Introduction to lidar observations relevant to boundary layer cloud studies

Winker, Trepte, Vaughan, Powell, ..., Hu (**CALIPSO**)

Hostetler, Ferrare, Hair, …, Hu (**HSRL**)

Ismail , Ferrare, Hair (LASE)

Ferrare , Turner, Clayton (DOE ARM Raman)

Kavaya (GWOS)

Xu, Cheng (Cloud Modeling)

Davis (Multiple Scattering Cloud Studies)

Summary

Lidars (e.g., **CALIPSO/HSRL**, DIAL, Doppler wind Lidar) can provide,

•boundary layer height, lapse rate

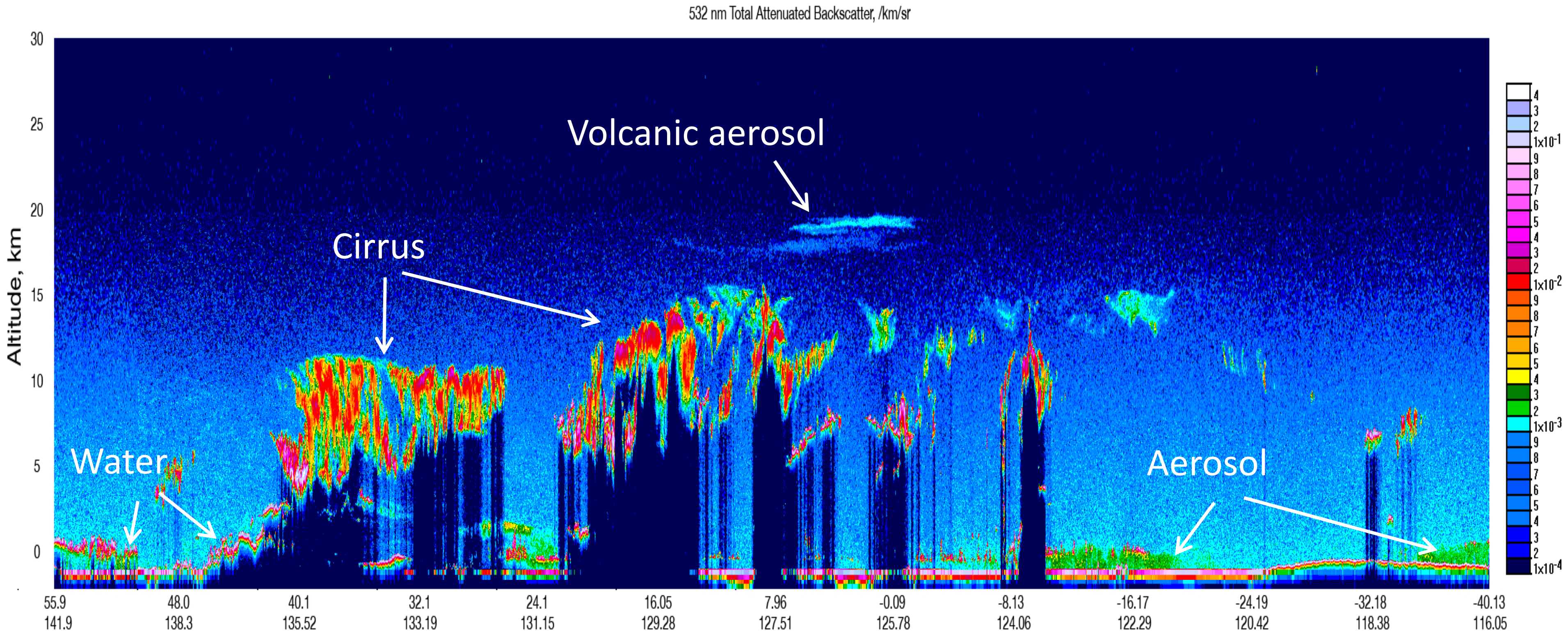
•high resolution information about boundary cloud top (sometime cloud base) height, cloud thermodynamic phase and extinction coefficient, and cloud top droplet number concentration (combined with imager measurements)

•high resolution air-sea turbulence transfer velocity (for heat and gas exchange) with the measurements of mean square slopes of ocean surface capillary and gravity waves

•other information such as wind profile, turbulence and water vapor measurements

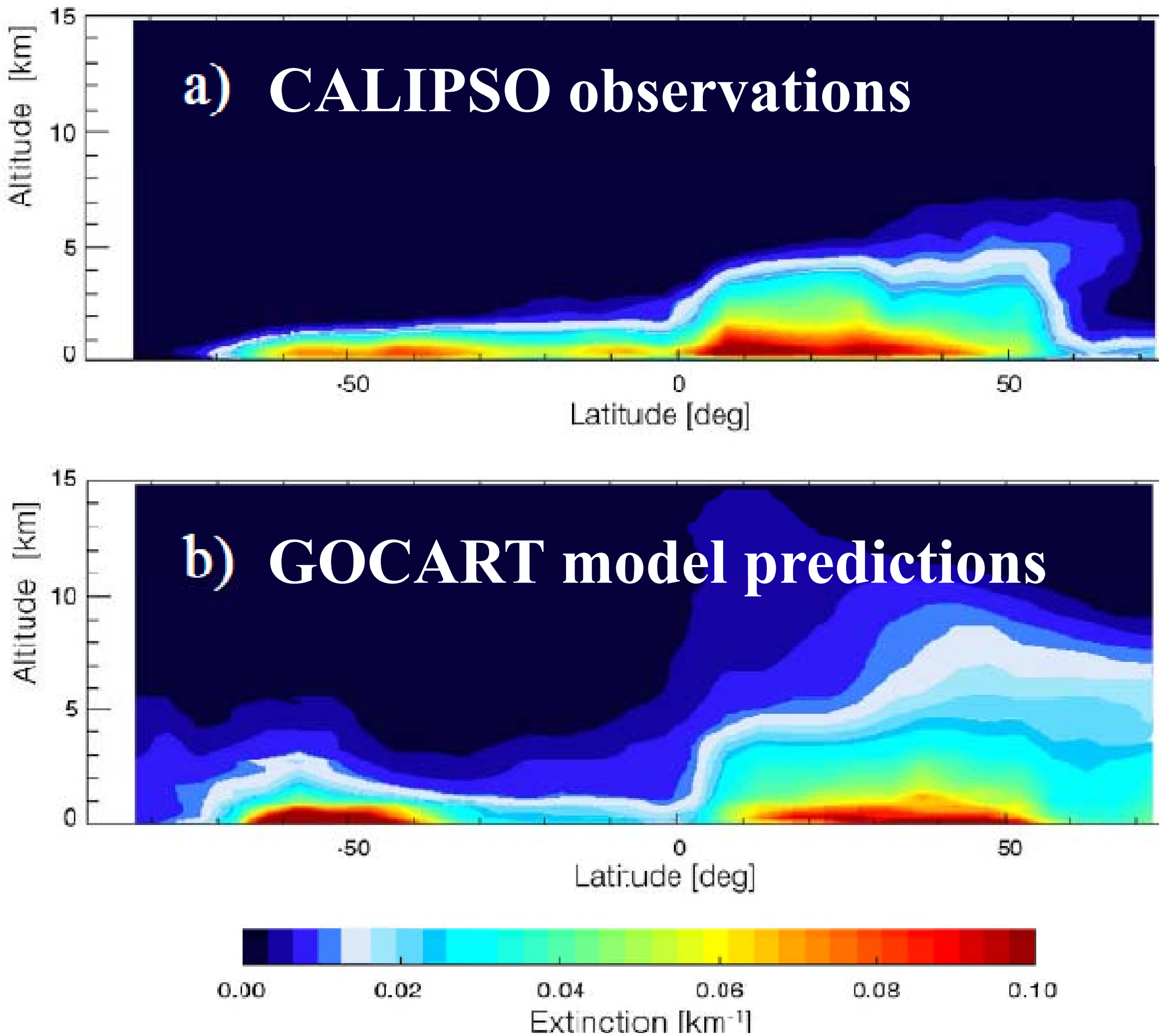
CALIOP “First Light”

7 June, 2006 – CALIOP *‘First Light’*

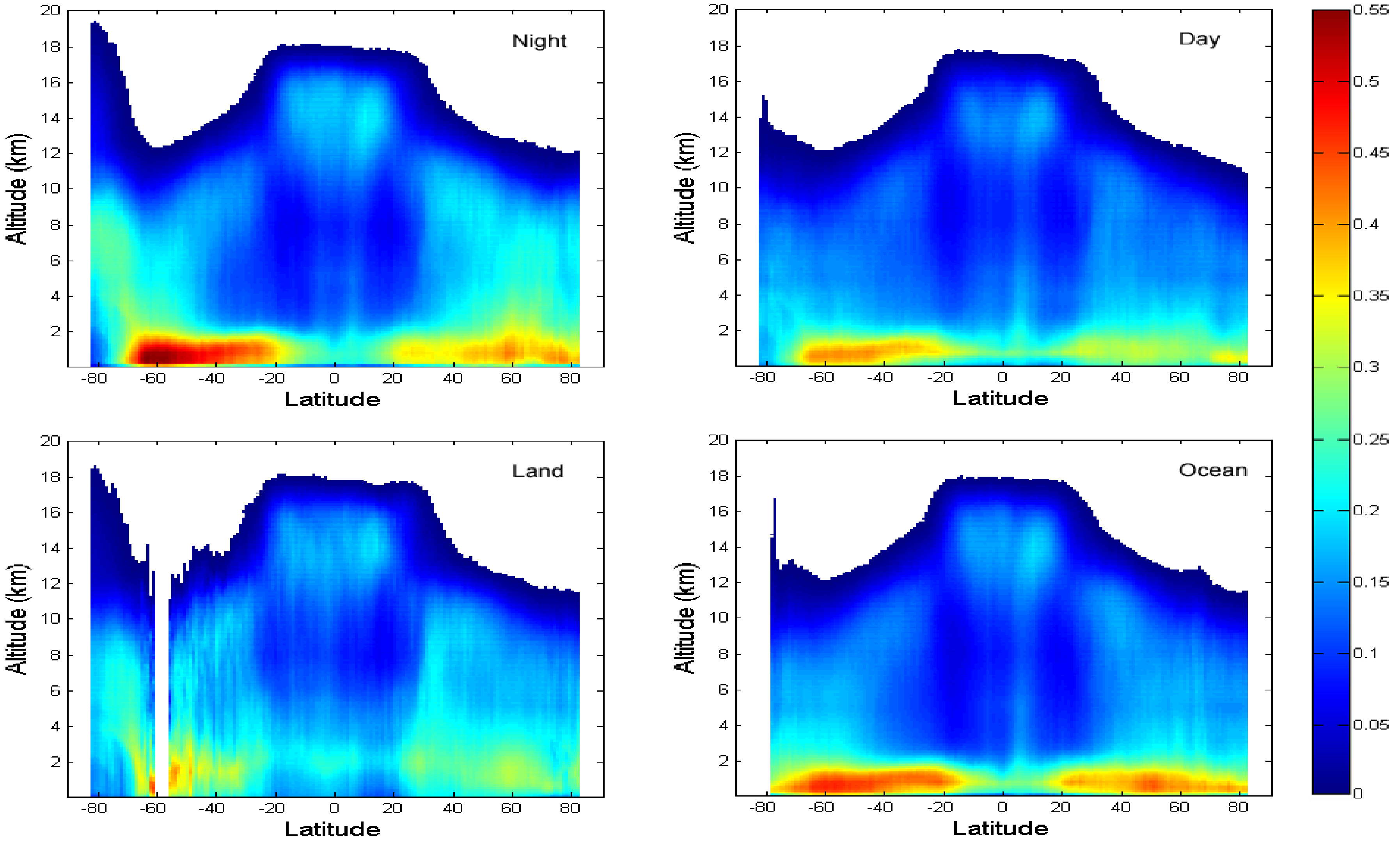


Scene classification:
Separating clouds and aerosols; identifying aerosol types and cloud thermodynamic phases

Vertical distribution of aerosol optical depth
(Winker et al., 2010)



Vertical distribution of cloud fraction (together with CloudSat)



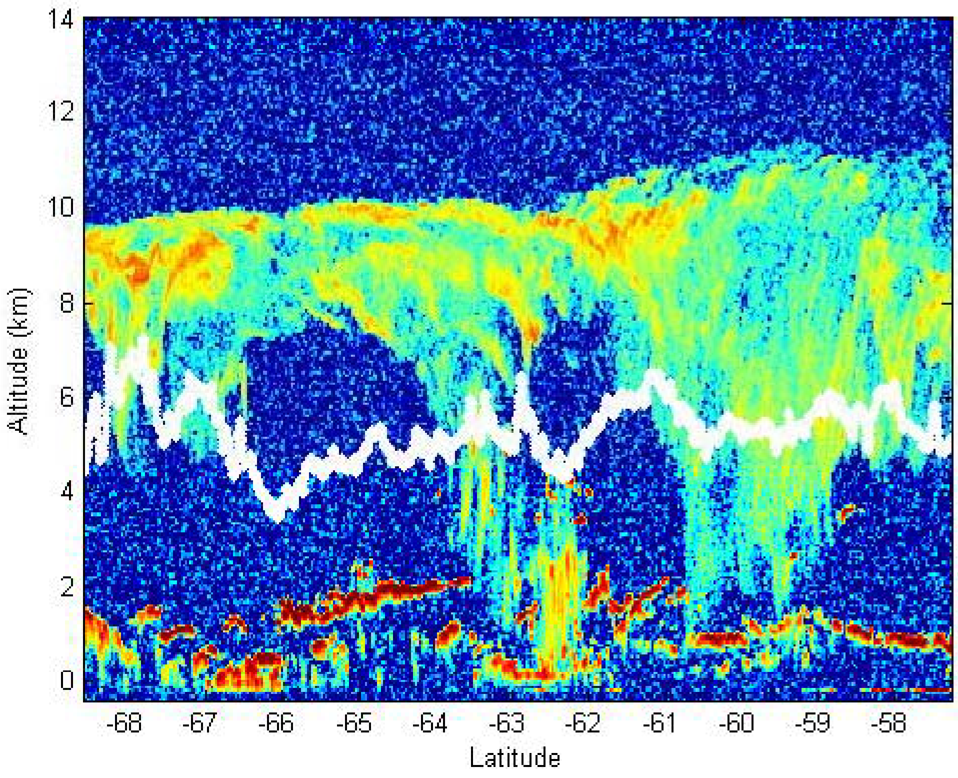
Vertical structure matters: one example

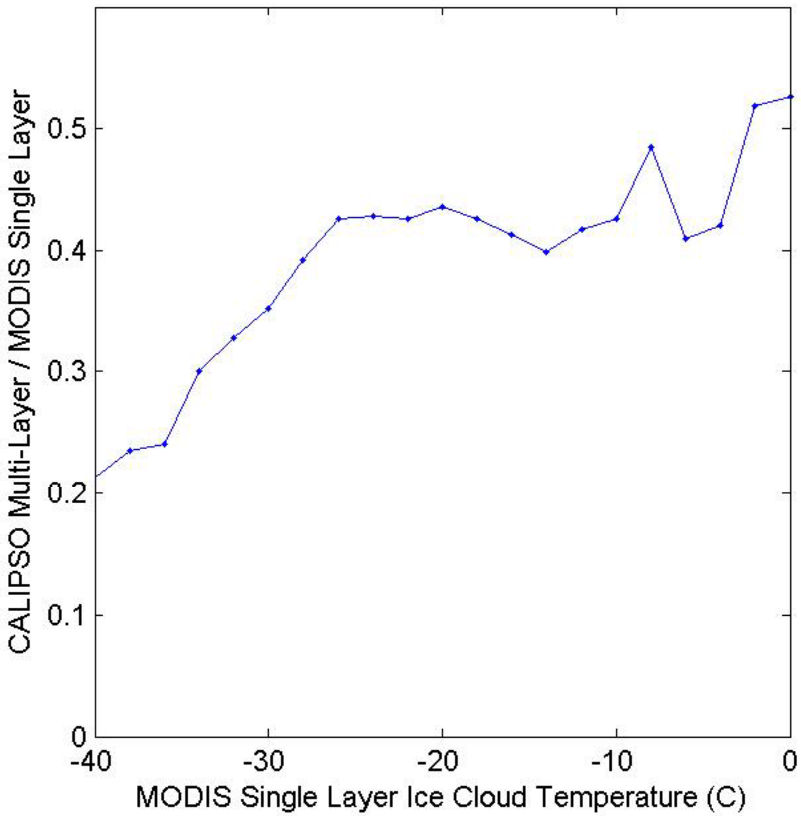
Passive sensors over-estimated ice cloud presence with temperature 0 to -40 C

CALIPSO scene with thin/cold ice over thick/warm water with overlay of MODIS-retrieved thick middle level ice cloud:

