

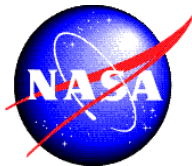
What have we learned from CALIPSO?

Dave Winker

NASA Langley Research Center

3rd International Lidar Workshop
Milos Greece, June 2023

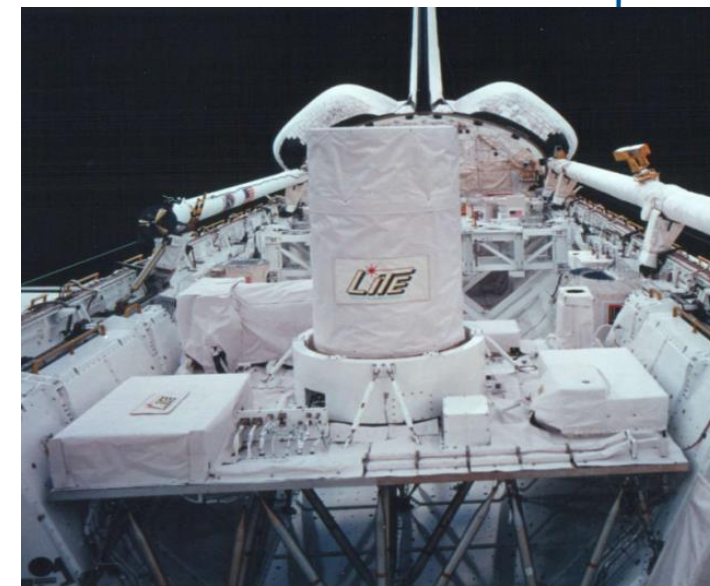


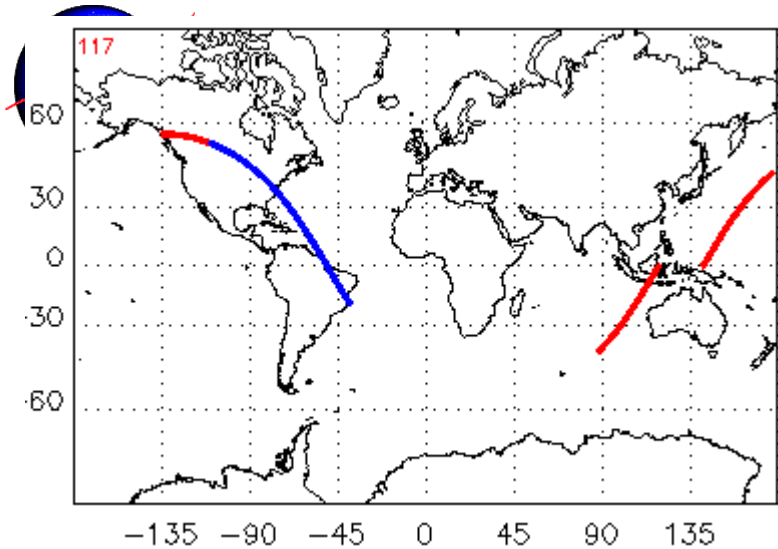


CALIPSO: Key Dates

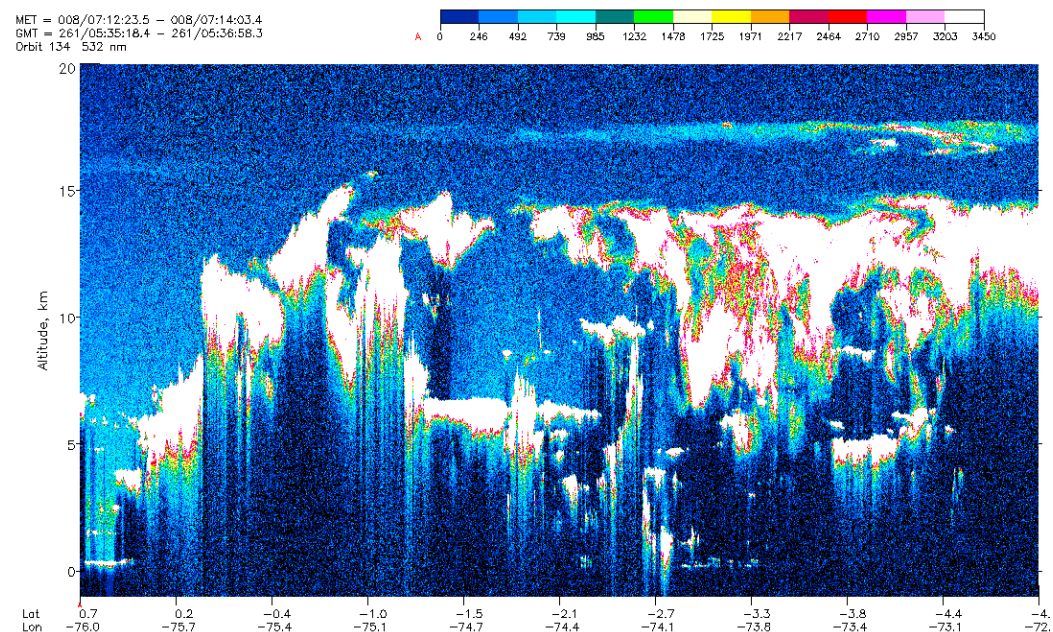
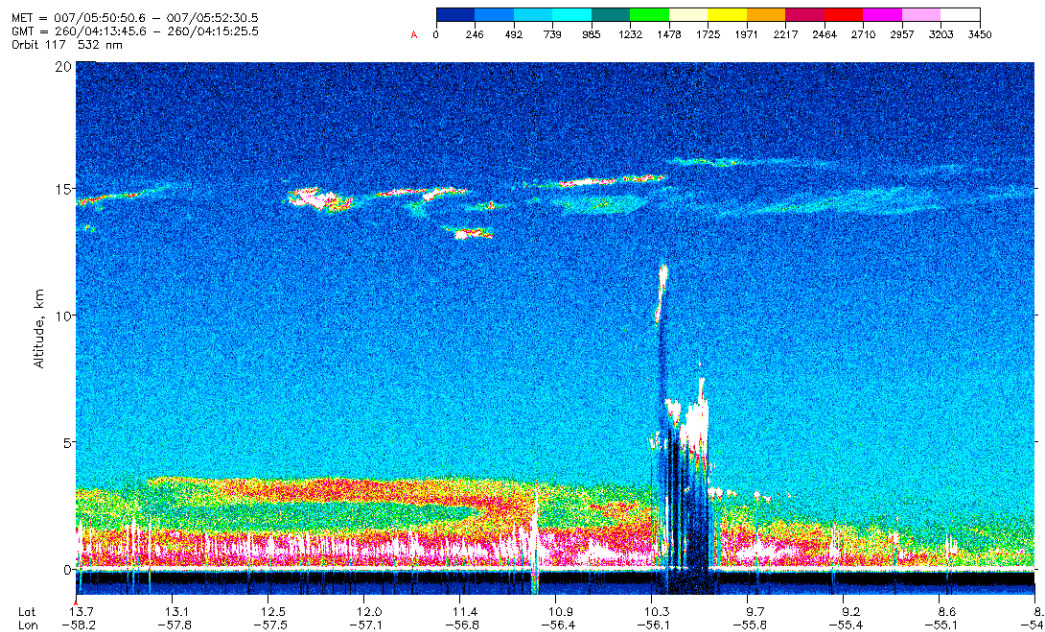
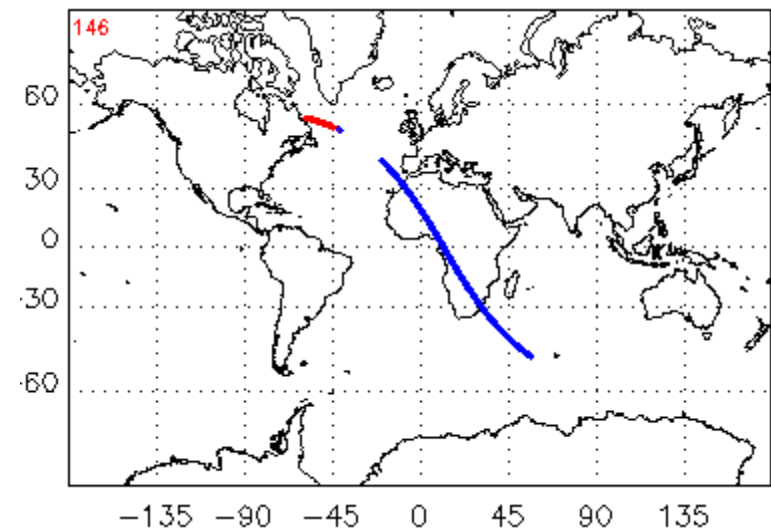
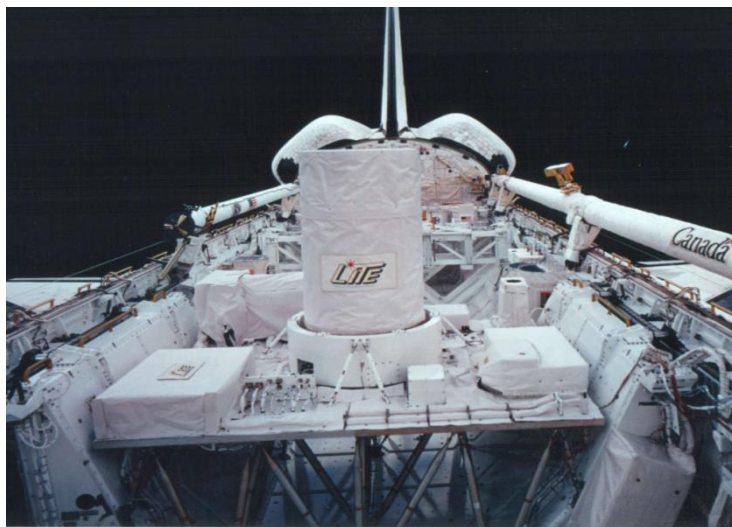
... CALIPSO started with LITE (September 1994 on STS-64)
proof of concept for CALIOP
critical information on lidar performance requirements
development of follow-on started immediately after

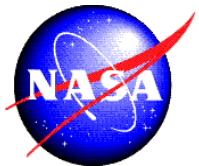
- Proposal selected by NASA ESSP (& CNES): 1998
- Launch: 28 April 2006
- First light: 7 June 2006
- Primary laser: June 2006 – February 2009
- Backup laser: March 2009 – June 2023
 - Formal science mission ends tomorrow
- Engineering experiments: July 2023
 - (Clayton's test of the primary laser)
- End of payload operations: August 2023





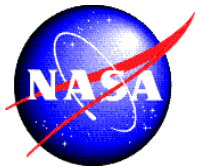
Our first look: LITE (1994)



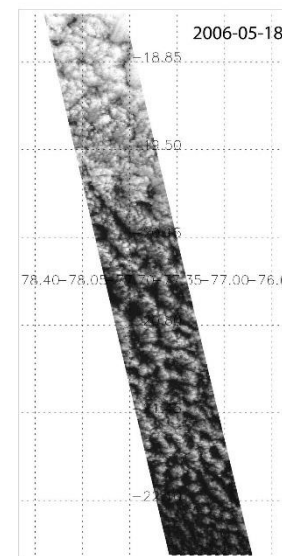
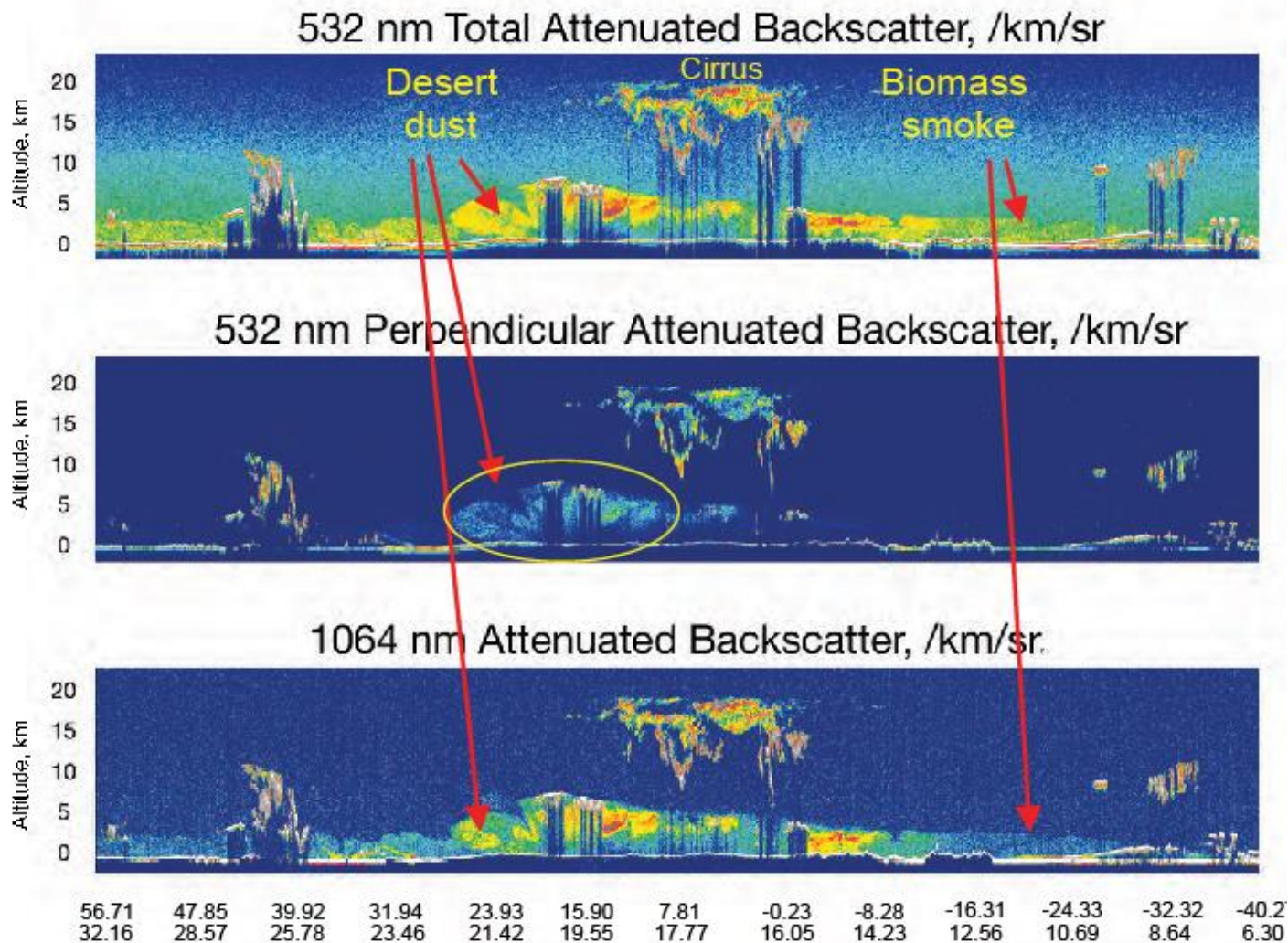


