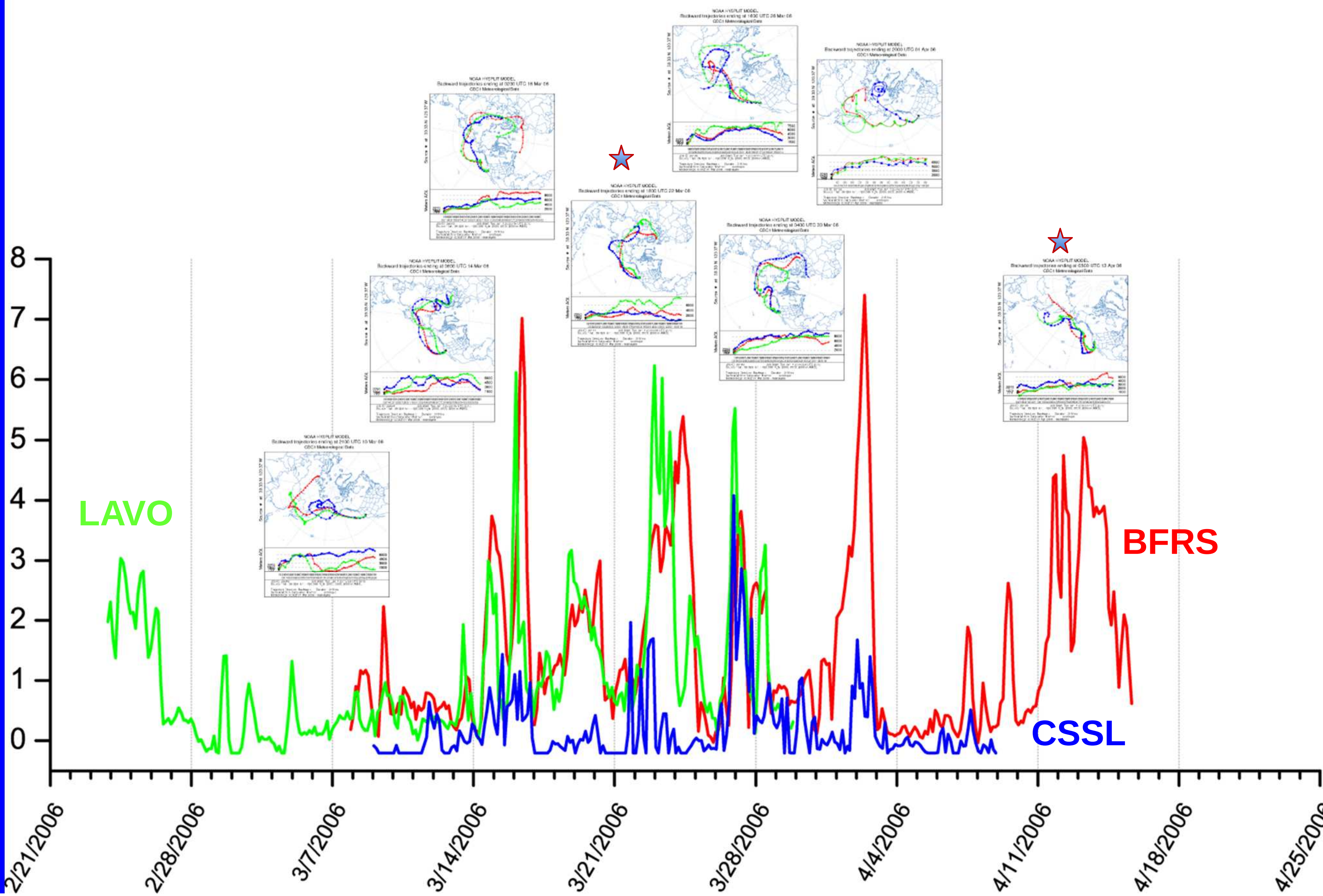


Spatial Disparity

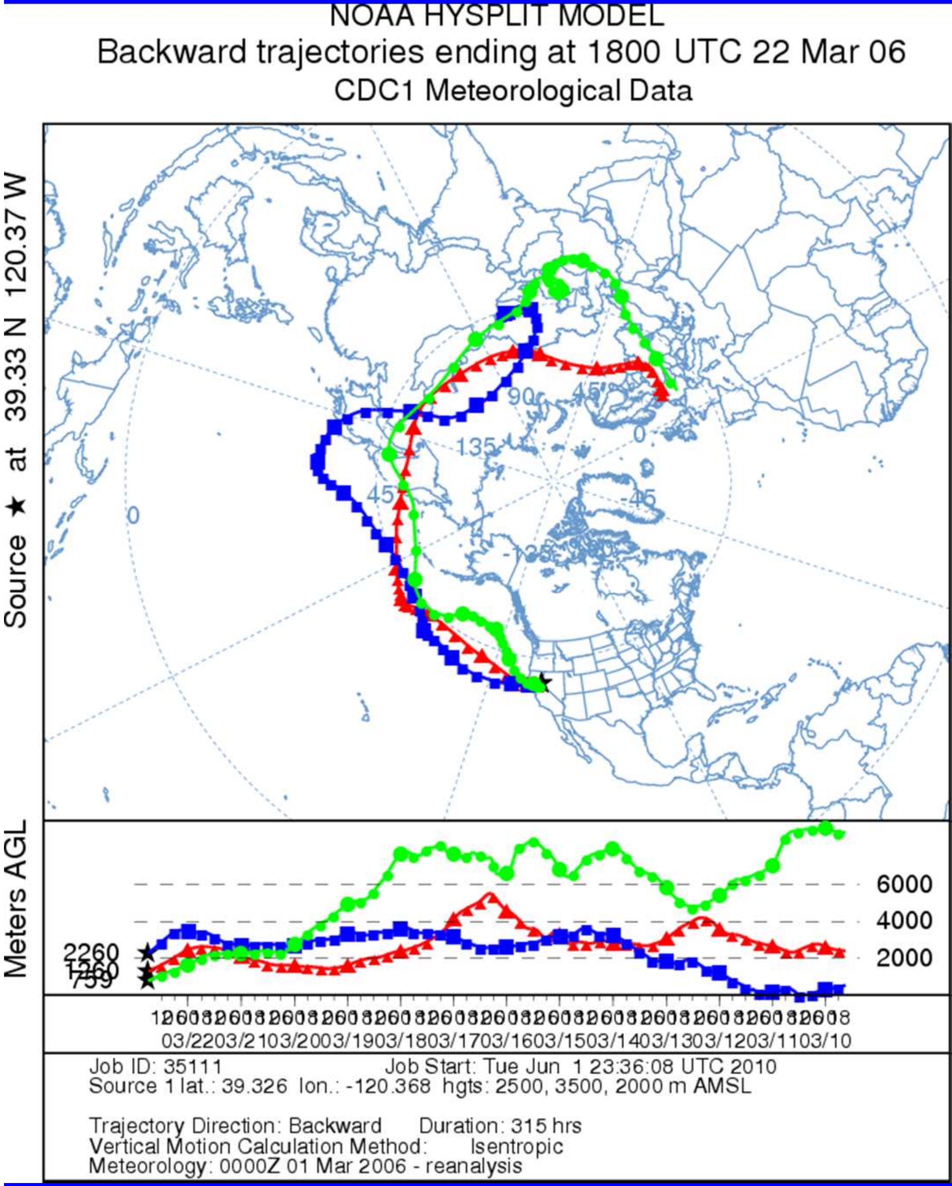