→ **passive sensors over-estimate of warm ice cloud**

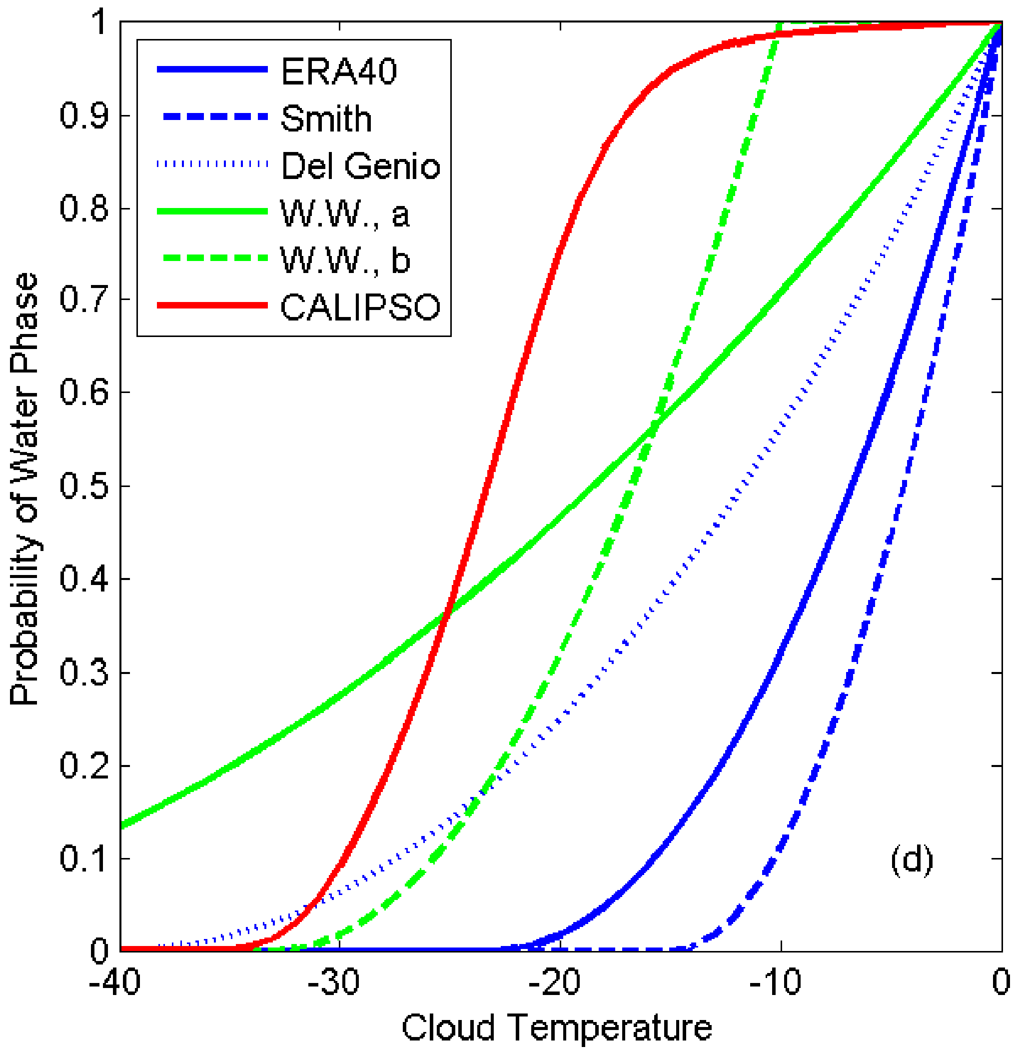
White line: MODIS cloud height





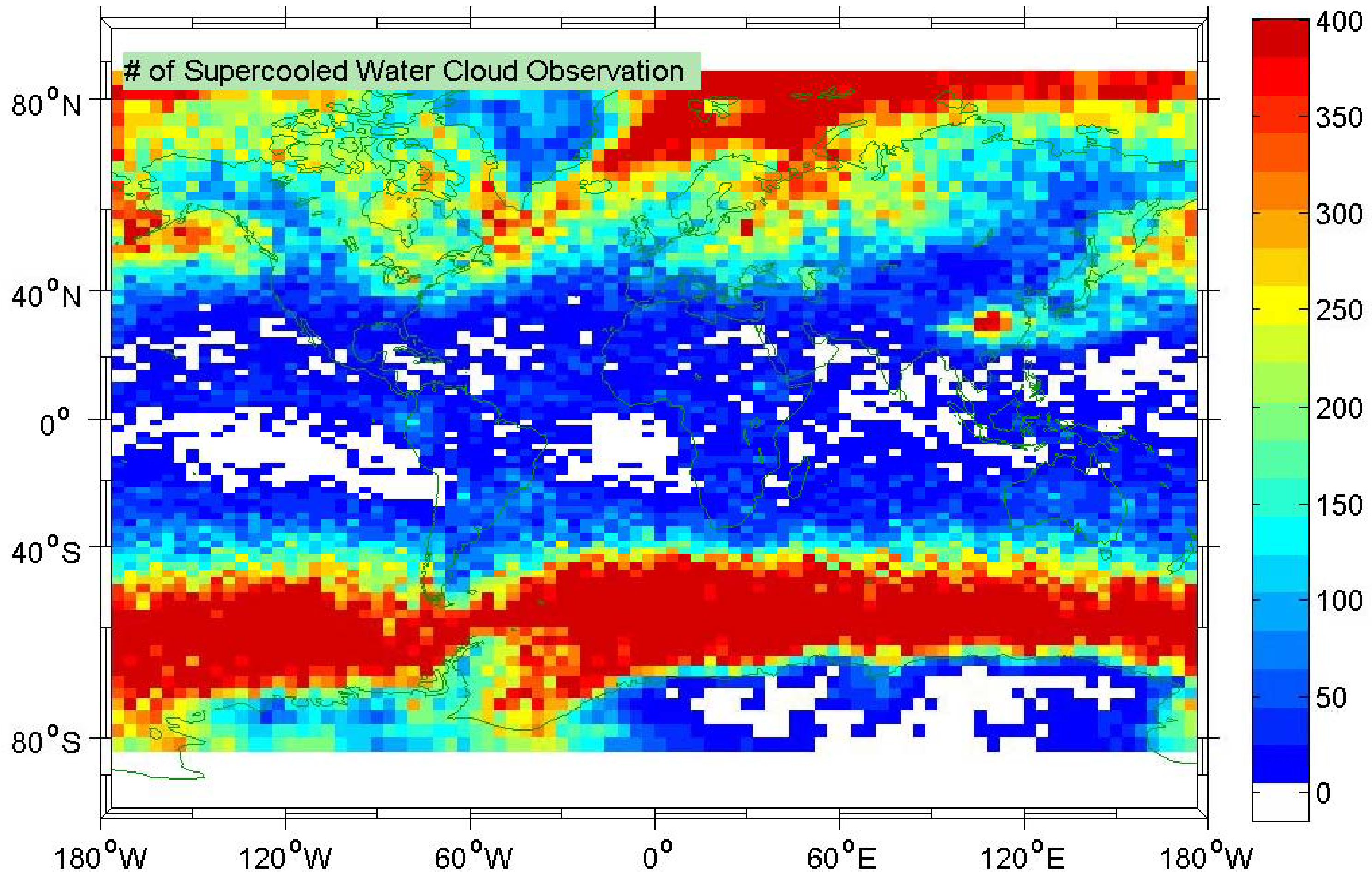
Supercooled water clouds from CALIPSO observation >> from existing models / observations

climate models with more supercooled water are more sensitive



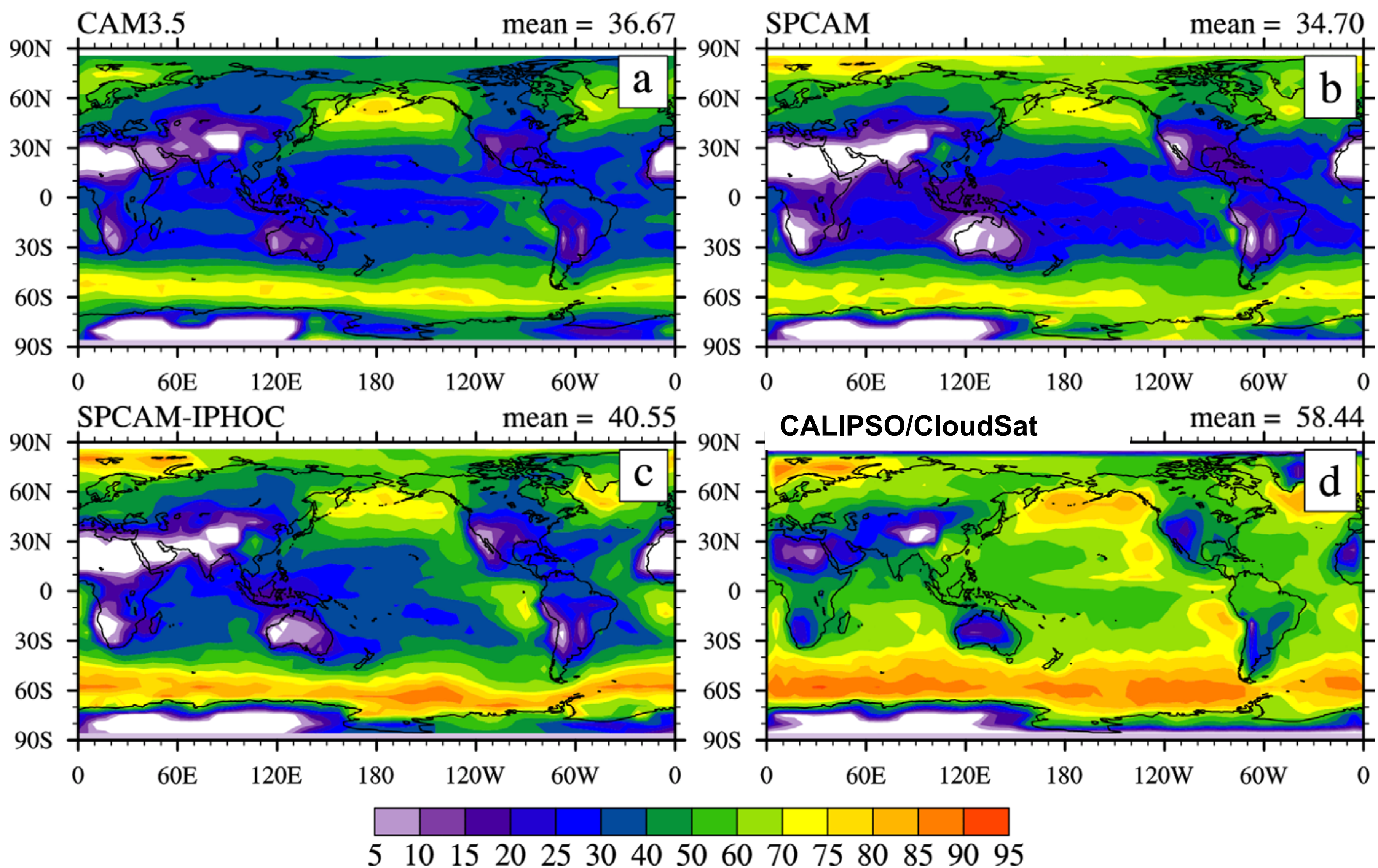
Hu et al. (2010, JGR): Occurrence, liquid water content, and fraction of supercooled water clouds from combined CALIPSO/IIR/MODIS measurements

Spatial distribution of supercooled water clouds



Low level cloud amount: model and CALIPSO/CloudSat comparison

(Cheng and Xu, NASA LaRC)



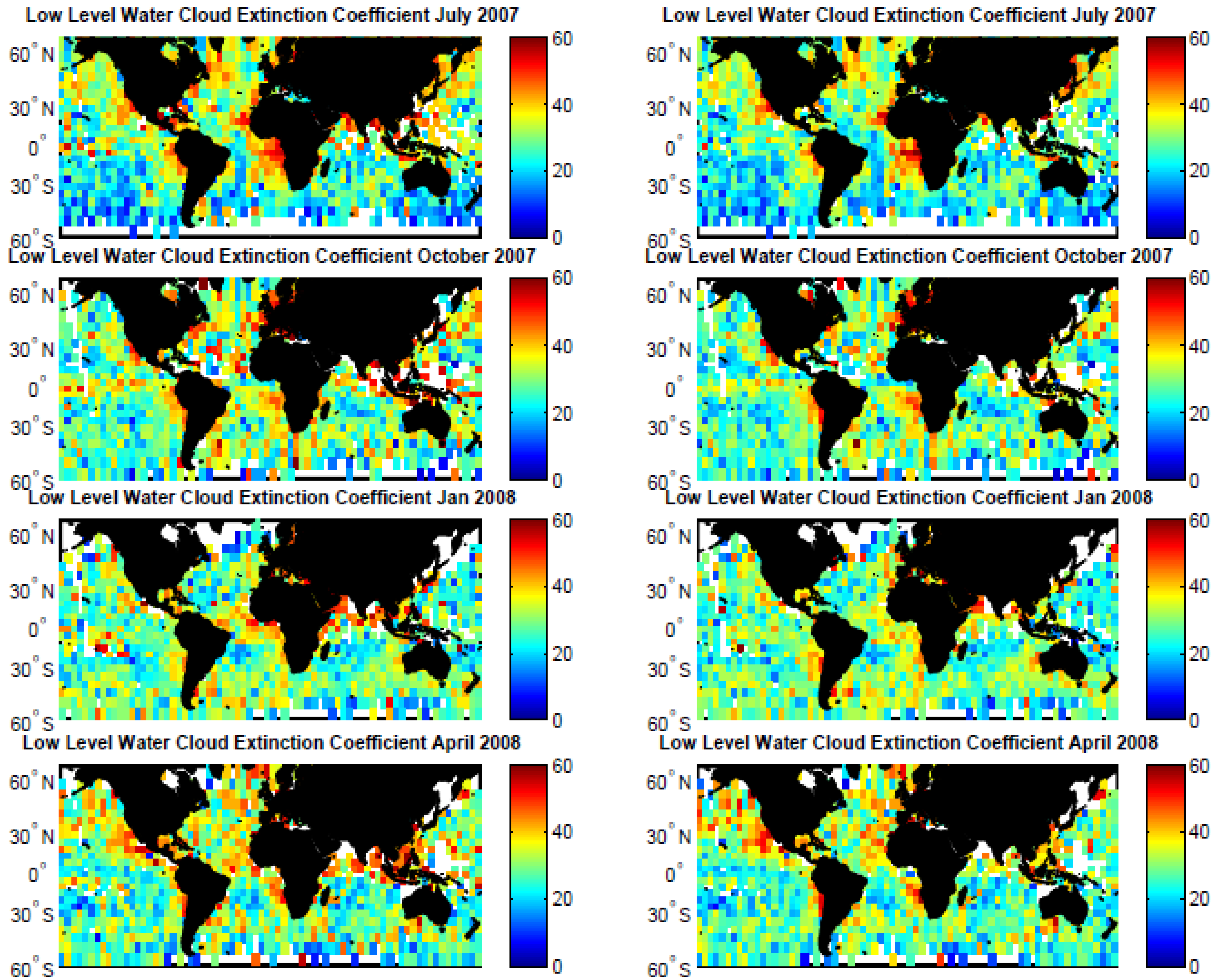
Climate sensitivity and poleward shift of storm track

- Albedo feedback due to poleward storm track shift: CO_2 increase → reduction in baroclinic instability → poleward shift → reduction of planetary albedo

- Current reanalysis and climate models under-estimate low level clouds at storm track, and thus climate sensitivity

- Hypothesis: underestimation of supercooled liquid water in the models is a primary factor in the model – observation discrepency

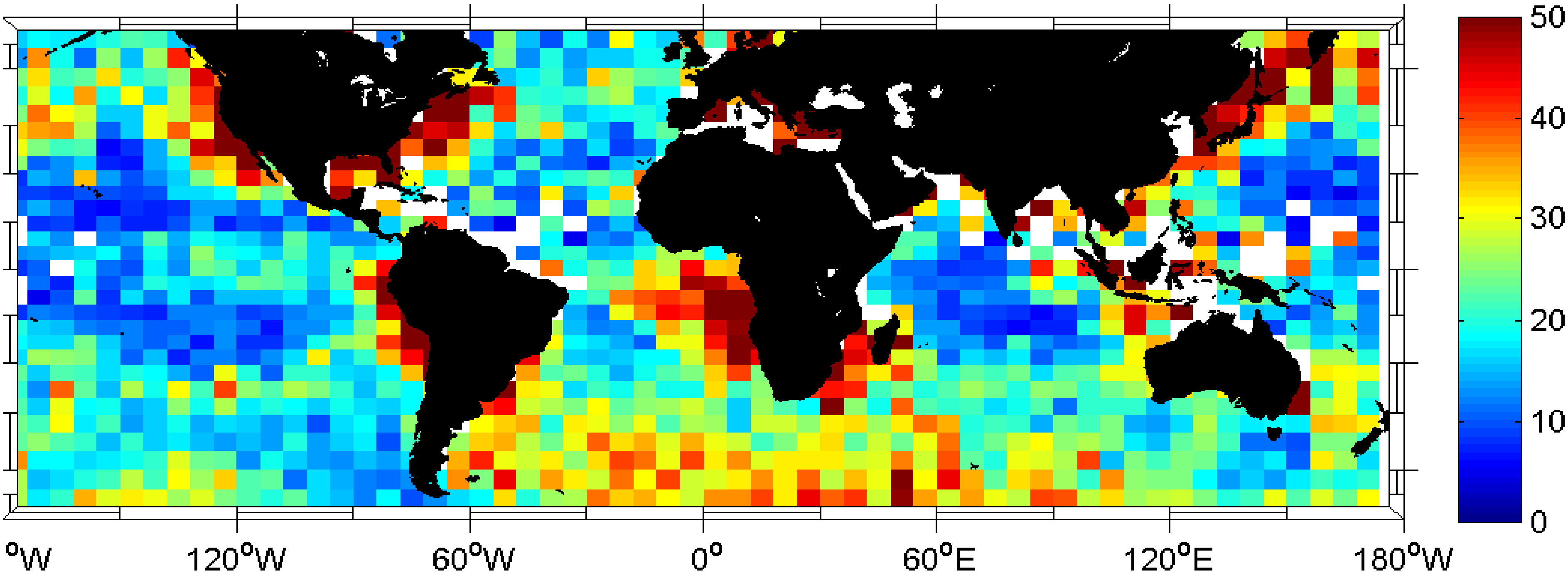
Extinction coefficient of water clouds: two different methods
Left: Li et al. 2010; Right: Hu et al. 2007