Major Early CALIPSO Decisions

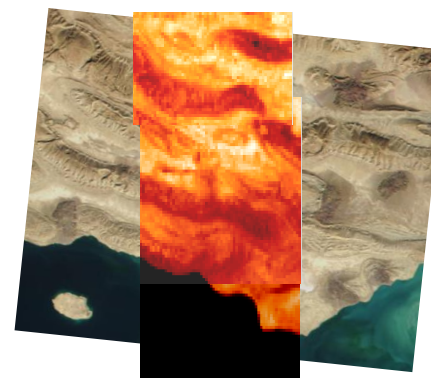
- Much wider receiver dynamic range ($1:10^6$) than LITE
- Dropped 355 nm channel
 - A risk to laser life, at the time
- Add cross-polarized receiver channel for depolarization
 - Depol not widely used in the 90's
 - Intended for discrimination of cloud ice-liquid phase
 - Proved useful for:
 - Identification of desert dust
 - Retrieval of dust extinction in regions with mixed aerosol types
 - Correction of multiple scattering effects in water clouds → constrained AOD retrievals
- Fly with EOS Aqua at 705 km
 - Higher than desired but enabled many synergies
- A need to add passive sensors (in case of Aqua launch failure)
 - LITE flew by itself, showed the need for observation of a small swath
 - WFC: a modified Ball star sensor (smaller, cheaper, ...)
 - IIR: a French contribution based on a microbolometer array
- Development of autonomous processing software necessary for an extended mission
 - Development effort began ~2000
 - In the end, took 10 years to develop a fully functional processing system with good retrieval performance



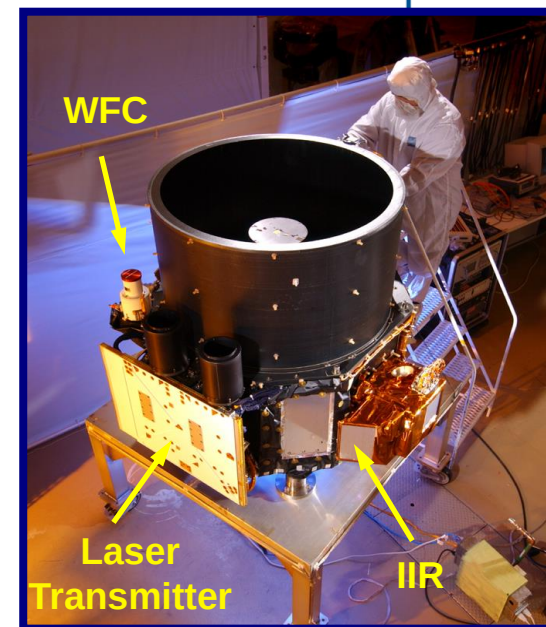
Data Examples

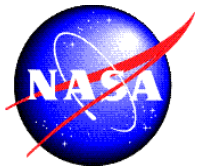


WFC First Light Image

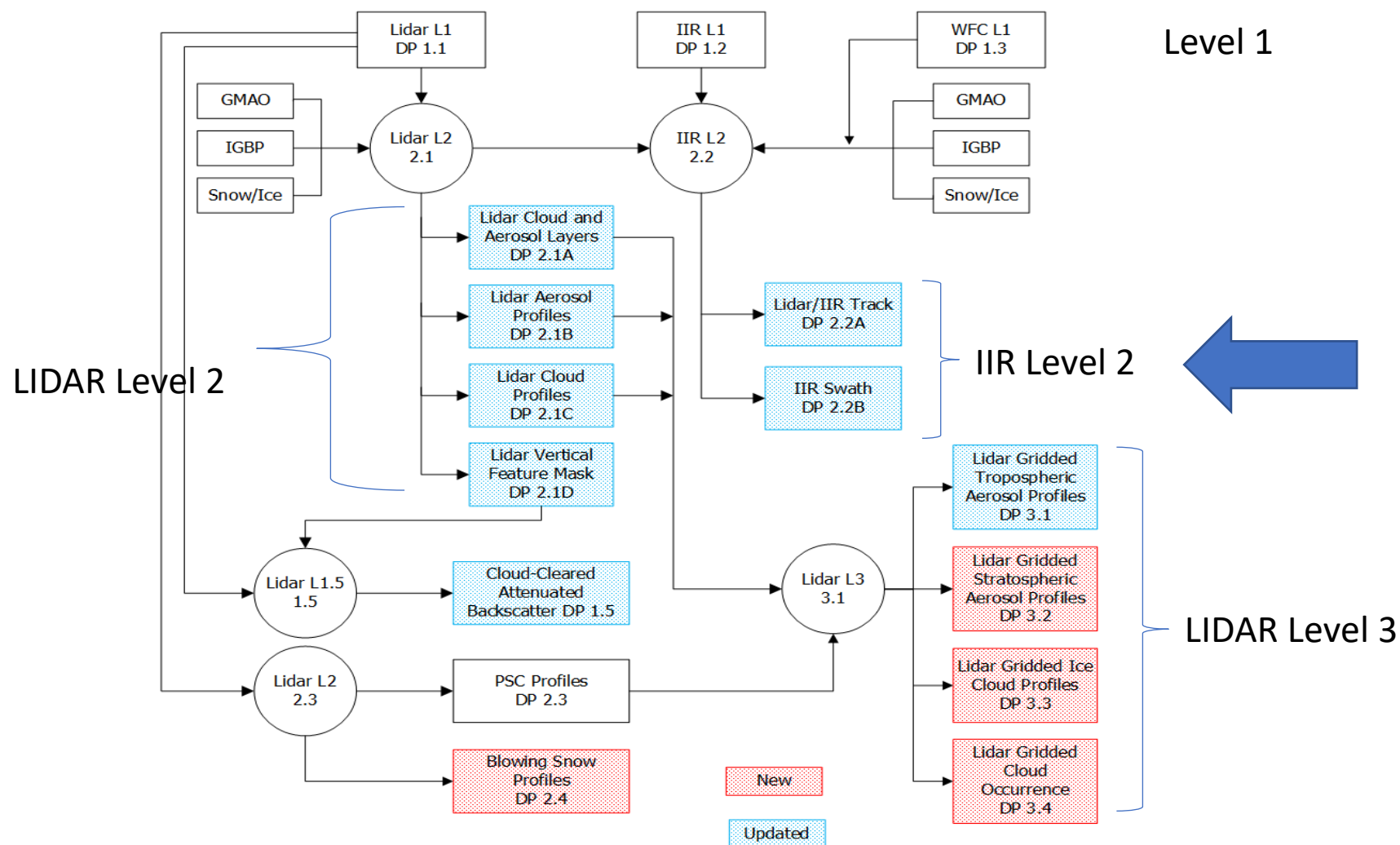


IIR First Light Image





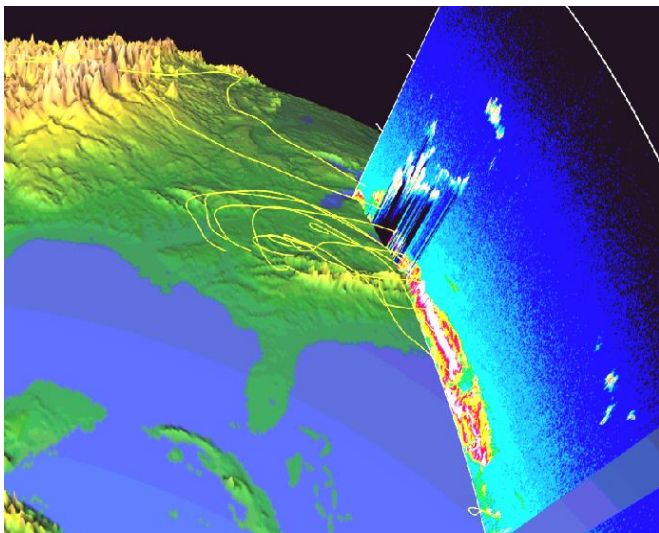
Have produced a large family of data products



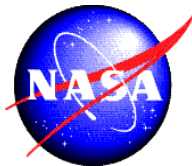
CALIPSO Science Objectives (c. 1998)

CALIPSO will fly in the A-train, providing observations to improve:

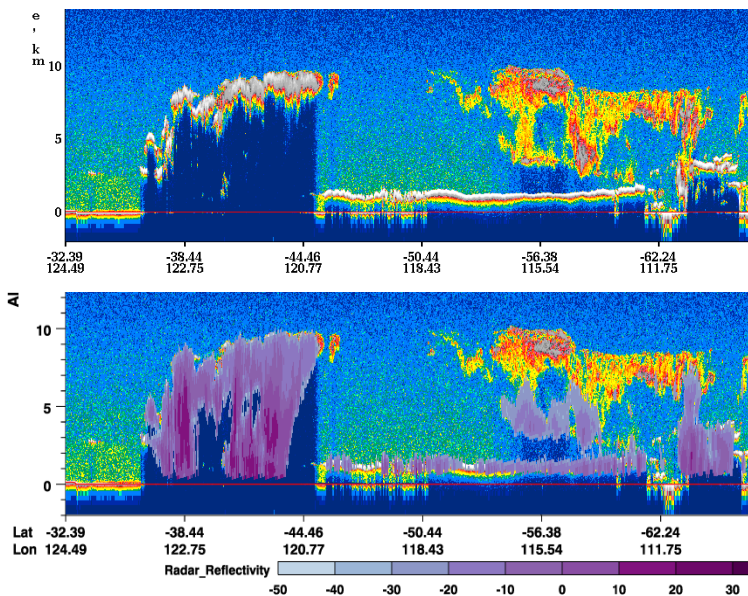
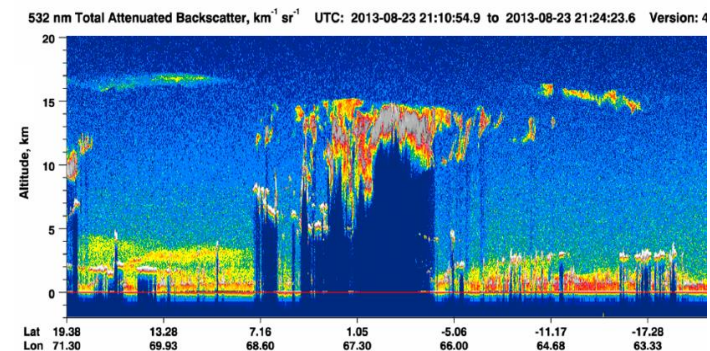
- Our understanding of the role of aerosols and clouds in the processes that govern climate responses and feedbacks
 - Direct and indirect aerosol effects
 - Cloud forcing and feedbacks



- The representation of aerosols and clouds in models of climate, air quality, weather, etc.
- Validation of other A-train sensors



Science Accomplishments

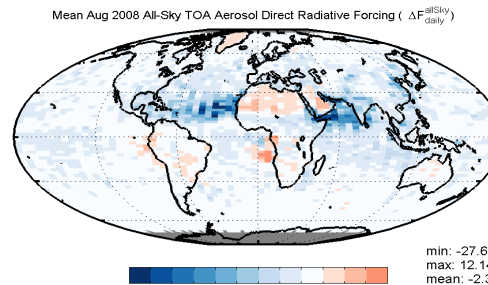
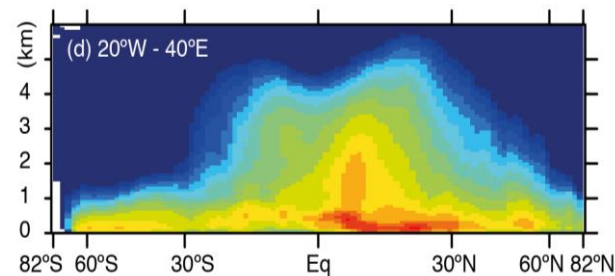


Vertically-resolved
aerosol climatology

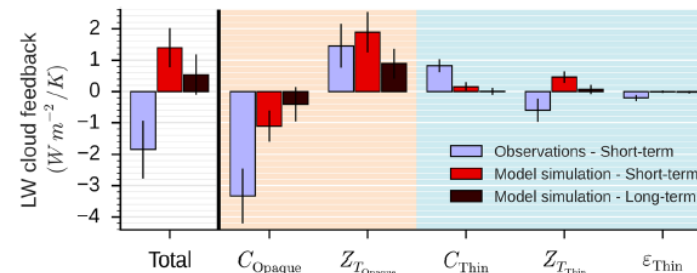
All-sky/clear-sky aerosol
radiative effects

LW Cloud Radiative
Feedbacks

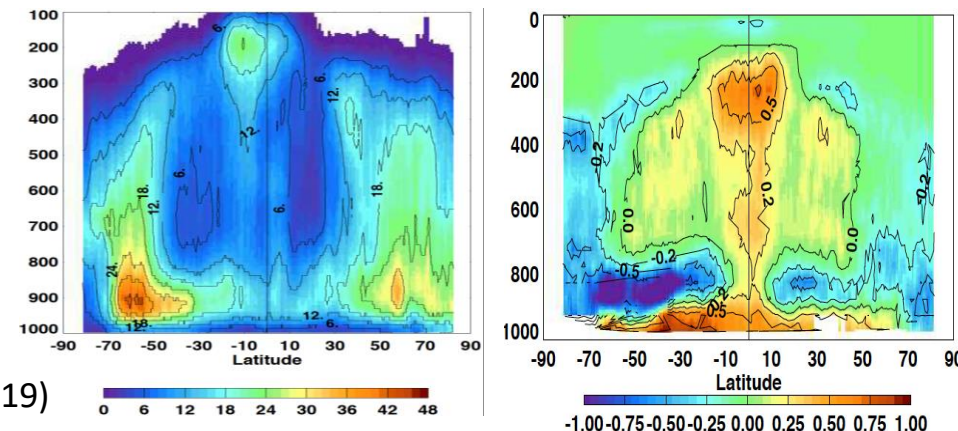
Cloud Climatology &
Radiative Heating Profiles



(IPCC AR5)

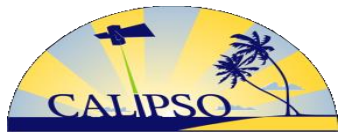


(Vaillant de Guelis et al., 2018)

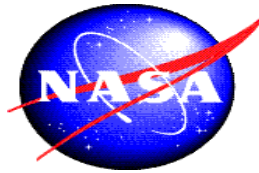


(Kato et al, 2019)

