The longest kilometer: Characterizing the PBL's aerosol environment by remote sensing

J. S. Reid[1], Robert Holz[2], Charles Trepte[3], Angela Benedetti[4], James Campbell[1], Boon Ning Chew[5], Arlindo Da Silva[6], Richard Ferrare[3], John Hair[3], Chris Hostelter[3], Kathleen Kaku[7], Ralph Kuehn[2], Peng Lynch[1], Alexa Ross[2], Juli Rubin[8], Jason Tackett[3], Travis Toth[9], E. Judd Welton[7], David Winker[3], Jianglong Zhang[9]

[1]Naval Research Laboratory, Marine Meteorology Division, Monterey CA.
[2]SSEC, University of Wisconsin, Madison WI.
[3]NASA Langley Research Center, Langley VA.
[4]European Center for Medium Range Weather Prediction, Reading UK.
[5]Meteorological Service Singapore, Singapore.
[6]NASA Goddard Space Flight Center, Greenbelt, MD.
[7]CSRA, Monterey CA.
[8]NRC Fellow, US Naval Research Laboratory, Monterey, CA
[9]Department of Atmospheric Science, U. of North Dakota, Grand Forks, ND.

CALIPSO-CloudSat Ten Year Progress and Path-Forward
Maison des Océans, Paris June 10, 2016

Happy Birthday CALIPSO! The morning after….

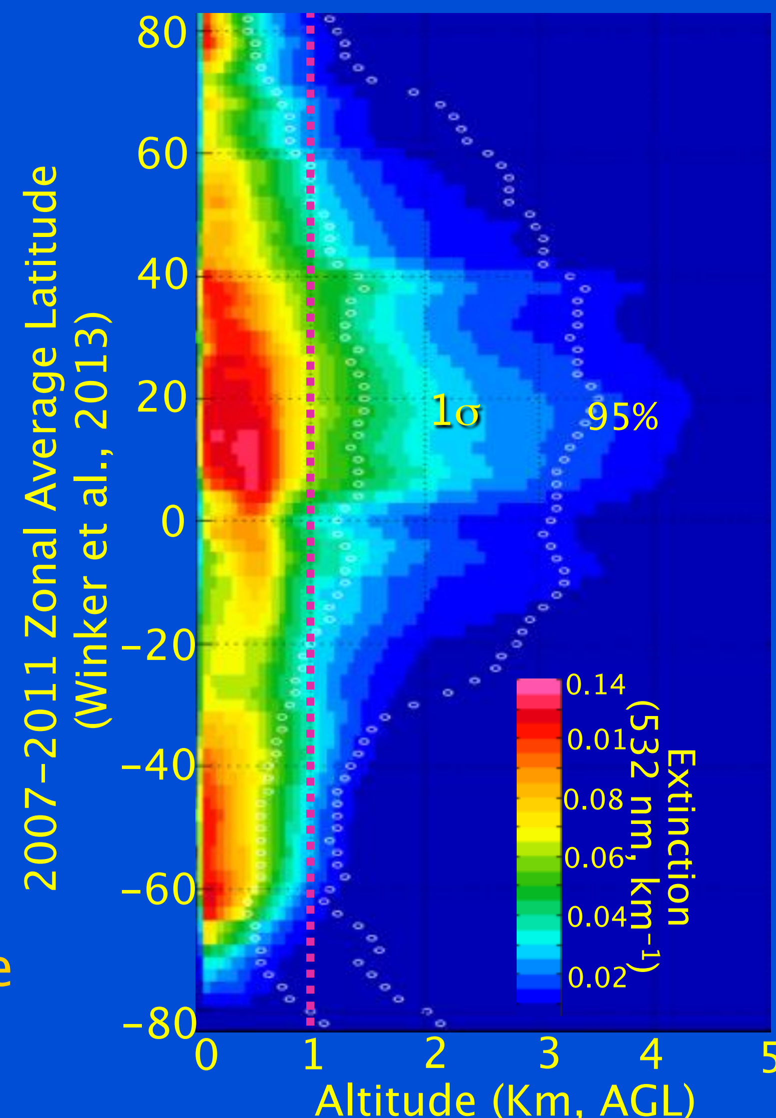
- Good morning! There is lots to celebrate. In my opinion, CALIPSO, along with MODIS, has provided the biggest technical advancements in global aerosol science. Together, they are even more powerful. Add models too to help close the system.
- This talk is to some degree a tag team with the next by Angela Benedetti on how to combine CALIPSO and model data through lidar data assimilation. Whereas AOT assimilation is now pretty common, the addition of vertical information is a very big step indeed.
- Assimilation is all about understanding error. Aerosol science is largely dependent on the PBL and its entrainment zone, mixed layer and surface layer. Therefore, any attempt of lidar assimilation needs to understand PBL measurement errors, and their vertical and horizontal error correlation.

CALIPSO, now we have vertical dimension!

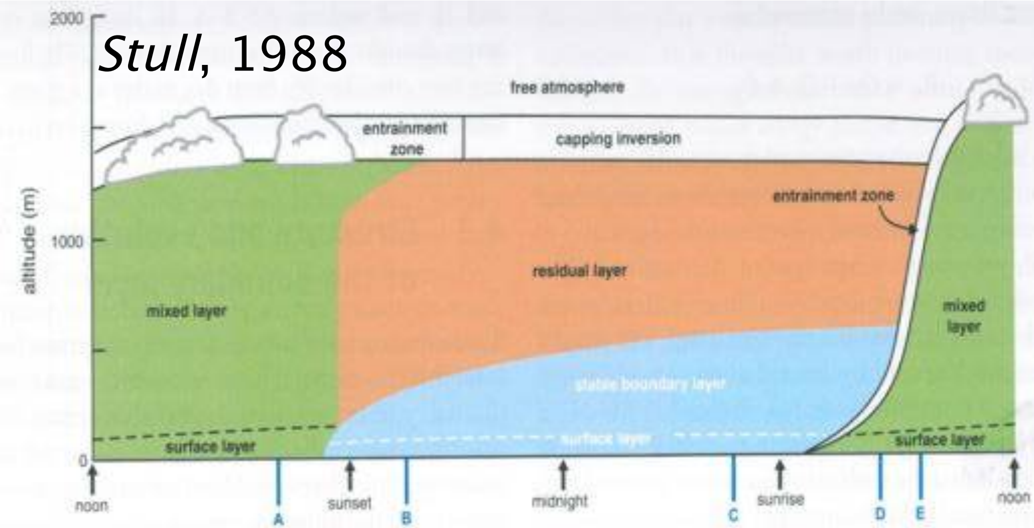
But, the dominant signal is in the lowest kilometer

- Primary pollution, sea salt, and dust are all surface emitters. Actually, so is probably most of the biomass burning.
- Dry deposition is not only physically important, but needs to be tuned in conjunction with the more common source function tuning. This leads to physics mis-matches.
- Convective clouds often have their base at the mixed layer top drawing in and lofting aerosol particles with all that indirect forcing jazz.
- Explosive secondary mass production can occur in boundary layer clouds, with entrainment back into the mixed layer (e.g., Eck et al., 2014).
- Hey, the surface layer is where we live!

=> So if we really want to study the primary physical drivers of aerosol science instead of the aftermath, we absolutely need good PBL measurements.



