A Look Back at CALIPSO

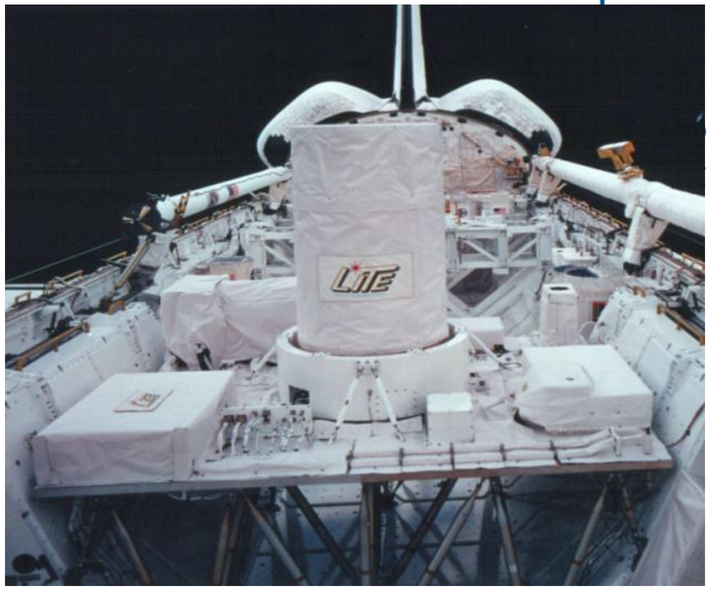
Dave Winker

NASA Langley Research Center

31st ILRC, Landshut DE, June 2024

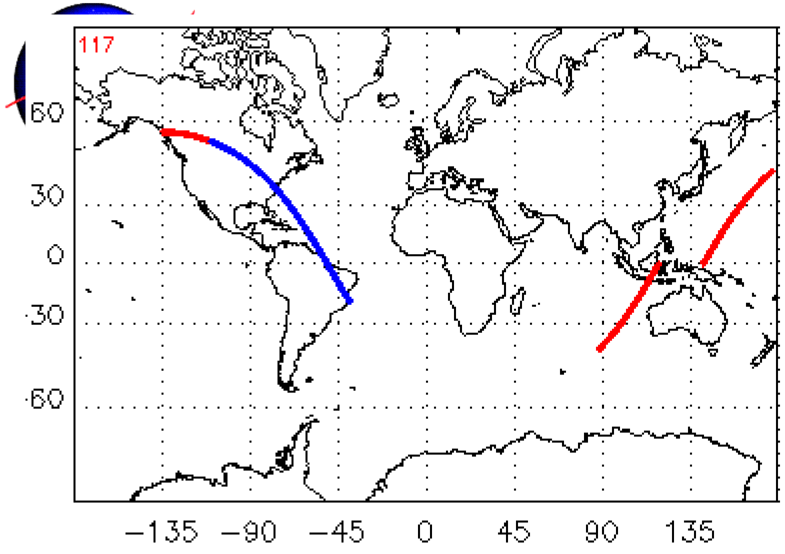
Key Dates

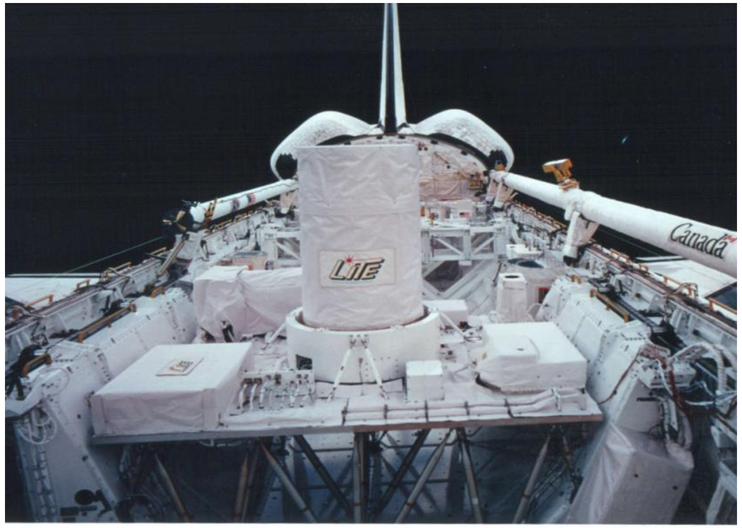
… CALIPSO started with LITE (September 1994 on STS-64)
- proof of concept for CALIOP
- critical information on lidar performance requirements
- development of follow-on started immediately after

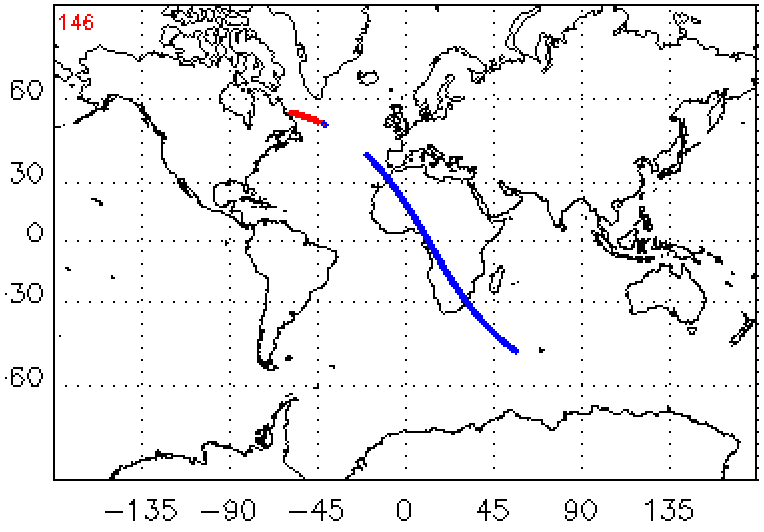


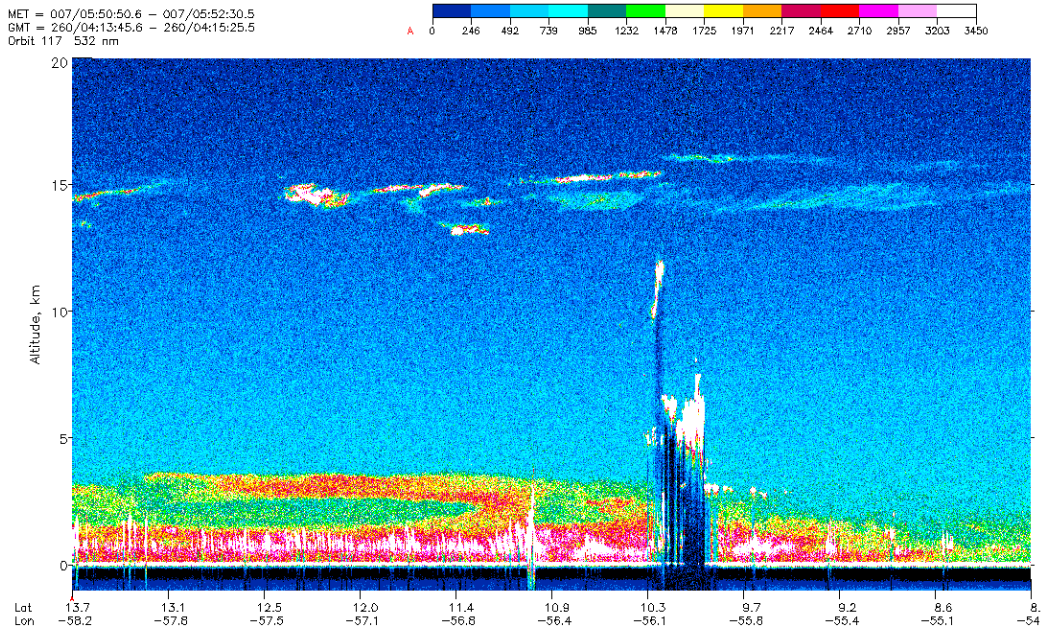
- Proposal selected by NASA ESSP (& CNES): 1998
- Launch: 28 April 2006
- First light: 7 June 2006
- Primary laser: June 2006 – February 2009
- Backup laser: March 2009 – June 2023
  - Formal science mission ends tomorrow
- Engineering experiments: July 2023
  - (Clayton's test of the primary laser)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

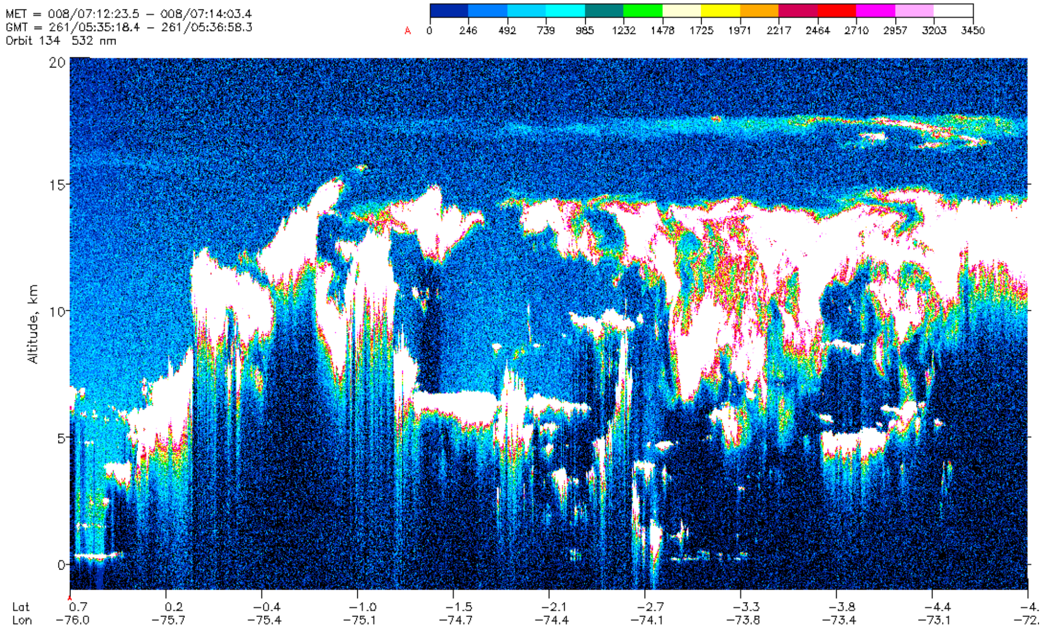
Our first look: LITE (1994)