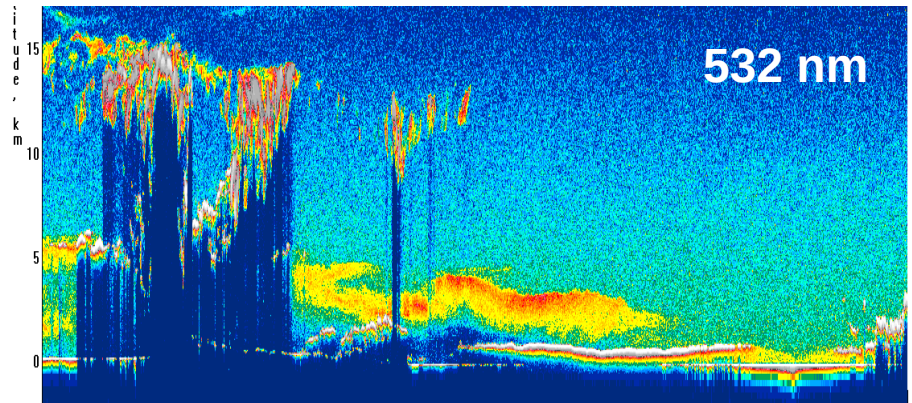




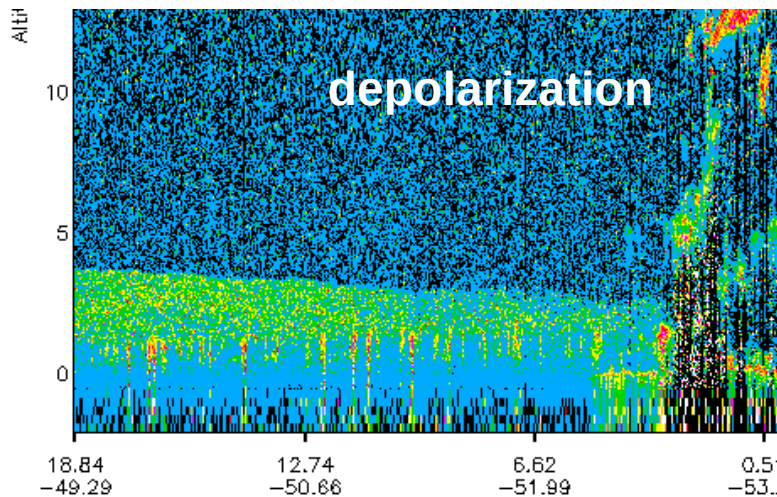
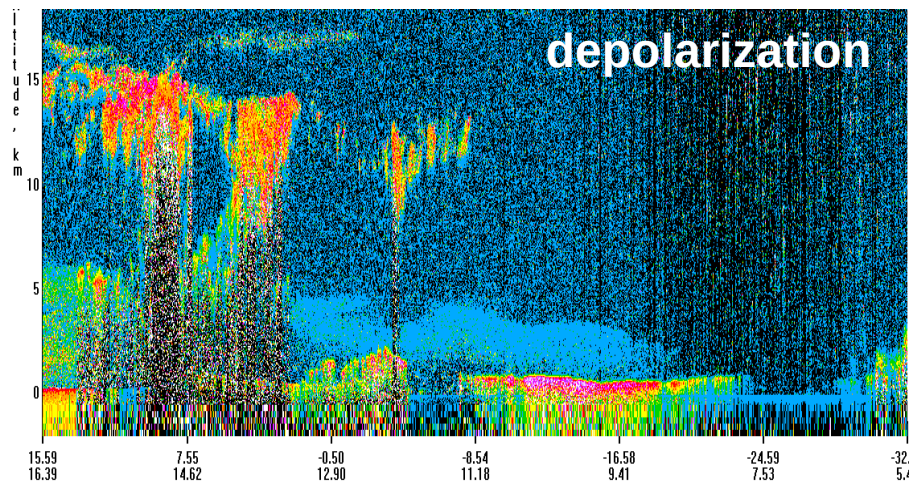
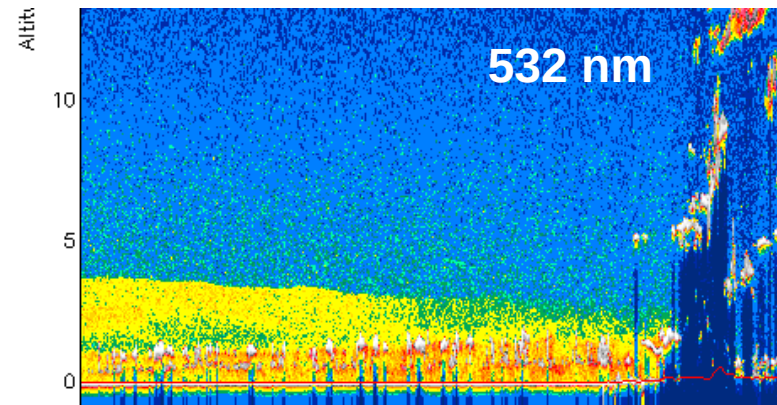
Gained Important Capabilities from Lidar Depolarization



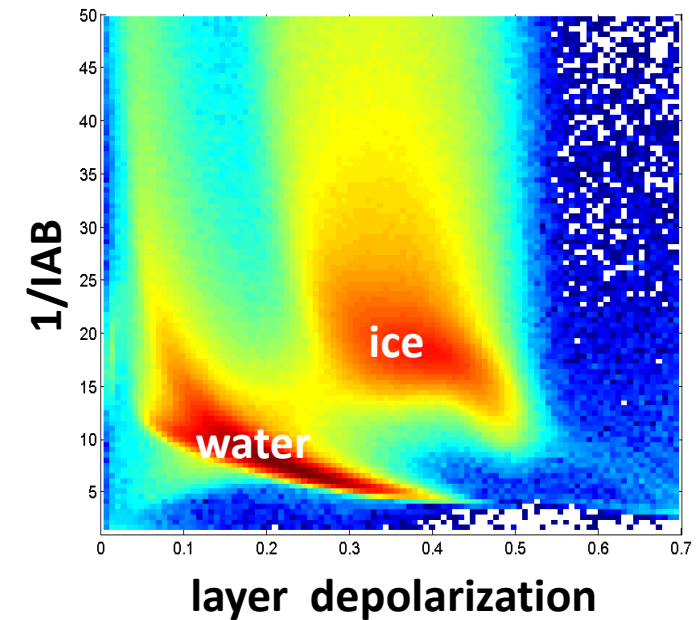
Smoke



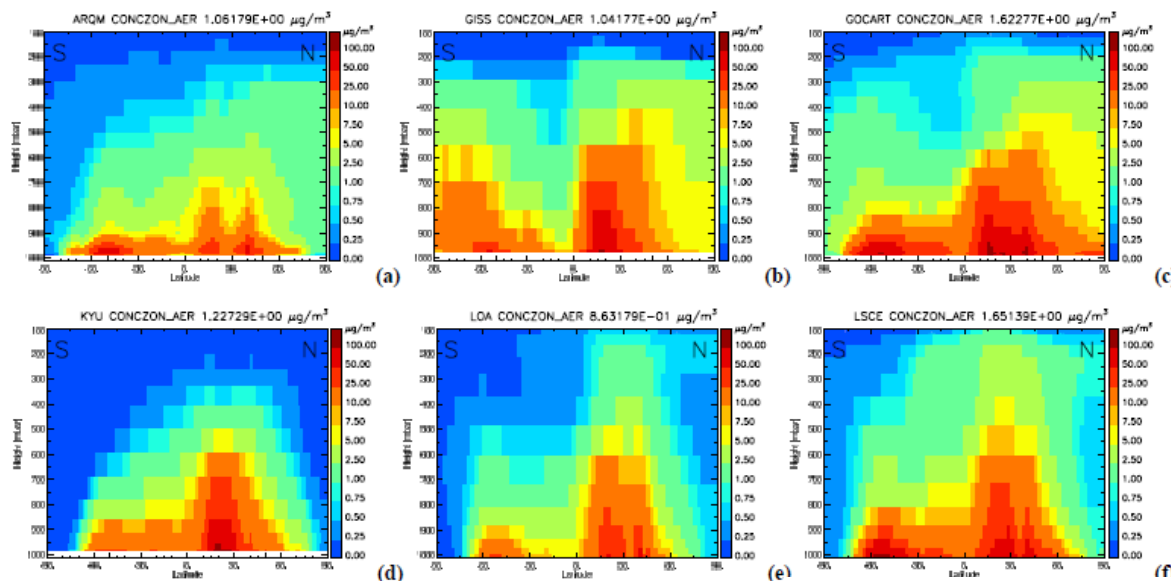
Sahara Dust



Vertically resolved cloud ice-water phase



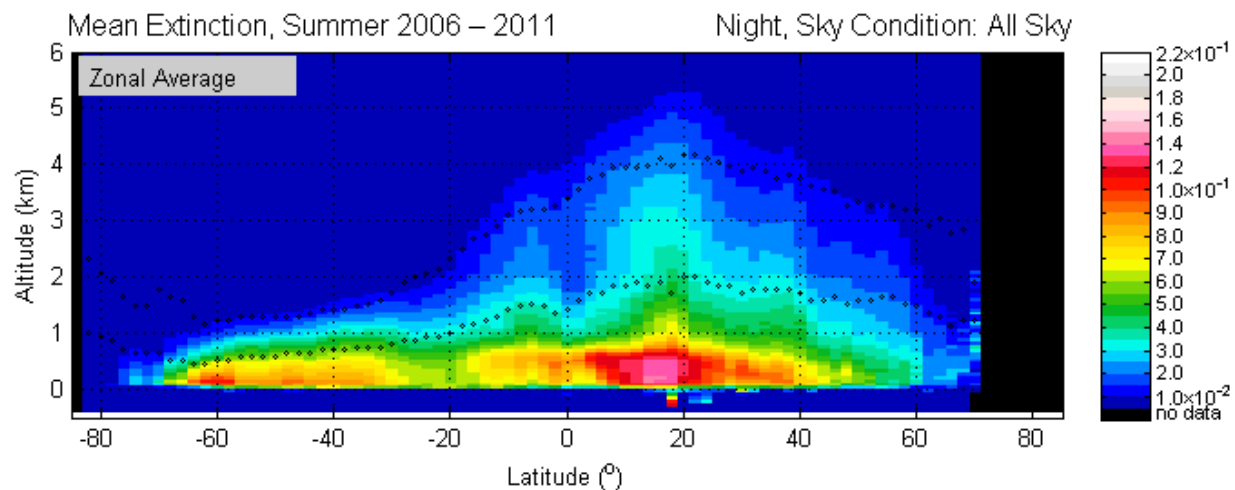
In 2006, the vertical distribution of aerosol varied widely between global aerosol models. Until CALIOP there were no global observations of vertical profiles

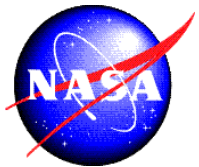


Zonal mean aerosol mass concentration from 6 global aerosol models

(Textor et al., 2006)

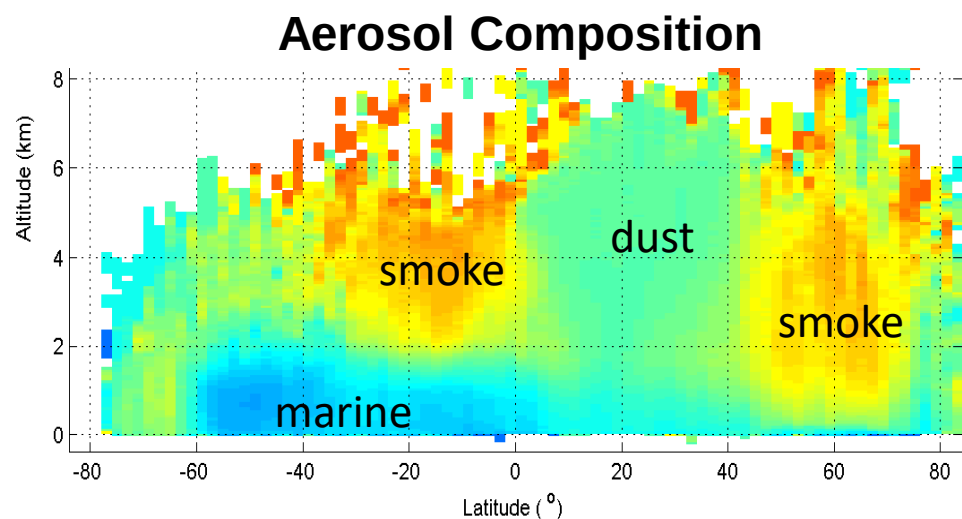
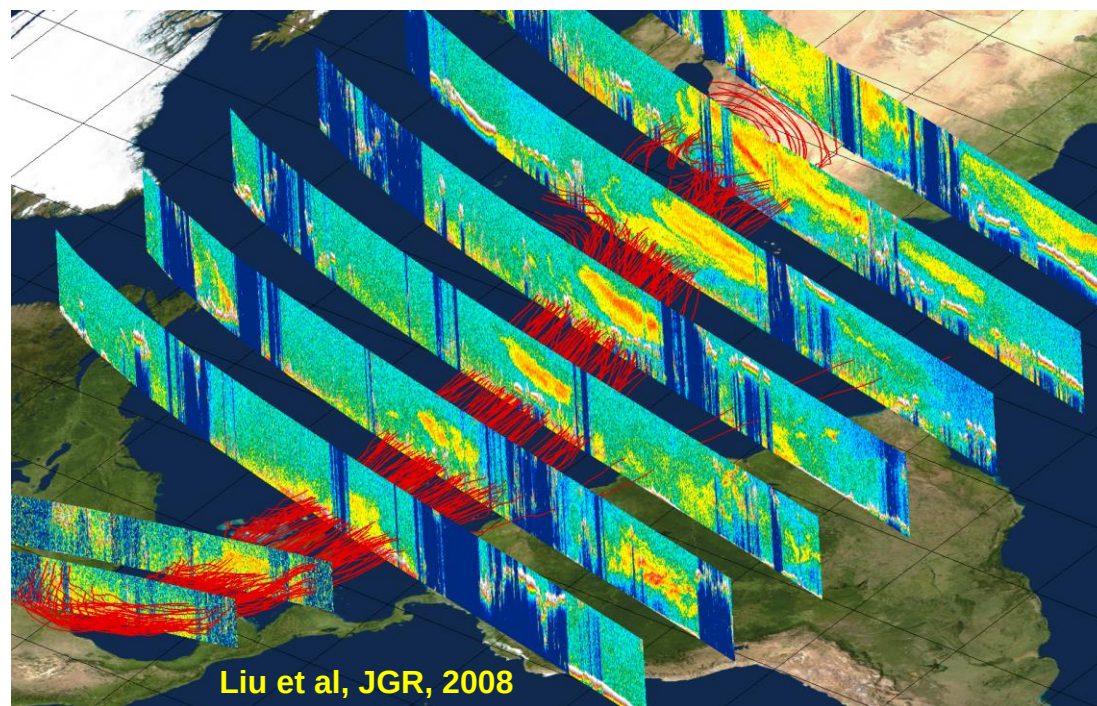
For the first time, CALIOP provided global observations of the vertical distribution of aerosols:





Aerosol Transport

Sahara dust outbreak, Aug 2007

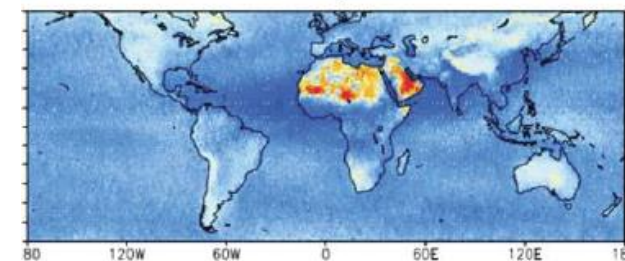


Zonal mean distribution of aerosol types, June through August

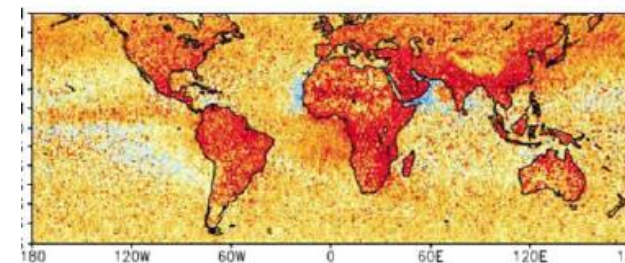
Aerosol Radiative Effects



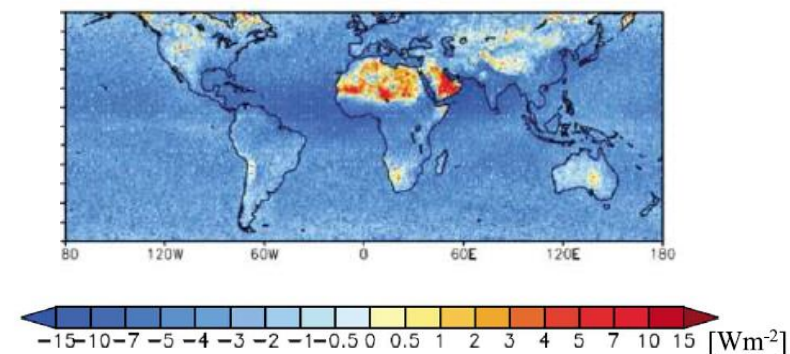
Clear-sky case



Above-cloud case



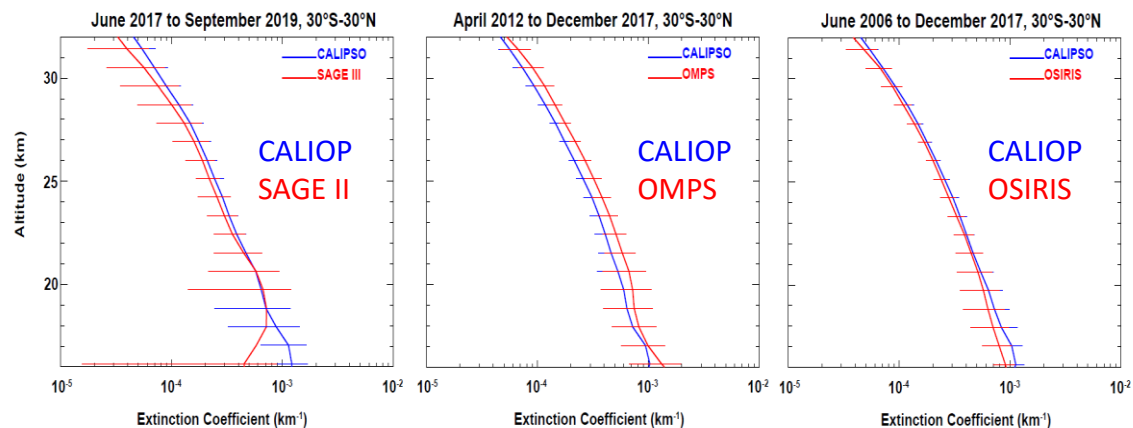
Below-cloud case



(Oikawa et al. 2018)