Unit: 1/km

Cloud droplet number density: derived from collocated CALIOP and MODIS measurements

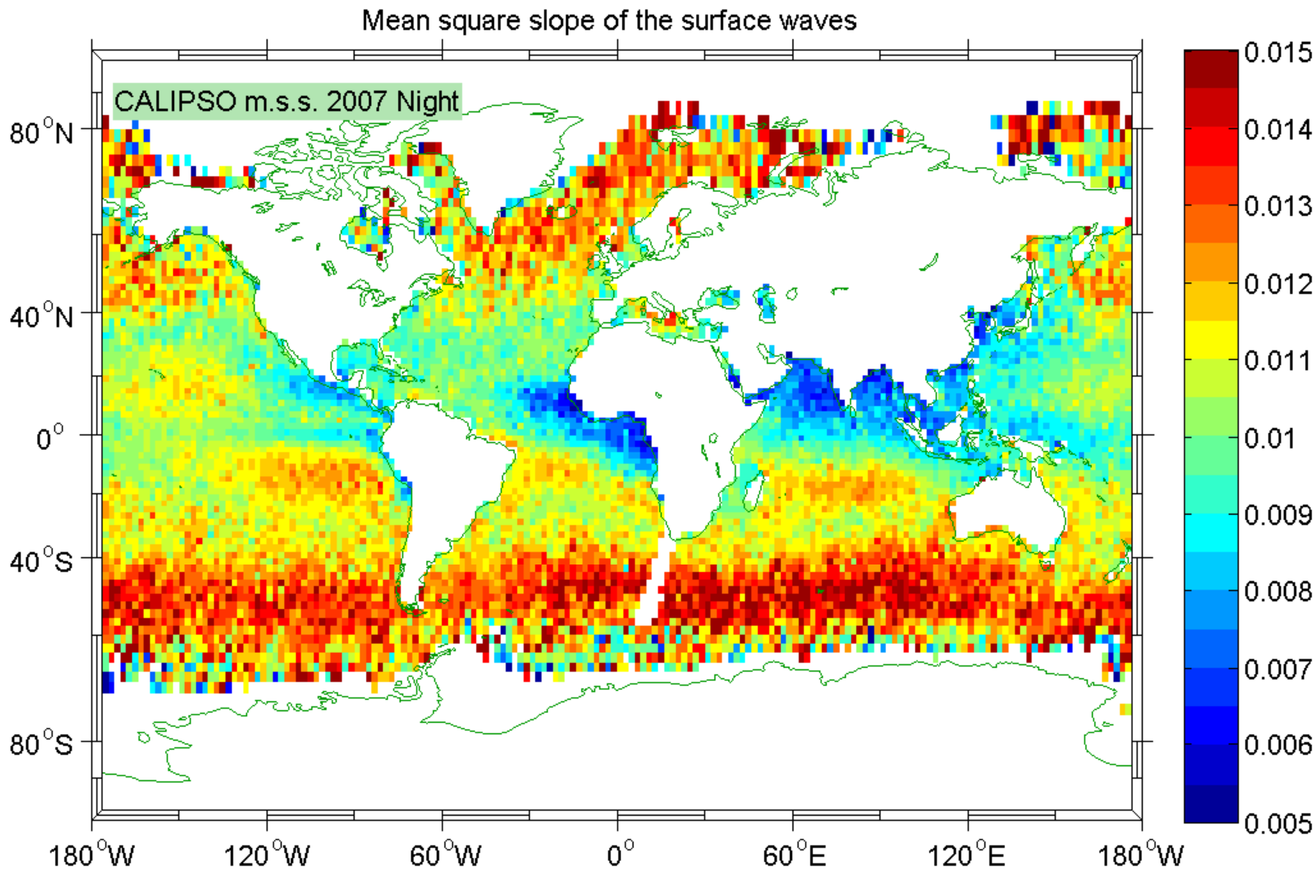
Low Level Water Cloud Effective Number Density (1/cm^3) October 2006



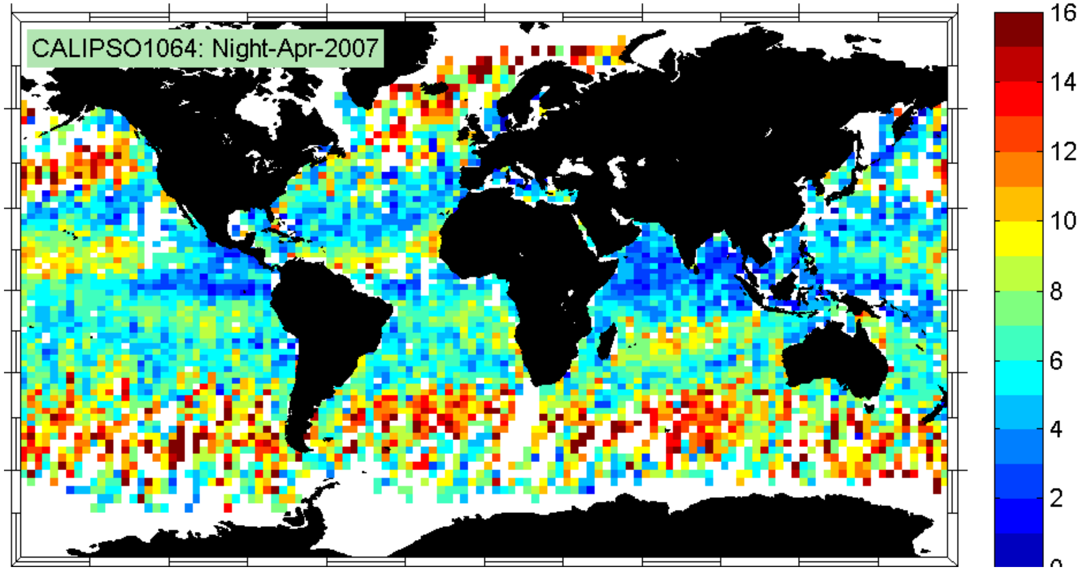
Cloud Droplet Number Density from CALIPSO+MODIS (Hu et al, 2007)

Mean square slope $\langle S^2 \rangle$ is directly measured by CALIPSO and can provide an accurate, physics-based estimate of air-sea CO_2

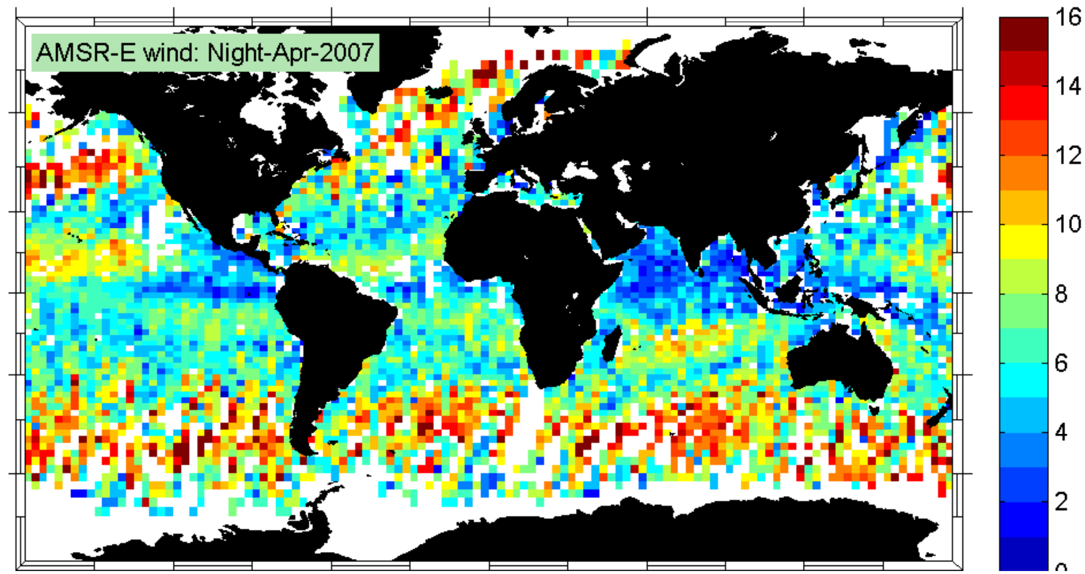
Ocean Surface Backscatter $\gamma = C^* [\sec^4\theta / \langle S^2 \rangle \exp(-0.5 \tan^2\theta / \langle S^2 \rangle] = C / \langle S^2 \rangle$



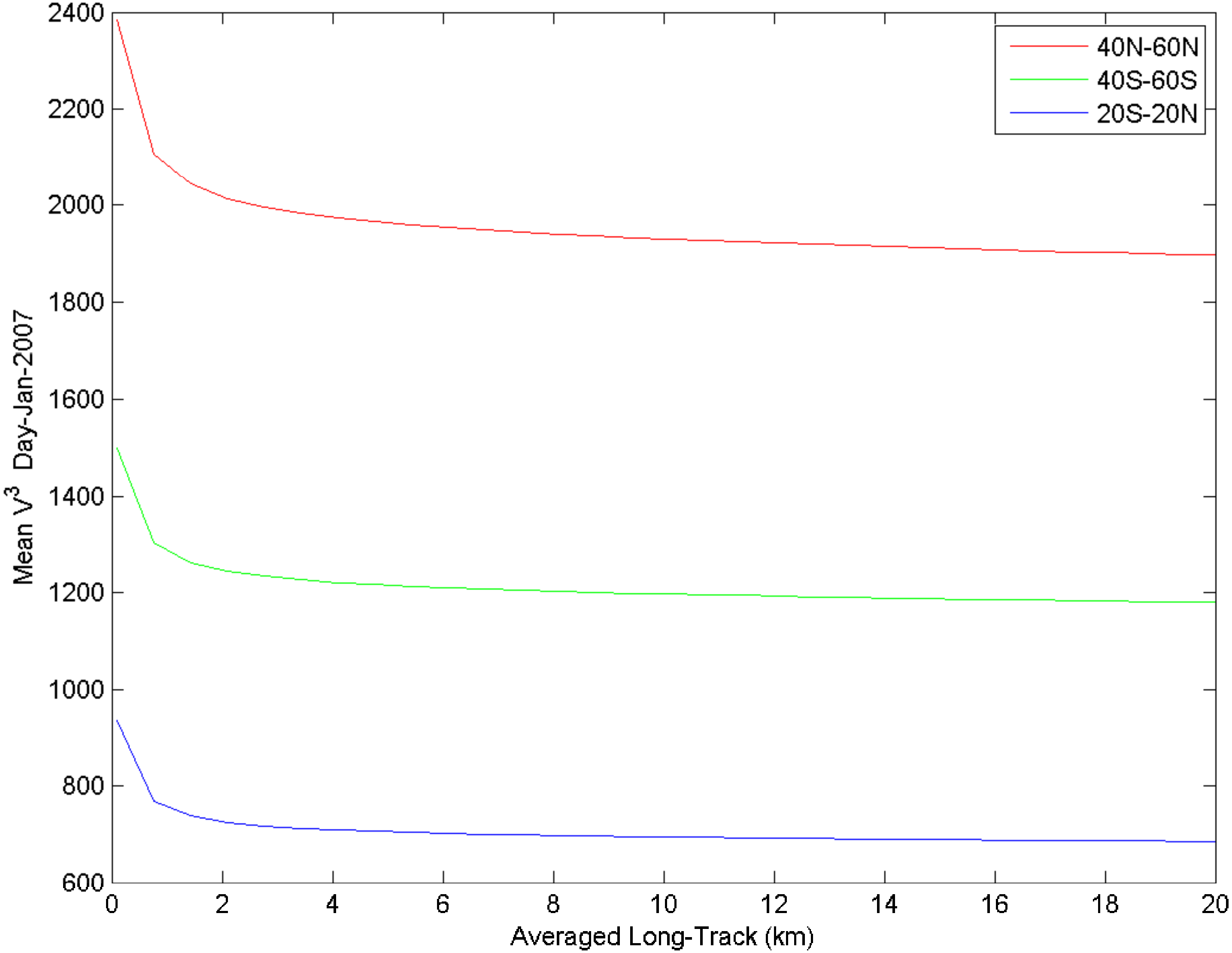
CALIPSO wind speed vs AMSR-E wind speed



Ocean surface wind comparison between CALIPSO (left) and AMSR-E (right) for April 2007 (lower).



Gas Exchange vs wind speed spatial averaging



Standard backscatter lidar vs HSRL

- Standard backscatter lidar measures *total attenuated backscatter*: a combination of backscatter and extinction from both molecules and particles; backscatter cross section of molecules and particles at single scatter limit.
  - Requires assumptions to retrieve particulate extinction cross section profiles and can be prone to error.
- High Spectral Resolution Lidar Technique provides accurate, independent measurements of particulate backscatter and extinction.

Structural Error in Retrieval: 1 equation, 2 unknowns

Measured Signal

Range from Instrument

Calibration Constant

Molecular Backscatter Coefficient

Molecular Extinction Coefficient

← **Known**

Determined from measured signals and meteorological data

$$P(r) = \frac{C}{r^2}\left[\beta_m(r) + \beta_p(r)\right]\exp\left\{-2\int_0^r\left[\sigma_m(r') + \sigma_p(r')\right]dr'\right\}$$

Particulate Backscatter Coefficient

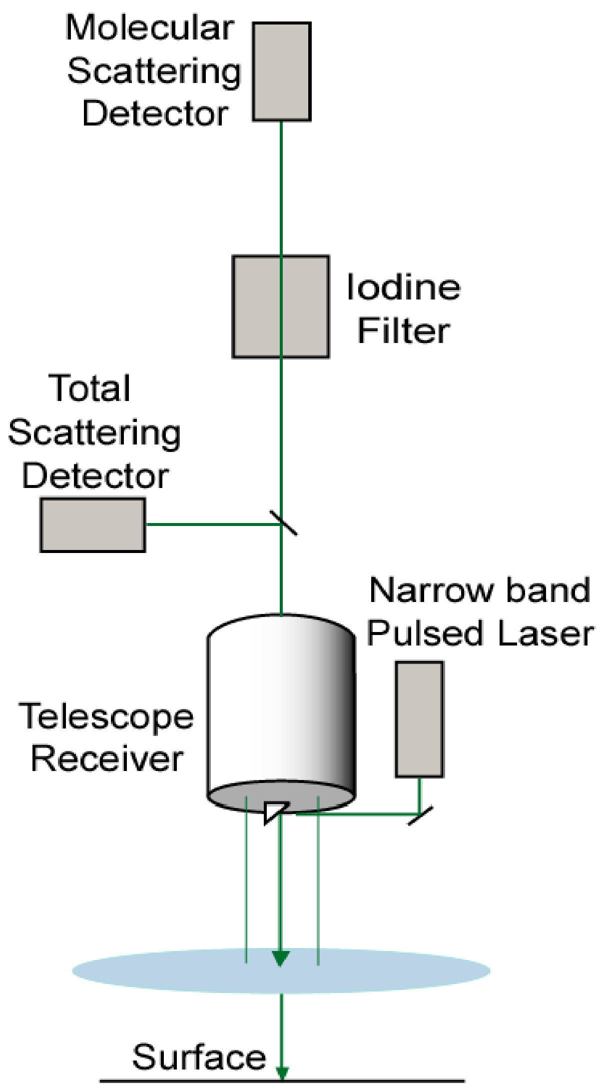
Particulate Extinction Coefficient

← **Retrieved Parameters**

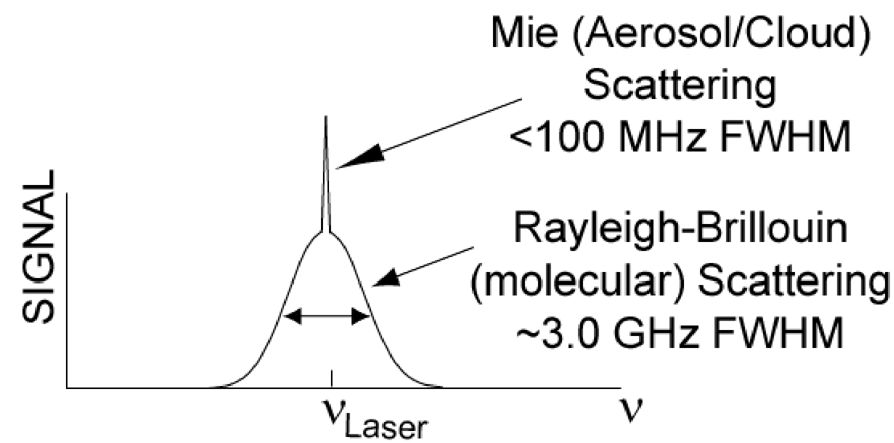
$$\frac{\sigma_p(r)}{\beta_p(r)} = S_p$$

← Assumption of value for extinction-to-backscatter (S_p) ratio required for backscatter lidar retrieval