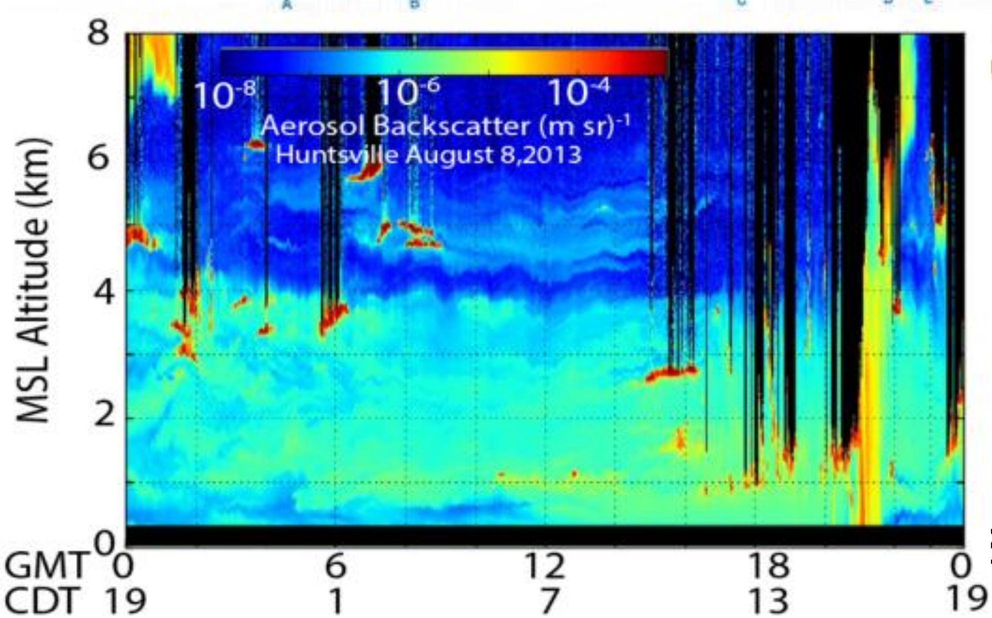
Conceptual model of PBL lifecycle

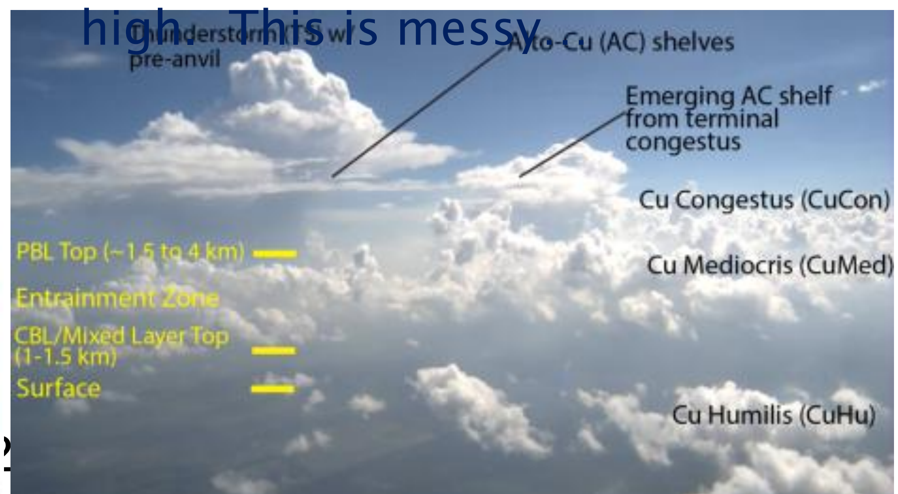


The surface and free troposphere are connected by mixed layer forced by solar radiation. Between the mixed layer and free troposphere is an entrainment zone, often aided by PBL clouds.

The mixed layer collapses at sundown leaving a residual layer of moisture and other atmospheric constituents.

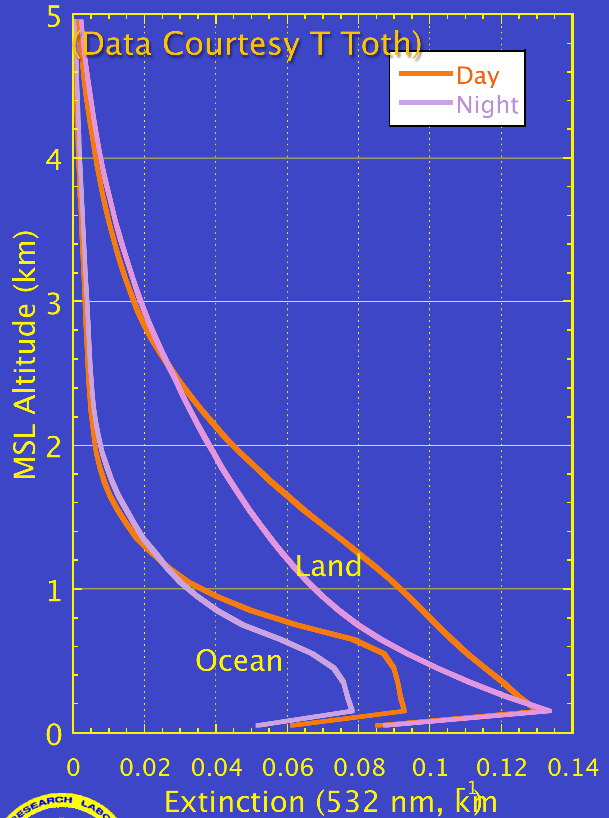
Fueled by latent heat the entrainment zone can be 2-5 km high. This is messy