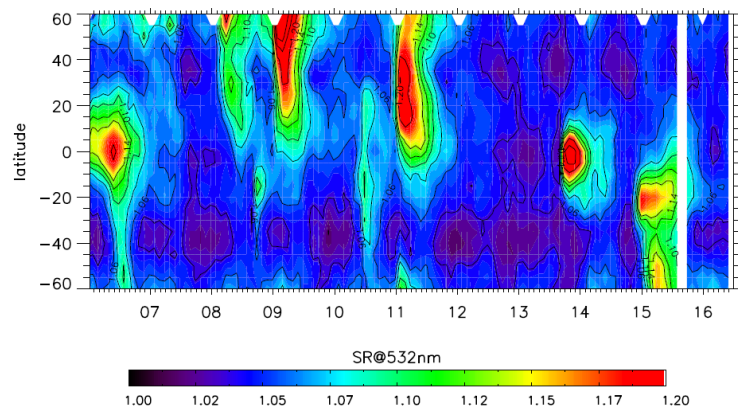
Stratospheric Aerosol Product

- CALIOP nighttime 532 nm stratospheric profiles are averaged on a 5° by 20° lat-long grid
- Aerosol extinction profiles are retrieved and reported as monthly means on a 3D global grid with 900 m vertical spacing

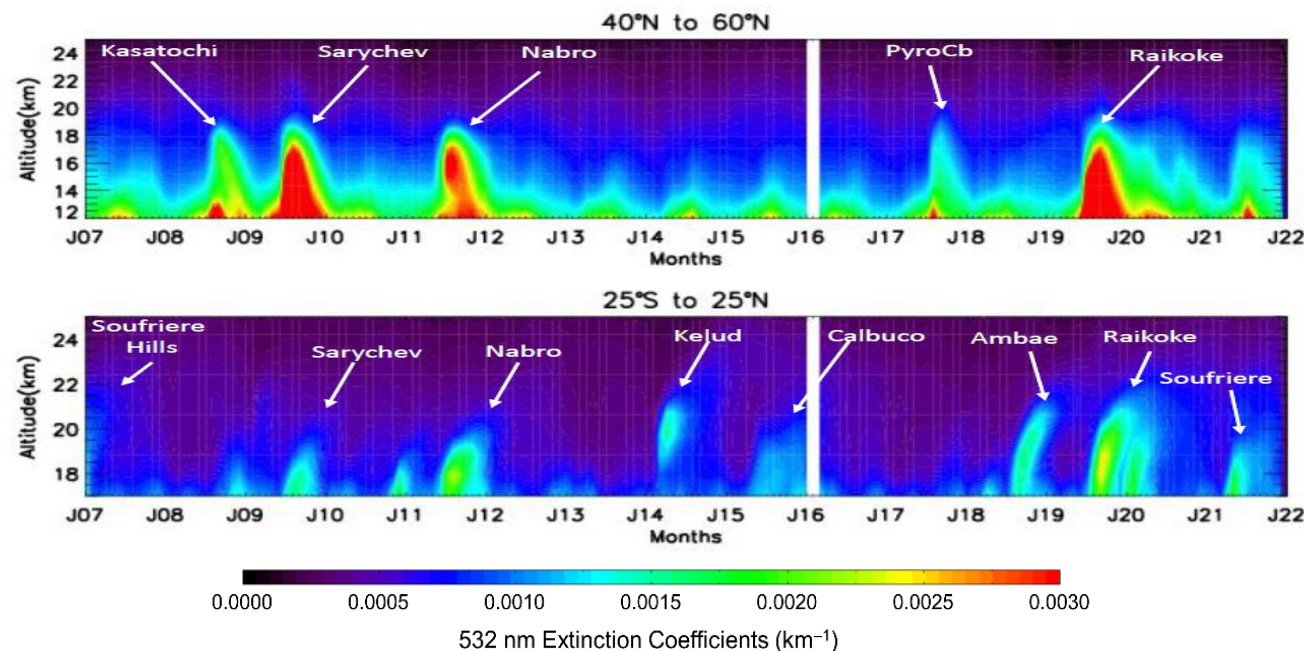


Zonally averaged CALIOP extinction coefficient profiles for data acquired between 30°N and 30°S compared to data from SAGE III-ISS, OMPS, and OSIRIS (Kar et al. 2019)

Latitudinal distribution



Evolution of the average SR profile, 10 km to 35 km



Time-height cross sections of CALIOP stratospheric aerosol extinction, Jan 2007 to Dec 2017 (Kar et al., 2019)

CALIPSO Weekly Performance (Laser # 1)



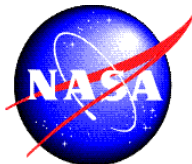
June 15, 2023

Laser #1 Shots On-Orbit: 8.46 Billion

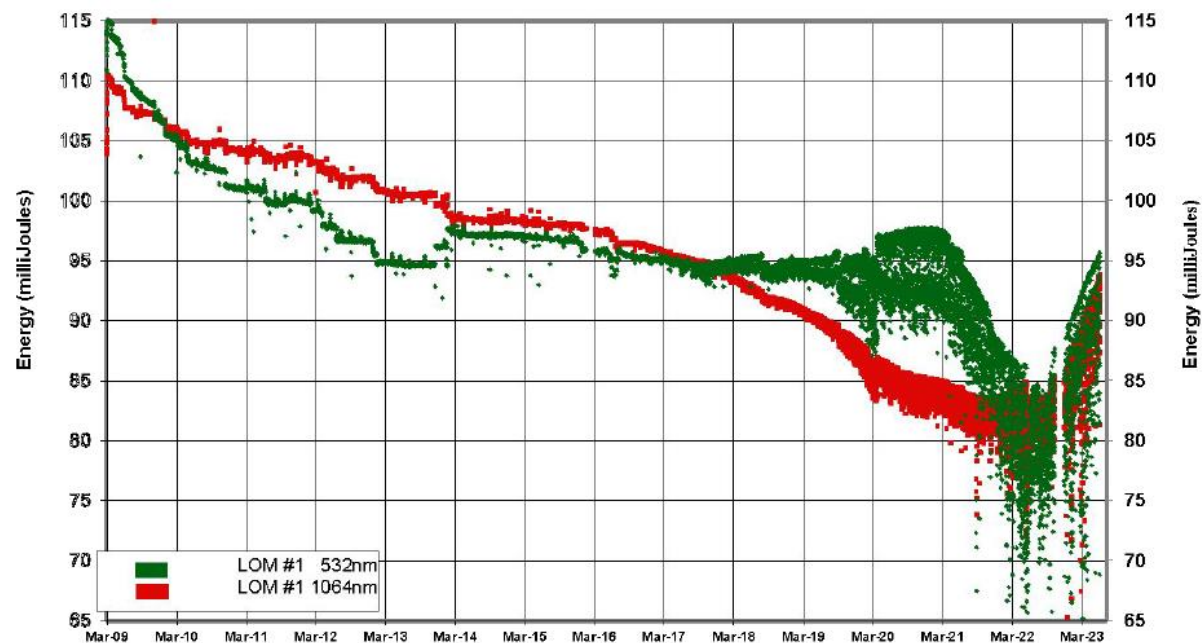
Total Laser Shots On-Orbit: 10.07 Billion

Total Light Emitted: 201.44s

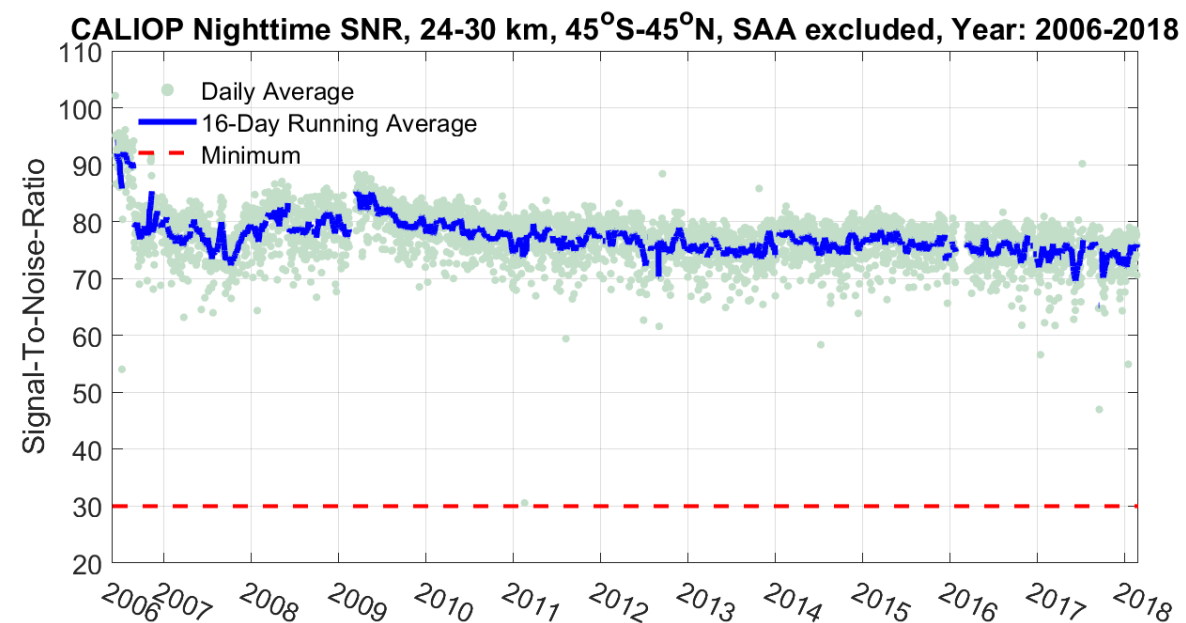


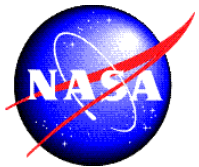


Laser #1: 532 nm and 1064 nm pulse energy

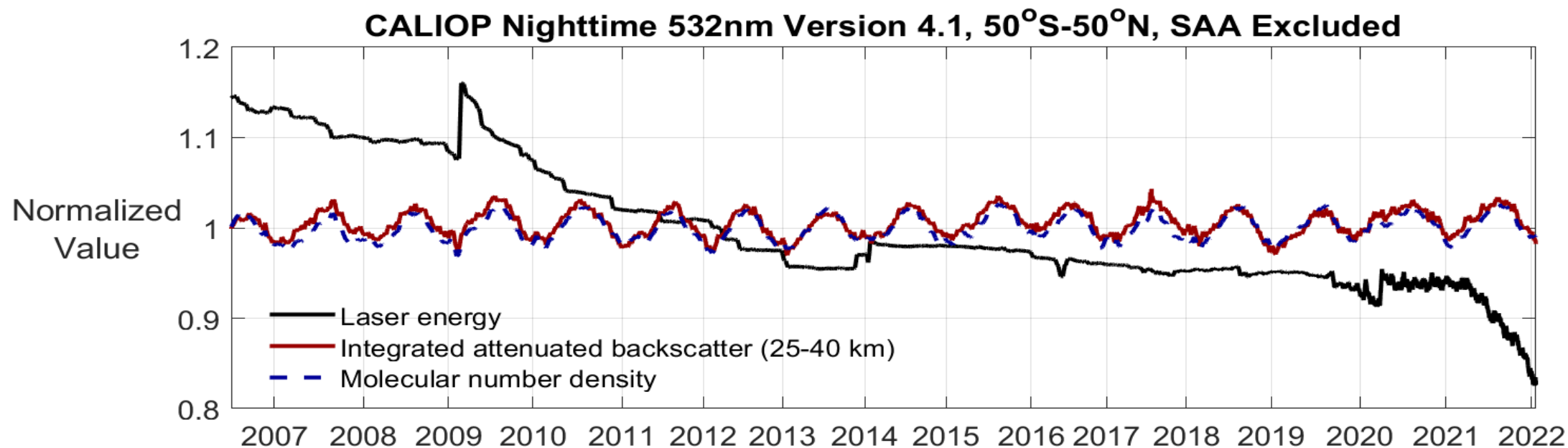


532 nm SNR time series: 2006-2018

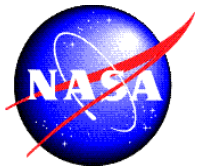




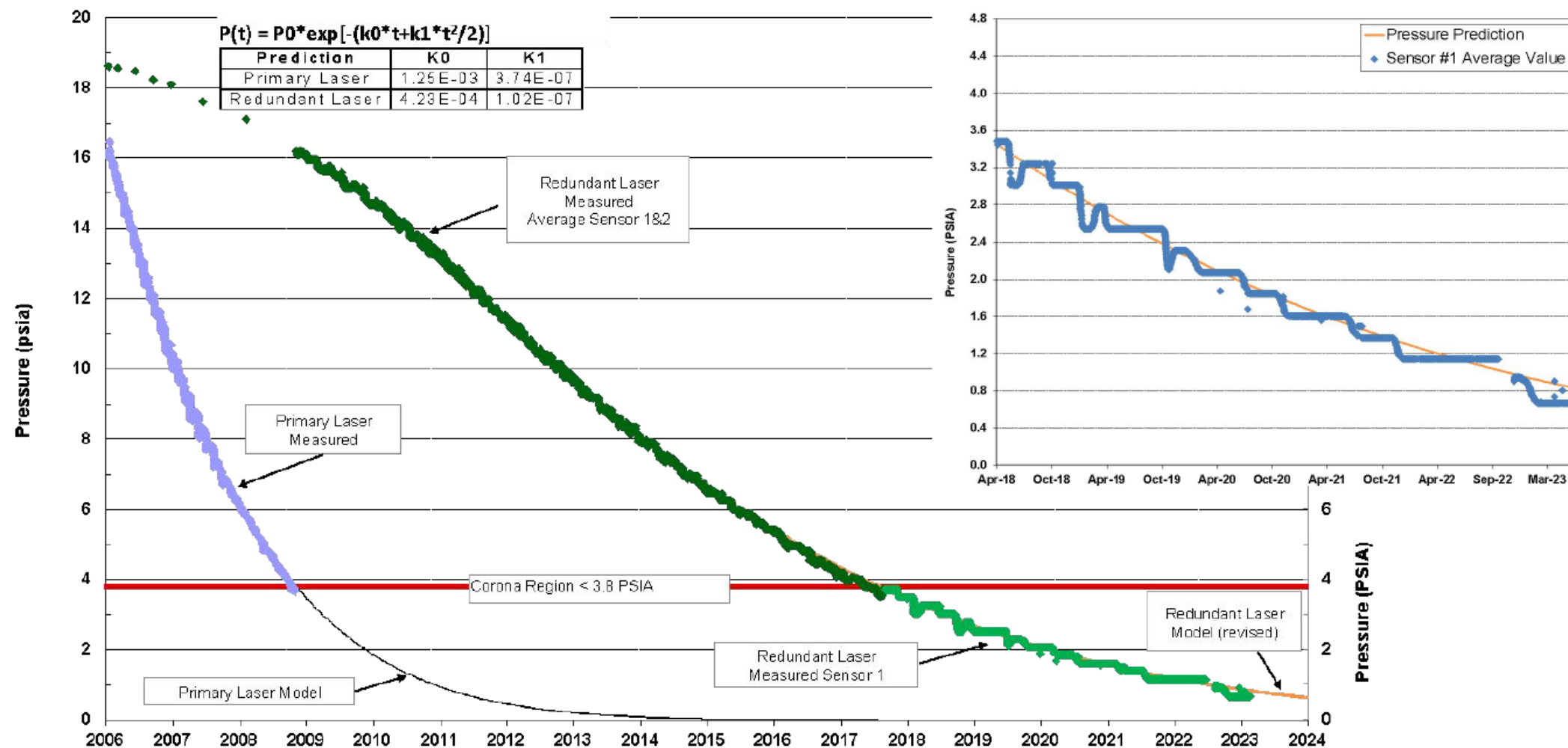
Stable calibration over 15-years

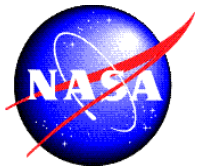


Normalized trends of mid-stratosphere 532 nm IAB and molecular number density (averaged over the same altitude range) and laser total pulse energy