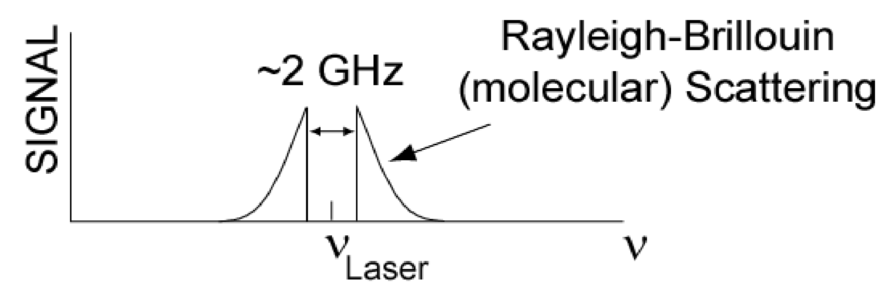
HSRL measurement concept:
(one possible realization at 532 nm)



Atmospheric Scattering



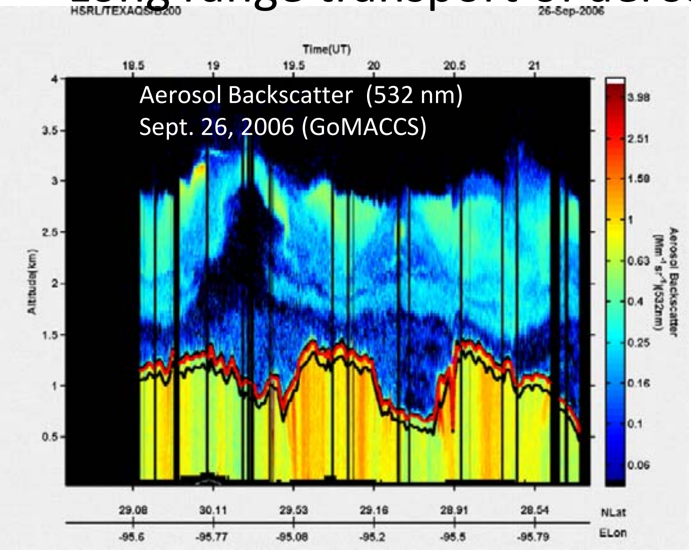
Effect of Iodine Vapor Notch Filter



Two channels → 2 equations to solve for 2 unknowns: backscatter and extinction

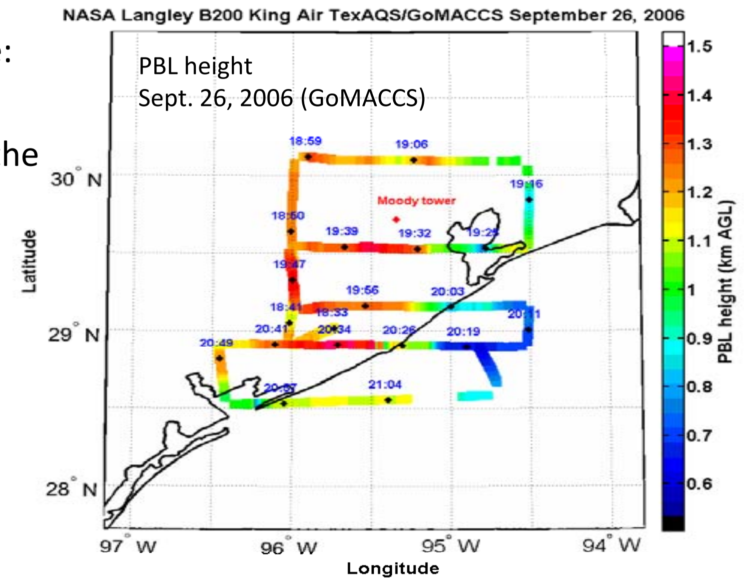
Planetary Boundary Layer (PBL) Height Retrievals and AOT from High Spectral Resolution Lidar (HSRL)

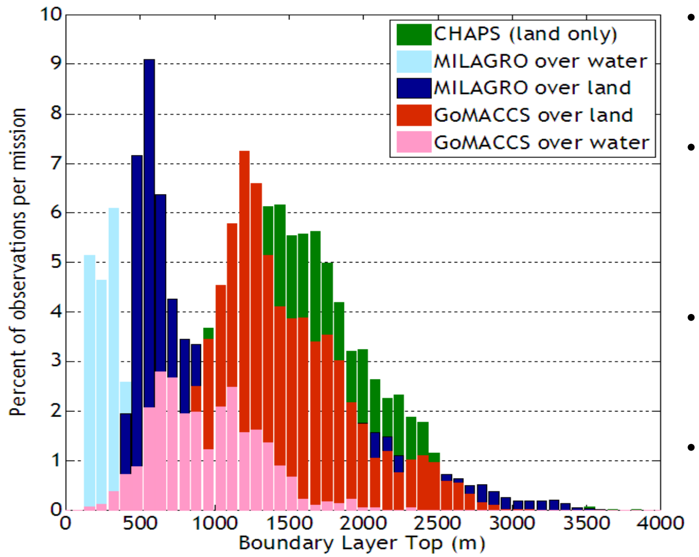
Long range transport of aerosols depends on whether aerosols injected above PBL



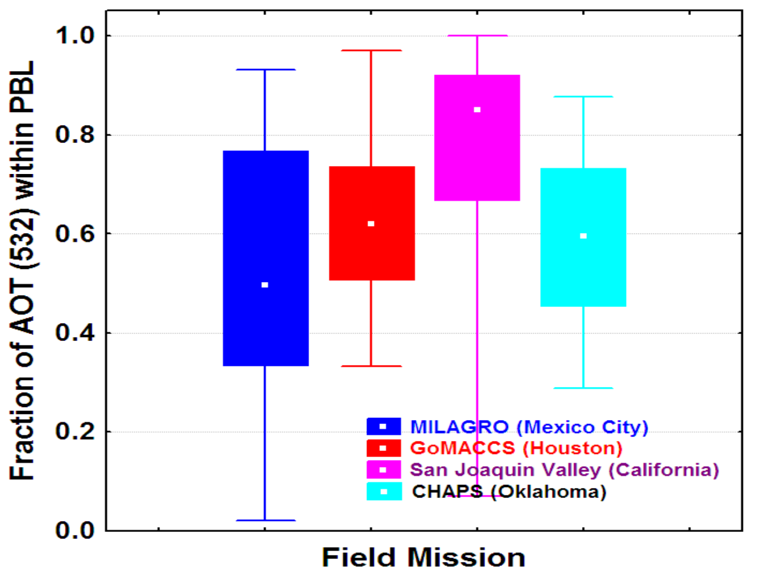
HSRL data used to determine:

- PBL height
- Upper and lower limits of the backscatter transition (i.e. entrainment) zone
- Fraction of aerosol optical thickness within PBL



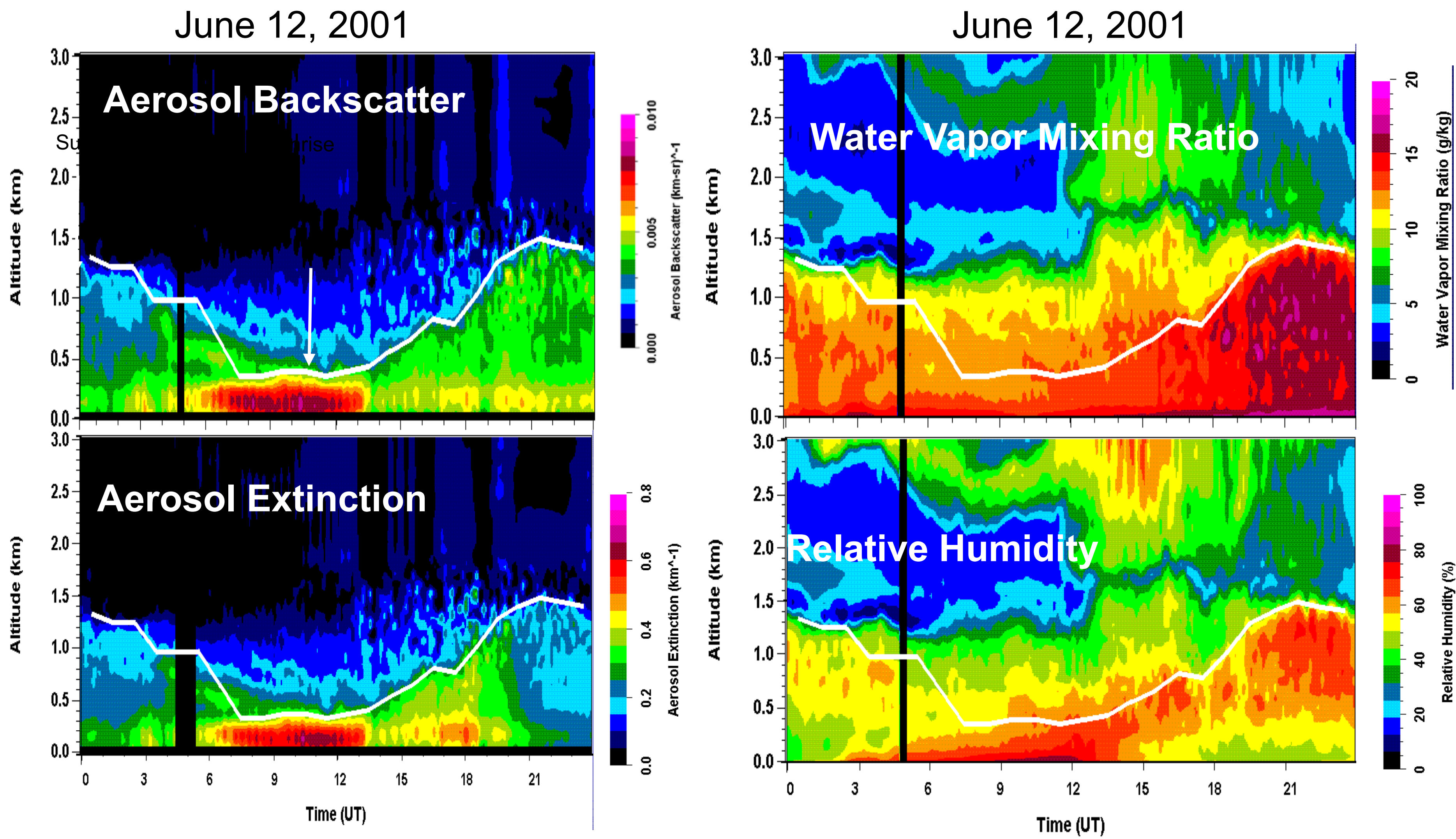


- PBL heights over water significantly lower than PBL heights over land
- Large fraction (40-50%) of AOT above PBL during MILAGRO, GoMACCS, CHAPS
- Most (80-90%) of AOT within PBL during San Joaquin Valley Mission
- HSRL PBL heights now routinely requested by other investigators



DOE SGP Raman Lidar PBL Height Retrievals

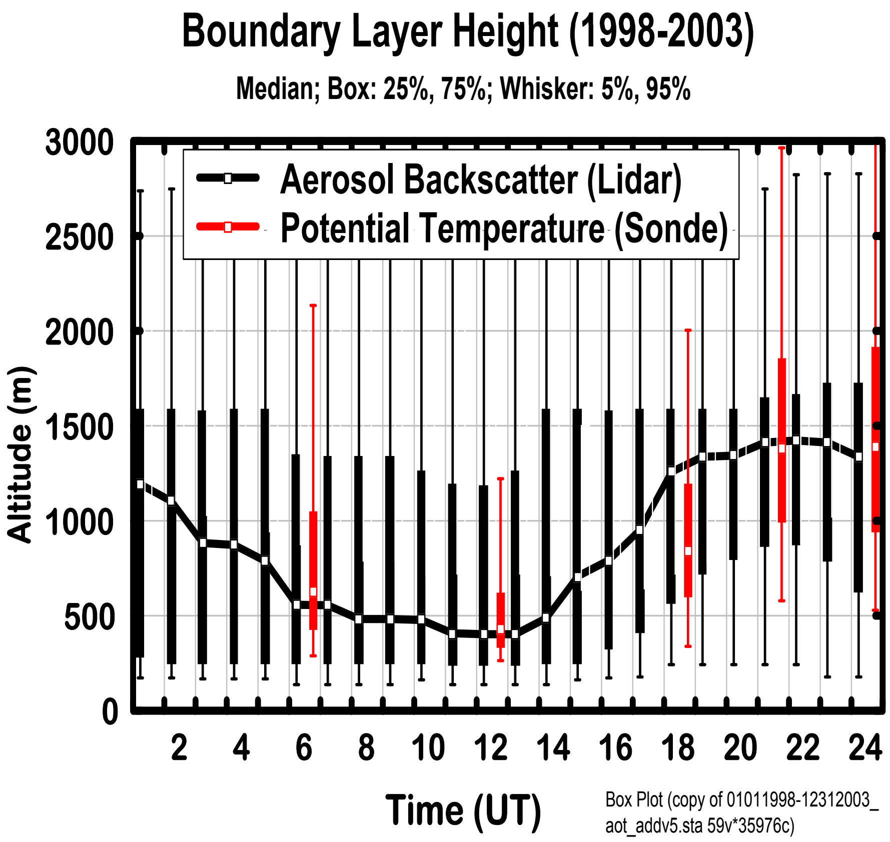
- DOE SGP Raman Lidar (Oklahoma) operates 24/7 measuring water vapor and aerosols
- Raman lidar data used to determine PBL height and aerosol and water vapor distributions

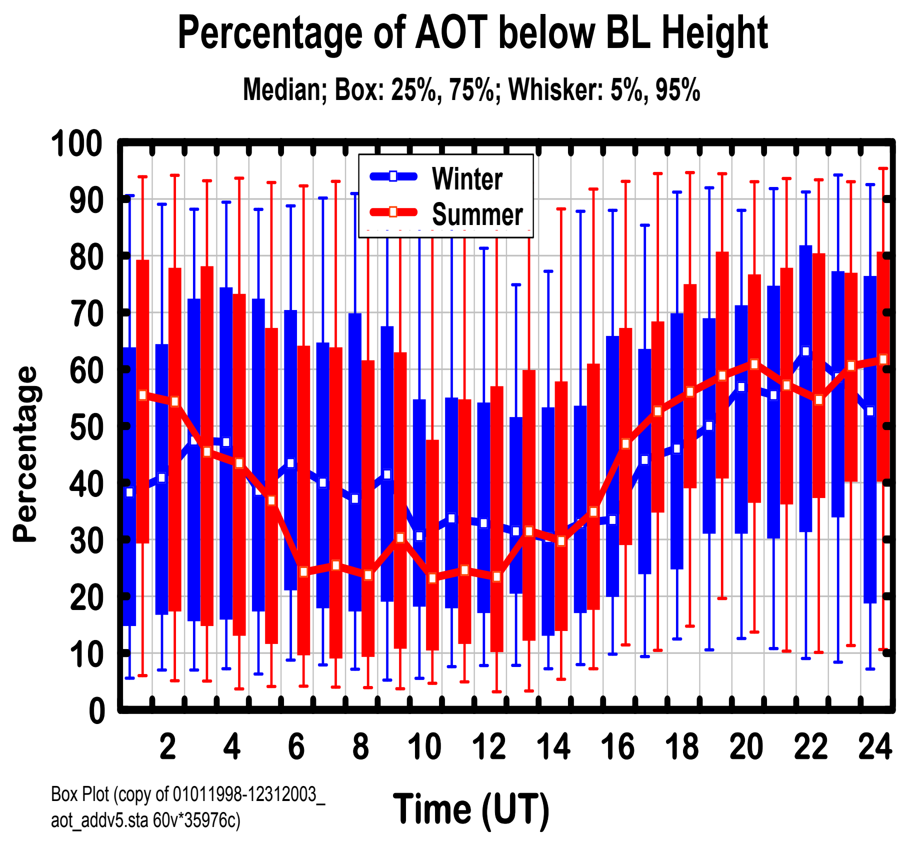


DOE SGP Raman Lidar PBL Height Retrievals

- PBL Height Methods:
  - Radiosonde - Potential temperature - (Heffter, 1980)
  - Raman Lidar - Aerosol backscatter, water vapor via Haar wavelet – (Brooks, 2003)
- Best agreement during afternoon, early evening

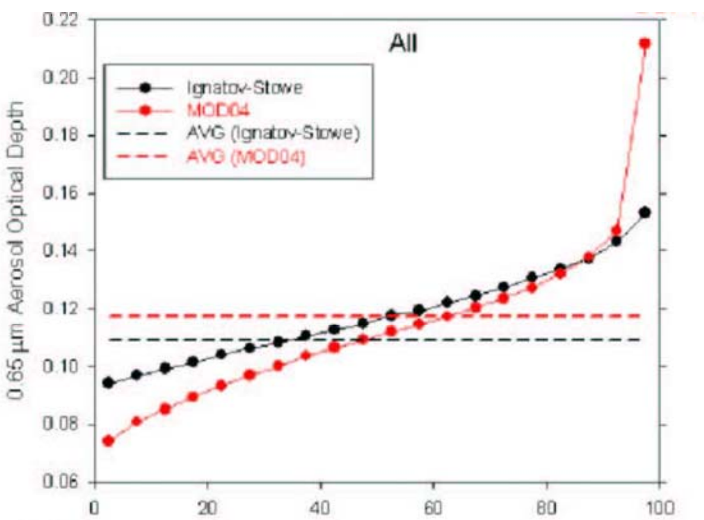
- Amount of AOT within PBL
  - varies with time of day
  - does not vary significantly with season or AOT
- Significant fraction of AOT (>25%) is above PBL

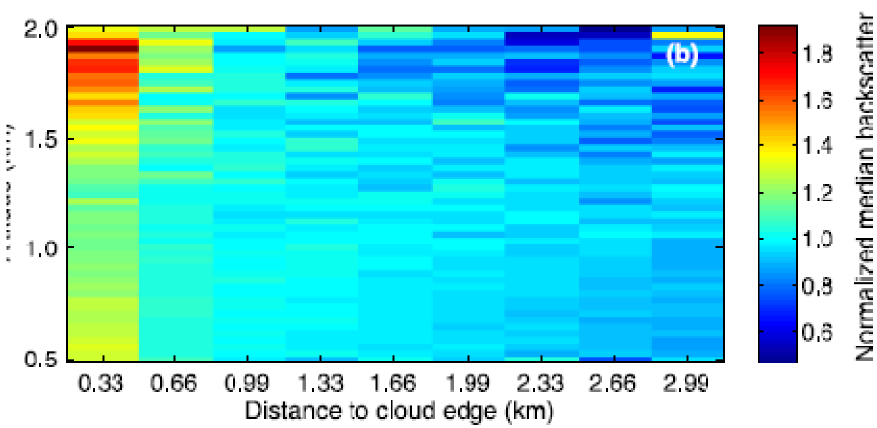


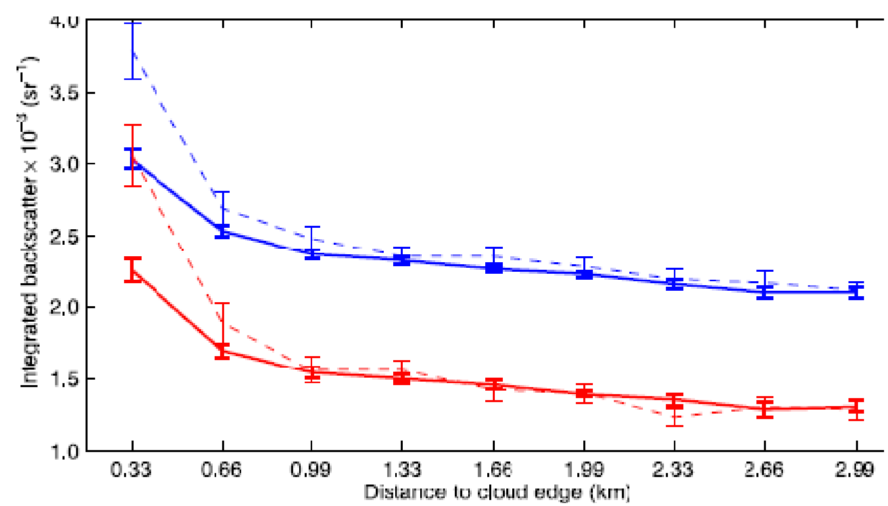


The “Twilight Zone” (Koren, Marshak, Wen, etc.)