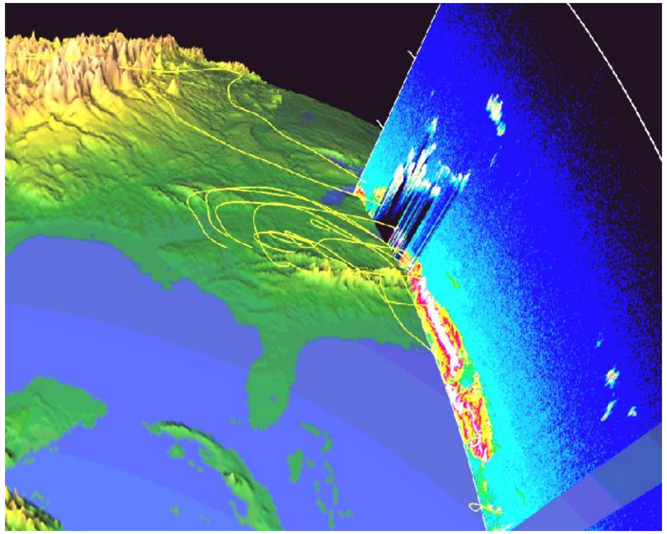




CALIPSO Science Objectives (c. 1998)

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

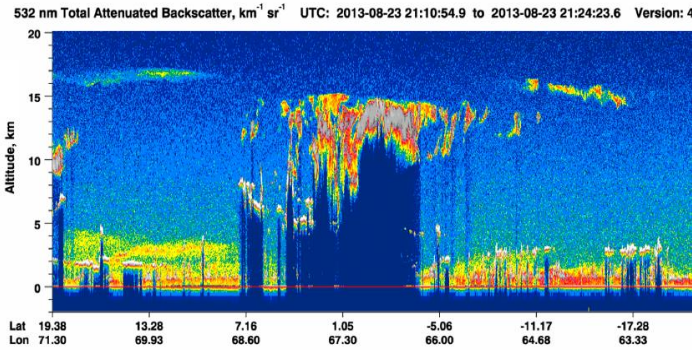


- The representation of aerosols and clouds in models of climate, air quality, weather, etc.
- Validation of other A-train sensors

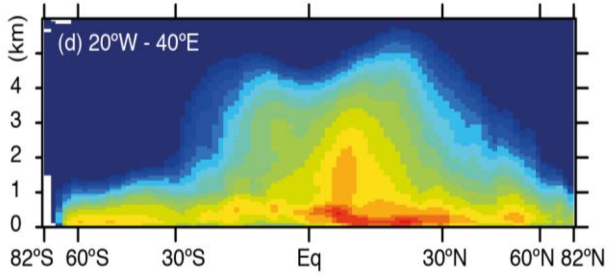
Major Early CALIPSO Decisions

- 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

Science Accomplishments

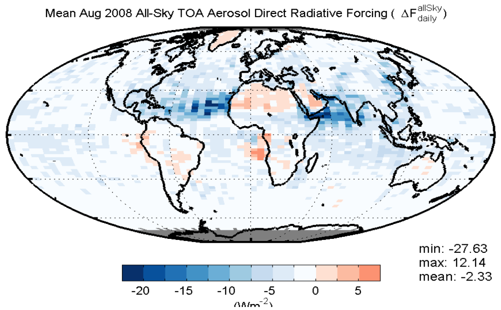


Vertically-resolved aerosol climatology

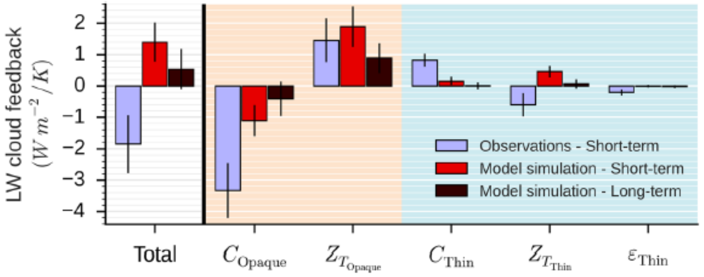


(IPCC AR5)

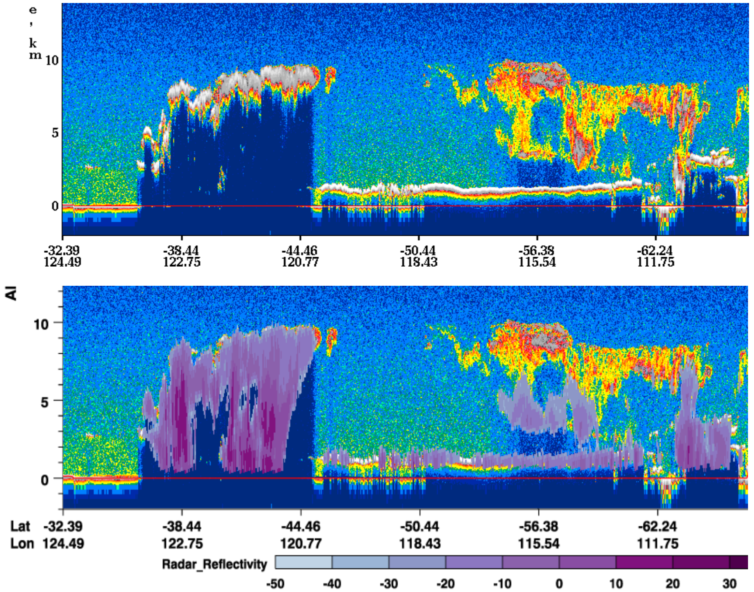
All-sky/clear-sky aerosol radiative effects



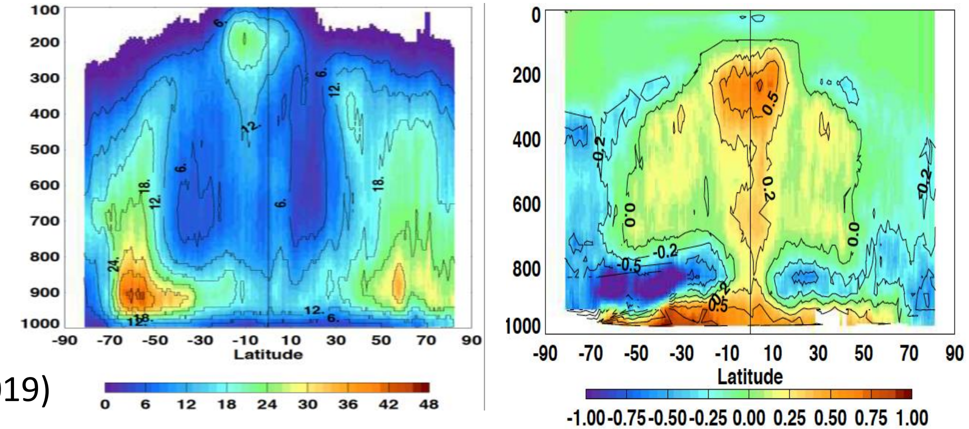
LW Cloud Radiative Feedbacks



(Vaillant de Guelis et al., 2018)



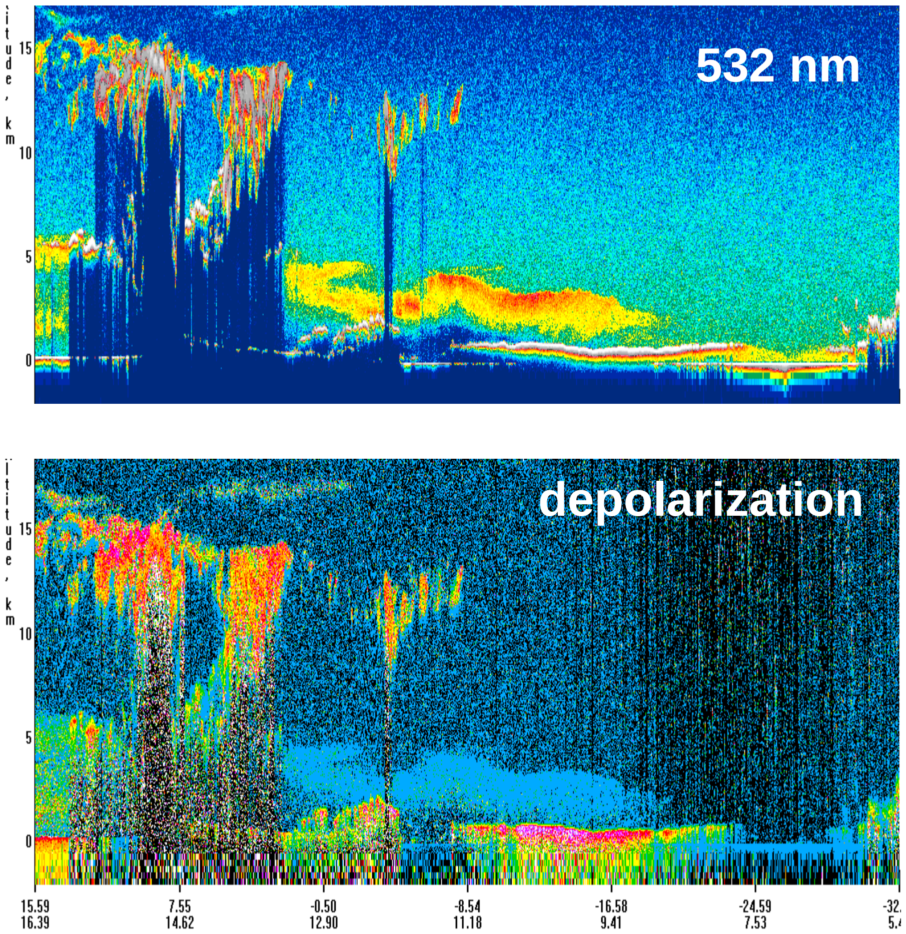
Cloud Climatology & Radiative Heating Profiles