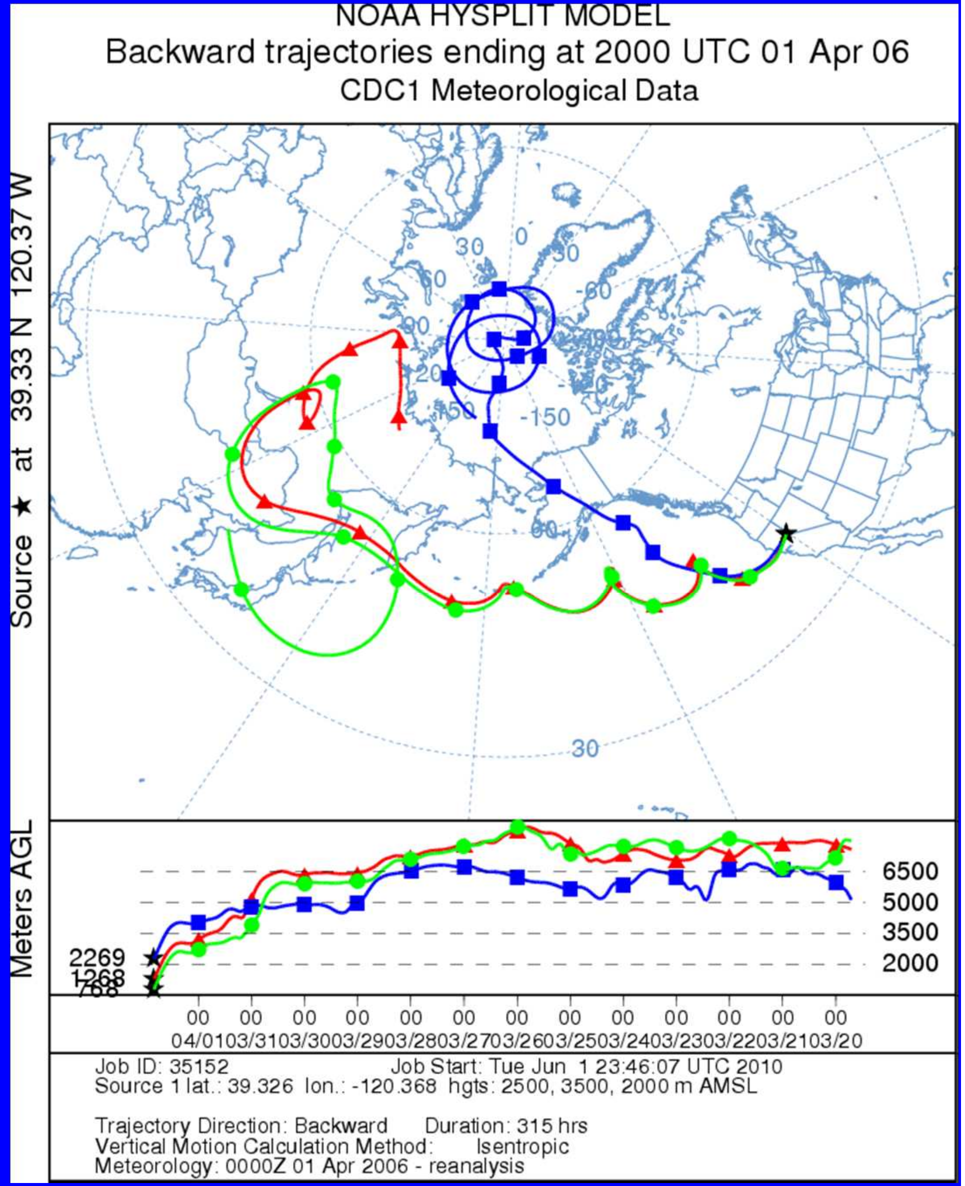
Back Trajectories – Asian & “Arctic” Aerosol