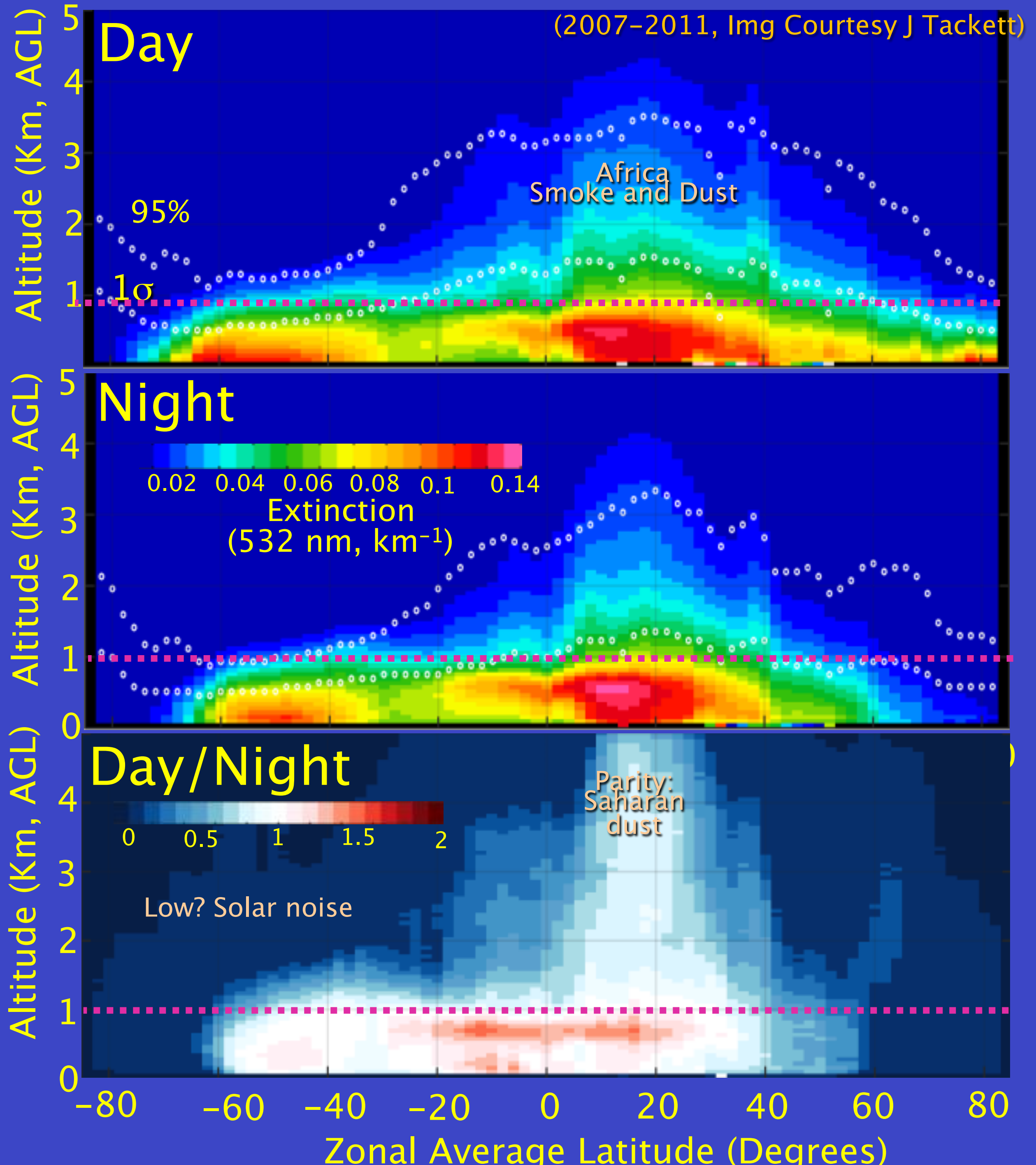




Global Diel Differences

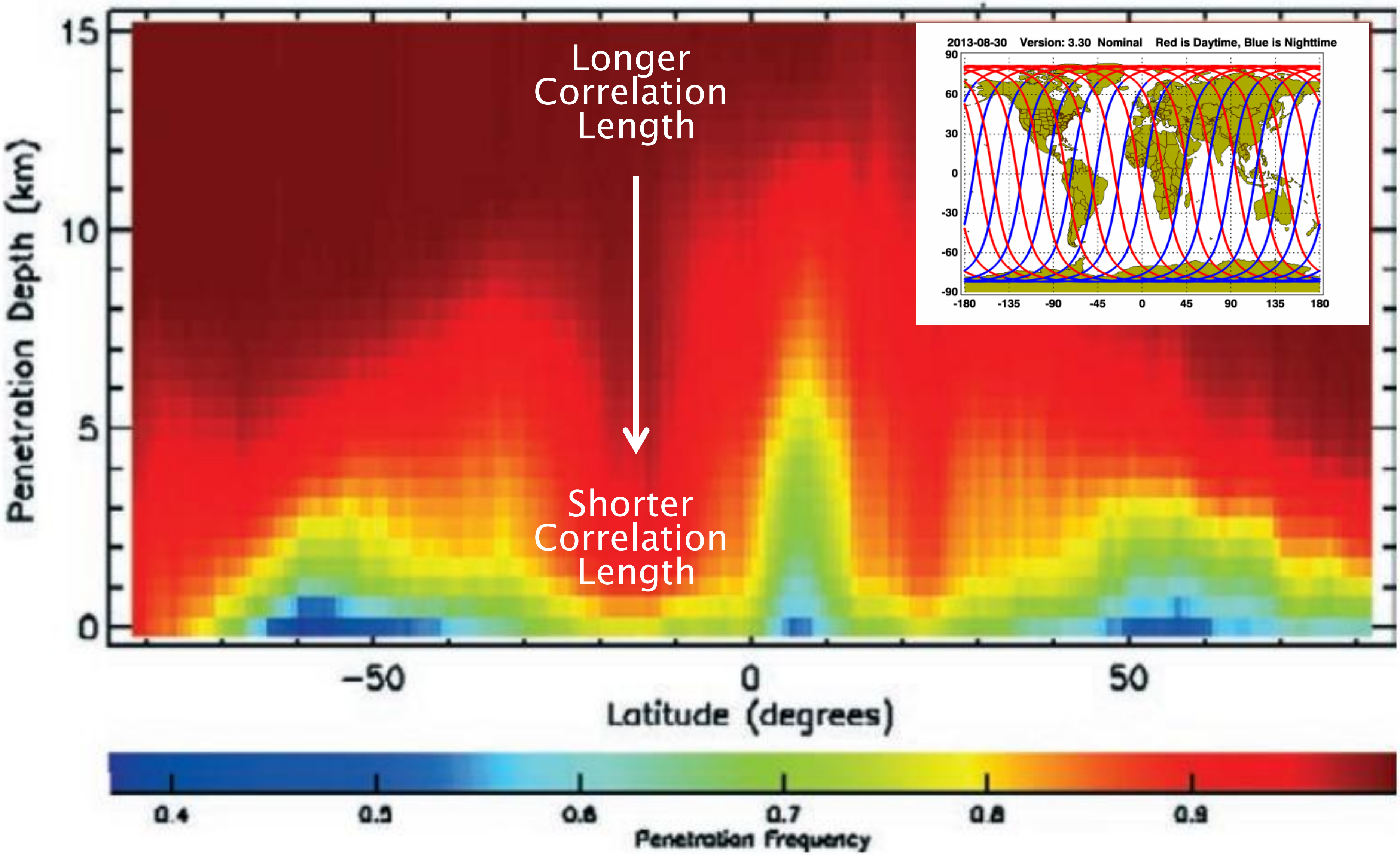
Average, All CALIOP Aerosol retrievals 2007-2011





How much of the PBL do we see?

Not that often (Winker et al., BAMS, 2010)



So lets predict error in the PBL!
It is a long way down. And these are the errors we know

From Winker et al., (2010) ICAP orig. M. Vaughn

Uncertainty in Particulate Backscatter Coefficients at Altitude *n*

$$\frac{\sigma^2(\beta_{p,n})}{\beta_{p,n}^2} = A_n^2\left(\left(\frac{\sigma^2(\mathcal{X}_n)}{\mathcal{X}_n^2}\right)+\left(\frac{1}{R_n}\right)^2\left(\frac{\sigma^2(\beta_{m,n})}{\beta_{m,n}^2}\right)+(2\eta\tau_{p,n})^2\left(\frac{\sigma^2(S)}{S^2}+\frac{\sigma^2(\eta)}{\eta^2}\right)+\left(\frac{\sigma^2(T^2_{p,n-1})}{(T^2_{p,n-1})^2}+B_n^2\left(\frac{\sigma^2(\beta_{p,n-1})}{\beta_{p,n-1}^2}\right)\right)\right)$$

Measurement Uncertainty

Molecular Number Density Uncertainty

Lidar Ratio Uncertainty

Multiple Scattering Uncertainty

Accumulated Aerosol Attenuation Uncertainty

Includes errors due to
- ⇨ Calibration
- ⇨ **SNR**
- ⇨ molecular density (again)
- ⇨ offset calculations
- ⇨ polarization gain ratio
- ⇨ polarization cross-talk
- ⇨ ranging

LEGEND

S = lidar ratio — β = backscatter coefficient
R = scattering ratio — $\sigma^2(x)$ = variance of x
T = transmittance — τ = optical depth
m = molecular — p = particulate (e.g., aerosol)
P = measured data — C = calibration constant
η = multiple scattering factor

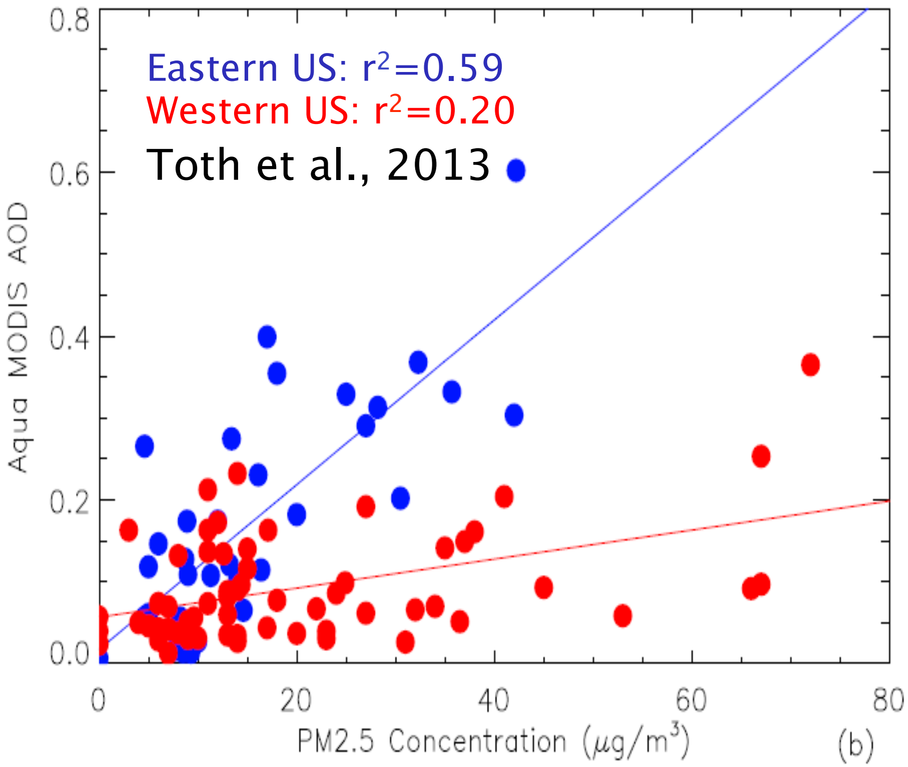
$$\mathcal{X}_n = \mathcal{X}(r_n) = \frac{r_n^2 \cdot P(r_n)}{C \cdot T_m^2(r_n)} \qquad A_n = \left(\frac{R_n}{R_n - 1}\right)\cdot\left(\frac{1}{1 - R_n \cdot \beta_{m,n} \cdot S \cdot \eta \cdot \Delta r_n}\right) \qquad B_n = S \cdot \eta \cdot \Delta r_n \cdot \beta_{p,n-1}$$