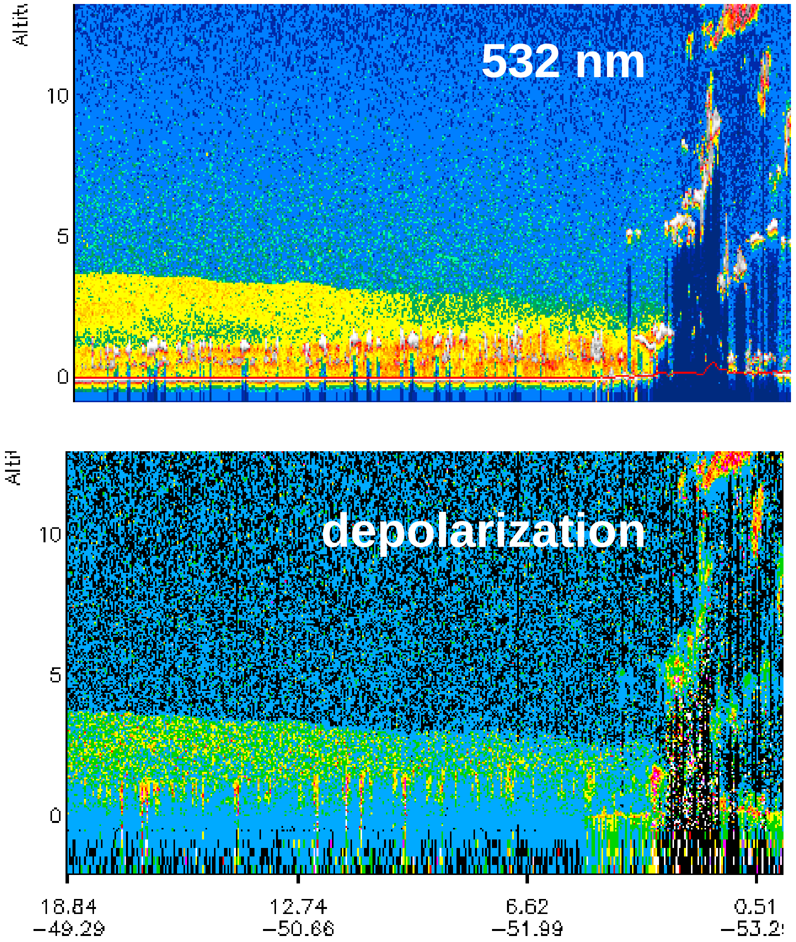
(Kato et al, 2019)

Gained Important Capabilities from Lidar Depolarization

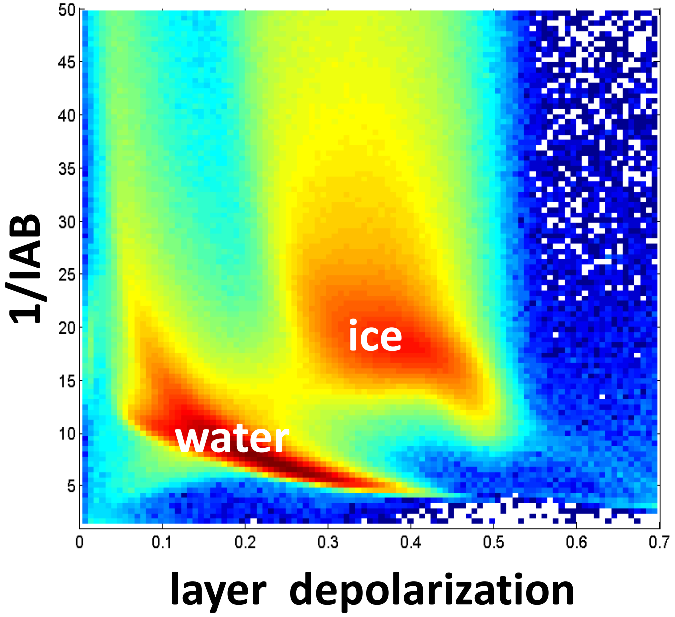
Smoke



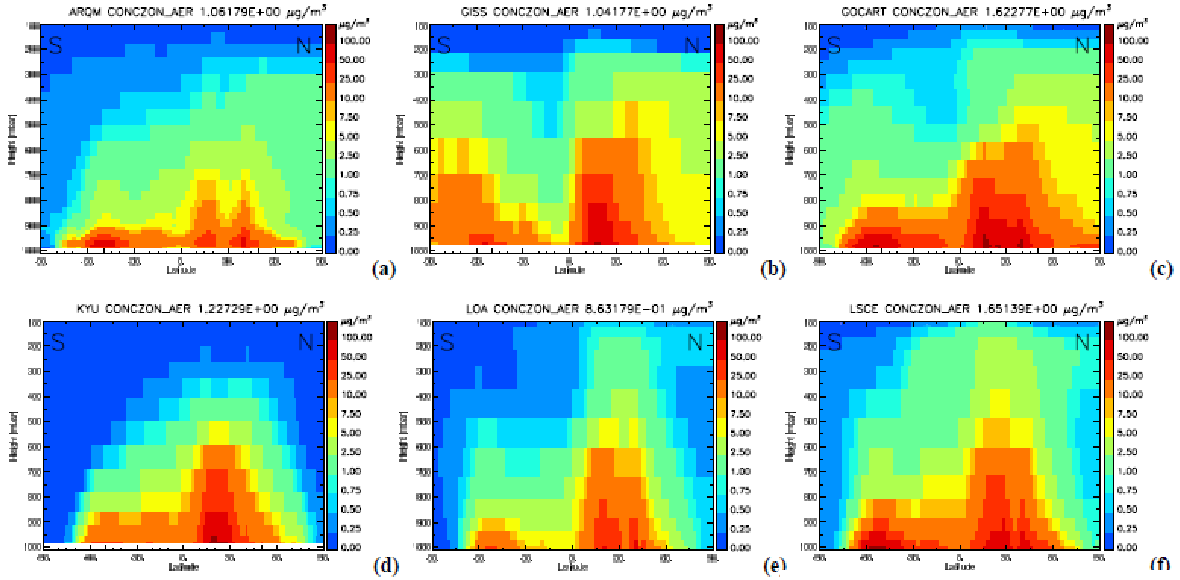
Sahara Dust



Vertically resolved cloud ice-water phase



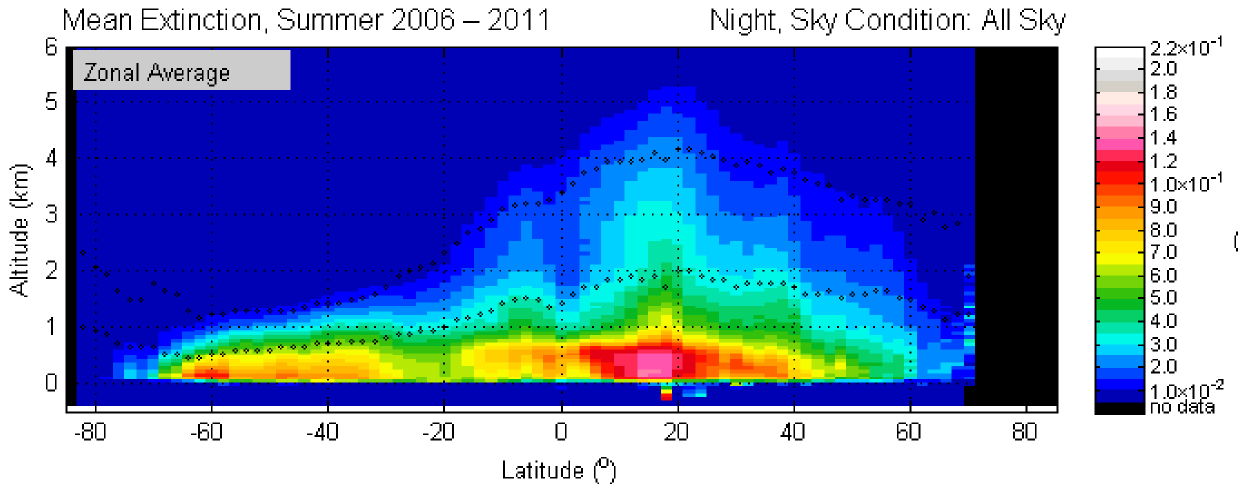
In 2006, the vertical distribution of aerosol varied widely between global aerosol models. Until CALIOP there were no global observations of vertical profiles