F4 of 8 - Asian Dust & SO_4 - “Arctic Haze”

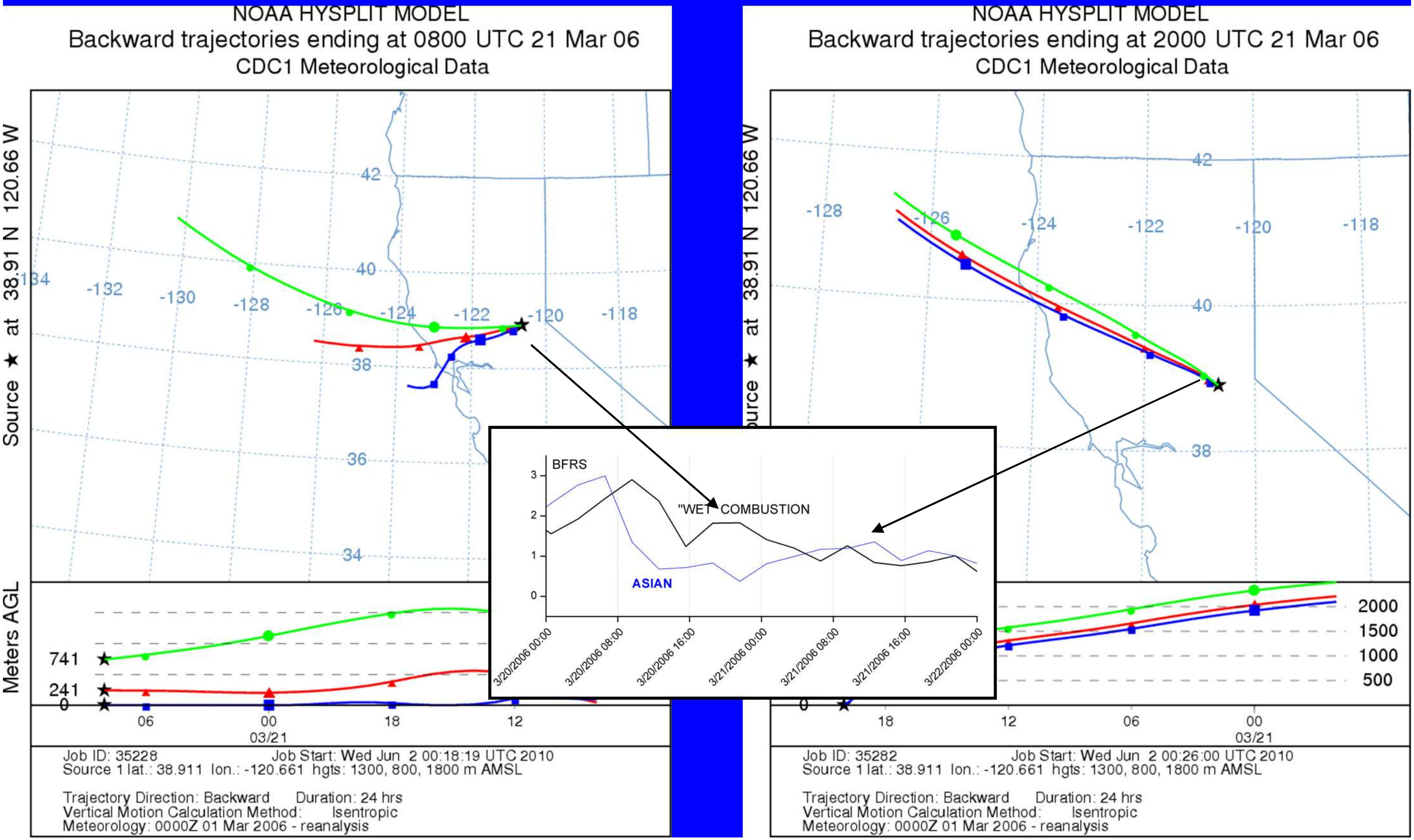


Arctic-Asian Trajectories

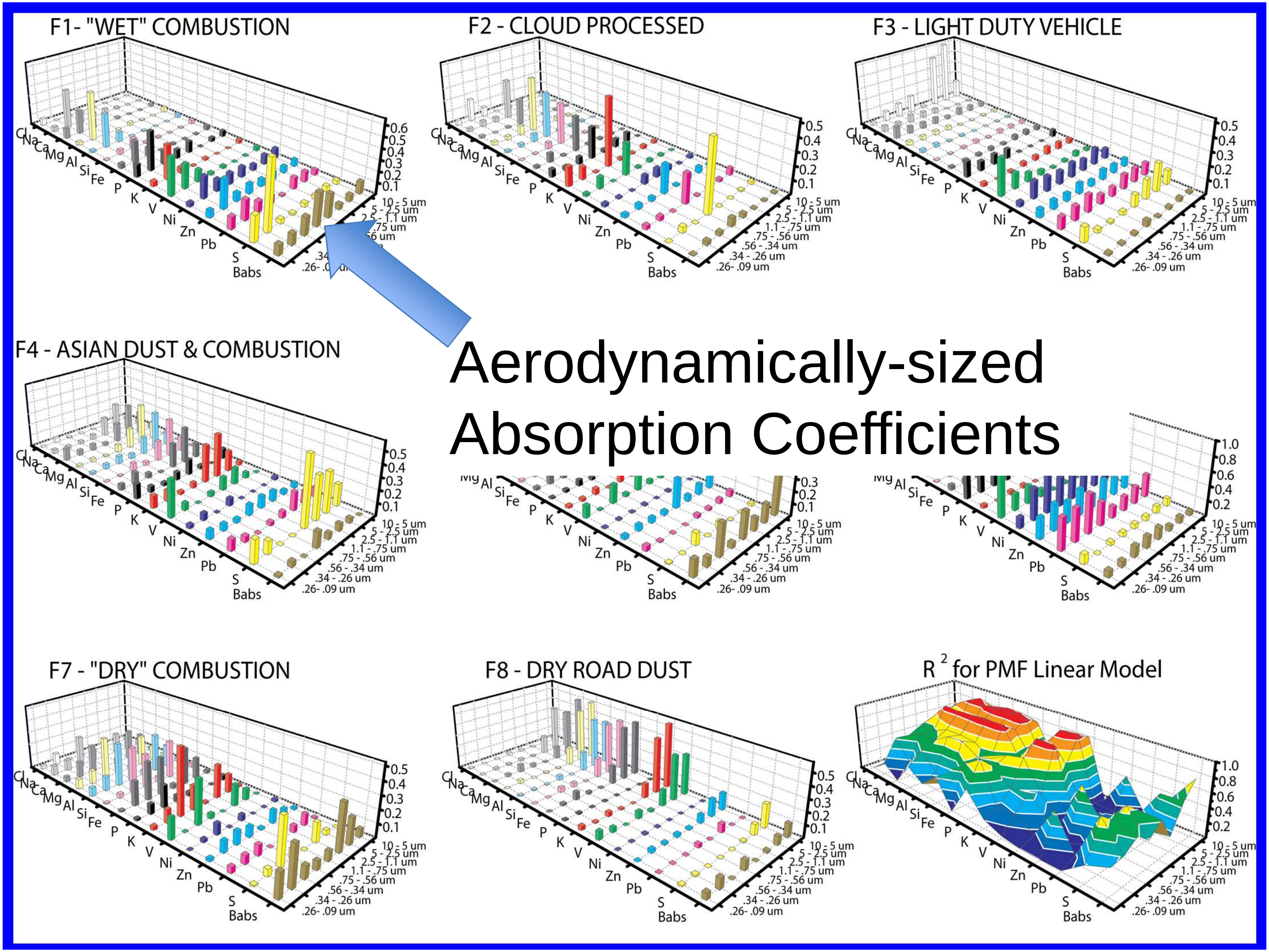