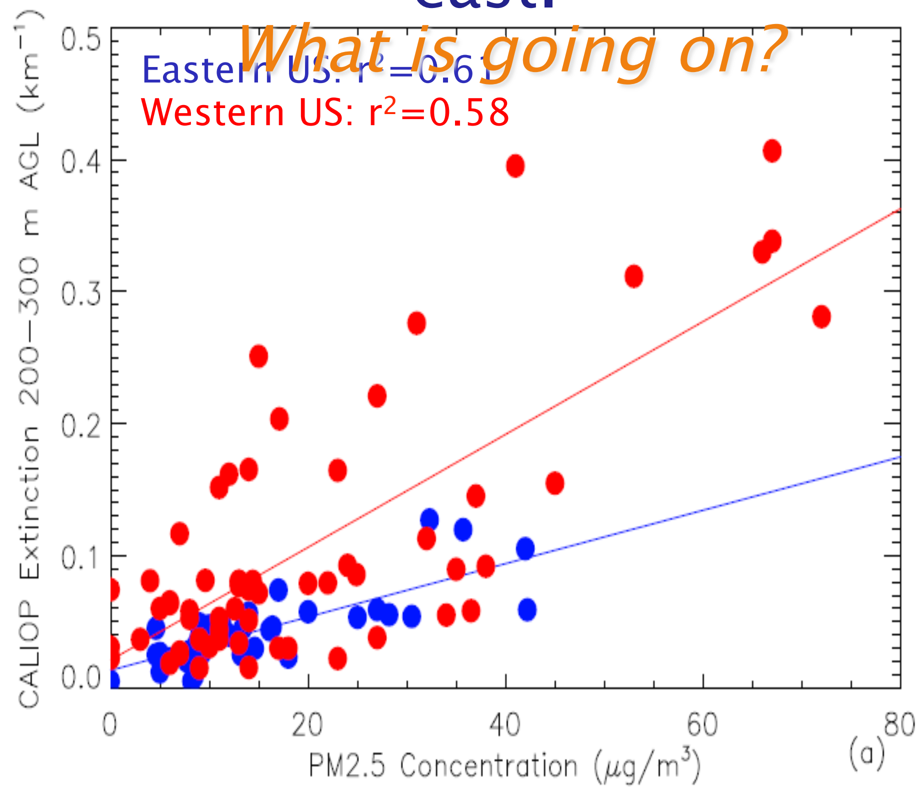
The air quality example: $PM_{2.5}$ –Satellite regressions. But this is true for any height resolved problem. How much more does CALIPSO buy us?

Disparity between regression skill in the Eastern and Western US is long noted.

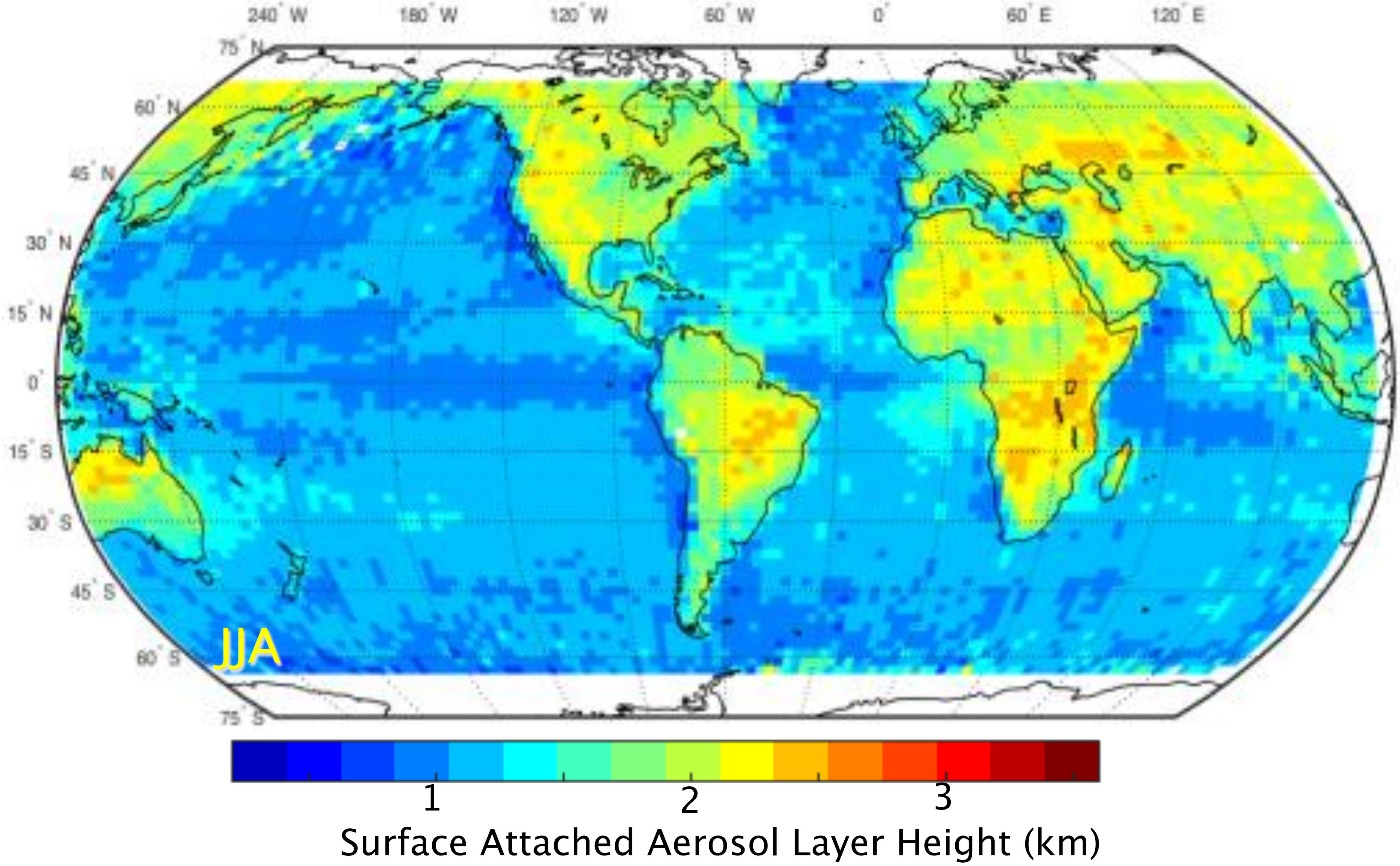
CALIOP backscatter at 200–300 m should be better right? For the west, yes, but not the east.

What is going on?





Spatially, what is the near surface aerosol layer depth? CALIPSO helps explain the west.
Kuehn Aerosol Surface Layer Product