Zonal mean aerosol mass concentration from 6 global aerosol models

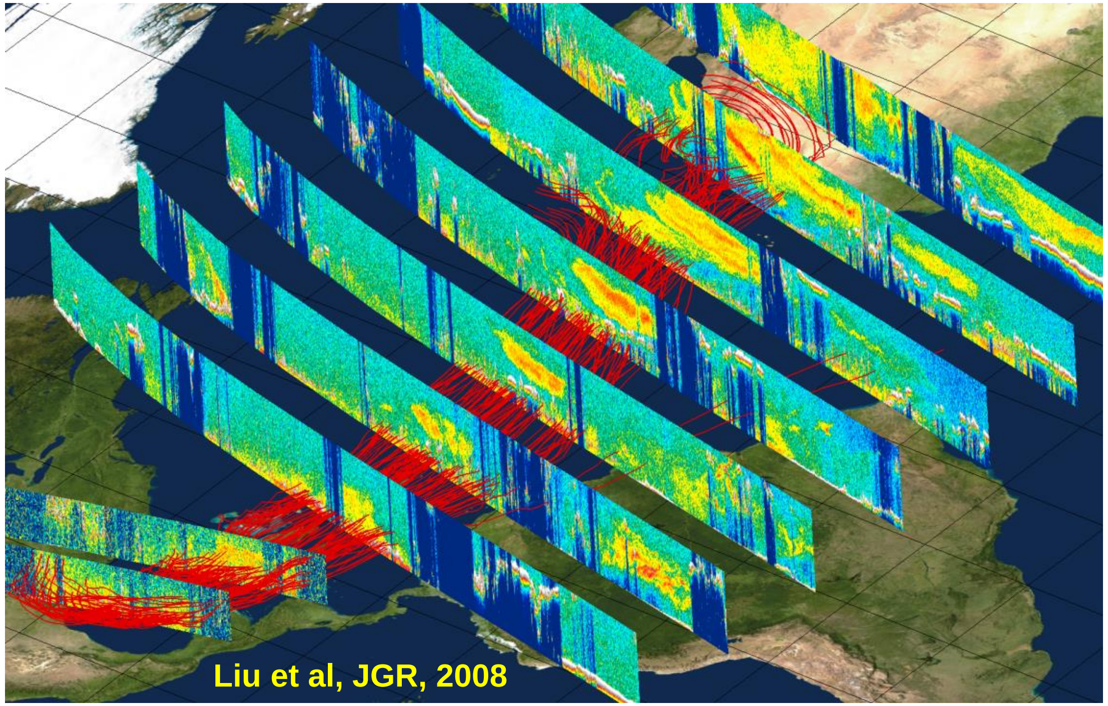
(Textor et al., 2006)

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

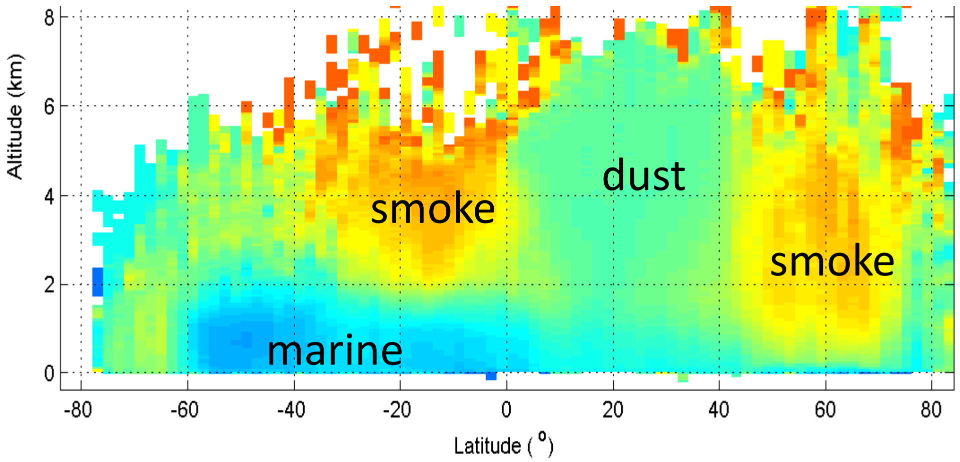


Aerosol Transport

Sahara dust outbreak, Aug 2007

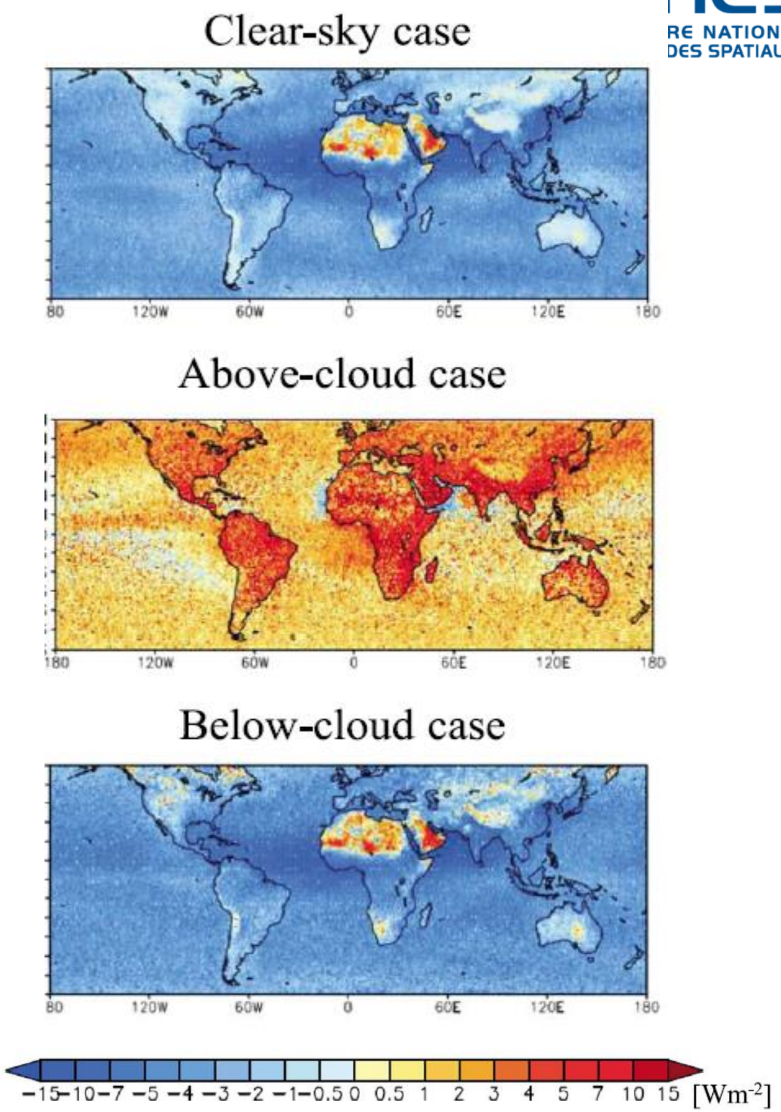


Aerosol Composition



Zonal mean distribution of aerosol types, June through August

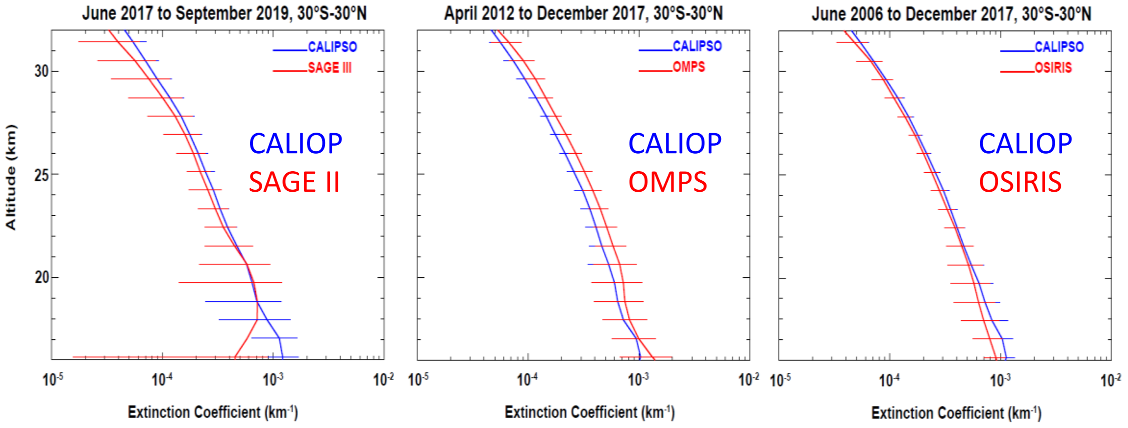
Aerosol Radiative Effects



(Oikawa et al. 2018)