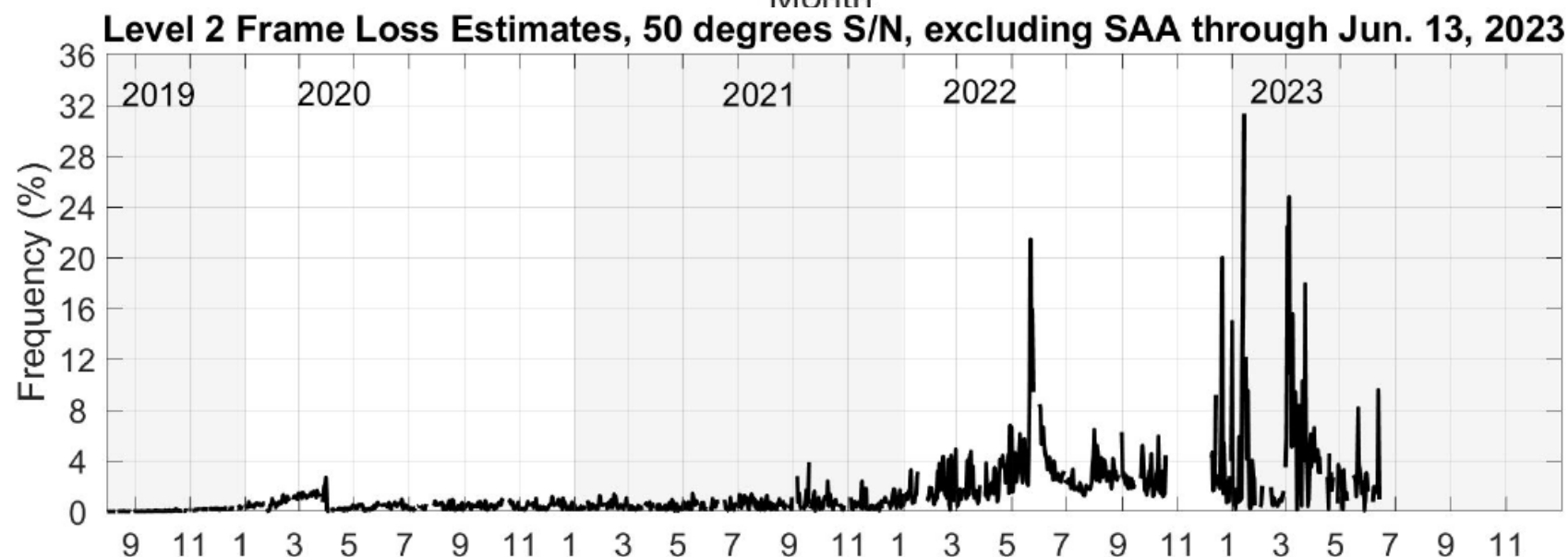
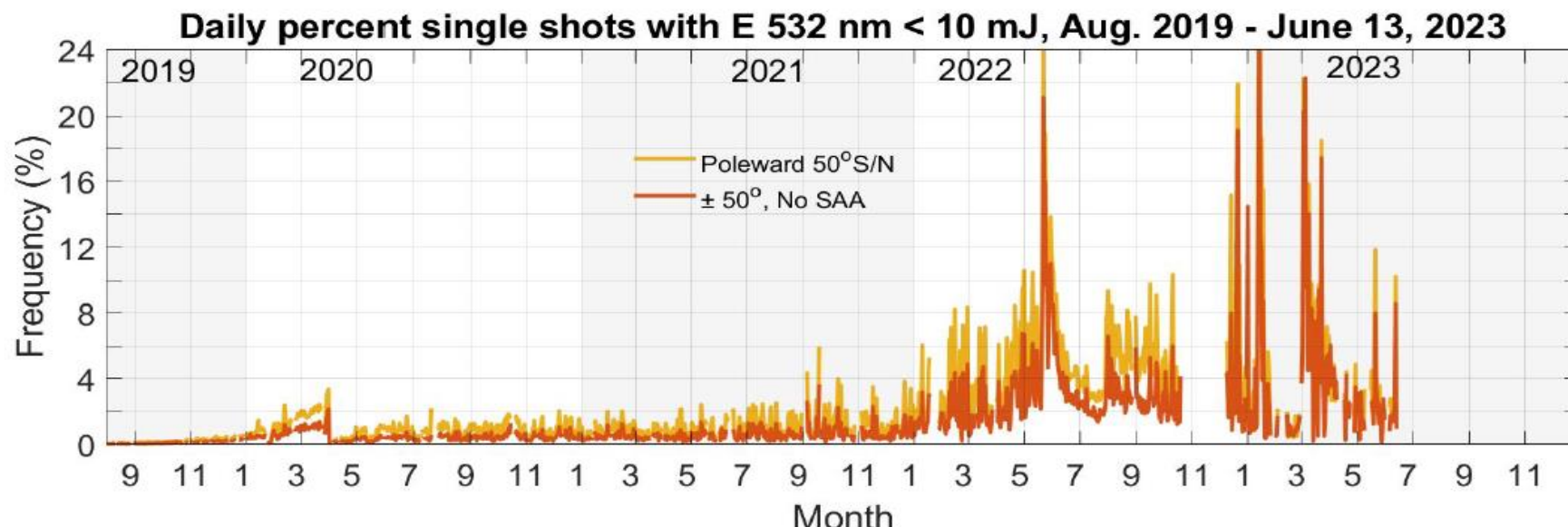


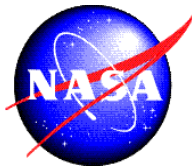
Laser Canister Pressure History





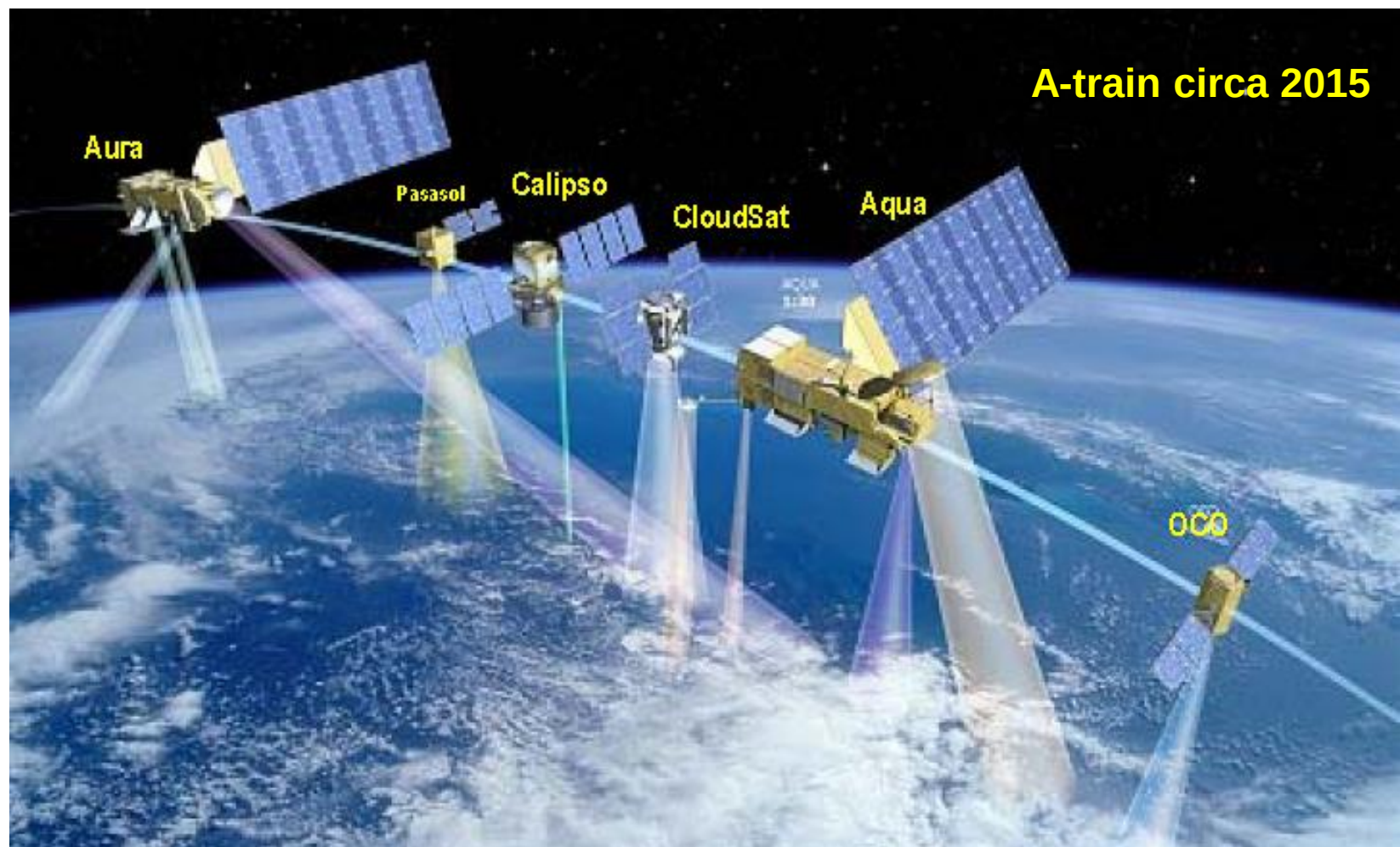
Frequency of Low Energy Laser Shots





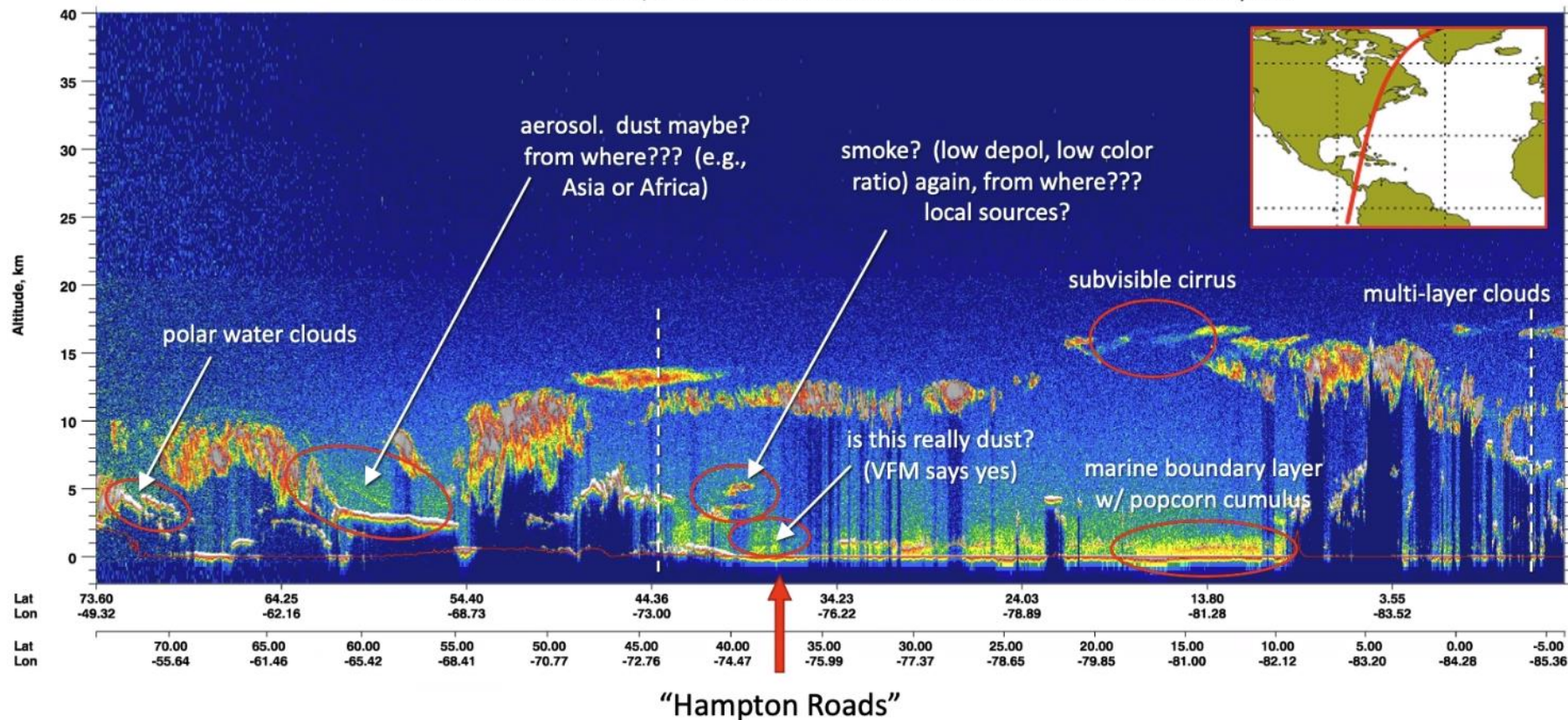
Synergies!