Regional Transport

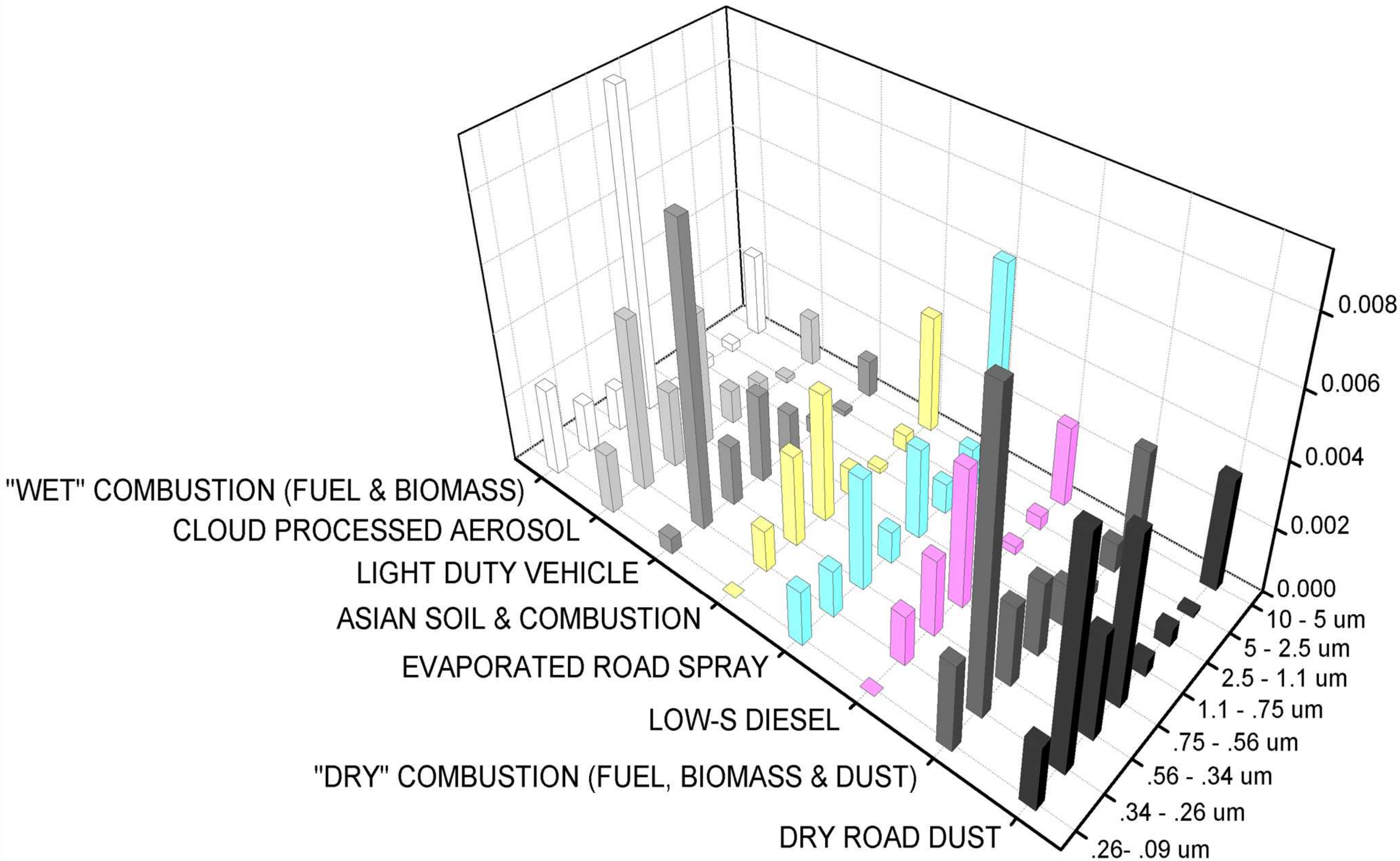


Analysis of Deposited Aerosols

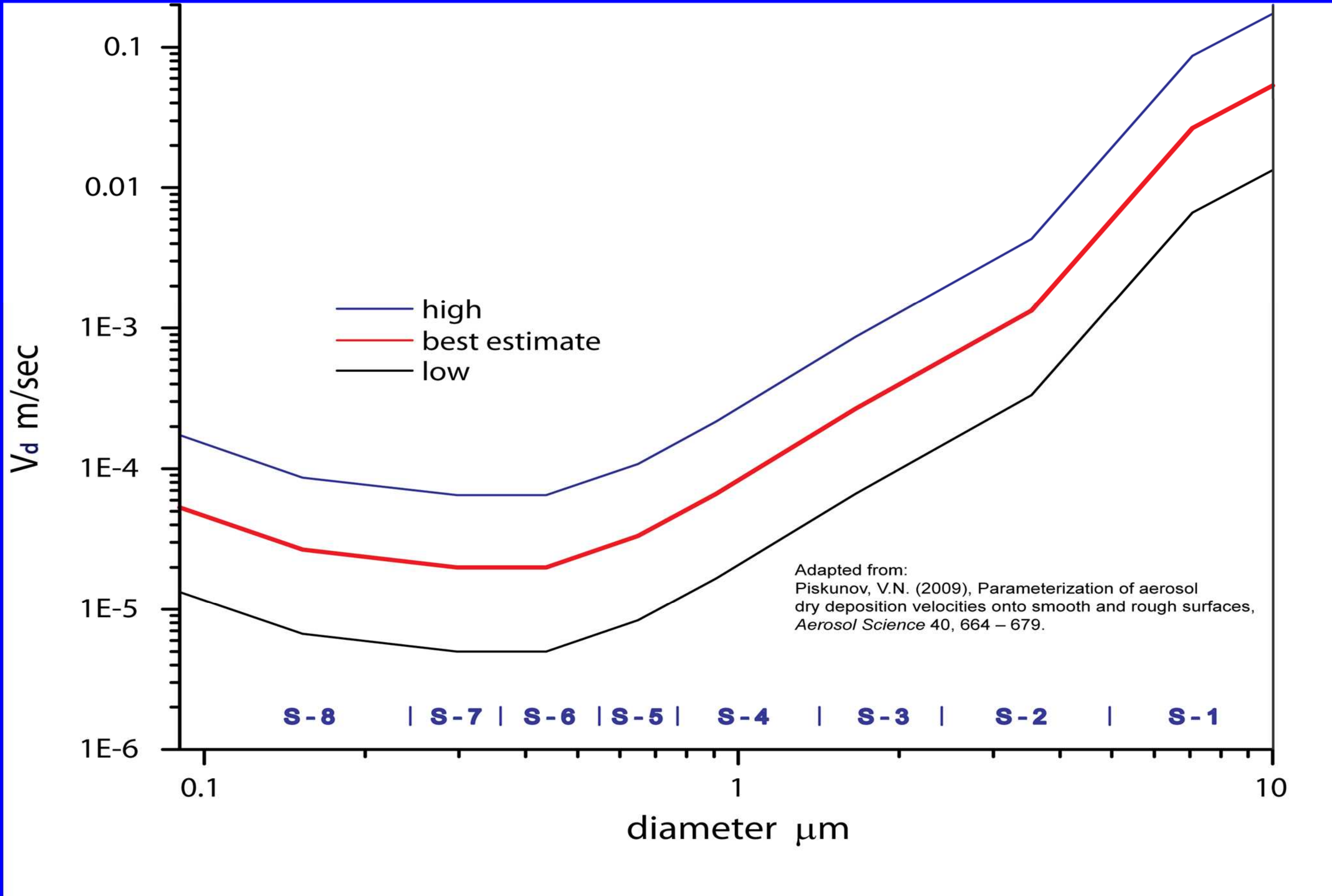


F1- "WET" COMBUSTION
F2 - CLOUD PROCESSED
F3 - LIGHT DUTY VEHICLE
F4 - ASIAN DUST & COMBUSTION
Aerodynamically-sized
Absorption Coefficients
F7 - "DRY" COMBUSTION
F8 - DRY ROAD DUST
R 2 for PMF Linear Model