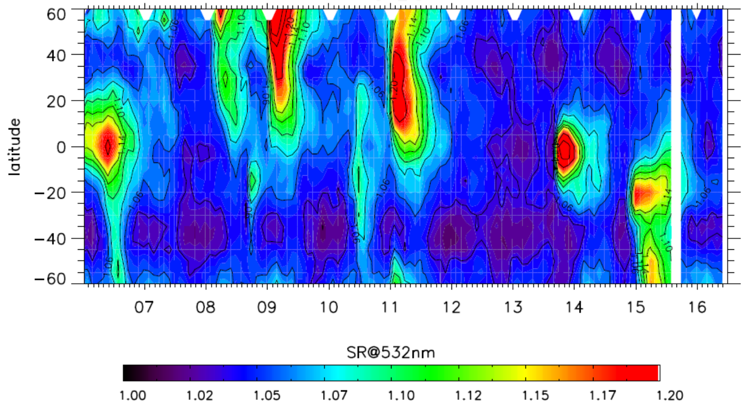
Stratospheric Aerosol Product

- 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

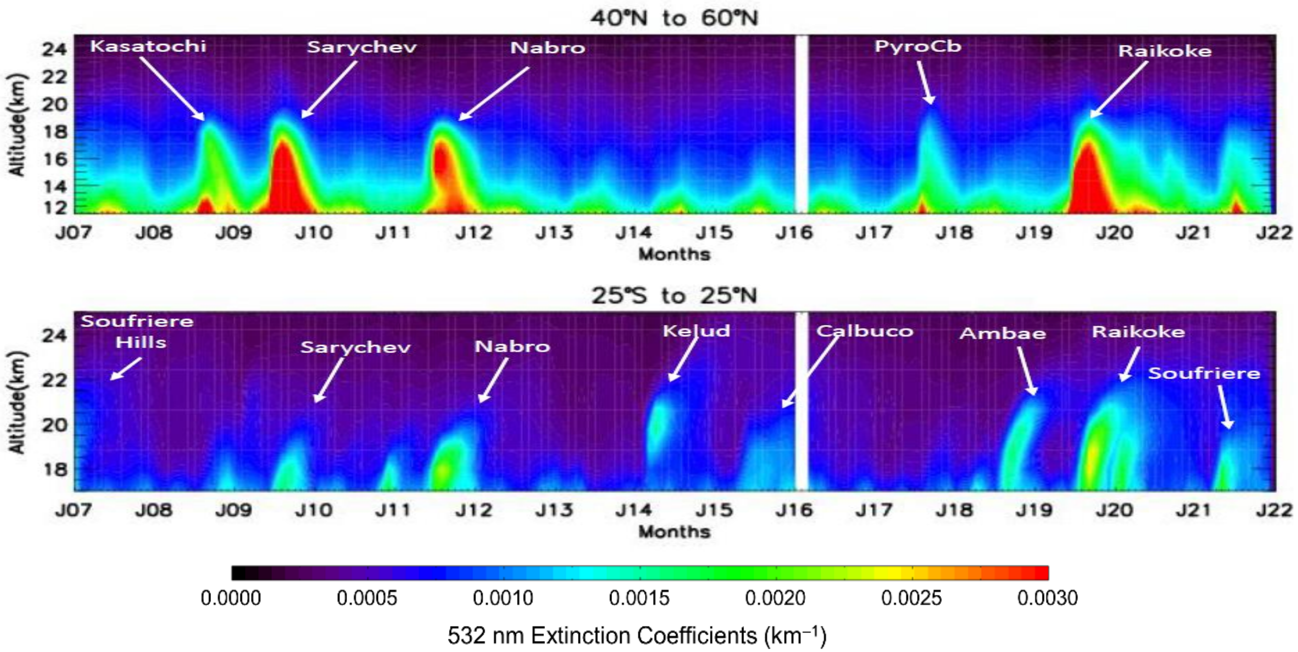


Zonally averaged CALIOP extinction coefficient profiles for data acquired between 30°N and 30°S compared to data from SAGE III-ISS, OMPS, and OSIRIS (Kar et al. 2019)

Latitudinal distribution



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

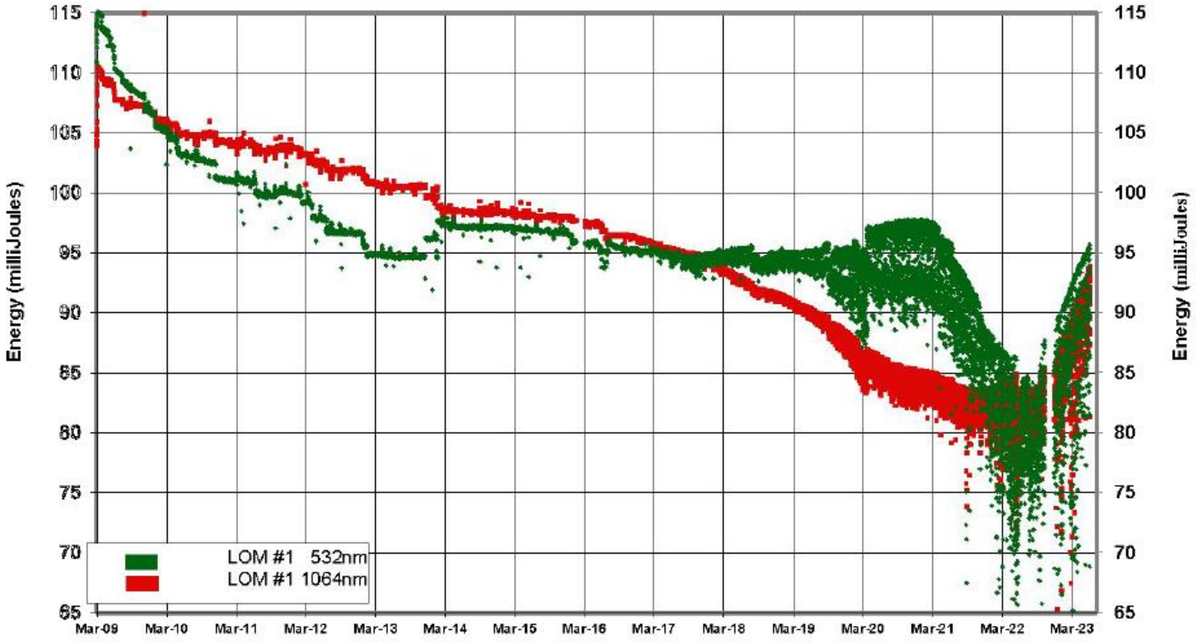


Time-height cross sections of CALIOP stratospheric aerosol extinction, Jan 2007 to Dec 2017 (Kar et al., 2019)

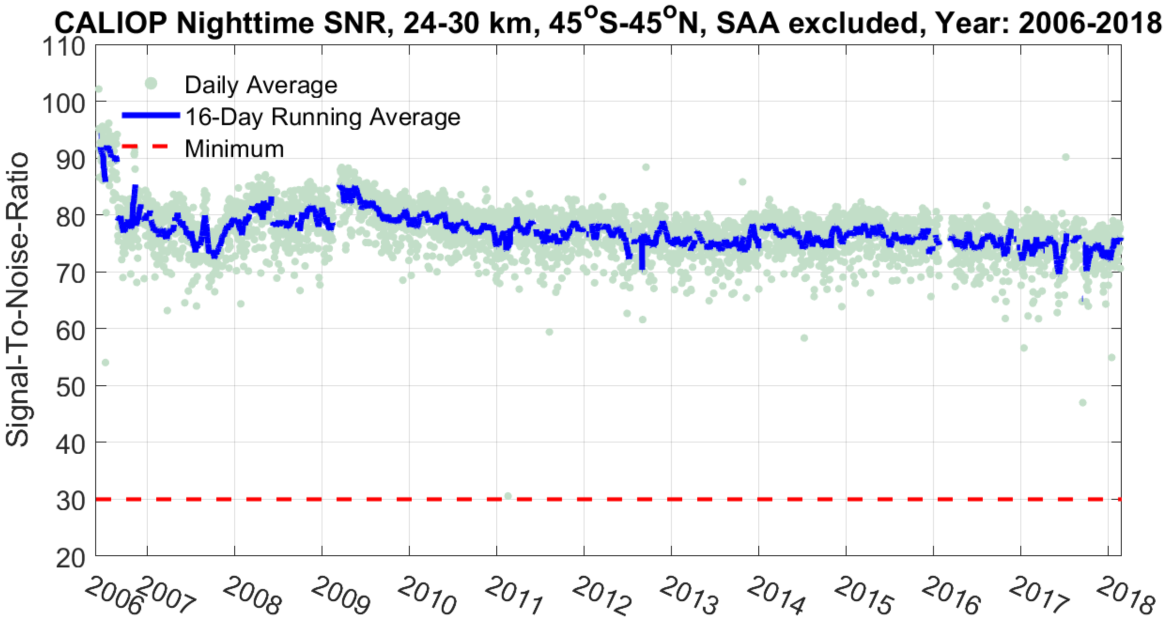
CALIPSO Weekly Performance (Laser # 1)

June 15, 2023
Laser #1 Shots On-Orbit: 8.46 Billion
Total Laser Shots On-Orbit: 10.07 Billion
Total Light Emitted: 201.44s

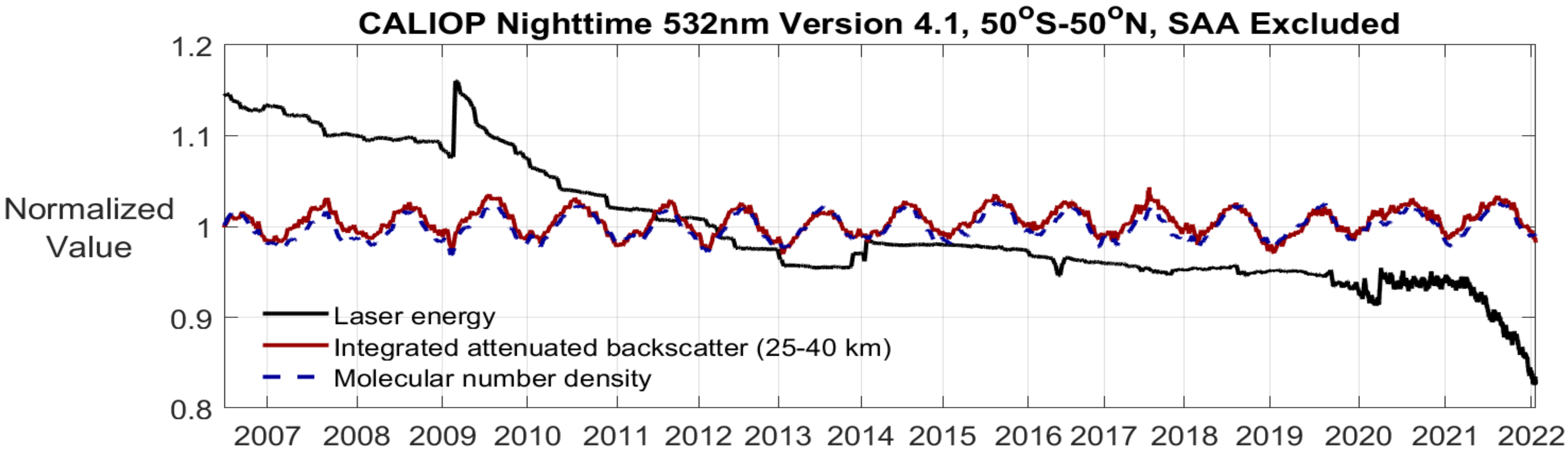
Laser #1: 532 nm and 1064 nm pulse energy