Correlation of AOD and cloud fraction - looks like the first indirect effect, but could be spurious

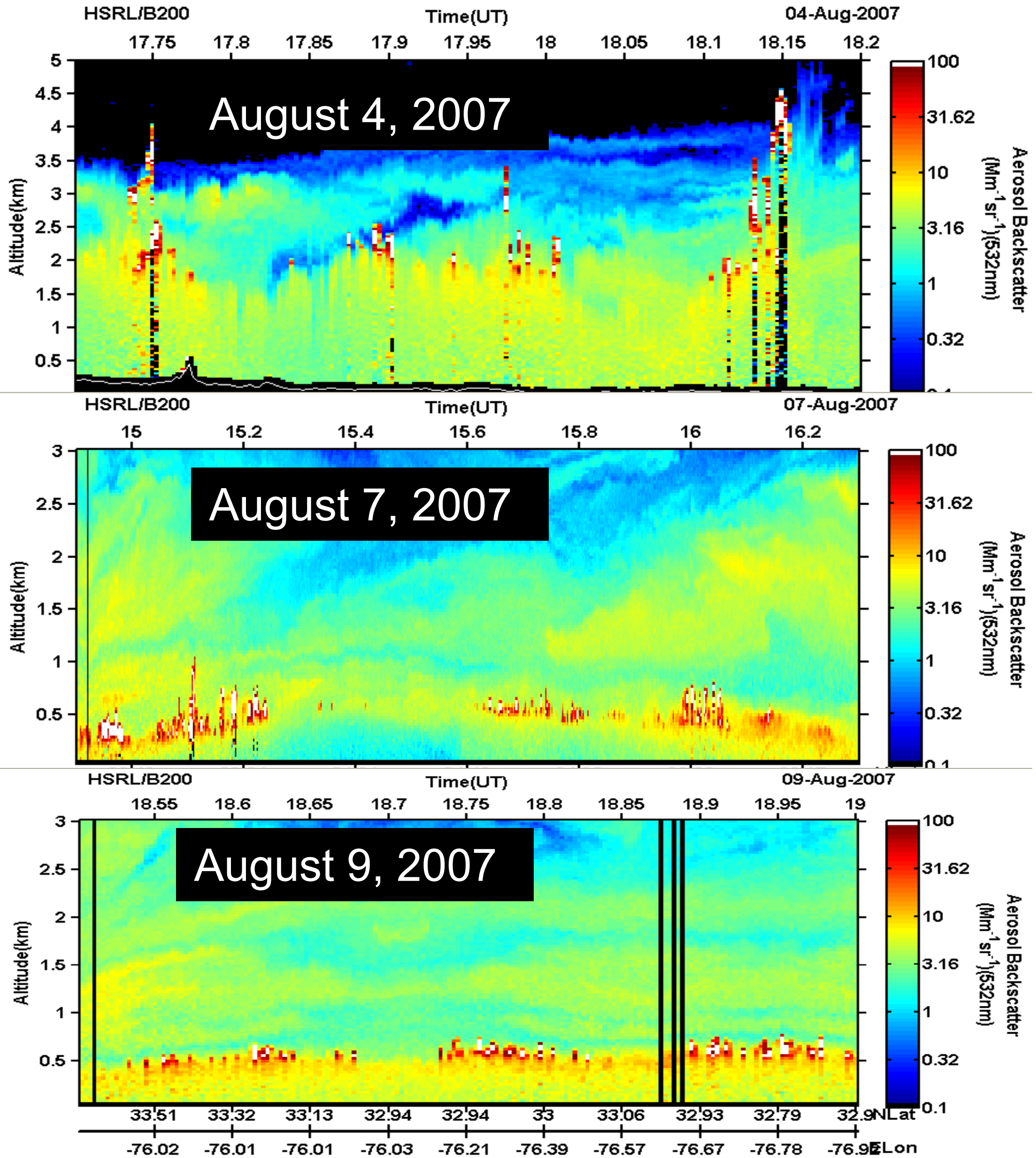






Tackett and di Girolamo, GRL, 2009

HSRL measurements of aerosols near clouds



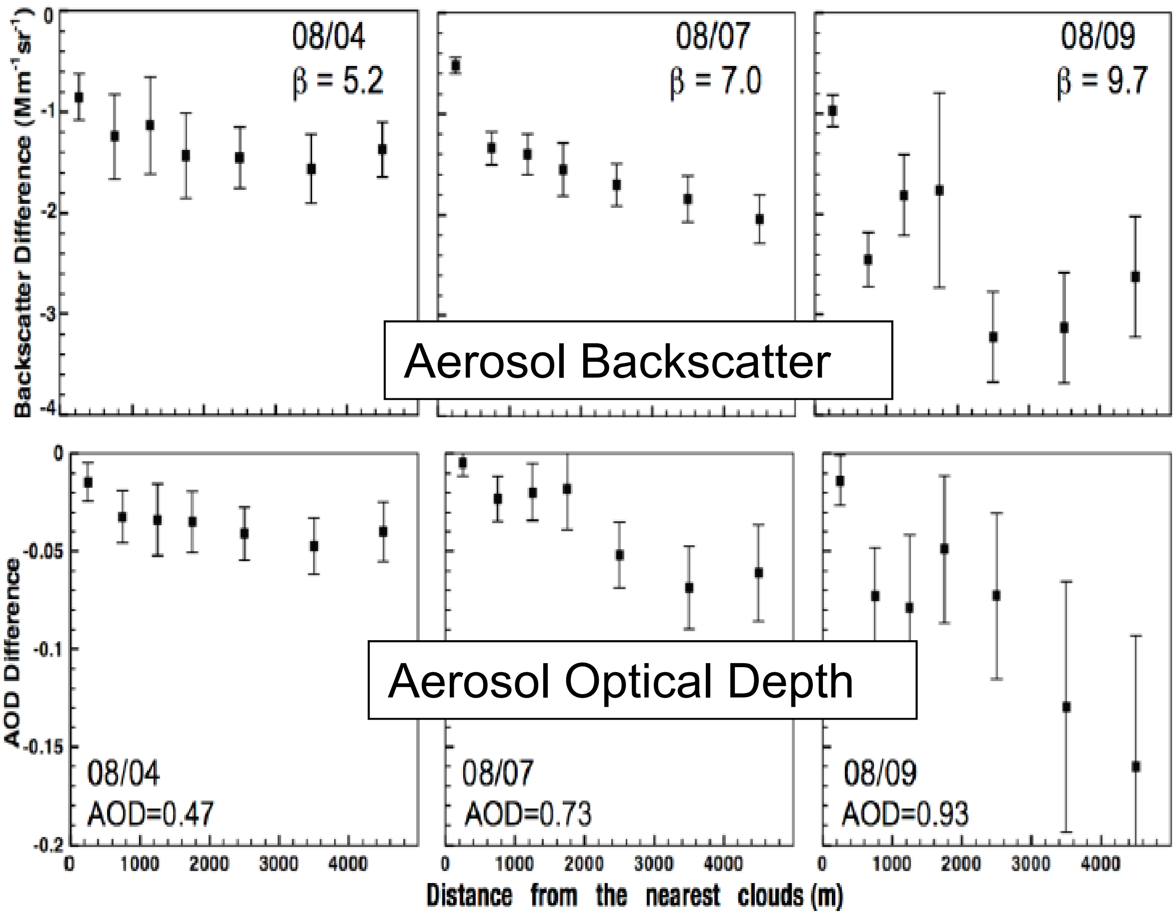
Study by Su et al. (2008, JGR) used HSRL measurements over the eastern U.S. to study spatial variations of aerosol optical properties near clouds

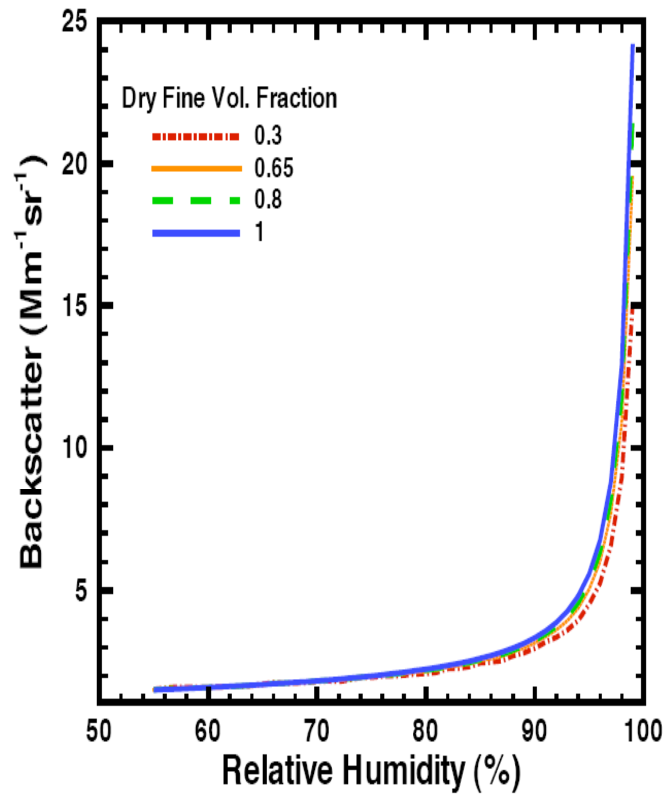
- Temporal resolution: 2 sec
- Vertical resolution:
  - 30 m backscatter
  - 300 m extinction
- Averaged data within +/- 60 m of cloud top
- Compare aerosol properties adjacent to cloud edge with properties as a function of distance away from cloud edge

HSRL measurements of aerosols near clouds

Study by Su et al. (2008, JGR, 2008) found using HSRL data…

- Aerosol backscatter and extinction ~ 20-30% higher in proximity to clouds as compared to 4-5 km away
- Aerosol optical thickness ~ 8-17% higher
- Changes are consistent with hygroscopic swelling

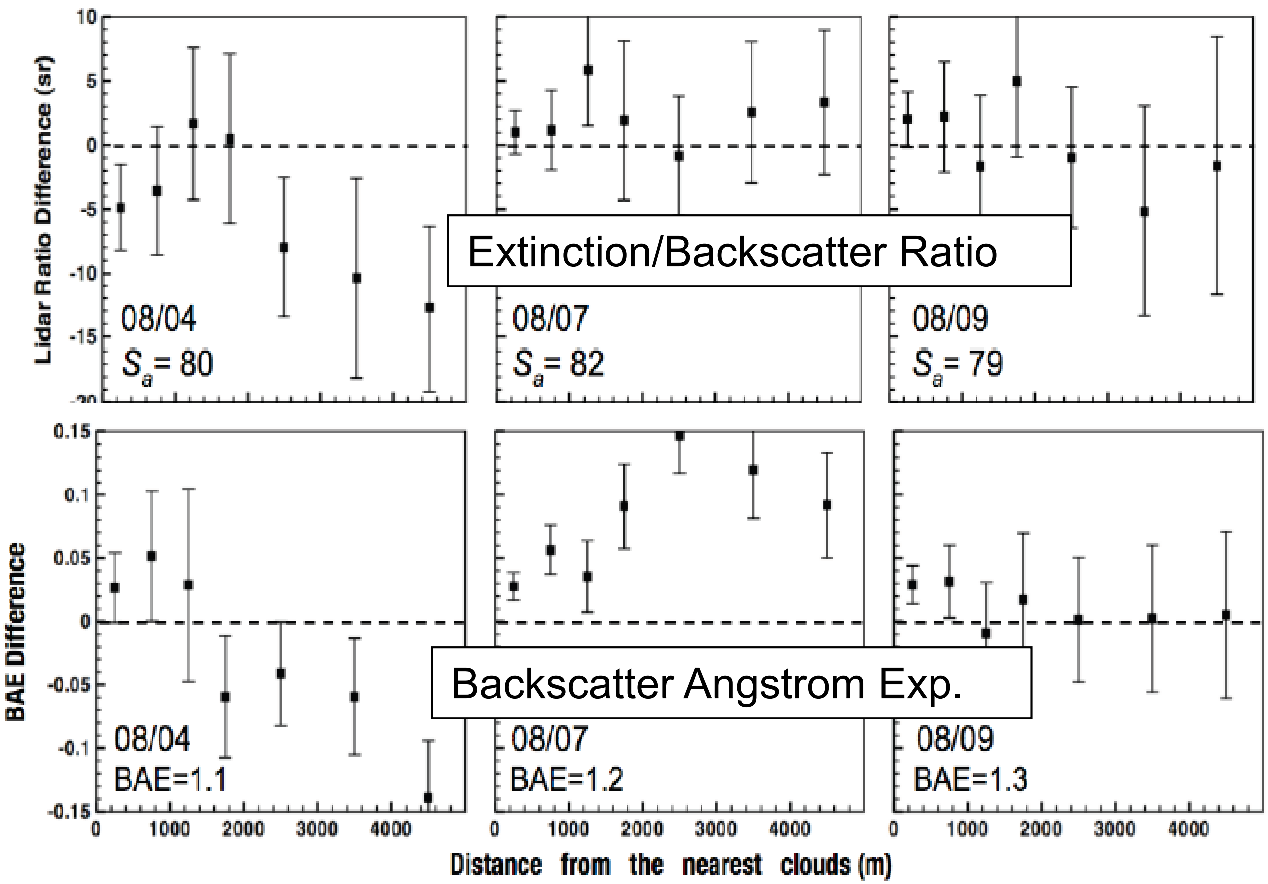


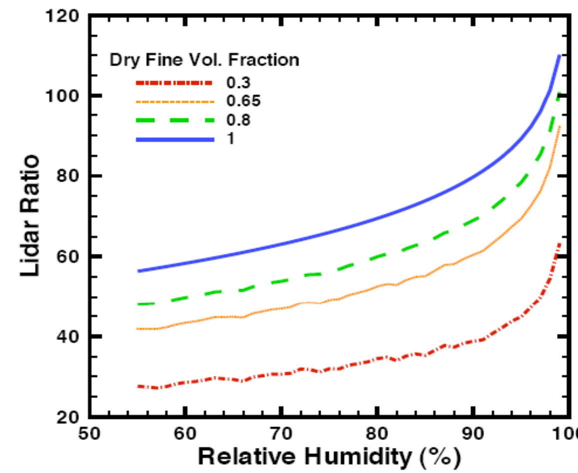


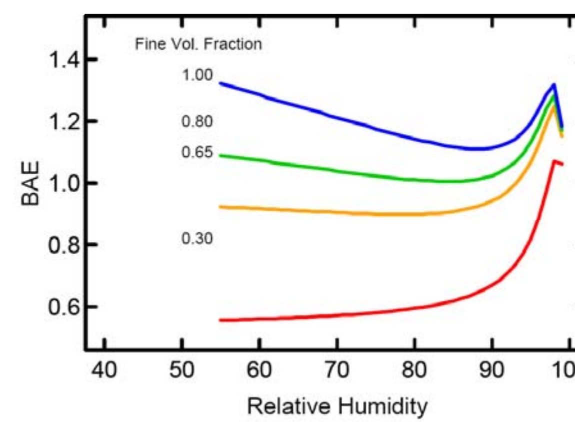
HSRL measurements of aerosols near clouds