Why does r^2 top out at 0.6? Fundamental Observability Part 1: Intensive

$$\sigma_e = c_m * \alpha_e * f(rh)$$

Extinction Coefficient | Mass Conc. | Mass Ext. Eff. | Hygroscopic Growth

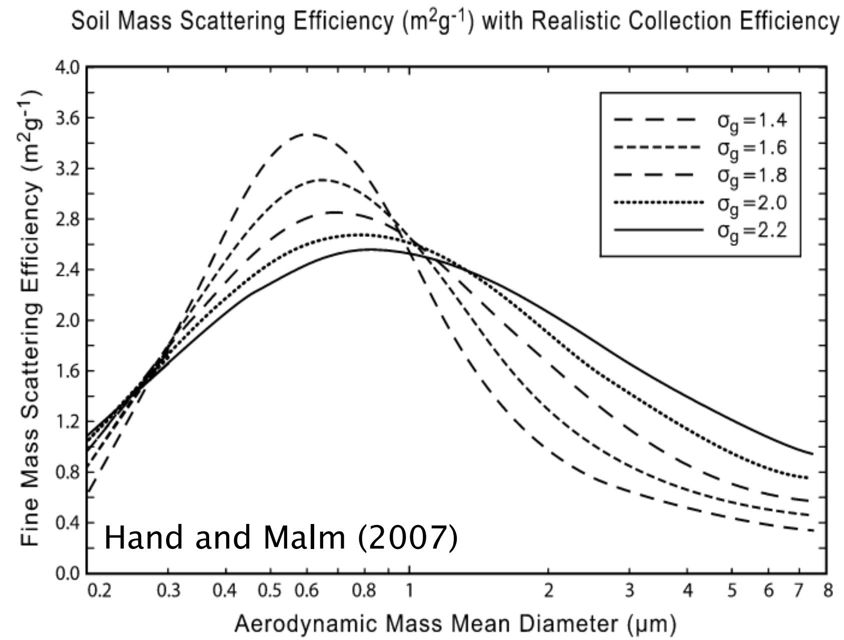
$$c_m = \sigma_e / \alpha_e * f(rh)$$

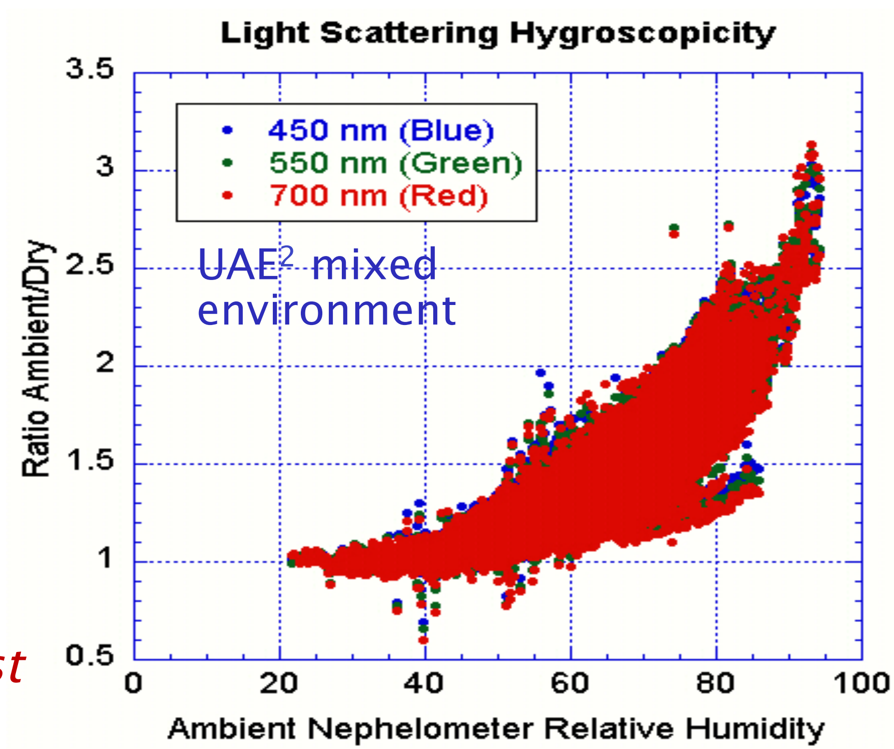
Define Mass? $PM_{10, 2.5, 1}$?
Species?
Integrate over a distribution?
Does your system carry number?

α_e? $PM_{10, 2.5, 1}$?
~linear in VMD & ρ^{-1}
Fine mode? 2.5–5 $m^2\ g^{-1}$
Common coarse 0.3–1 $m^2\ g^{-1}$

f(rh): Pretty grim, don't forget error on both

BTW, we need to figure out σ_e first. This may be the strongest rationale for multi wavelength





Fundamental Observability Part 2–Extensive

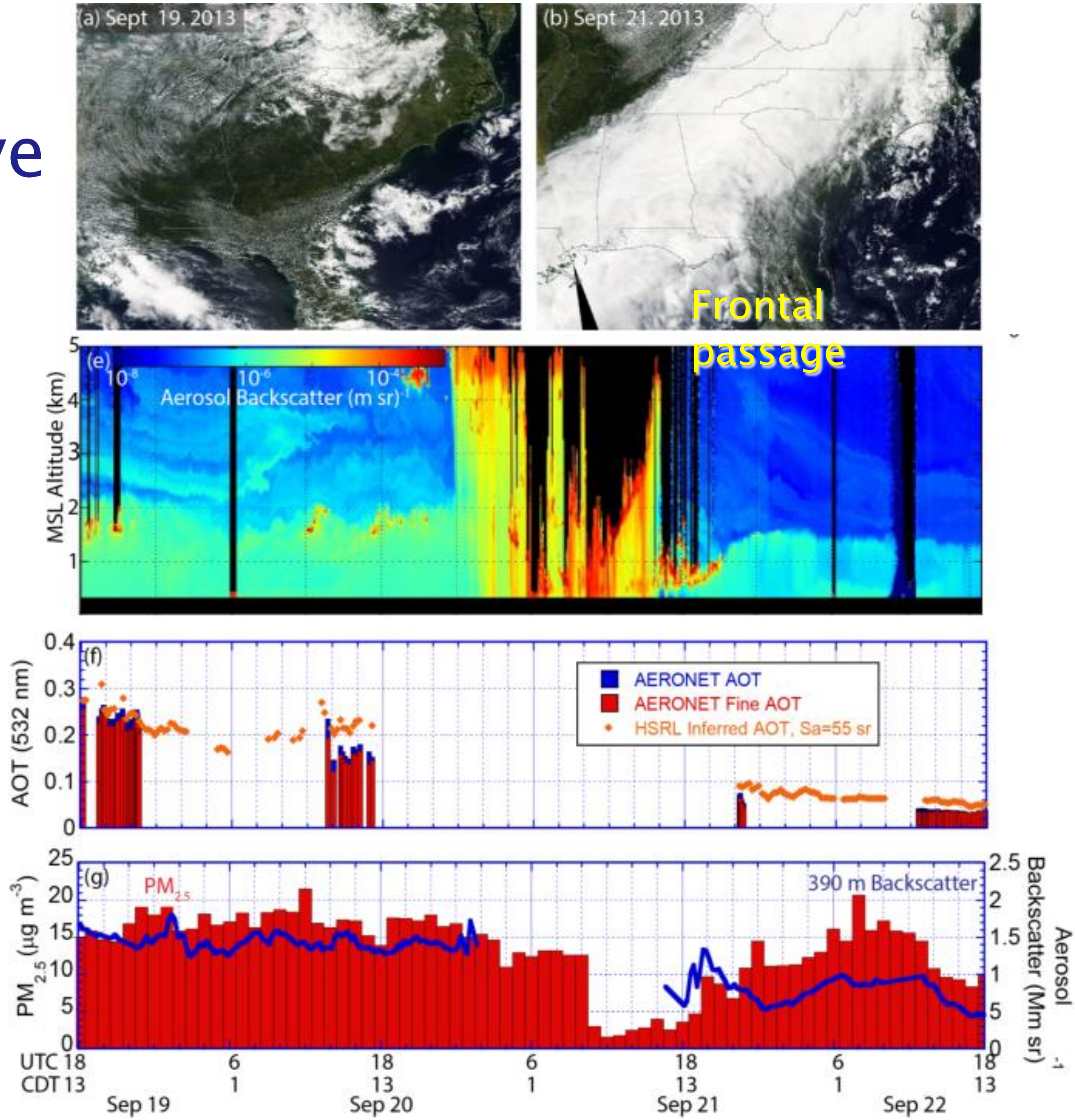
Take all of part 1, and add the vertical dimension

CALIPSO can take care of the free troposphere, but there is lots of variability in the free troposphere & boundary layer.

Even low concentrations, when integrated over a long distance contribute significantly to the surface signal.

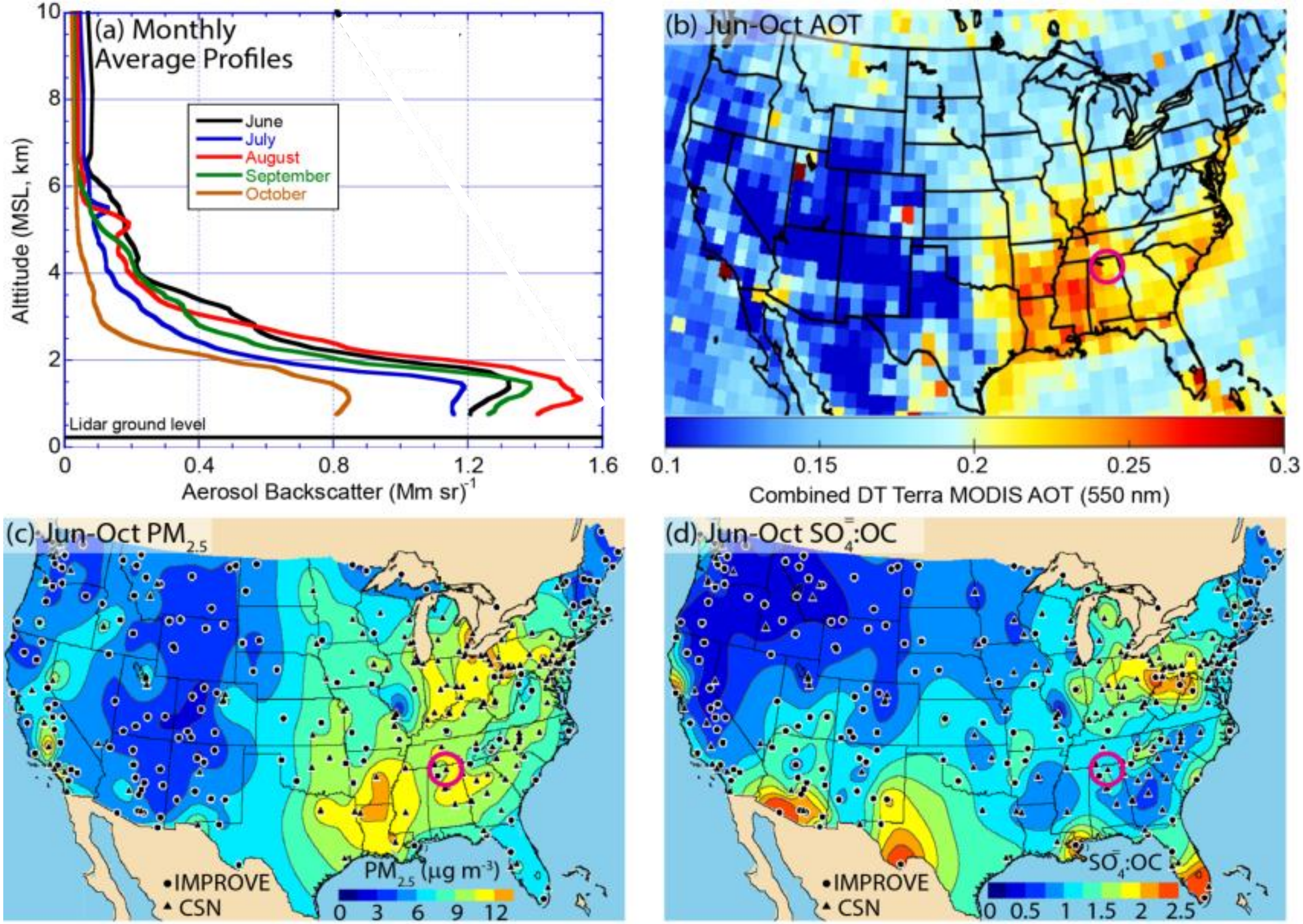
Did I mention correlated error?