532 nm SNR time series: 2006-2018

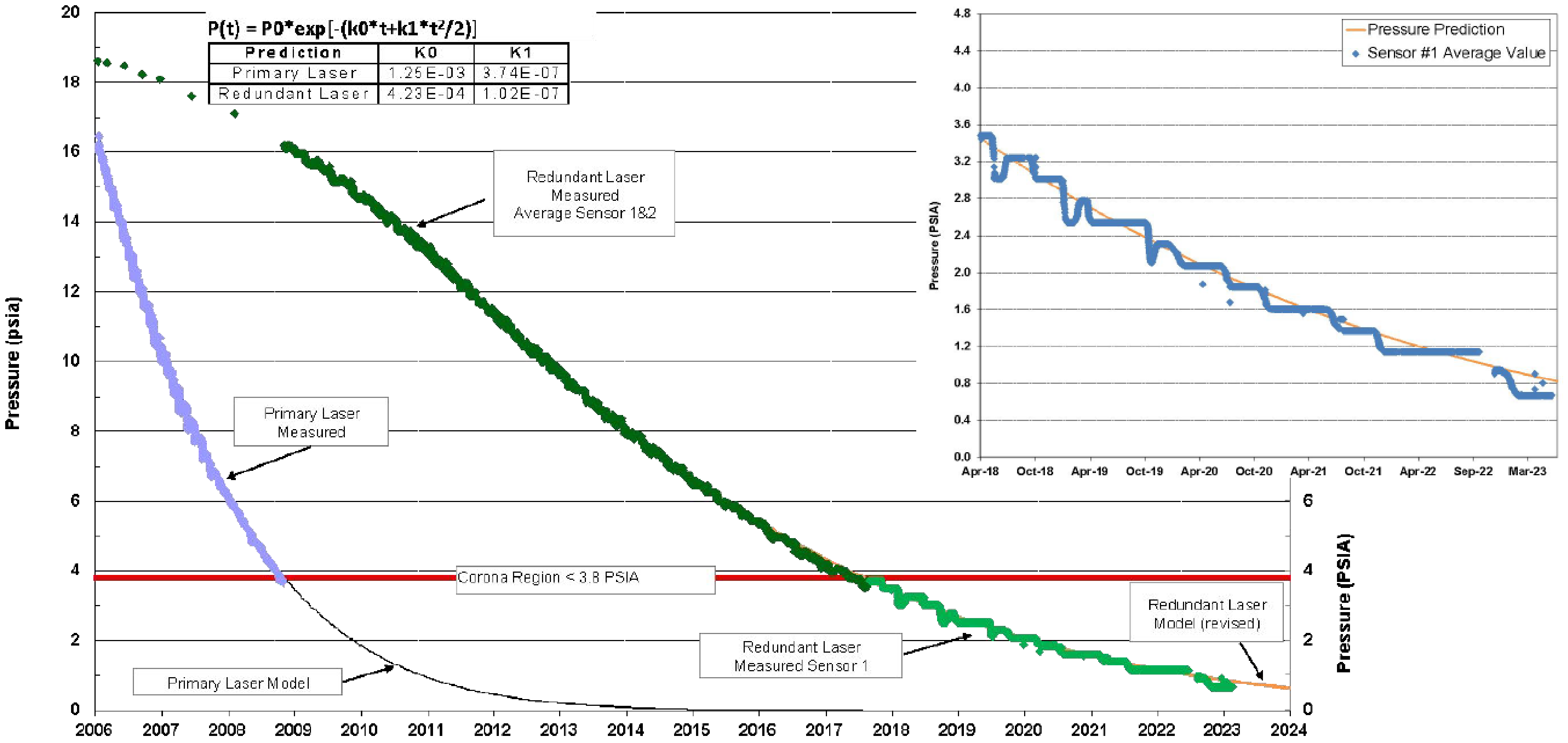


Stable calibration over 15-years

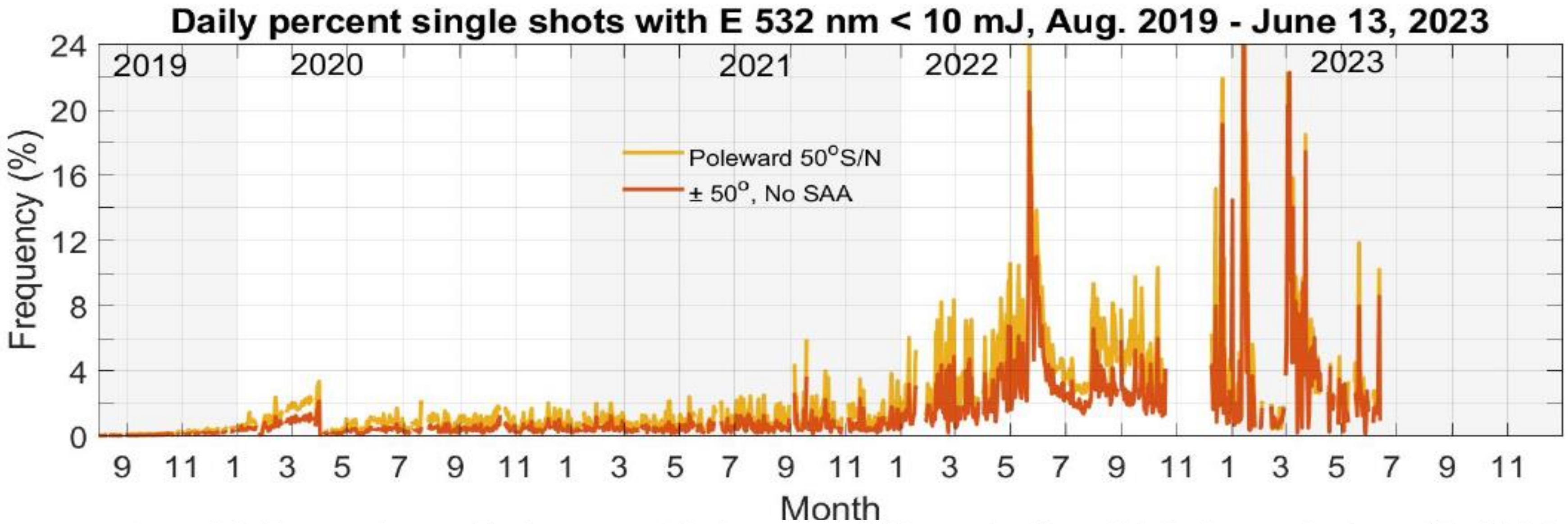


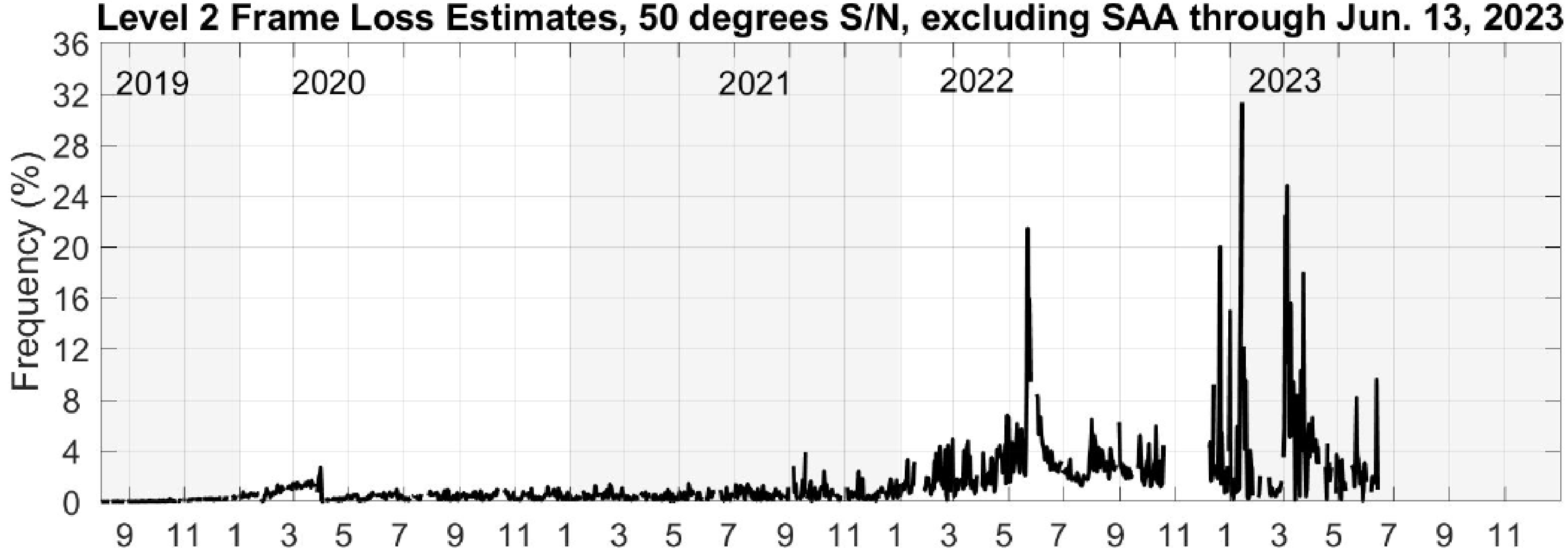
Normalized trends of mid-stratosphere 532 nm IAB and molecular number density (averaged over the same altitude range) and laser total pulse energy