Study by Su et al. (2008, JGR, 2008 in press) found using HSRL data…

- No clear systematic trend in extinction/backscatter ratio or BAE
- Effect of aerosol swelling offset by in cloud processing increasing coarse mode fraction
- Changes in BAE depend on RH and size distribution
- ➢ Need concurrent RH and aerosol size distribution measurements







Changes in aerosol properties near clouds measured by airborne HSRL during DOE CHAPS/CLASIC Mission

HSRL measurements used to study spatial variations of aerosol optical properties near clouds

- Temporal resolution: 2 sec
- Vertical resolution:
  - 30 m backscatter
  - 300 m extinction
- Averaged data within +/- 60 m of cloud top
- Compare aerosol properties adjacent to cloud edge with properties some distance away from cloud edge

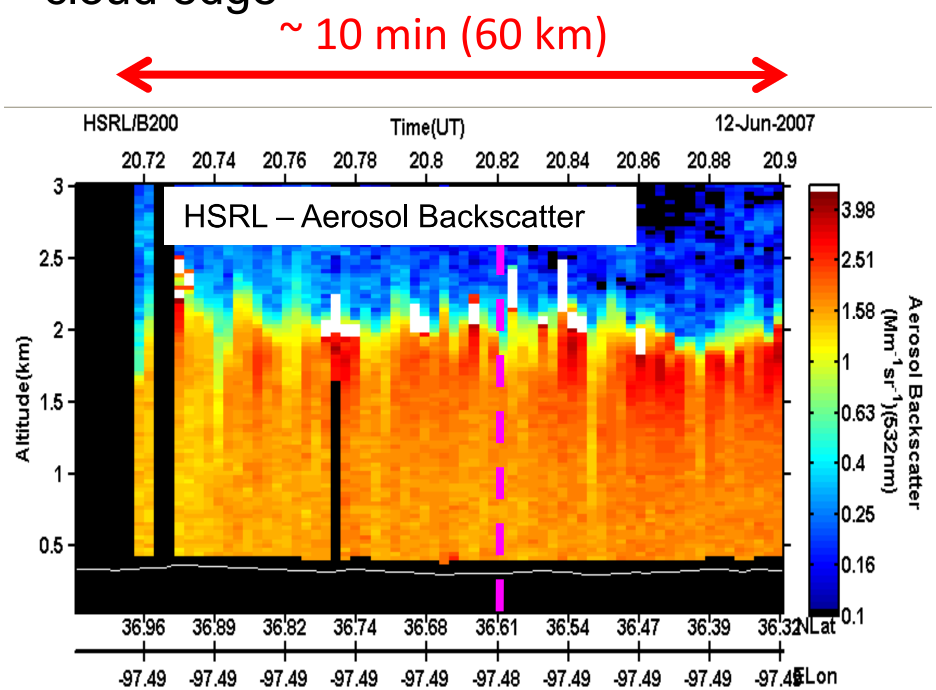
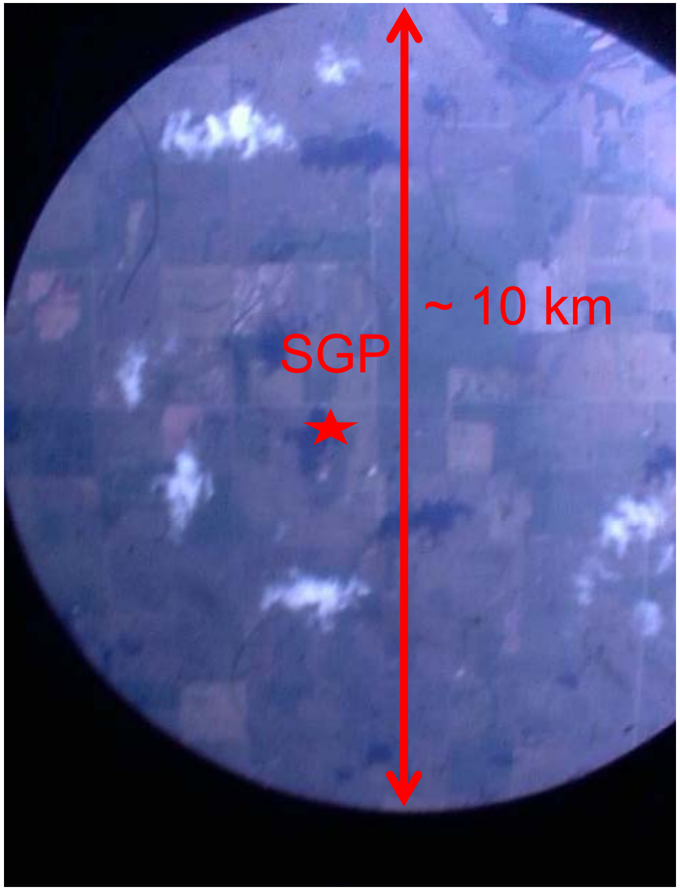


Image from digital camera on NASA B200 King Air

20070612_204915



Changes in aerosol properties near clouds measured by airborne HSRL during DOE CHAPS/CLASIC Mission

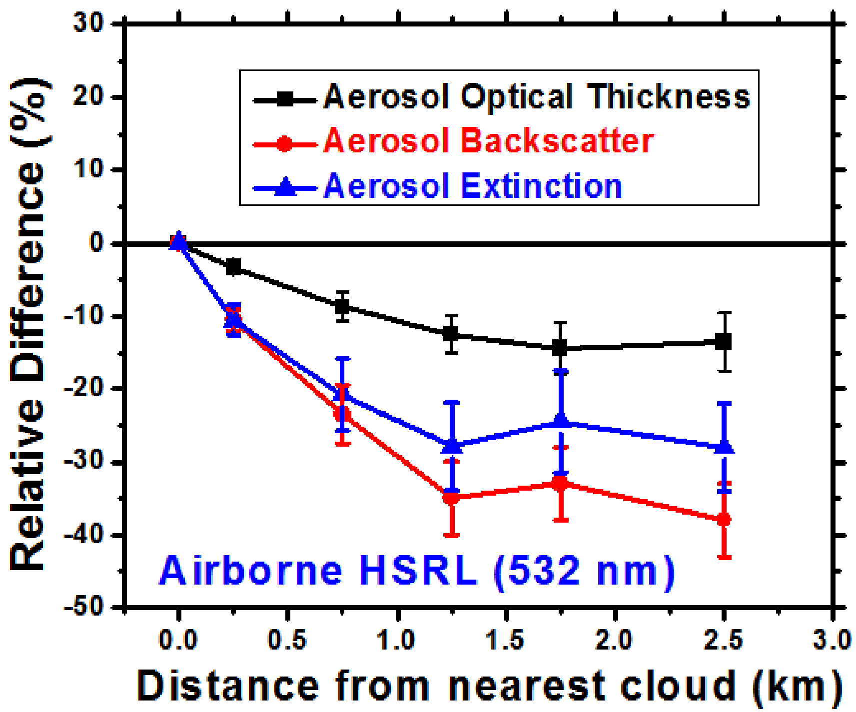
June 12, 2007 case

Significant changes in aerosol properties within 1-2 km of clouds. As distance from cloud increases:

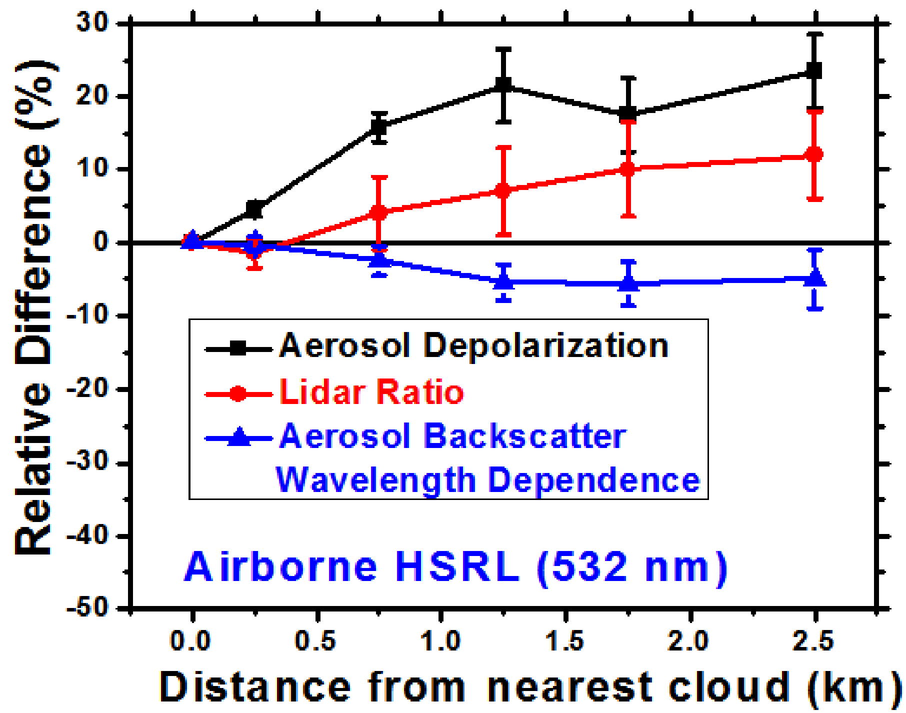
- AOT decreases 10-15%
- Aerosol backscatter and extinction decrease 25-40%
- Aerosol depolarization increases 10-20%
- Lidar ratio increases 5-10%
- Small (~5%) decrease in backscatter wavelength dependence

How much explained by changes in RH?

Aerosol Extensive Parameters



Aerosol Intensive Parameters

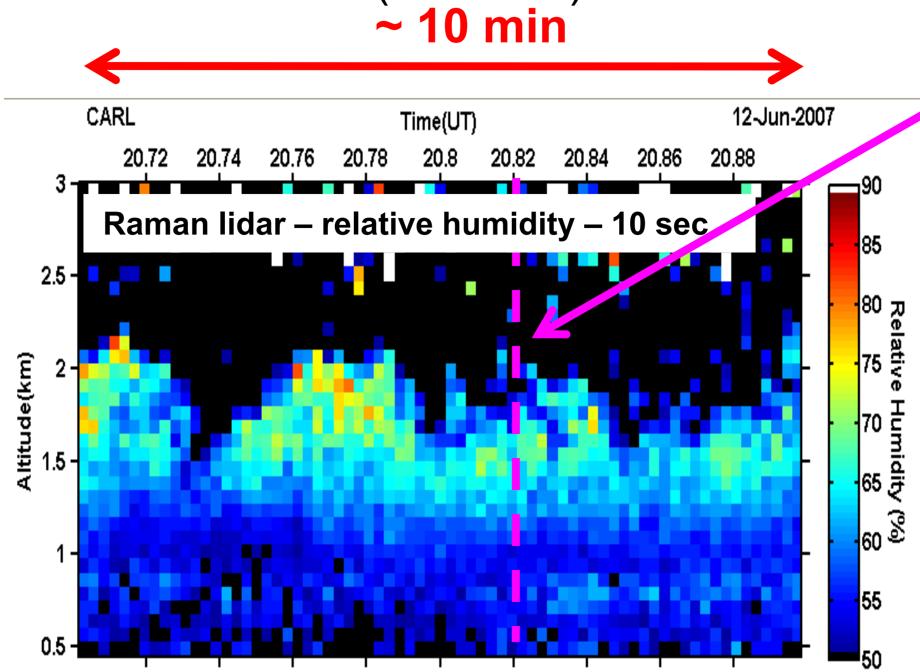


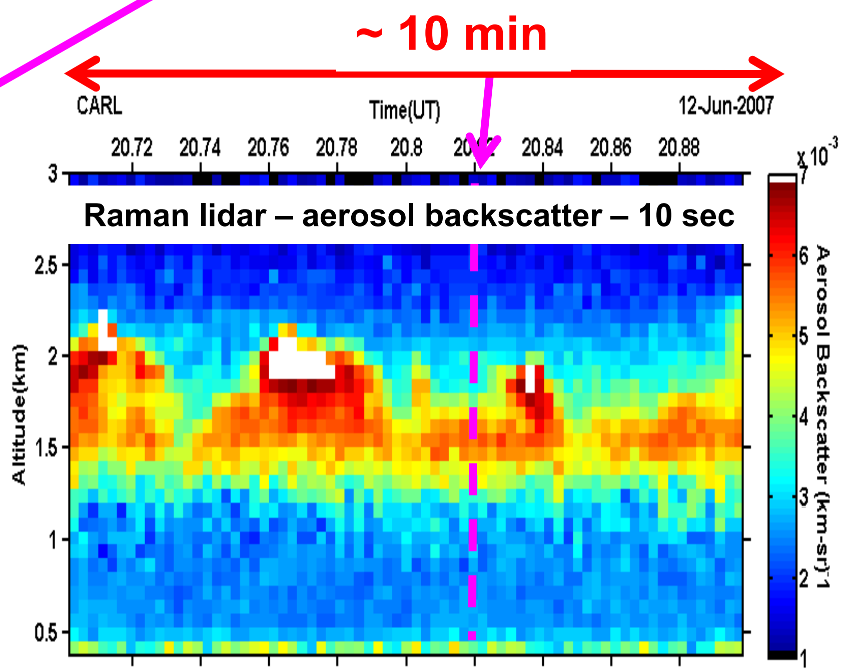
Changes in aerosol properties near clouds measured by SGP Raman Lidar

SGP Raman lidar measurements used to study spatial variations of relative humidity and aerosol optical properties near clouds

- Temporal resolution: 10 sec (RH, backscatter)
- Vertical resolution: 75 m (possible to go lower)
- Compare RH and aerosol properties adjacent to cloud edge with properties some time (distance) away from cloud edge
- Examined several altitudes above/below cloud base
- Both Raman lidar data and TSI images are used to determine time (distance) from cloud