CALIPSO & CloudSat teamed in mid-90's and originally planned to fly with Aqua (MODIS & CERES)
... and then the A-train happened

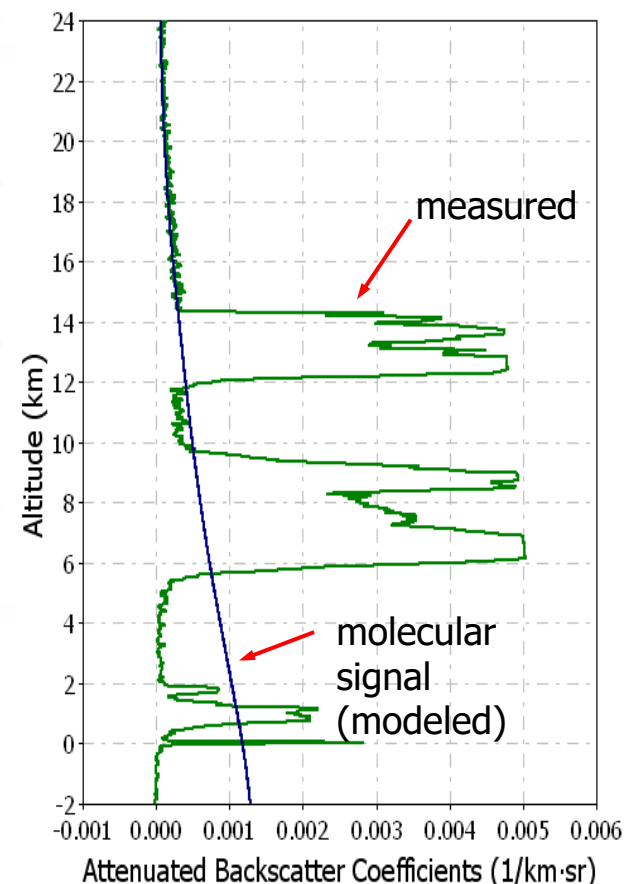


Synergies: lidar shows “what you’re looking at”

532 nm Total Attenuated Backscatter, $\text{km}^{-1} \text{sr}^{-1}$ UTC: 2023-04-22 08:37:44.7 to 2023-04-22 09:00:03.2 Version: 3.41 Expedited



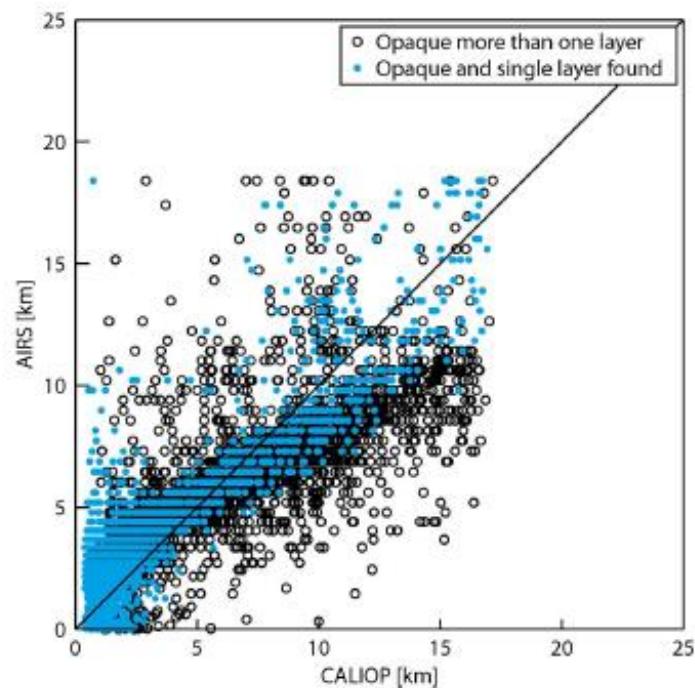
... and provides very precise cloud boundaries:



CALIPSO widely used to evaluate and improve passive cloud retrievals

Evaluation of MODIS cloud mask/cloud heights:

- MODIS low-cloud heights biased by PBL temperature inversions
- Cirrus heights biased in multi-layer situations



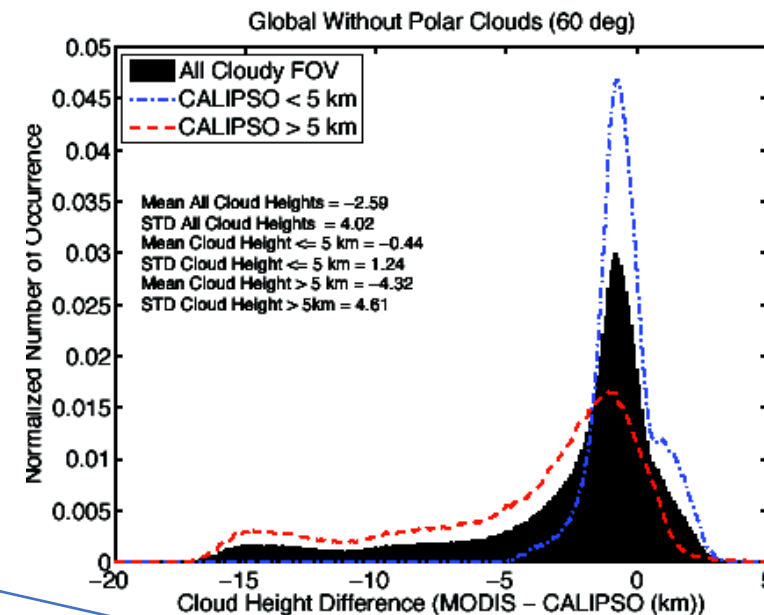
(Di Michele et al., 2013)

CALIOP cloud heights vs. AIRS

- AIRS height retrievals biased for:
 - Non-opaque cloud
 - Multi-layer cloud



CALIOP comparisons improved height assignments of AMVs



(Holz et al. 2008)

- Passive retrievals of cirrus involve assumptions which are poorly constrained
- CALIOP observations are used to improve accuracy of:
 - R_{ref} radiance observed in cloud-free columns
 - R_{Tcloud} – radiance observed from cloud at temperature T

IIR retrievals of cirrus OD are constrained by cloud boundaries from CALIOP

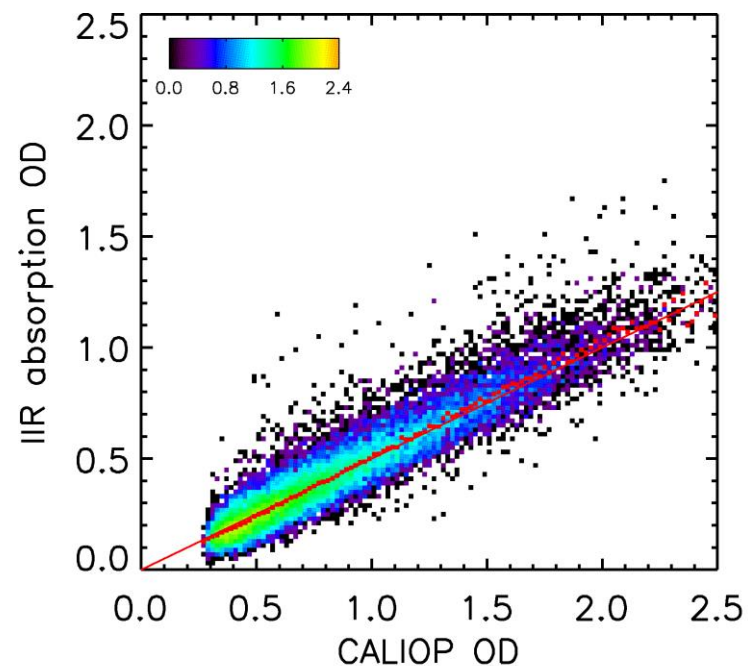
Infrared retrieval of effective emissivity and optical depth:

$$\varepsilon_{eff} = \frac{R_m - R_{ref}}{R_{Tcloud} - R_{ref}}$$

$$OD_{eff} = -\ln(1 - \varepsilon_{eff})$$

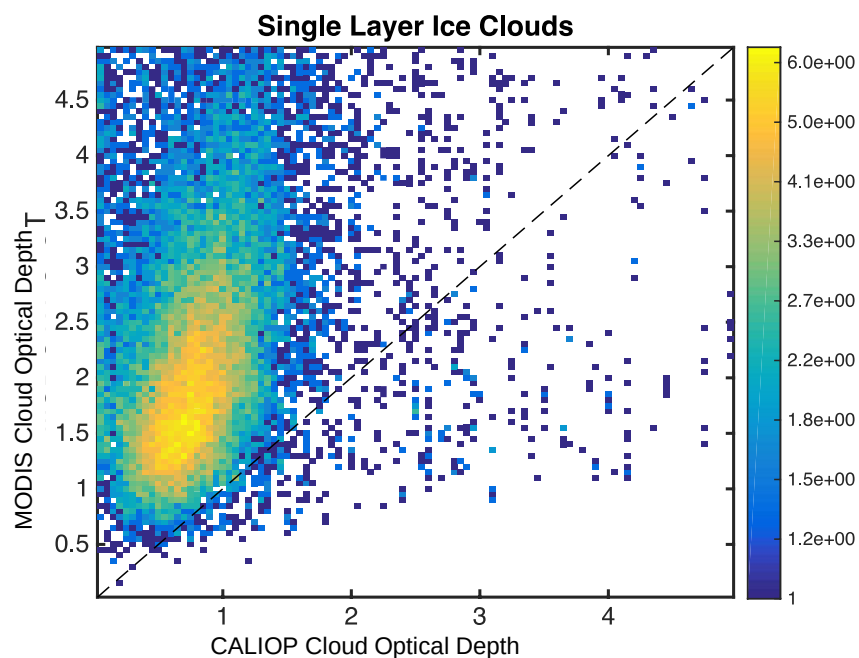
(Garnier et al. 2012)

IIR cirrus OD retrievals vs CALIOP “constrained” retrievals

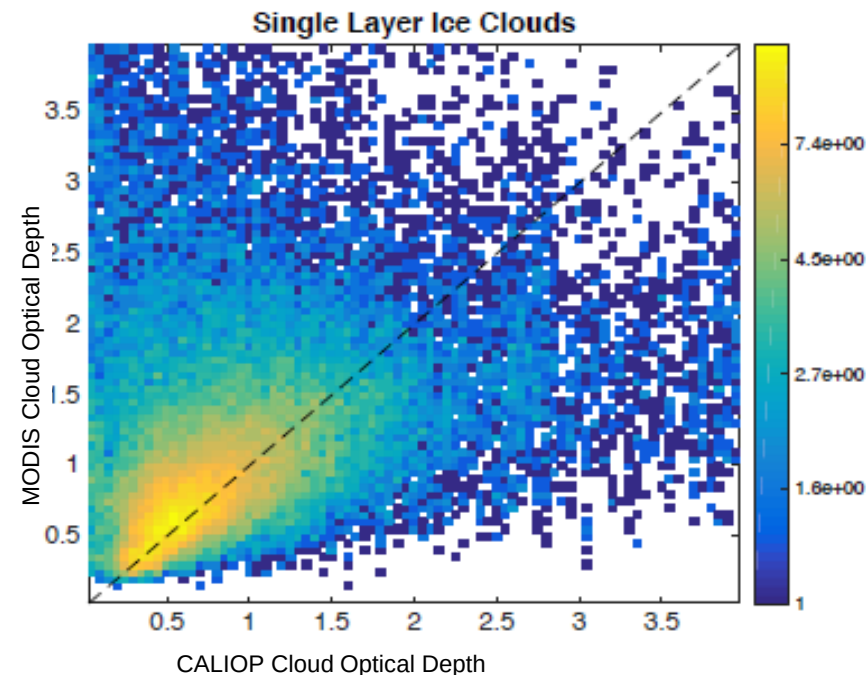


IR-Lidar Synergy

- Inconsistency of cirrus OD between MODIS C5 and CALIOP V3 led to changes in both the C6 and V4 algorithms
- IIR used to constrain CALIOP cirrus lidar ratio in Version 4 retrievals



MODIS C5 vs CALIOP V3
single layer ice clouds, daytime,
January 2010 ($\pm 60^\circ$ latitude)



MODIS C6 vs CALIOP V4

(Holz et al., ACP 2016)