Light Absorption by Aerosol Types

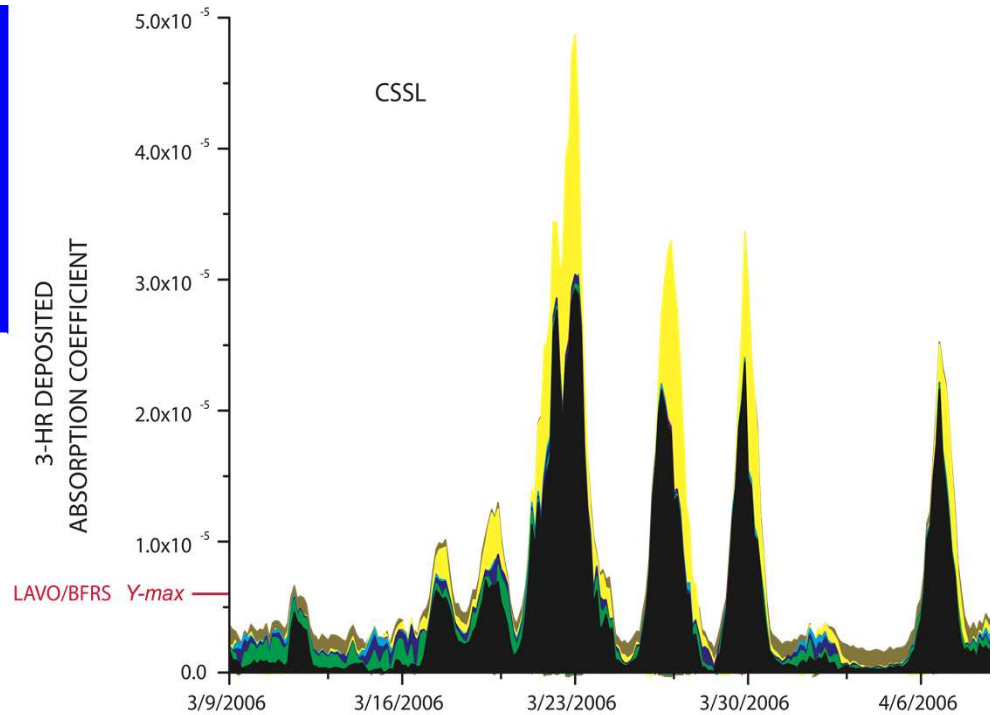


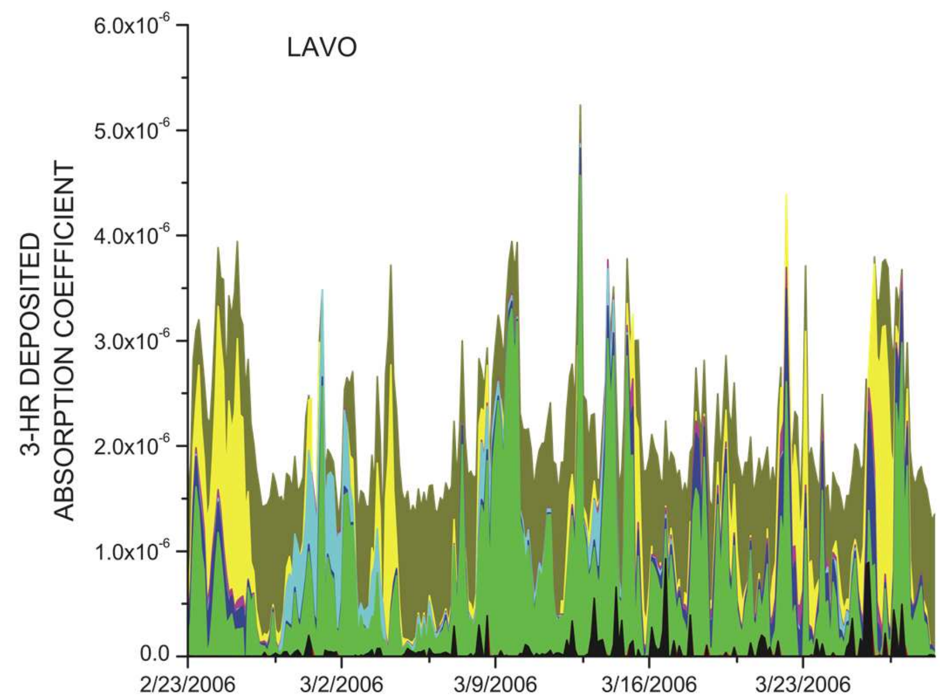
Aerodynamic Dry Deposition Velocities

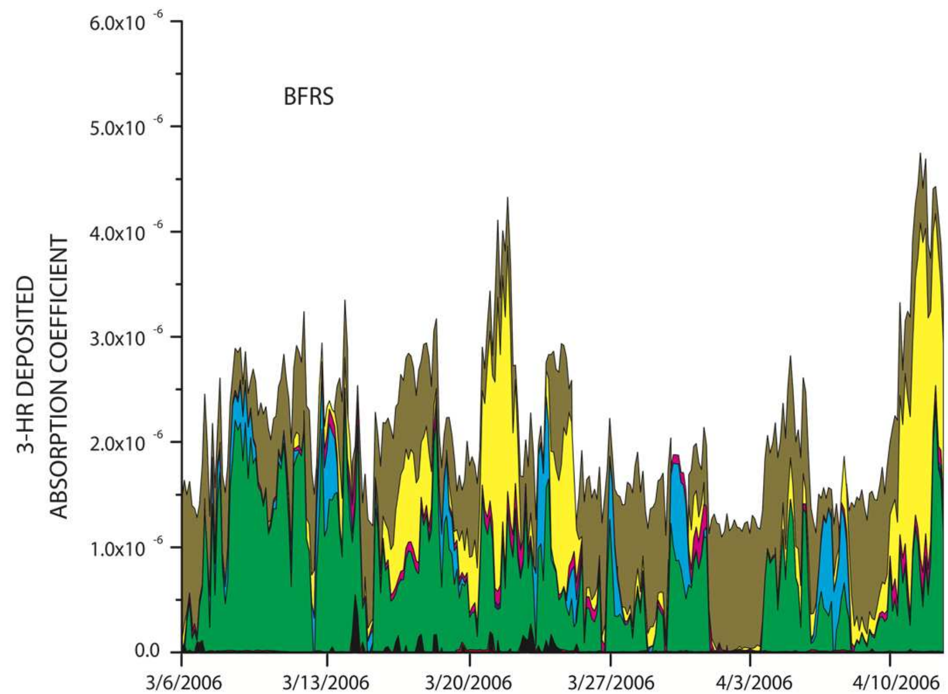


3-hour Time- and Source-Resolved Dry Deposition