Laser Canister Pressure History



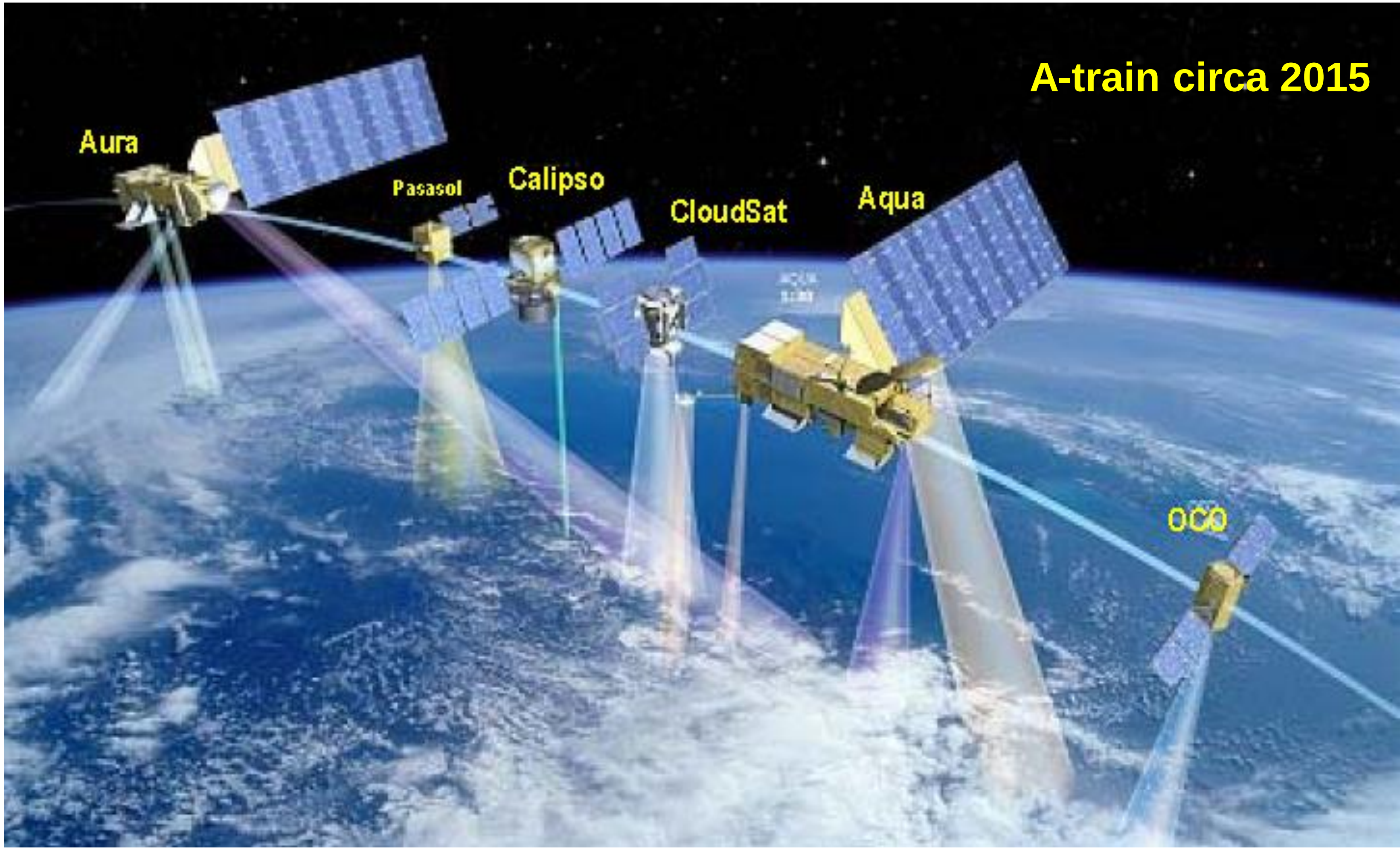
Frequency of Low Energy Laser Shots



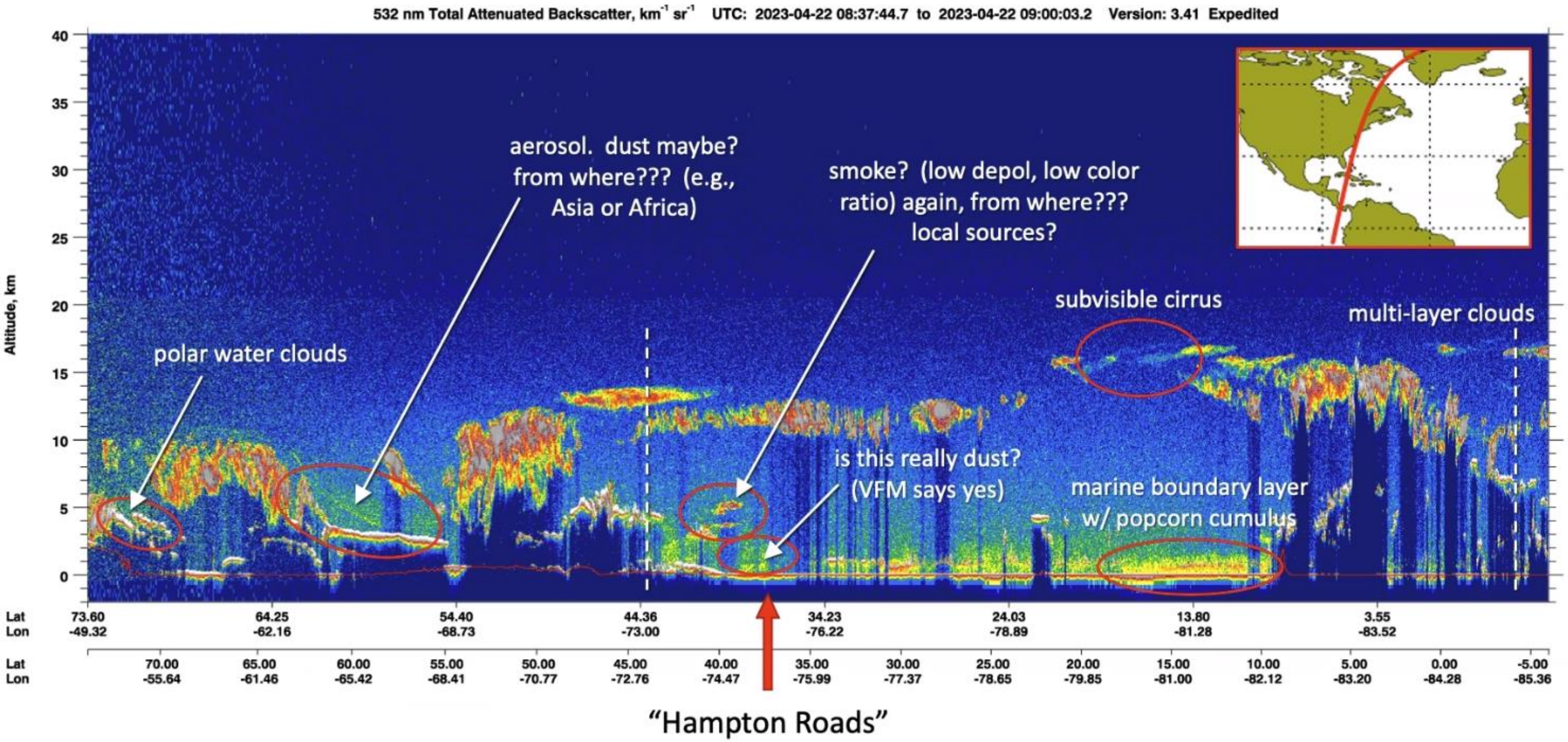


Synergies!

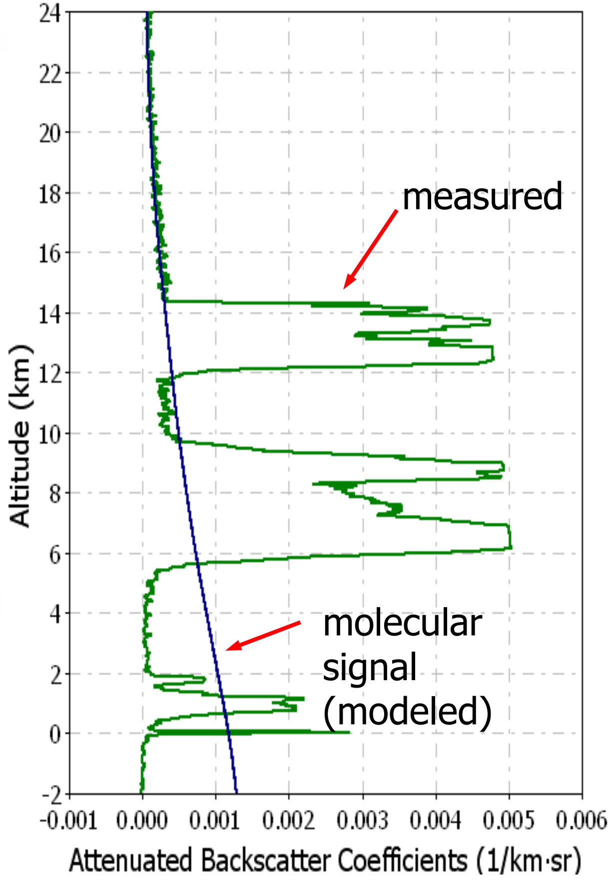
CALIPSO & CloudSat teamed in mid-90's and originally planned to fly with Aqua (MODIS & CERES)
… and then the A-train happened



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



… and provides very precise cloud boundaries:



Lidar-IR Synergy

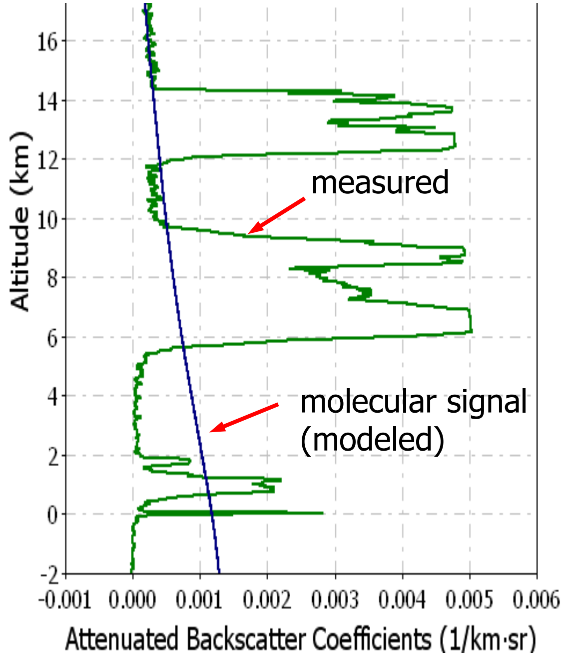
- Passive retrievals of cirrus involve assumptions which are poorly constrained
- CALIOP observations are used to improve accuracy of:
  - R_m : measured radiance
  - R_{ref} : radiance observed in cloud-free columns
  - R_{Tcloud} : radiance observed from cloud at temperature T