⇒ Multi λ HSRL again

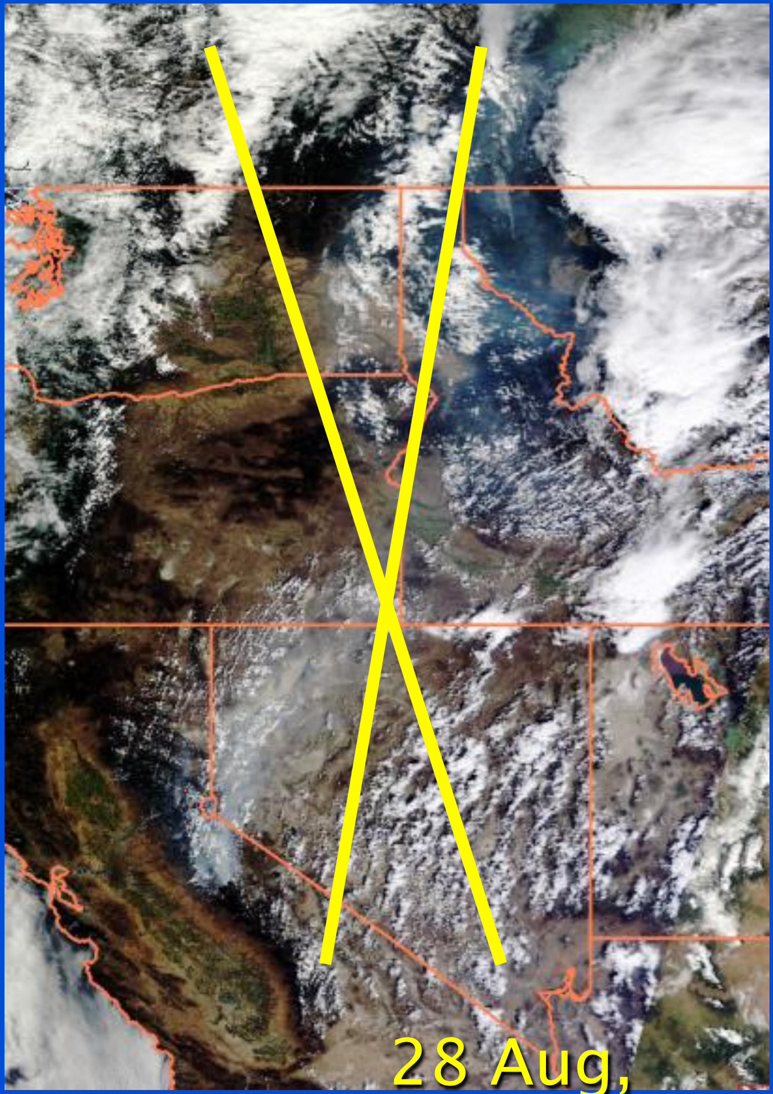


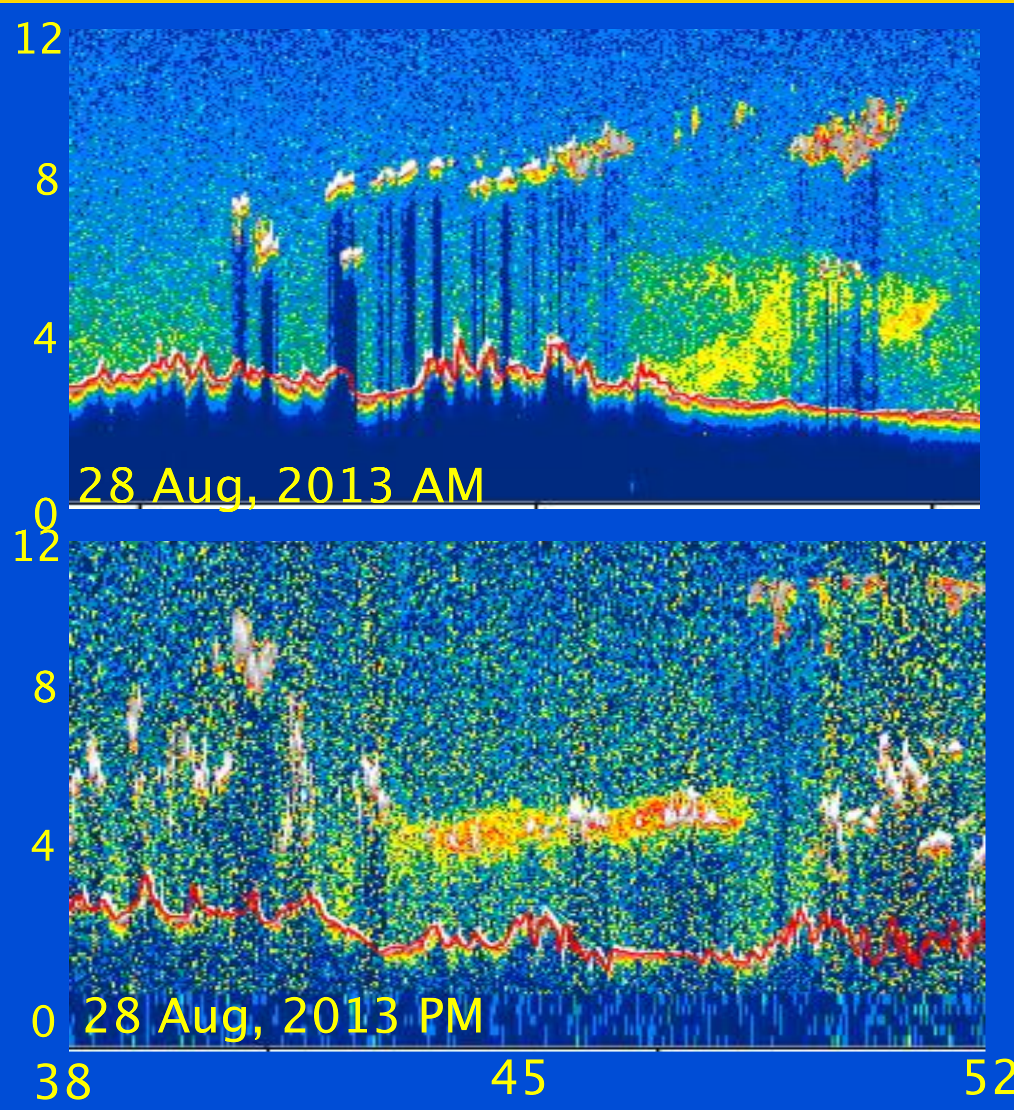
Use 2013 SEAC^{4}RS as an example

Southeast US is one of the "easiest" regions there is.