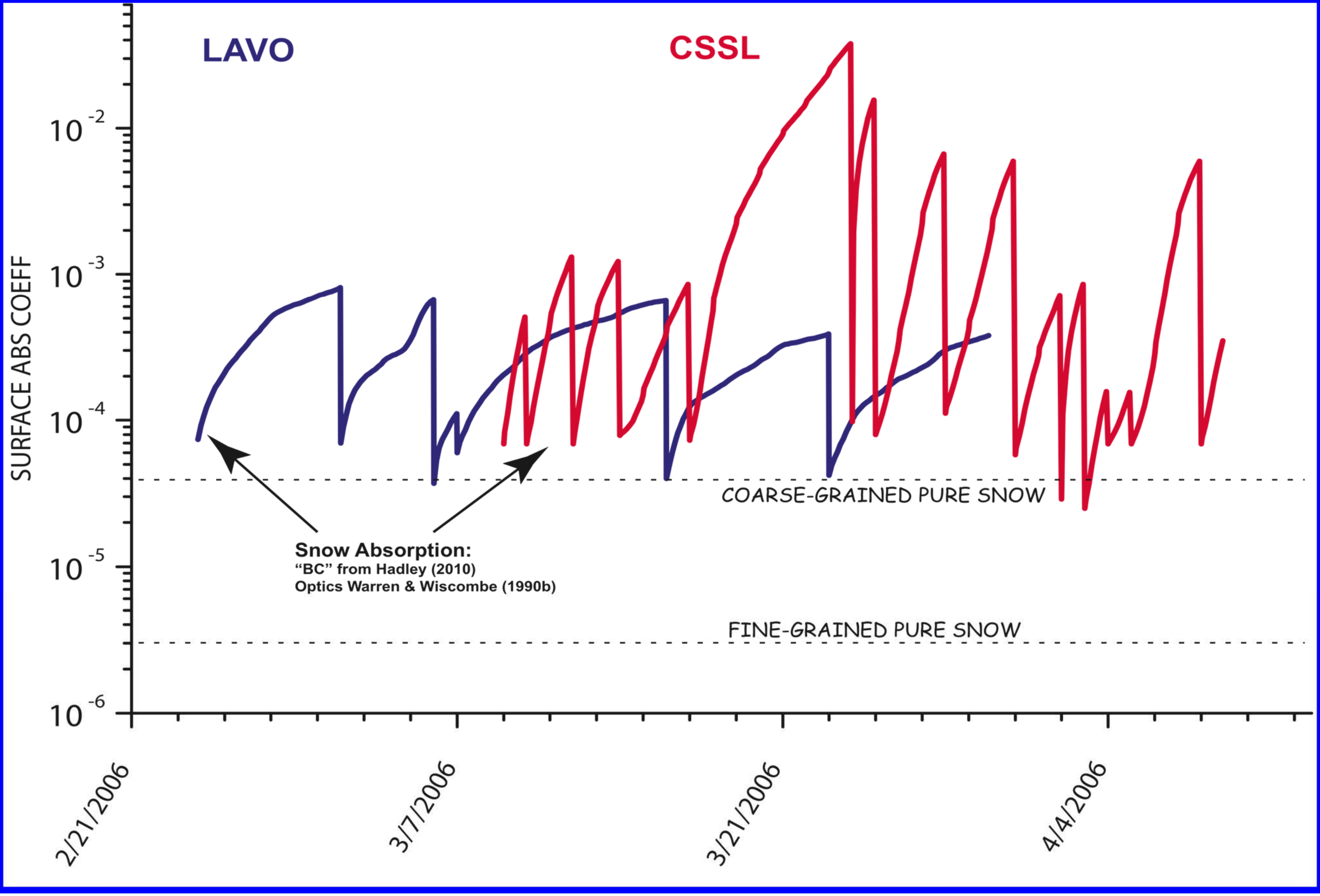
- LOW SULFUR DIESEL
- DRY ROAD DUST
- ASIAN DUST AND COMBUSTION
- LIGHT DUTY VEHICLE (w/ ROAD SALT)
- "DRY" COMBUSTION (FOSSIL & BIOMASS)
- "WET" COMBUSTION (FOSSIL & BIOMASS)
- CLOUD PROCESSED AEROSOL
- EVAPORATED ROAD SPRAY