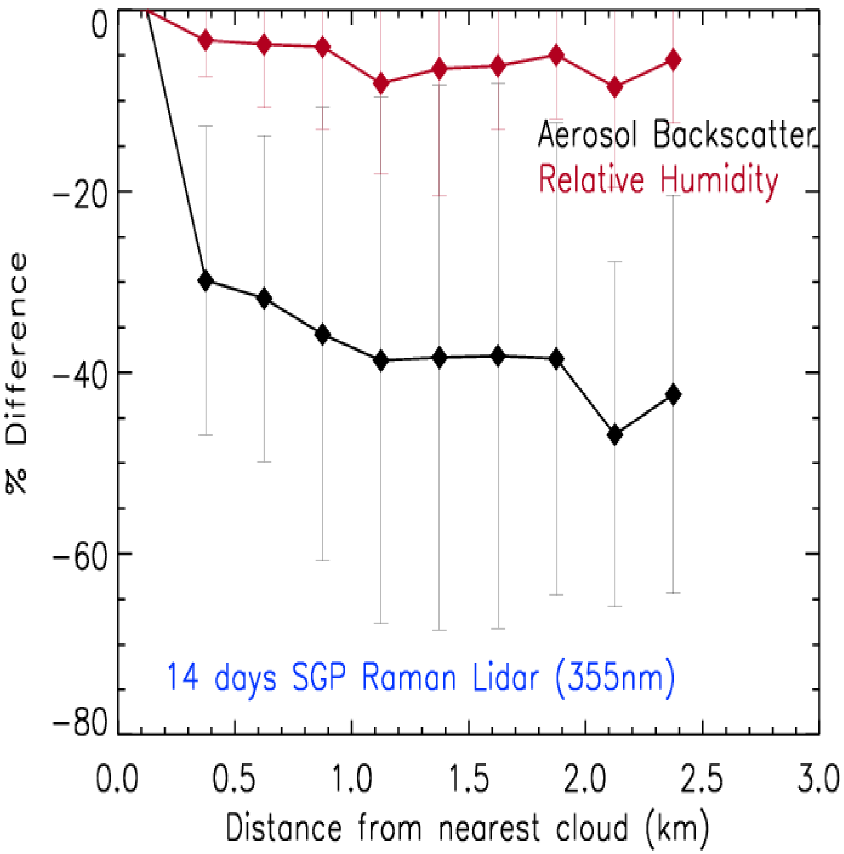
SGP TSI image

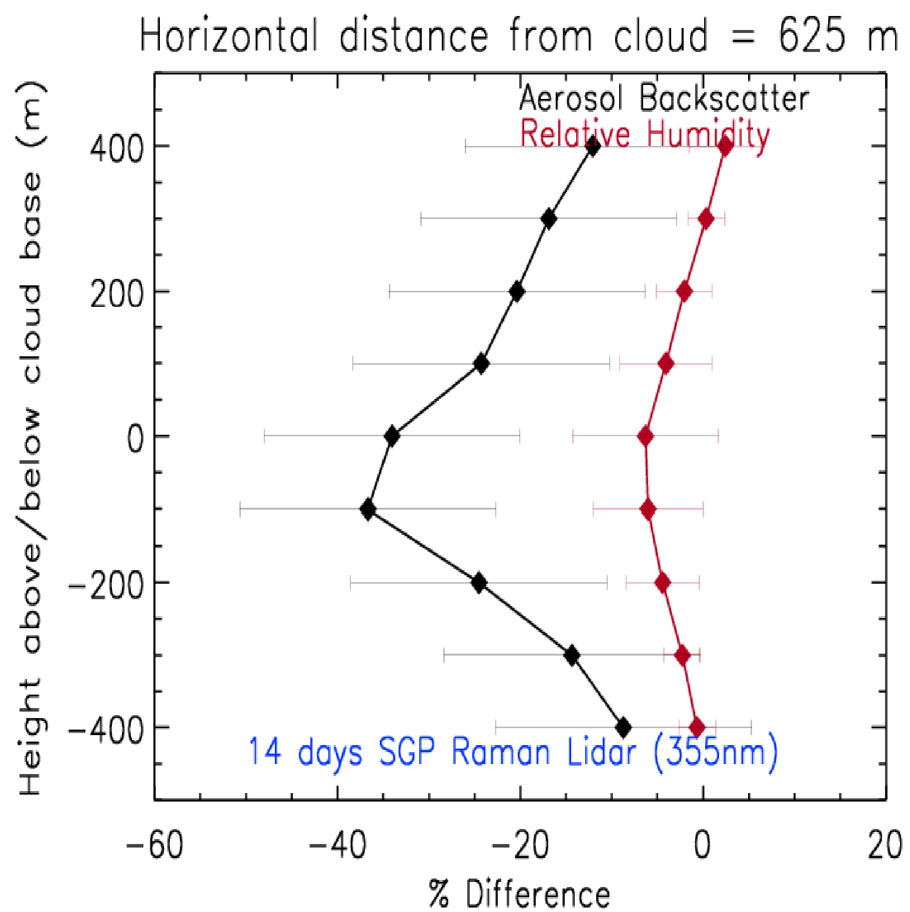




Changes in aerosol backscatter and RH near clouds measured by SGP Raman Lidar

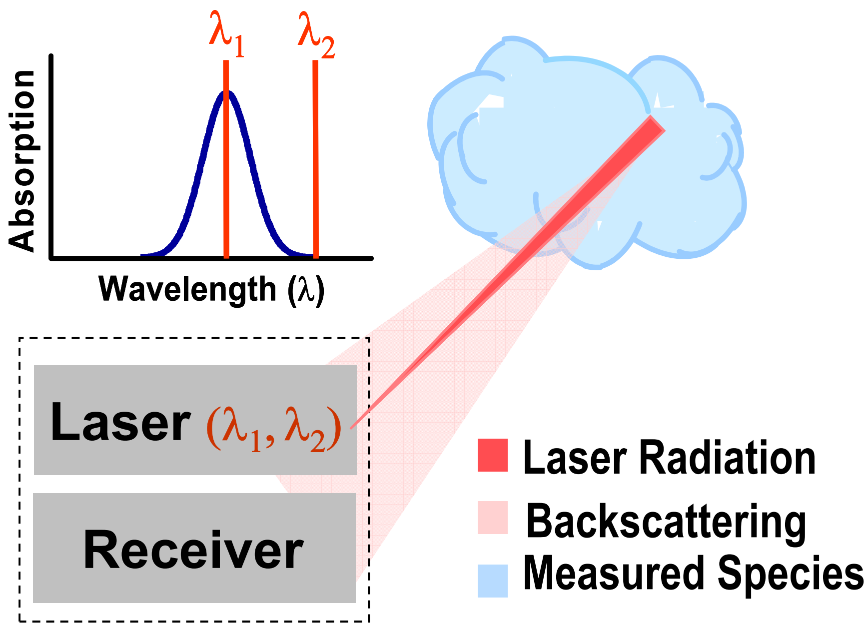
- Results from 14 days in Sept. 2005 and June 2007
- Significant changes in aerosol properties within 1-2 km of clouds. Ground based Raman lidar measurements show that as distance from cloud increases:
  - On average, 20-40% decrease in aerosol backscattering
  - On average,   5-10% decrease in relative humidity
- Variations confined to altitudes between ~200-400 m above/below cloud base





Differential Absorption Lidar (DIAL) Technique and Advantages

DIAL Concept

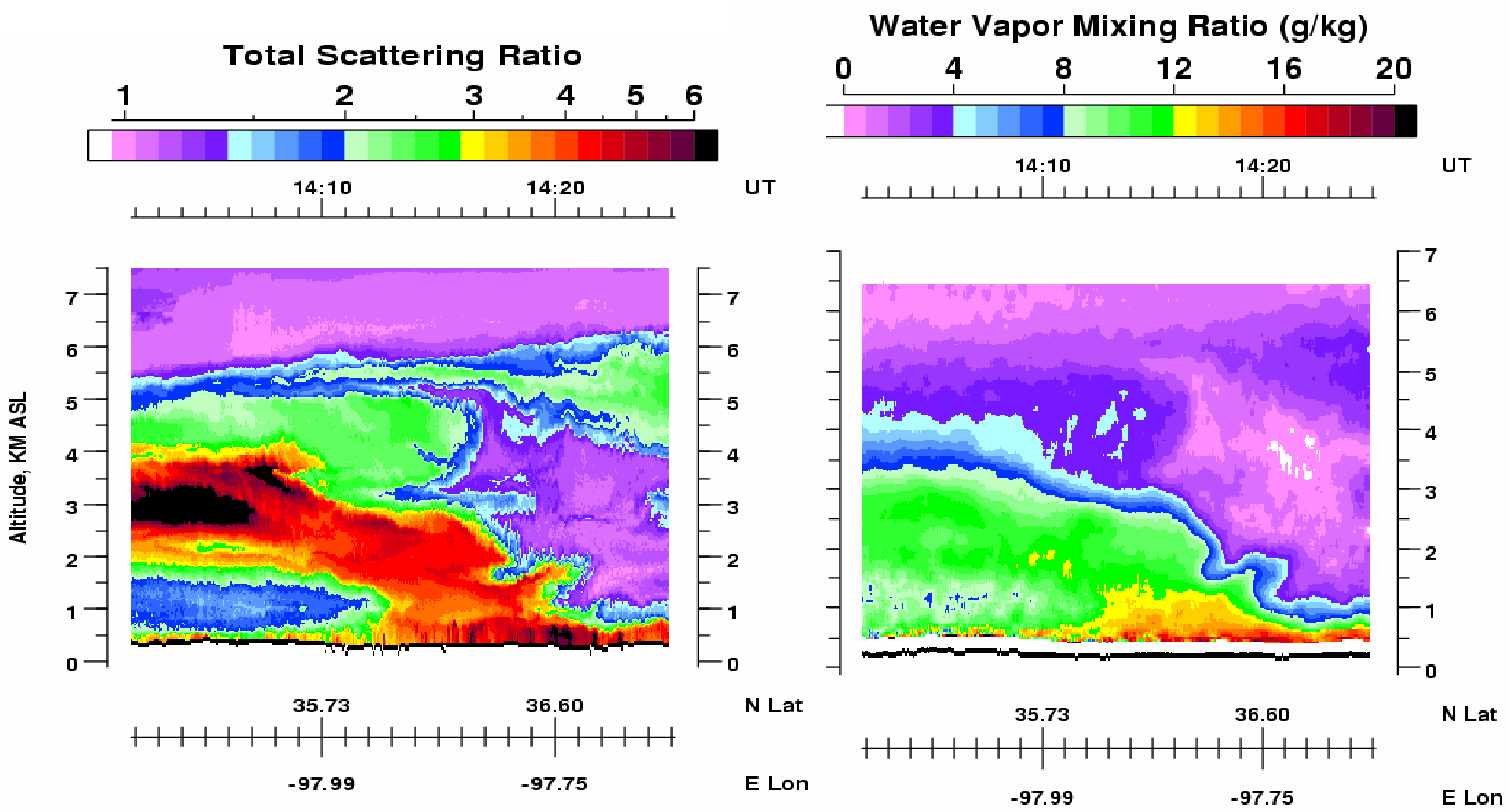


Advantages

- **High vertical and horizontal resolution**
- **DIAL data permit direct inversion and absolute concentration measurements**
- **Simultaneous species and aerosol profiles, and cloud distributions**
- **Day and night coverage and no dependence on external radiation**

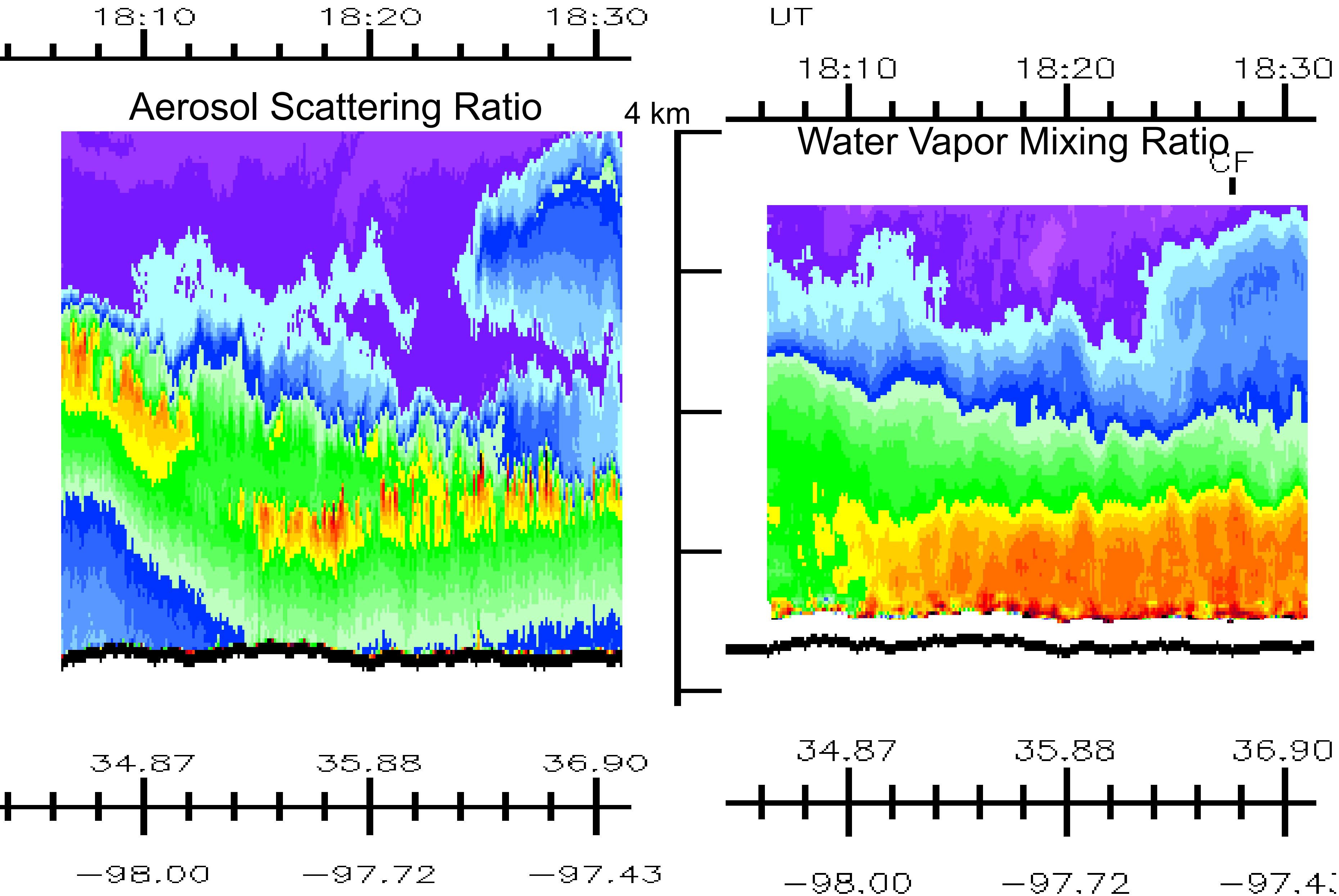
- DIAL technique suitable for Atmospheric O_3, H_2O, CO_2, and CH_4 measurements.
- Lidar Atmospheric Sensing Experiment (LASE) has demonstrated high accuracy H_2O , and high resolution aerosol profiling capability from NASA aircraft during 13 major field experiments.

LASE Measurements of Boundary Layer Development)
SGP97 (July 09, 1997)

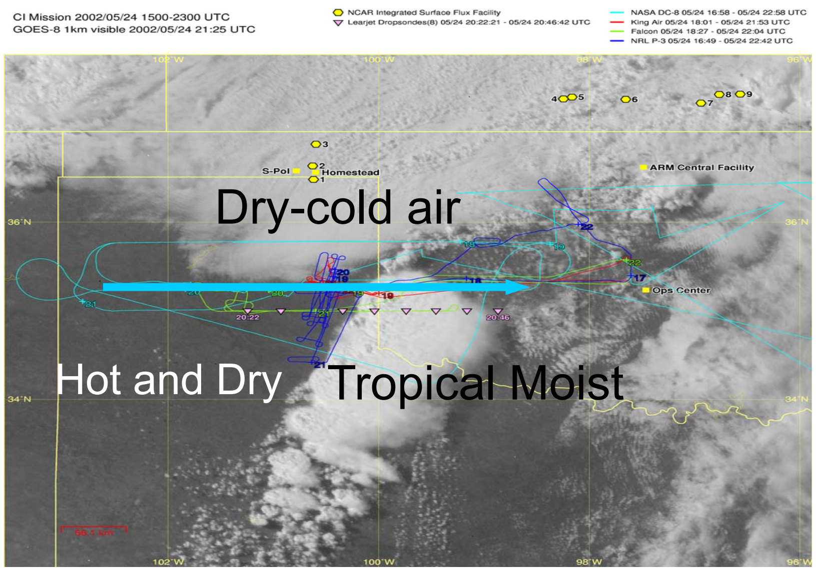


LASE Measurements of Boundary Layer Development)

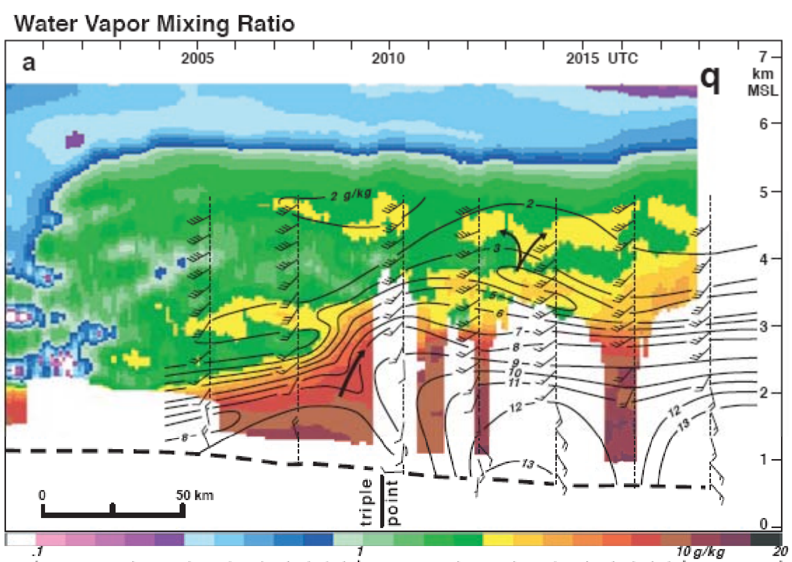
SGP97 (July 12, 1997)

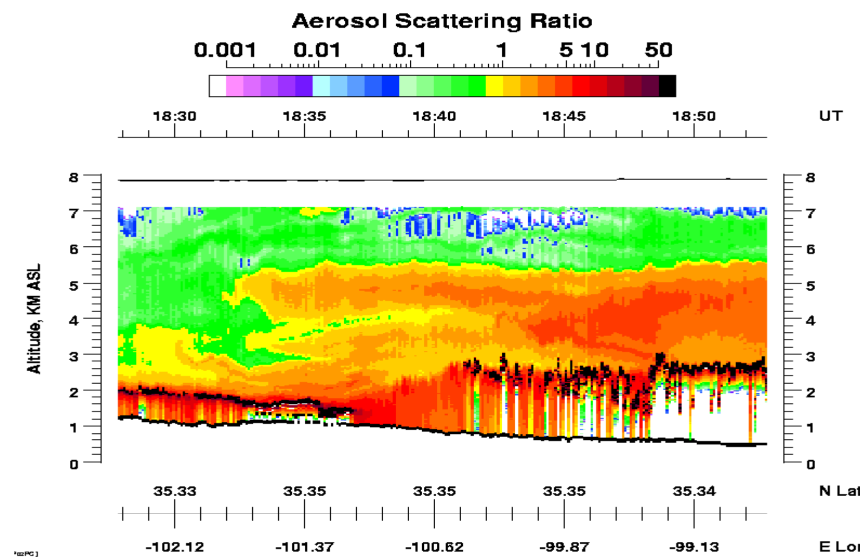


Convective Initiation (CI), IHOP Field Experiment, 24 May 2002



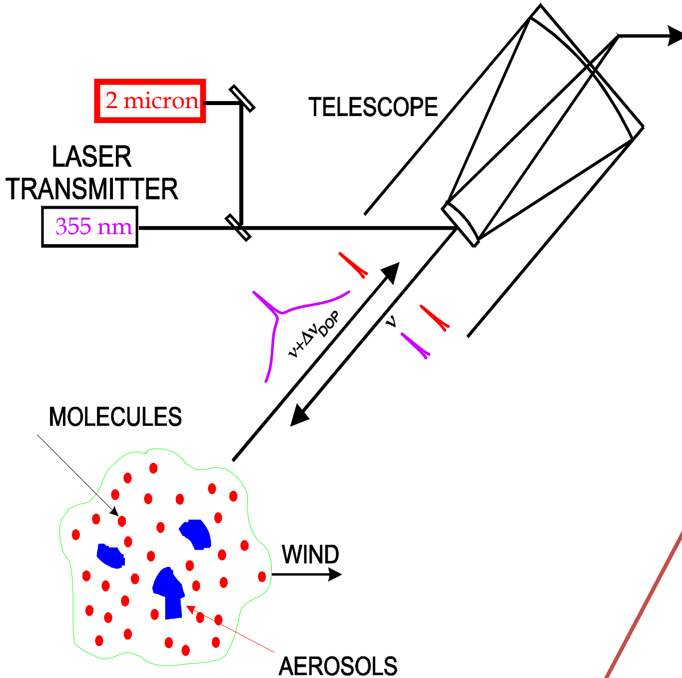
- **LASE data used in convection initiation (CI) studies and to locate regions of convection development.**
- **High resolution LASE H_2O data improved quantitative weather forecasting.**