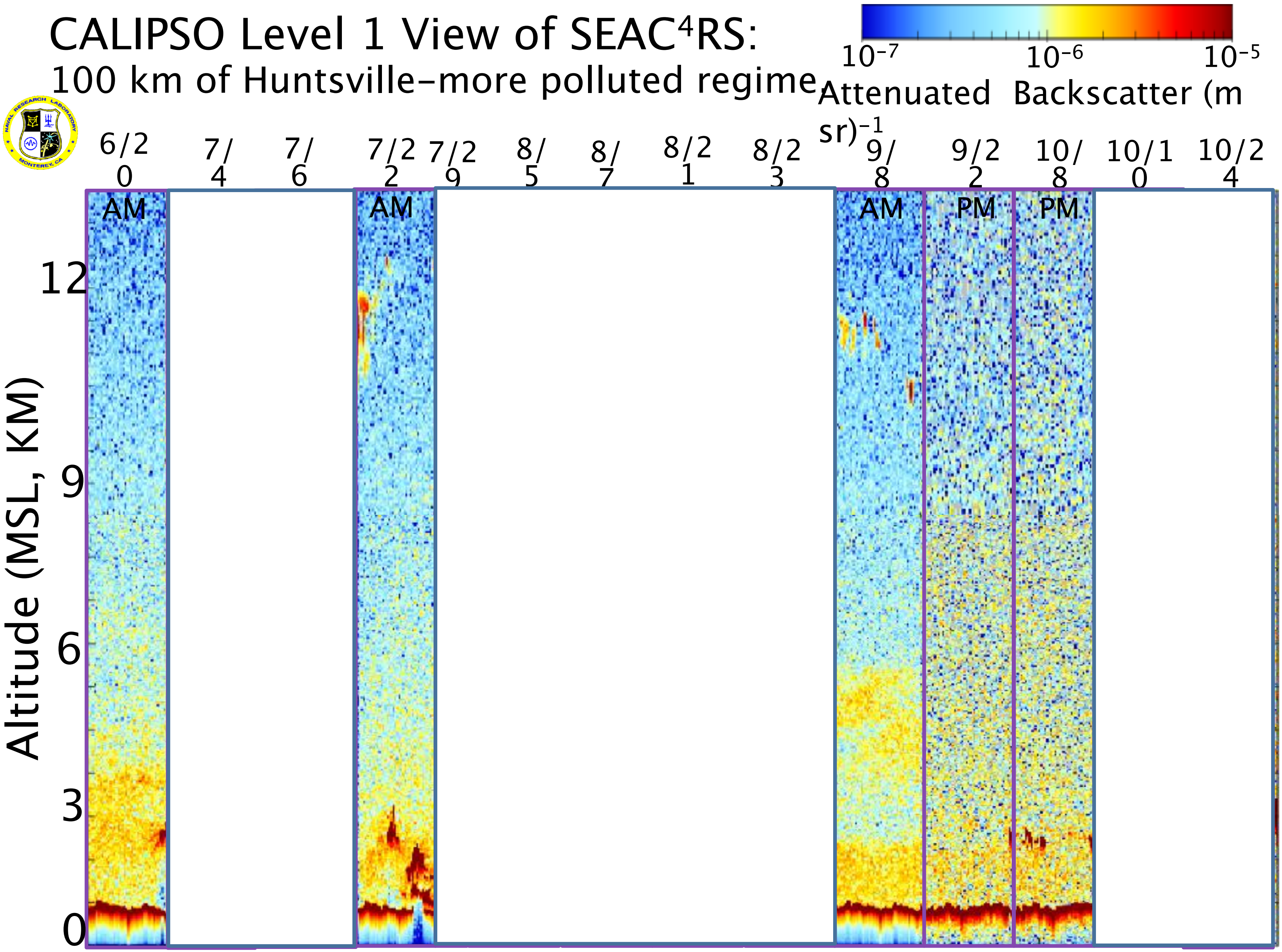
Where CALIOP Shines
Free troposphere layers & long range transport





CALIPSO Level 1 View of SEAC^{4}RS:

100 km of Huntsville–more polluted regime



Mammoth Cave (0.24)

Mingo (0.13)

Huntsville (0.47)

Yorkville (0. 5)

Leland (0.5)

Birmingham (4star–)

Centreville x2 (0.4–0.5)

Aug 30, 2013
AOTS

Aug 30 Stats

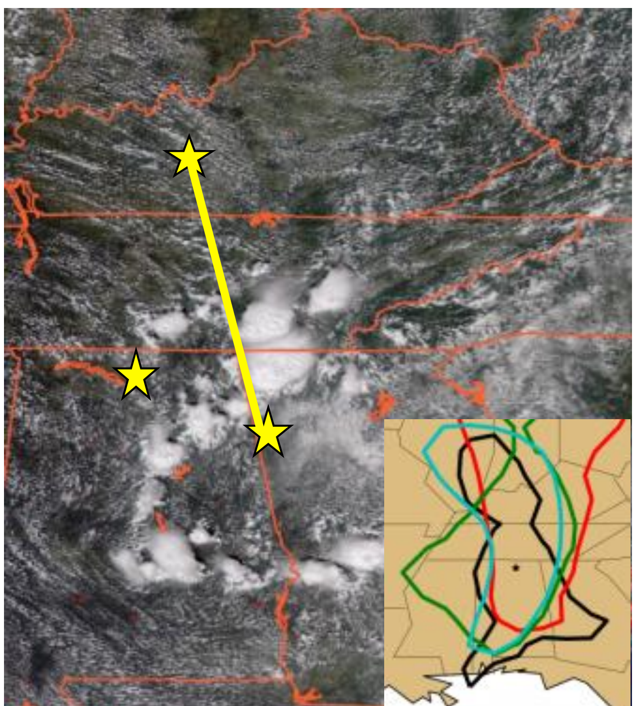
Qualitatively what I expect, what about quantitative?

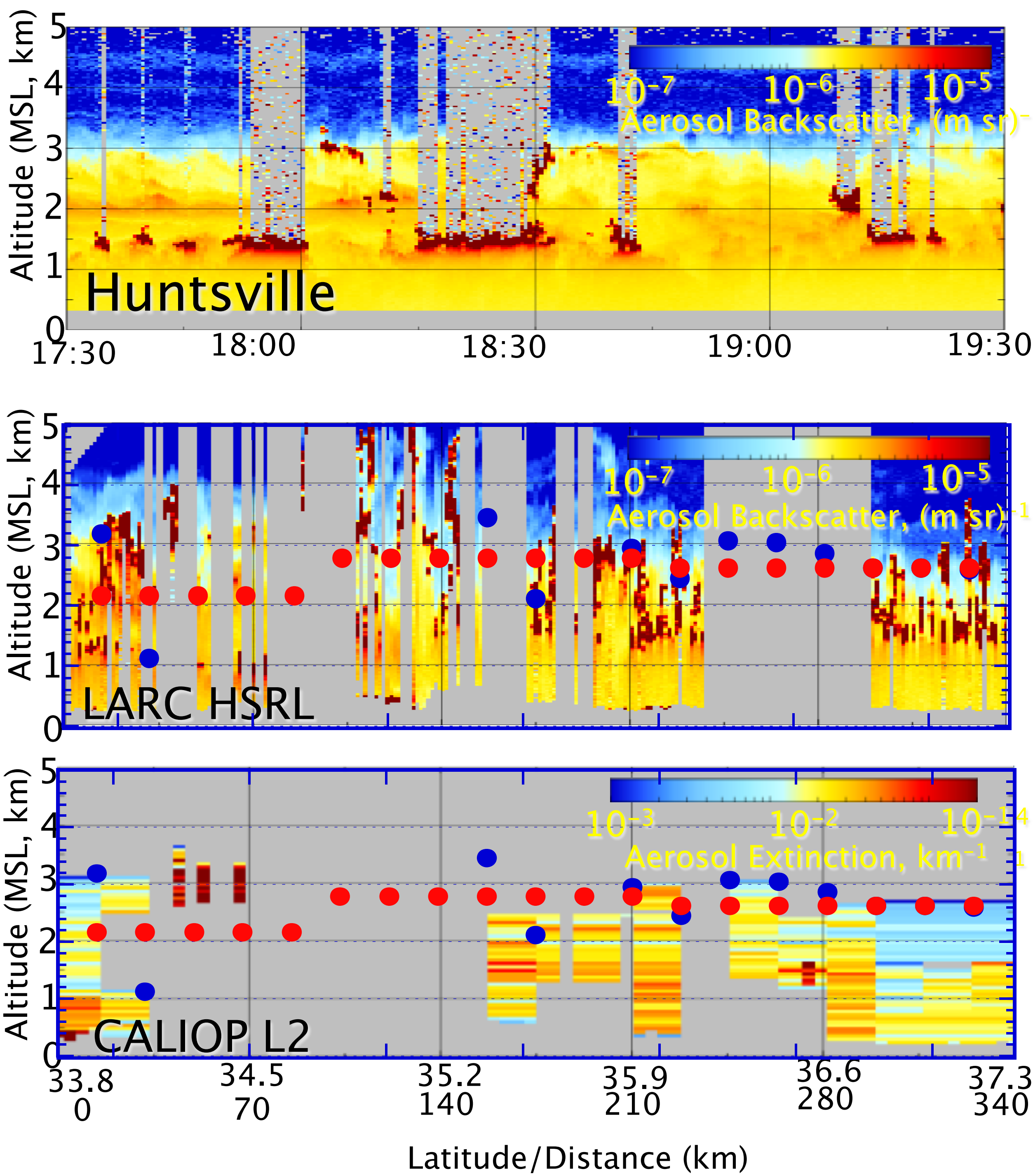
Region	PM1 CU	$SO_4^{=}$:Org CU	AOT 500nm	Mixed Layer Lidar ratio	$kappa_{GF}$ DASH-SP	F(80) LARGE	F(90) NOAA
S LA	27/16	0.6/0.65	~0.3	~66	0.39 / 0.47	1.5/1.45	2.3/2.36
S Miss	24/19	0.3/0.3	~0.35	n/a	0.26 / 0.32	1.3/1.35	2.0/1.85
S Birm/Cent	19	0.4	~0.4	58	0.33	1.38	2.2
Mammoth Cave	18	1.2	~0.25	44	0.53	1.7	2.5
Ohio RV	12	0.8	0.2-0.3	54	0.40	1.55	2.65
Ozarks	9	0.6	0.13	42	0.34	1.4	2.4
NE Miss	18	0.6	0.2	n/a	0.41	1.45	2.2
Variability	3	4	4	1.6	2	1.3	1.3