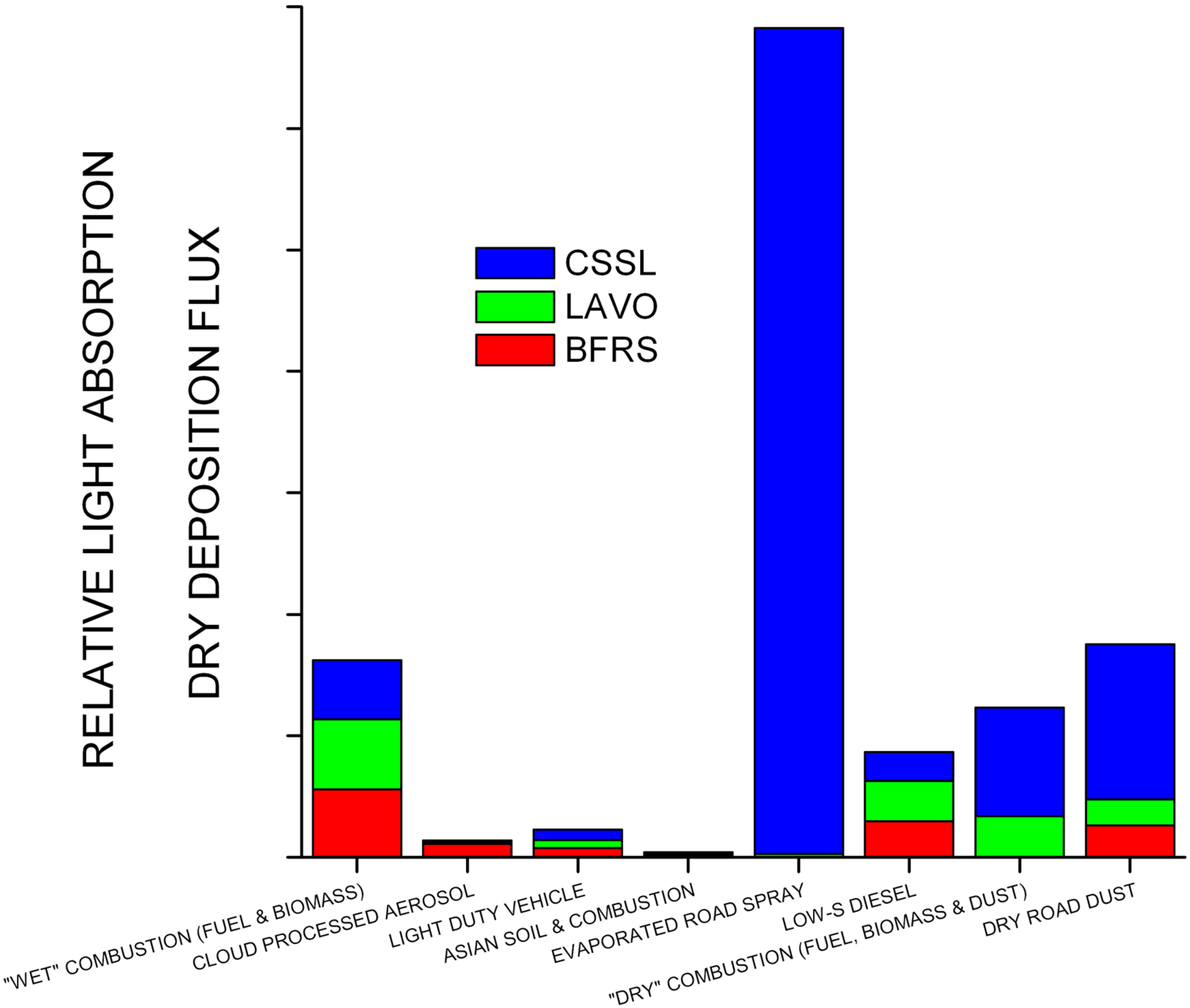




Combined Wet and Dry Short-Wave Snow Surface Absorption



Site- & Source- Resolved Dry "Black" Deposition



Conclusions

- There is significant locally-generated winter LAA even in sparsely populated areas. Only a fraction of it is "BC".
- Local human activity dominates LAA in transportation corridors and settlements. Much of this is greater than 1 μm diameter, and has the potential to locally enhance melt and confound "regional" deposition measurements.
- Entrainment of regional pollution in clouds is observed, at lower elevations, but dry transport of LAA upslope from urbanized lowlands appears weak.
- Direct observation of regional LAA inputs to the persistent snowpack (>2.5km elevation) will require sampling at high elevation remote sites.

Acknowledgements

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Thanks for your kind attention.