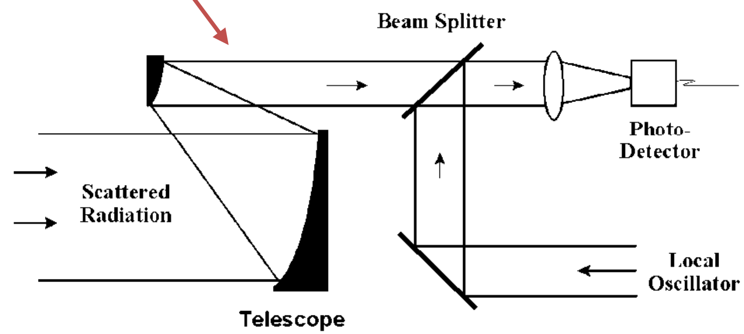
Wakimoto et al., 2006; Wulfmeyer et al., 2006

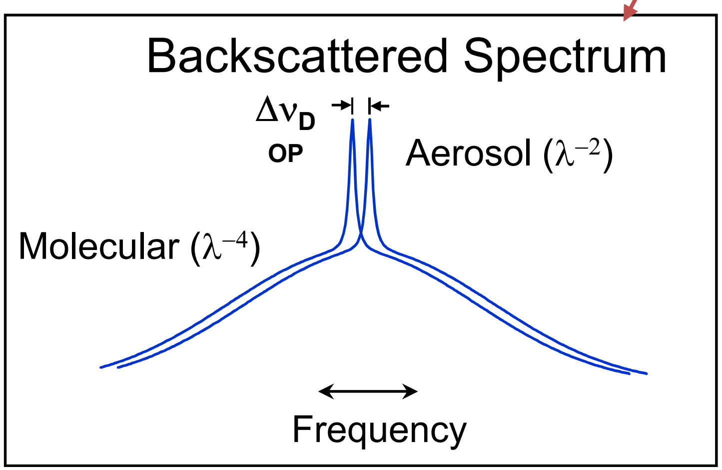
Measurement Concept (GWOS, Gentry, Kavaya, …)

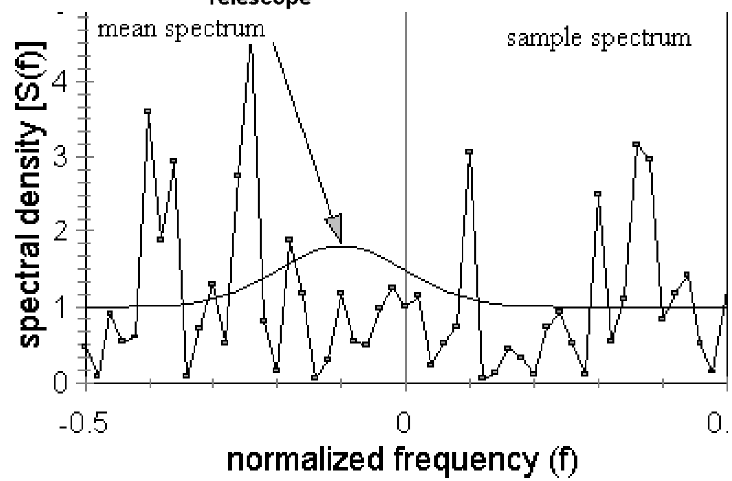


DOPPLER RECEIVER - Multiple flavors - Choice drives science/technology trades

- Coherent or heterodyne aerosol Doppler receiver
- Direct detection e.g., "Double Edge" molecular Doppler







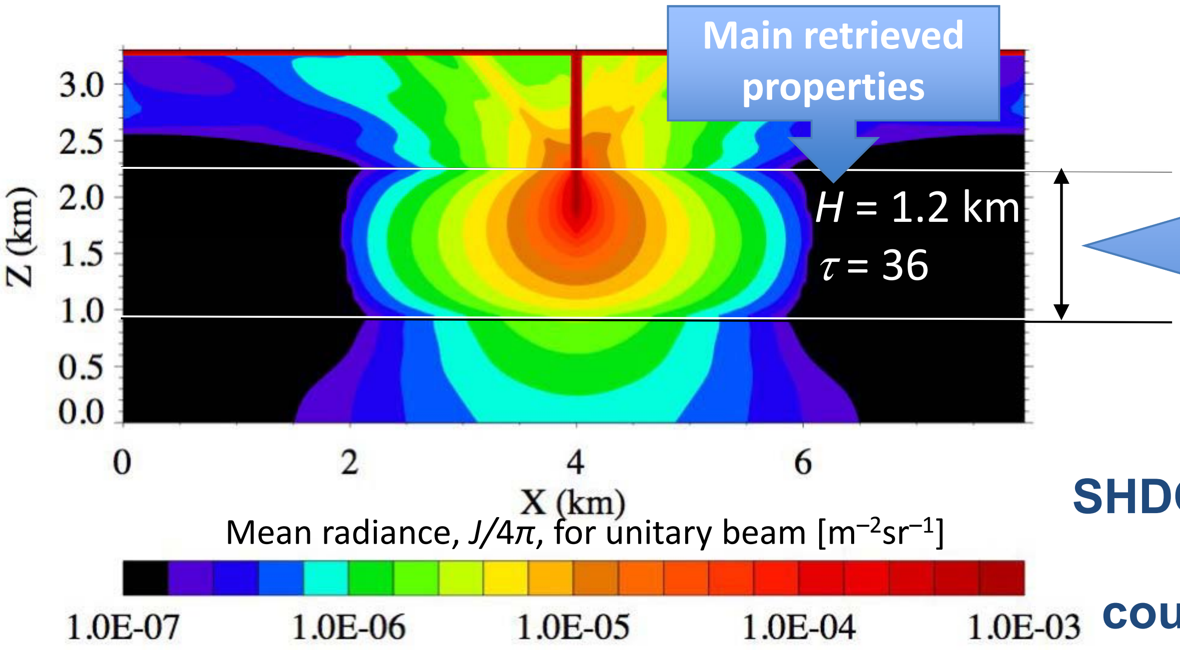
Coherent wind lidar measures wind speed and many turbulence parameters (e.g., energy dissipation rate, structure parameter of refractive index fluctuations C_n^2,…)

Optical Time-Domain Remote Sensing of BL Clouds from Space:
Back to the Future with LITE and kin, with a little help from the O_2 A-band

Anthony Davis for KISS workshop

Multiple-Scattering / Wide-FOV Cloud Lidar

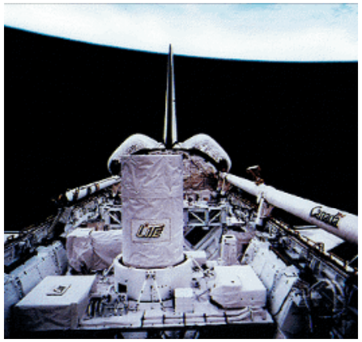
- **Lidar technology …** without the lidar equation, which is just about a single scattering!
- Need model for **time-dependent multiple scattering signal**: diffusion theory, at least for info content analysis
- Need to quantify horizontal light transport, to understand spatial **resolution of retrieved cloud properties**



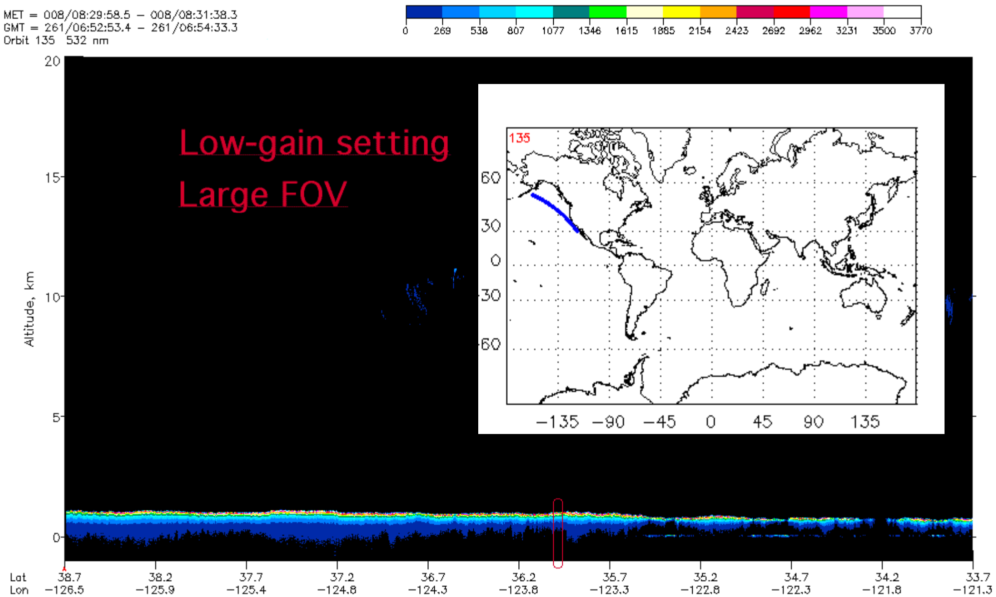
In the absence of absorption by water at 532 nm, pulsed laser light permeates the whole cloud!

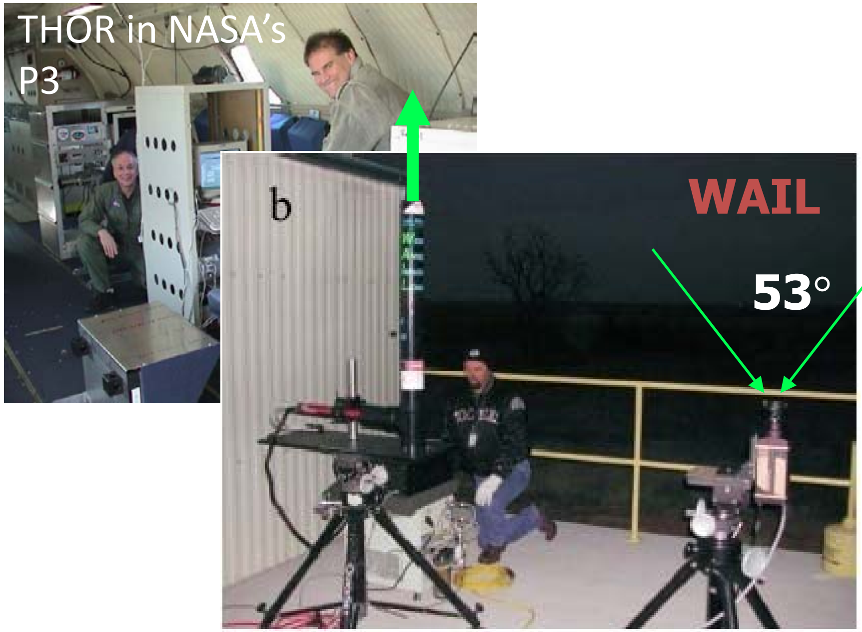
SHDOM simulation of narrow beam (search light) 3D RT problem, courtesy of Frank Evans (U of Co)

Multiple-Scattering / Wide-FOV Cloud Lidar



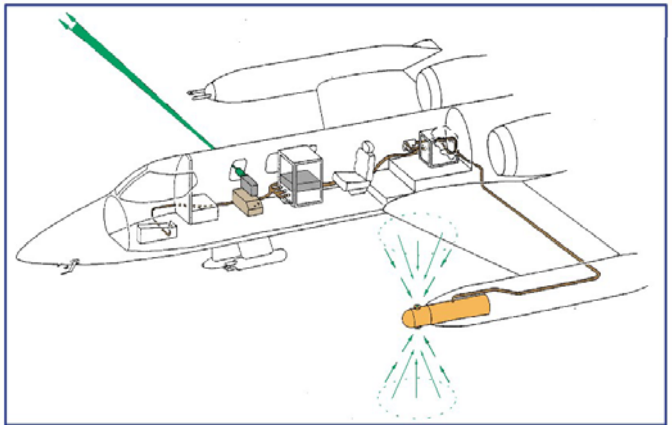
- **Back to the Future:**
  - 1st demo by LITE (night orbit #135), in Sept. 1994
  - Numerical simulations, at about same timeframe
- **Late 90s / Early 00s:**
  - Analytical (diffusion-theoretical) signal modeling
  - Airborne and ground-based demos at ARM SGP site





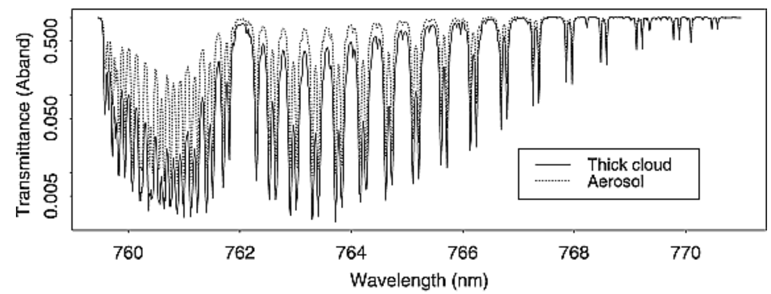
Multiple-Scattering / Wide-FOV Cloud Lidar

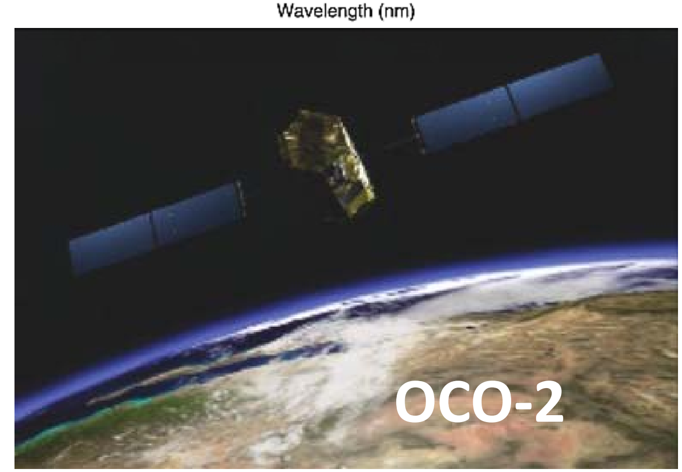
- **Theory:**
  - Davis, A. B., R. F. Cahalan, J. D. Spinhirne, M. J. McGill, and S. P. Love, 1999: Off-beam lidar: An emerging technique in cloud remote sensing based on radiative Green-function theory in the diffusion domain, *Phys. Chem. Earth (B)*, **24**, 177-185 (Erratum 757-765).
  - Polonsky, I. N., and A. B. Davis, 2004: Lateral photon transport in dense scattering and weakly-absorbing media of finite thickness: Asymptotic analysis of the space-time Green function, *J. Opt. Soc. Am. A*, **21**, 1018-1025.
- **Data analyses:**
  - Polonsky, I. N., S. P. Love, and A. B. Davis, 2005: The Wide-Angle Imaging Lidar (WAIL) Deployment at the ARM Southern Great Plains site: Intercomparison of cloud property retrievals, *J. Atmos. and Oceanic Techn*., **22**, 628-648.
  - Cahalan, R. F., M. J. McGill, J. Kolasinski, T. Várnai, and K. Yetzer, 2005: THOR, cloud THickness from Offbeam lidar Returns, *J. Atmos. and Oceanic Techn*., **22**, 605-627.
  - Davis, A. B., D. M. Winker, and I. N. Polonsky, A case for more multiple-scattering lidar signal from space: Marine stratocumulus properties retrieved from LITE returns, *Journal of Geophysical Research – Atmospheres*, **in preparation**.
- **"In-situ" cloud lidar (same signal physics):**
  - Evans, K. F., R. P. Lawson, P. Zmarzly, and D. O'Connor, 2003: In situ cloud sensing with multiple scattering cloud lidar: Simulations and demonstration, *J. Atmos. Ocean. Tech.*, **20**, 1505-1522.
  - Evans, K. F., D. O'Connor, P. Zmarzly, and R. P. Lawson, 2006: In situ cloud sensing with multiple scattering lidar: Design and validation of an airborne sensor. *J. Atmos. Ocean Tech.*, **23**, 1068-1081.



Multiple-Scattering / Wide-FOV Cloud Lidar

- **Daytime problem:**
  - Overwhelming solar background!
- **Solution #1: *Stay active …***
  - Sophisticated ultra-narrow filtering technology (Faraday/magneto-optic, Lyot, etc.)
- **Solution #2: *Go passive …***
  - Pass the relay to O_2 A-band spectroscopy of BL clouds
  - *Same signal physics:* spatially-unresolved signal in the time-domain (via DOAS of a major gaseous constituent of the air)





Summary

Lidars (e.g., CALIPSO/HSRL, DIAL, Doppler wind Lidar) can provide,

•boundary layer height, lapse rate

•high resolution information about boundary cloud top (sometime cloud base) height, cloud thermodynamic phase and extinction coefficient, and cloud top droplet number concentration (combined with imager measurements)

•high resolution air-sea turbulence transfer velocity (for heat and gas exchange) with the measurements of mean square slopes of ocean surface capillary and gravity waves

•other information such as wind profile, turbulence and water vapor measurements