The grand finale,

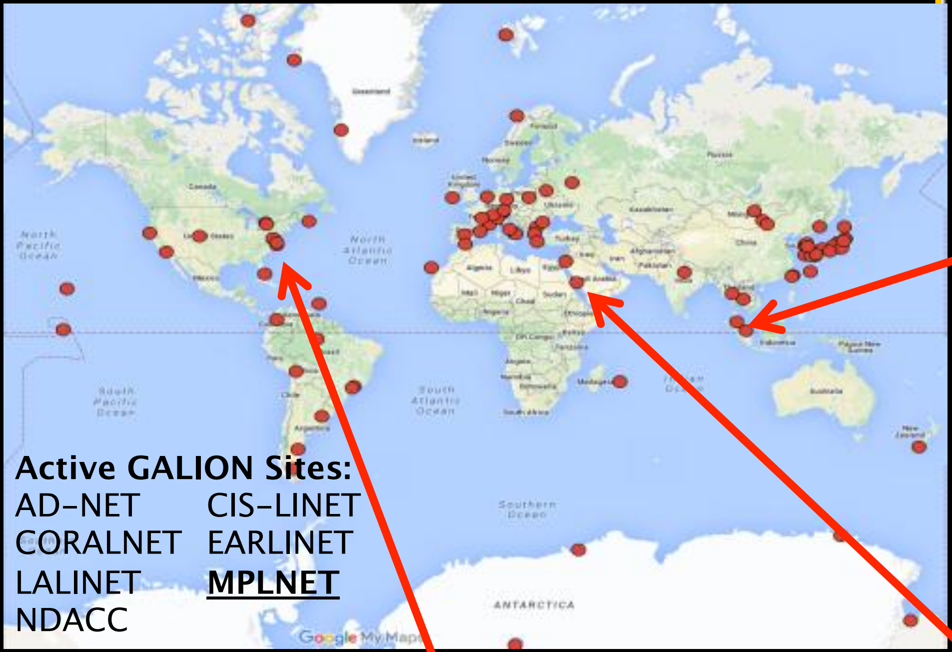
Aug 30, 2013

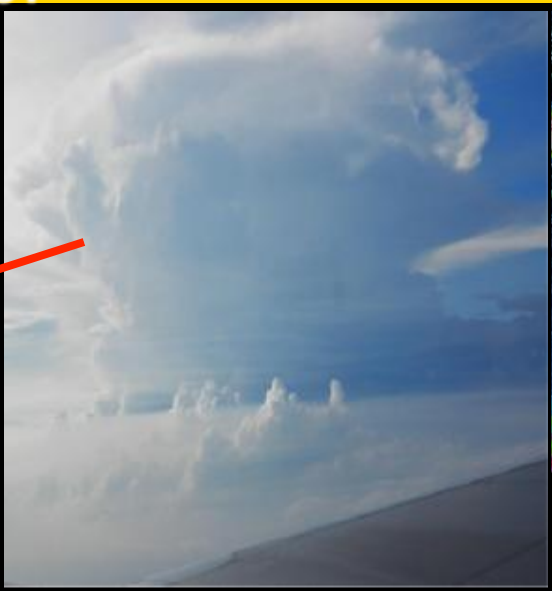
We need all lidar points of view

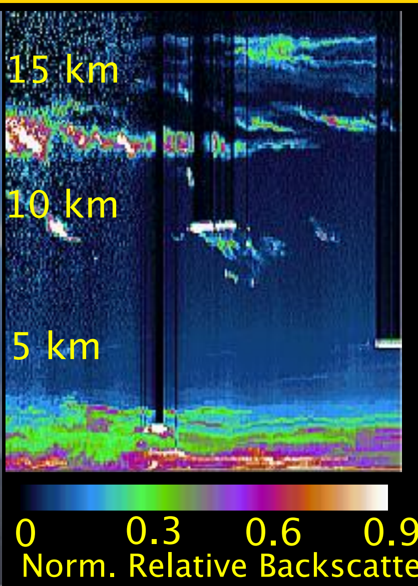


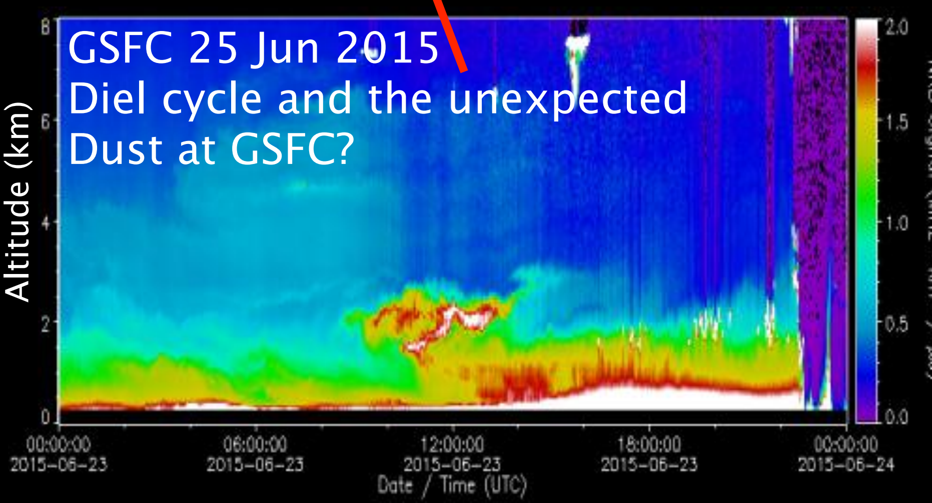


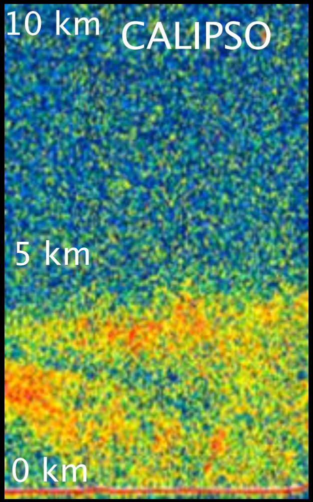
That was one day in one place.
How do we generalize?
Need to systematically link the top down to bottom up.

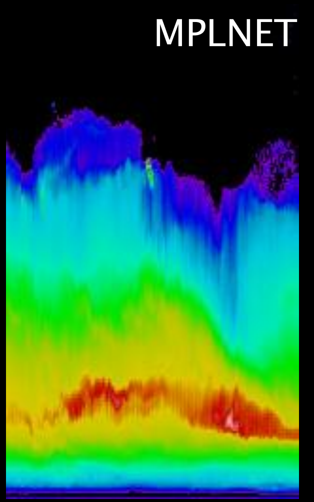












The bottom line of the lowest kilometer? Making due or stepping up….

CALIPSO has changed the way we look at long range aerosol transport. But, to get at surface monitoring or processes, we are just warming up.

Making due:
Context and sampling issues need careful consideration. For that we need models.

Can't change the hardware, so back to signal processing?

Need to integrate the top down with the bottom up views.

Next generation:
HSRL like capabilities would make the PBL more quantitative. But do we need/risk 2β–3α? Cross fingers for EarthCARE!

More wavelengths=> more microphysical => better estimates for the things that matter **if** we have the SNR and can understand the signal.

Learn from the past, design an instrument with signal processing in mind.