WATER CYCLE PREDICTION

EAGLE-EYED OBSERVING

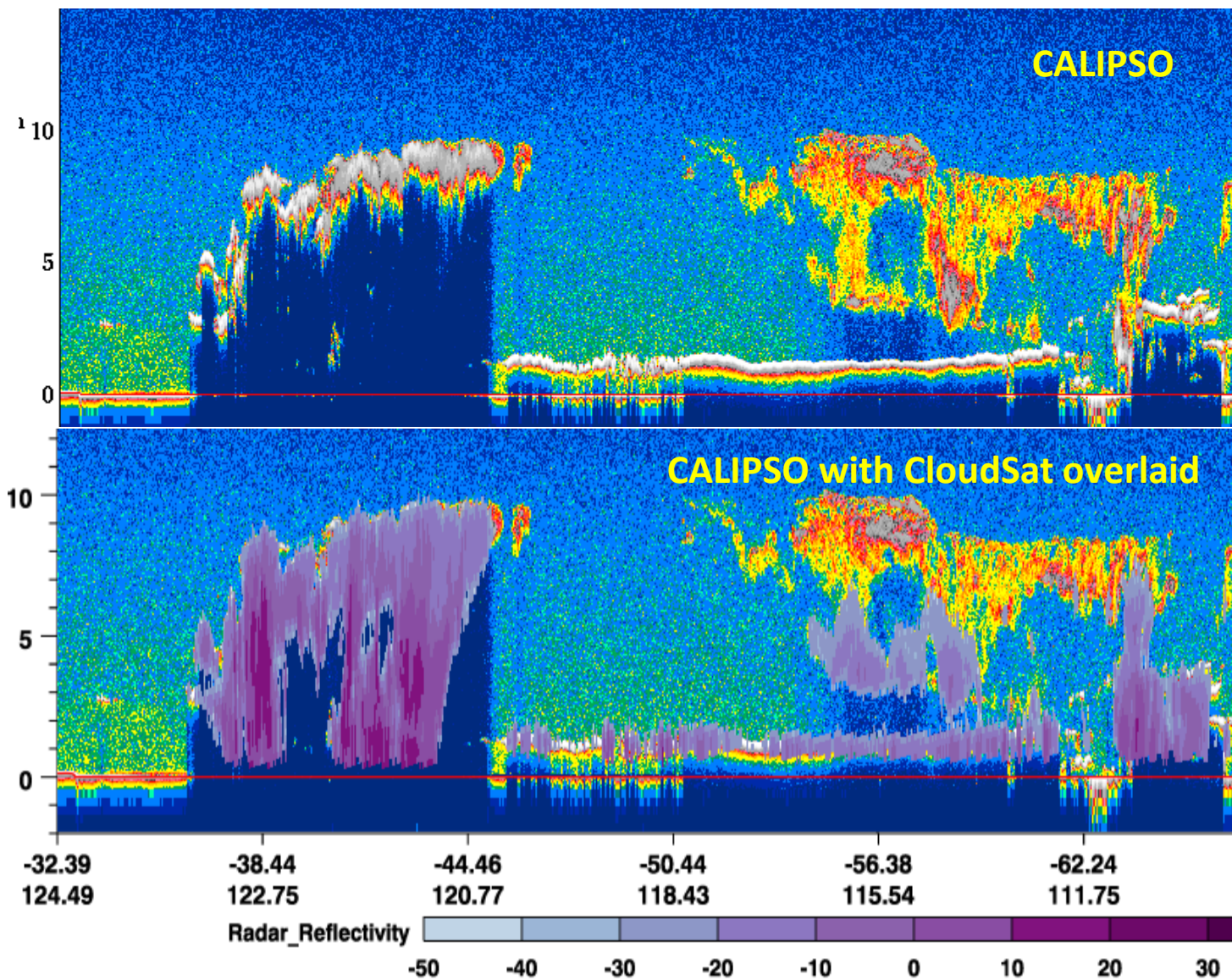
MAKING OUR OWN CHAOS

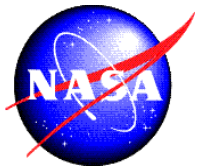
Partners in Profiling

The Legacy of CALIPSO and CloudSat

Lidar-Radar Synergies

Observations over the Indian Ocean and Antarctica



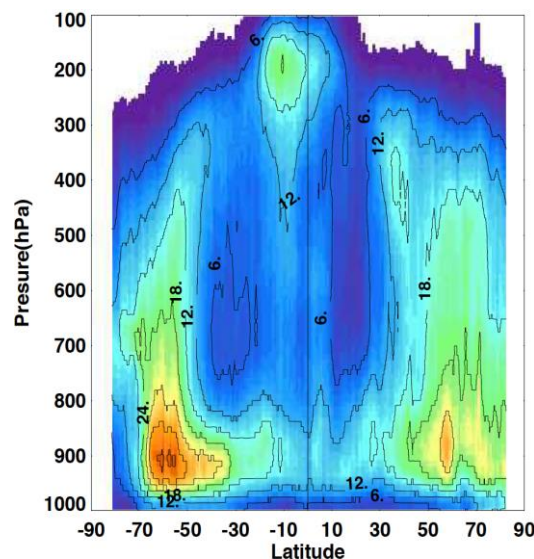


Our first true view of cloud vertical distribution

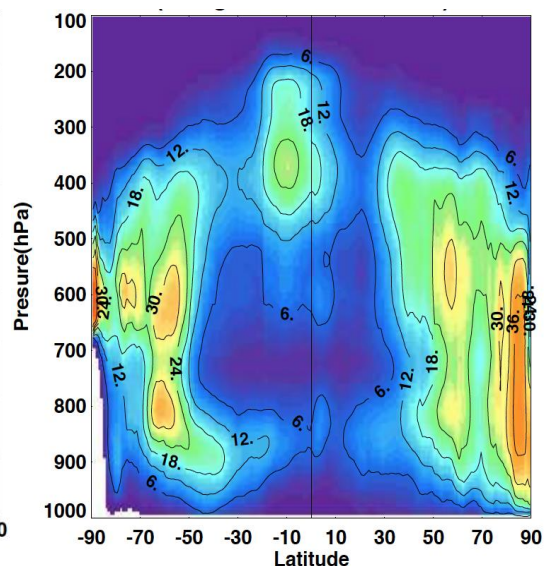


Vertical
Cloud
Fraction

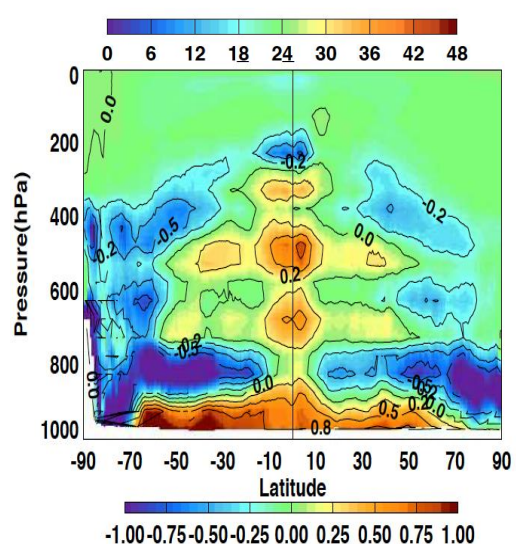
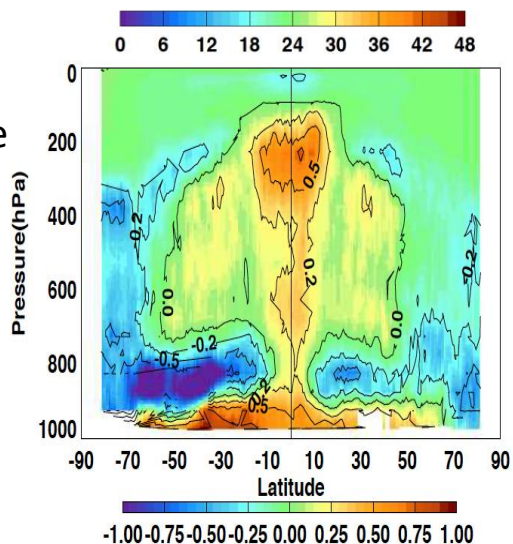
CALIOP-CloudSat



MODIS + GEO



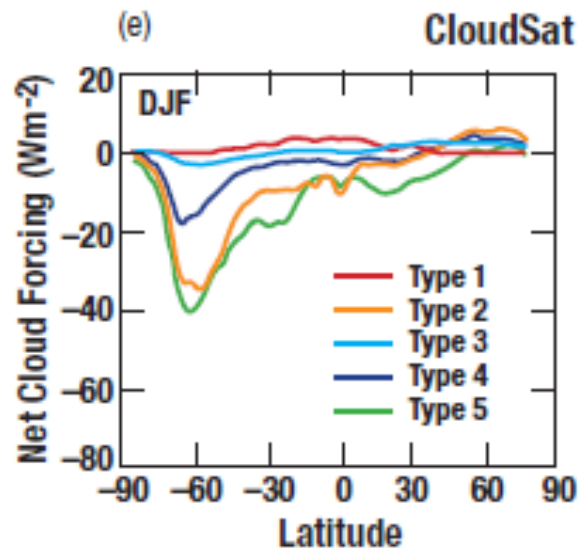
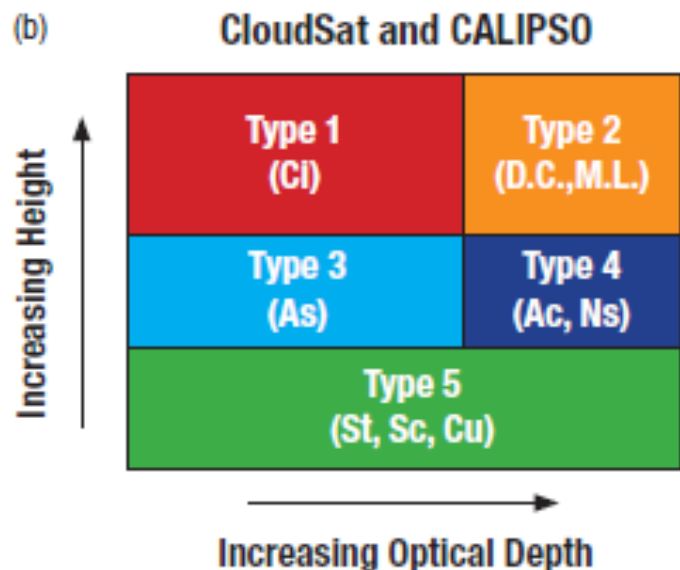
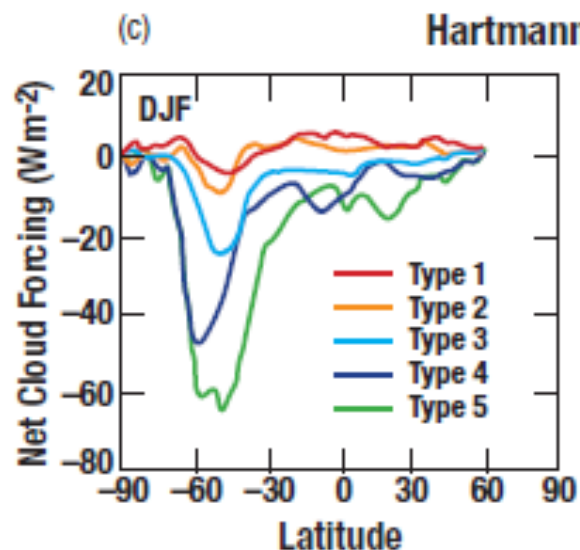
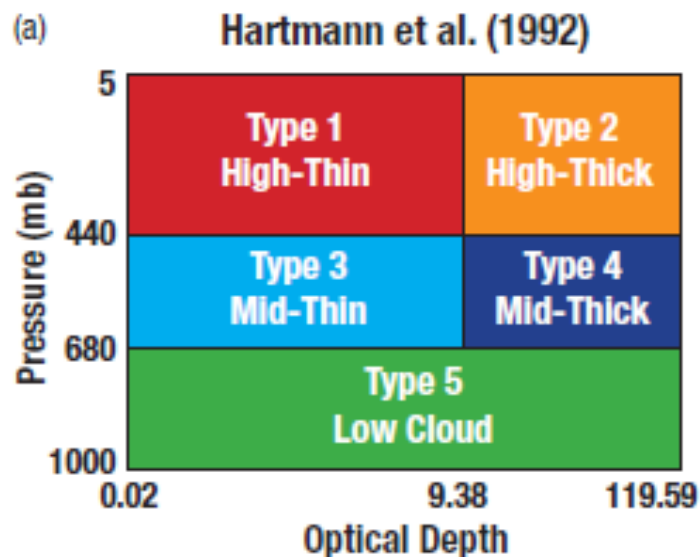
Cloud
Radiative
Effect
(K/day)



- Cloud climatologies from passive sensors are 'top-heavy'
 - Passive sensors only view tops of deep clouds
 - View of lower clouds blocked by upper clouds
- This leads to large errors in estimates of atmospheric heating from clouds
- Important for coupling of clouds and atmospheric circulation

(Kato et al. 2019)

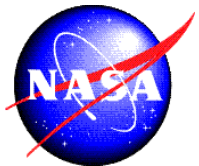
Improved understanding of the impacts of cloud on climate



Estimate from passive sensors of the contribution to cloud radiative effects (CRE) of 5 classes of clouds

The equivalent analysis but with cloud classification from CloudSat and CALIPSO. The differences in CRE underscore the effects of misclassification of clouds on interpretation of their radiative effects

(Stephens et al. 2018)

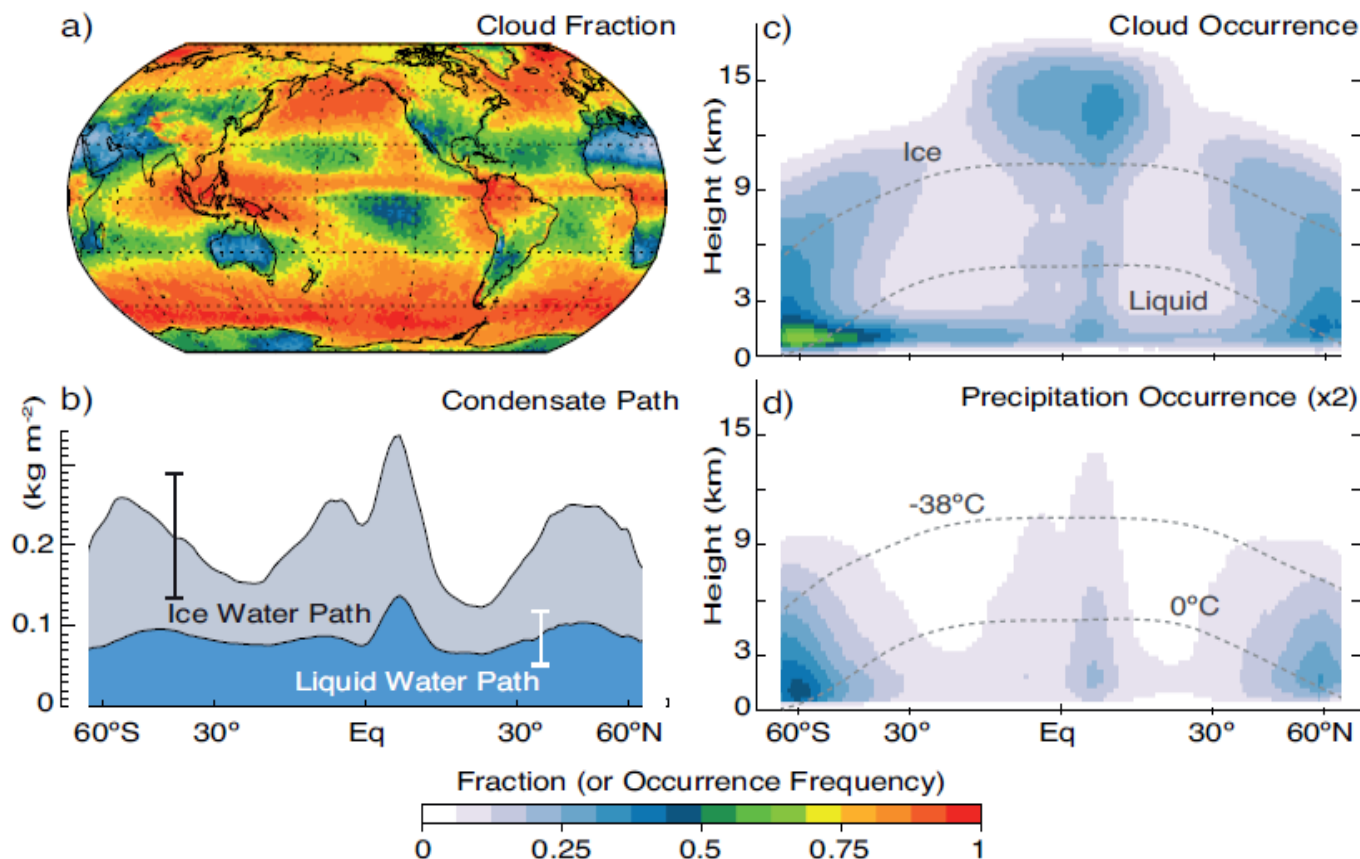


Synergistic Radar-Lidar Products

- Many data products combining CALIOP and CloudSat have been developed

Data Product	Description	Developers
SODA	Synergized Optical Depths of Aerosols derived from simultaneous ocean surface echoes measured by CALIPSO and CloudSat; http://www.icare.univ-lille1.fr/projects/soda/	NASA-LaRC, LATMOS/IPSL, and AERIS/ICARE (France)
DARDAR	Feature mask and cloud properties derived using a variational algorithm from collocated raDAR (CloudSat) and LiDAR (CALIPSO) measurements; http://www.icare.univ-lille1.fr/projects/dardar/	University of Reading (UK) and LATMOS/IPSL (France)
C3M	Integrated CERES-CALIPSO-CloudSat-MODIS data set; http://ceres.larc.nasa.gov/products.php?product=CCCM	CERES science and data product teams
2B-FLXHR-LIDAR	CloudSat, CALIPSO and MODIS data combined to generate estimates of broadband fluxes and heating rates; http://www.cloudsat.cira.colostate.edu/dataSpecs.php?prodid=80	CloudSat Data Processing Center at Colorado State University's Cooperative Institute for Research in the Atmosphere (CIRES)
GEOPROF-LIDAR	vertical occurrence and classification of hydrometeors derived by combining the CALIPSO VFM and the CloudSat cloud mask; http://www.cloudsat.cira.colostate.edu/dataSpecs.php?prodid=10	
2C-ICE	Ice water content, effective radius and extinction coefficients derived from the synthesis of CALIPSO and CloudSat data; http://www.cloudsat.cira.colostate.edu/dataSpecs.php?prodid=112	

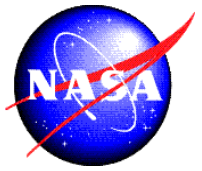
CALIPSO-CloudSat Highlighted in IPCC AR5 (2013)



“Active sensors show more clearly that low clouds are prevalent in nearly all types of convective systems, and are often underestimated by models. Cloud layers at different levels overlap less often than typically assumed in General Circulation Models ... New observations have led to revised treatments of overlap in some models, which significantly affects cloud radiative effects.”

“Active sensors have also been useful in ... improving our ability to test climate model simulations of the interaction between sea ice loss and cloud cover.”

Figure 7.5 (a) Annual mean cloud fractional occurrence (CloudSat/CALIPSO 2B-GEOPROF-LIDAR data set for 2006–2011). (b) Annual zonal mean liquid water path (microwave radiometer data for 1988–2005) and ice water path (from CloudSat 2C-ICE data set for 2006–2011 from Deng et al. (2010)). (c–d) latitude-height sections of annual zonal mean cloud occurrence and precipitation occurrence; (2B-GEOPROF-LIDAR data set). (IPCC, 5th Assessment Report, 2013)



Looking Ahead



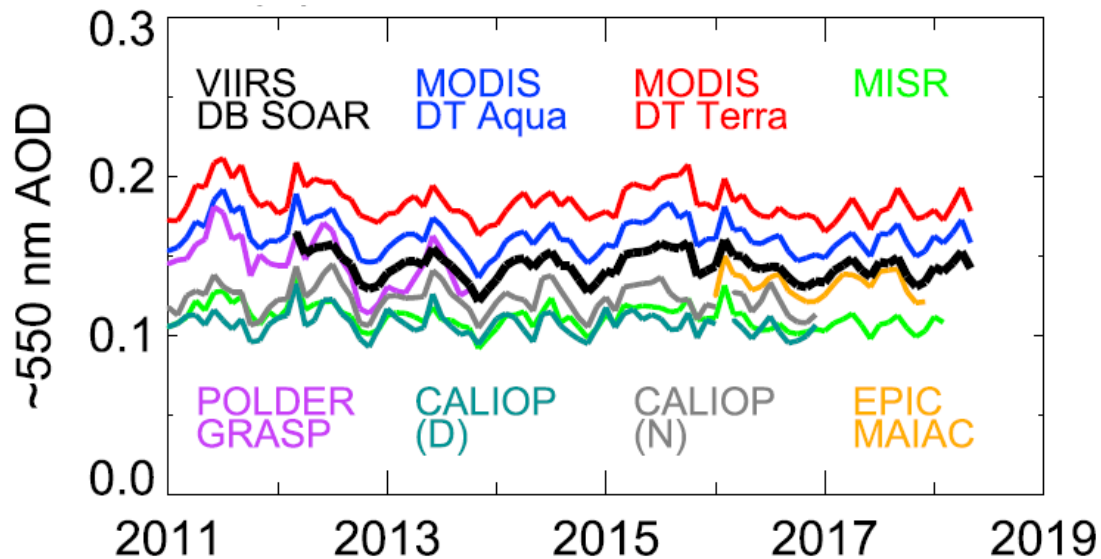
EarthCARE (with ATLID) to launch (in 2024 ?)

What's left to do?

We require more accurate AOD, aerosol extinction (especially near surface) to:

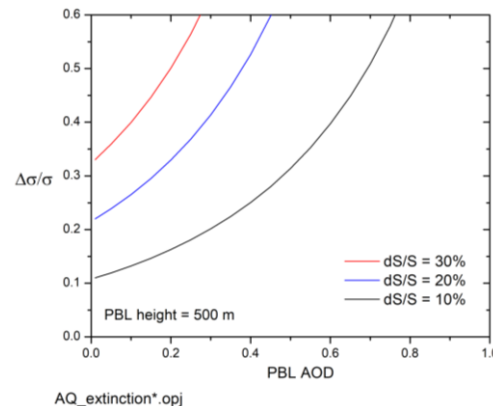
- Quantify climate forcing of aerosols
- Improve representation of aerosol in models

Global AOD from Observations

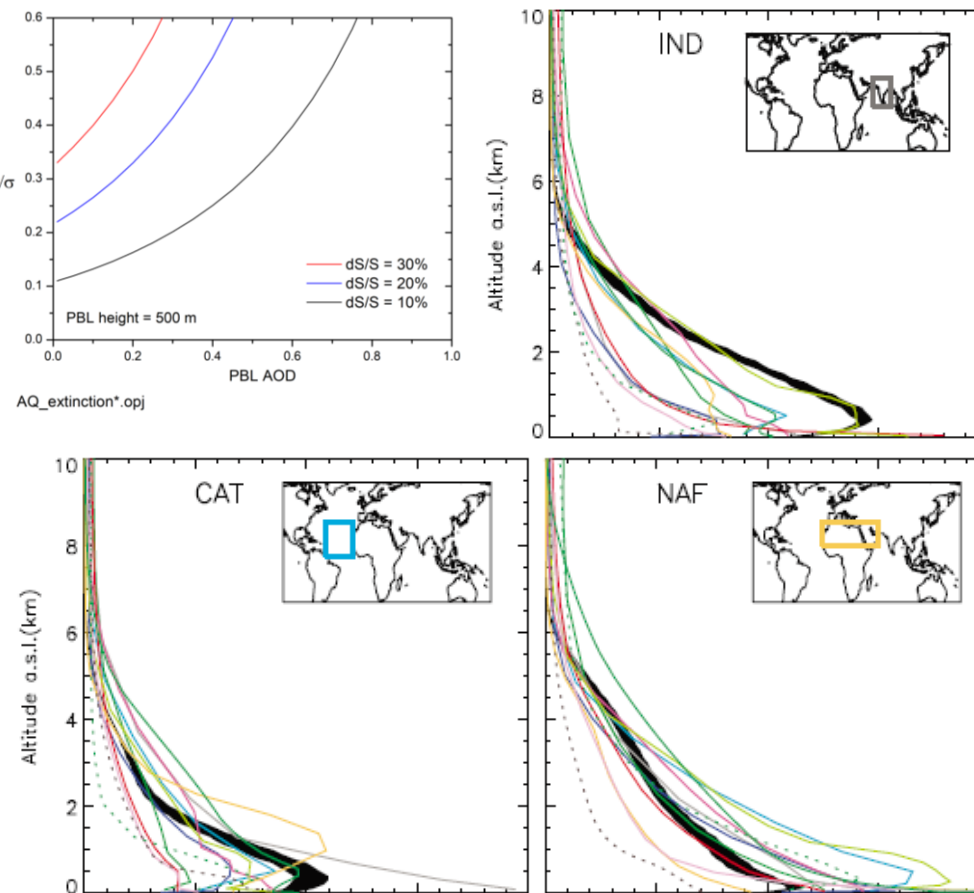


(Sayer et al. 2018)

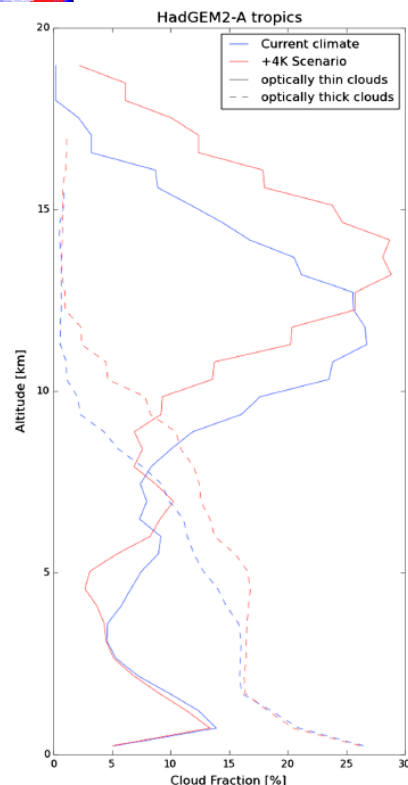
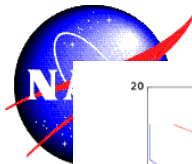
Near-sfc extinction uncertainty due to lidar ratio (bksctr lidar)



Model Comparisons



(Koffi et al. 2012)

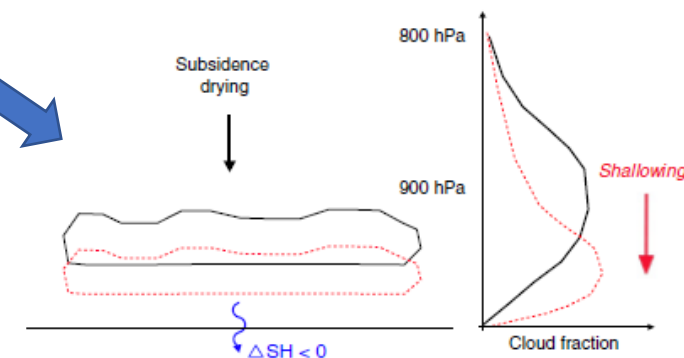
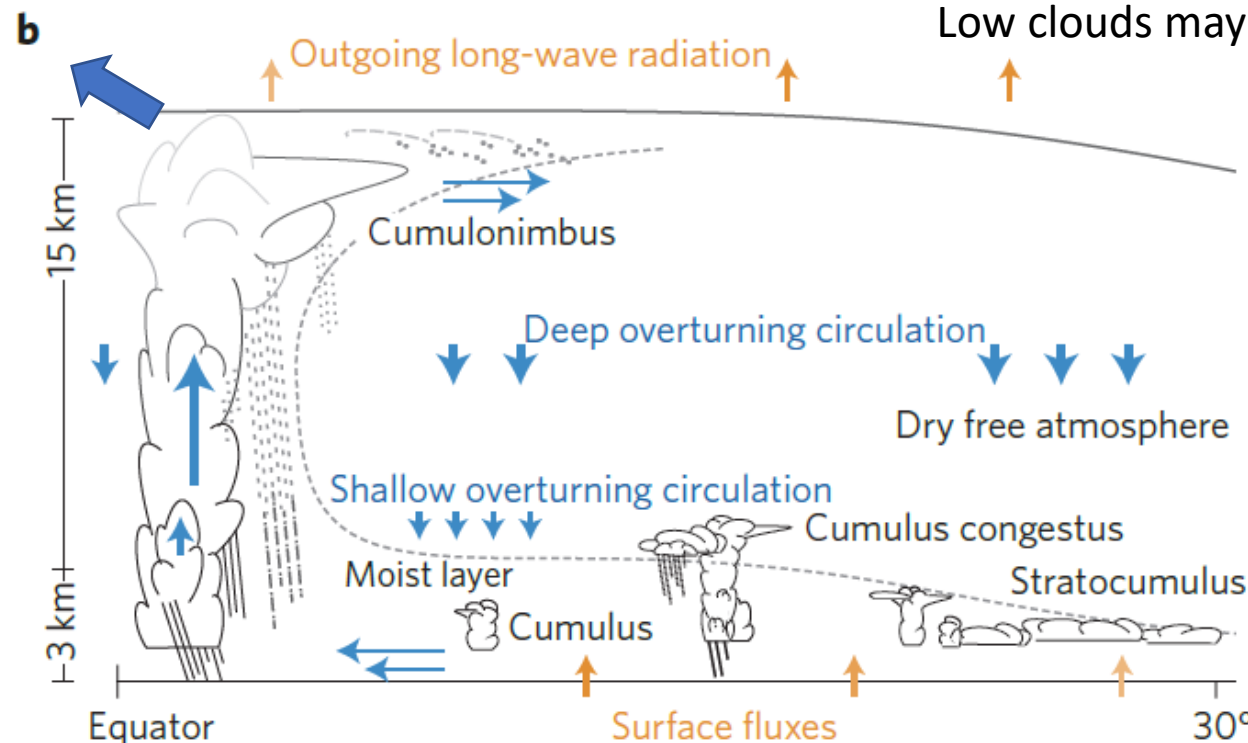


Cloud fraction profiles simulated by HadGEM2. Blue: current climate Red: +4K climate
(Chepfer et al. 2014)

Clouds are coupled via atmospheric circulation
With warming:

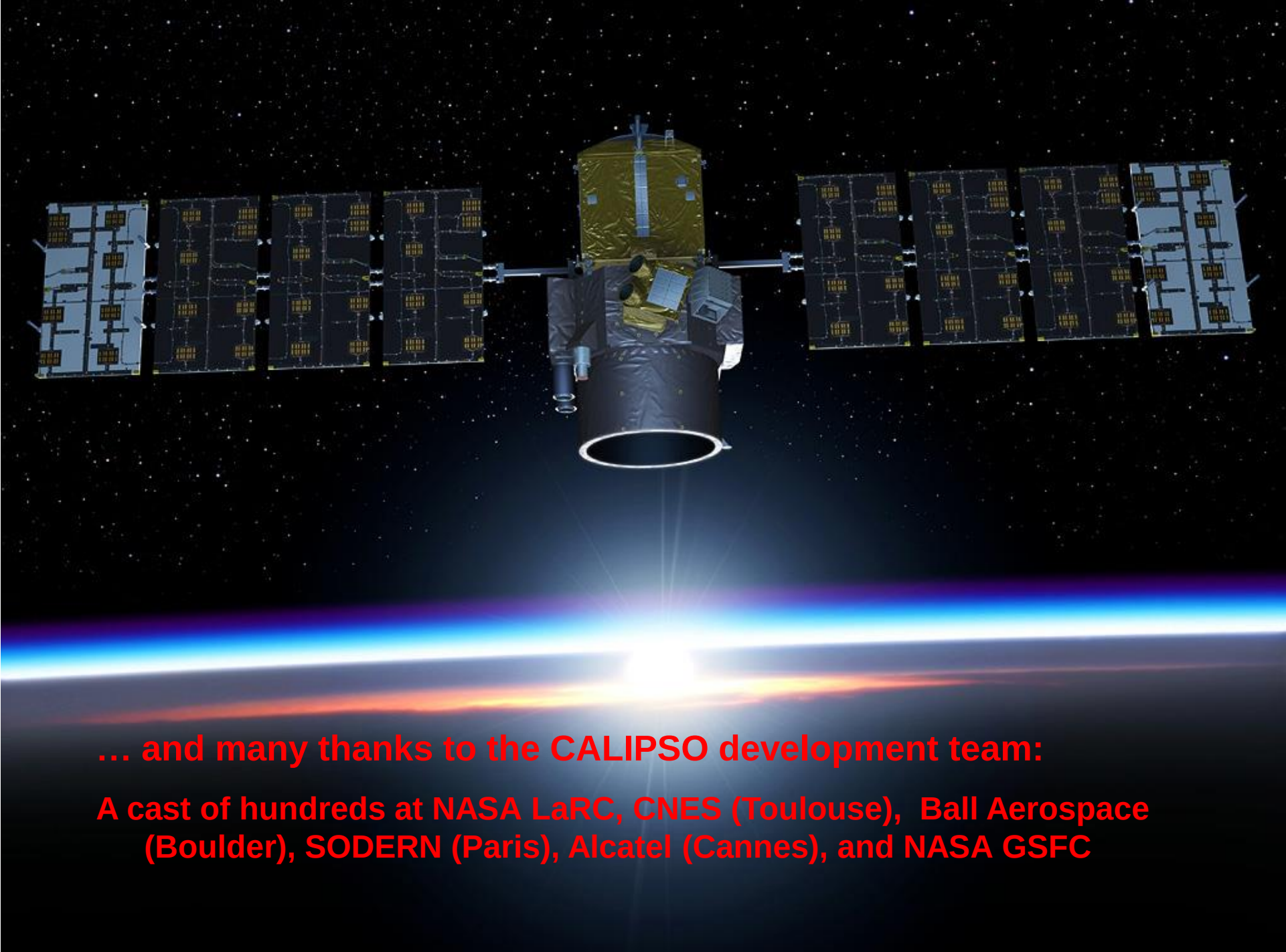
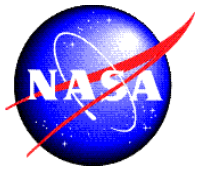
High clouds get higher

Low clouds may get shallower, or deeper



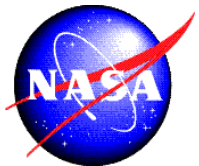
- Some of the largest uncertainties in predicting the climate response to rising GHG concentrations involve predicting how clouds will change, and the radiative impacts of these cloud changes.
- Accurate monitoring of changes in cloud distribution and properties over decades is necessary.

(Brient et al. Clim Dyn, 2015)



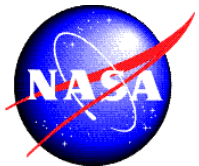
... and many thanks to the CALIPSO development team:

A cast of hundreds at NASA LaRC, CNES (Toulouse), Ball Aerospace (Boulder), SODERN (Paris), Alcatel (Cannes), and NASA GSFC



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