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

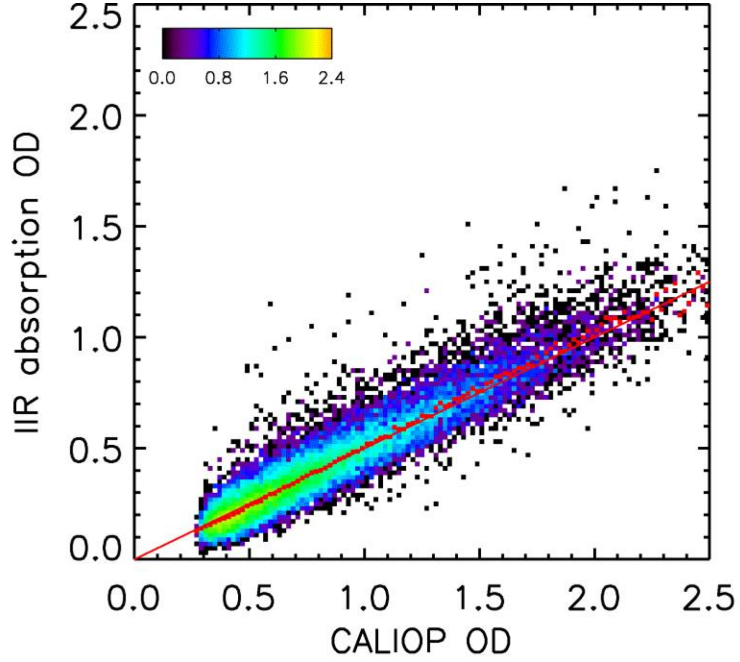
Infrared retrieval of effective emissivity and optical depth:

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

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



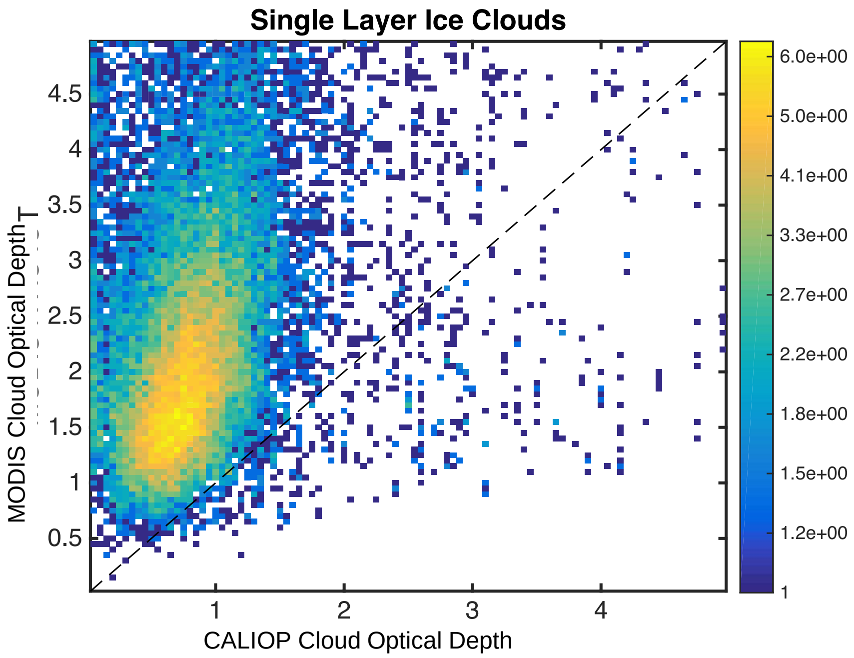
IIR cirrus OD retrievals vs CALIOP "constrained" retrievals



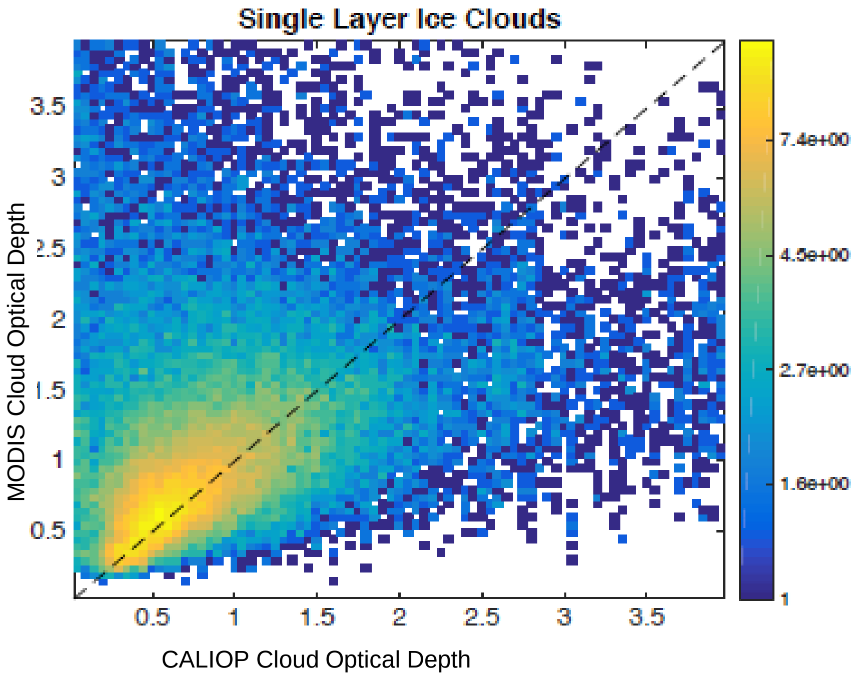
(Garnier et al. 2012)

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 (±60° latitude)



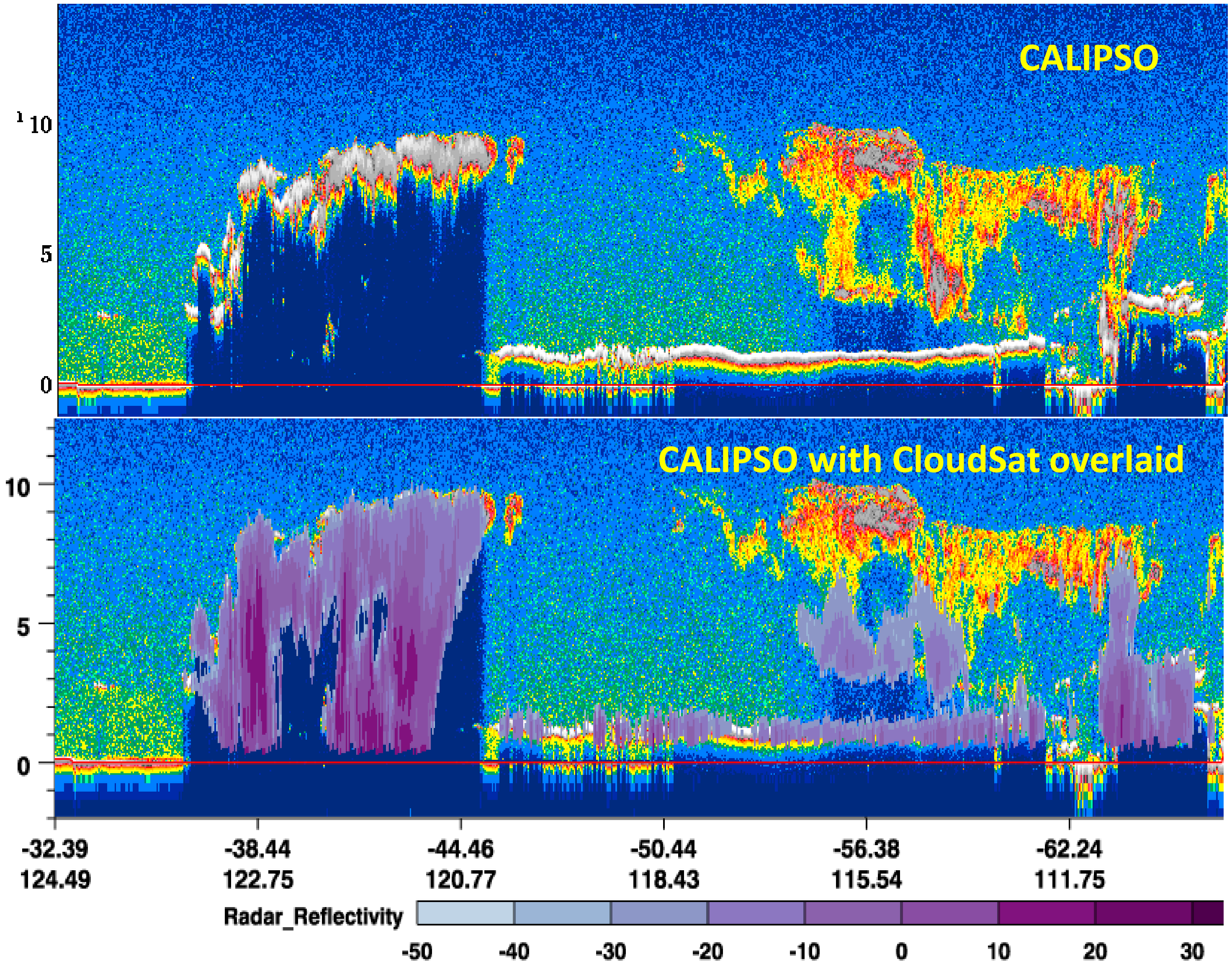
MODIS C6 vs CALIOP V4

(Holz et al., ACP 2016)

Lidar-Radar Synergies

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

Observations over the Indian Ocean and Antarctica

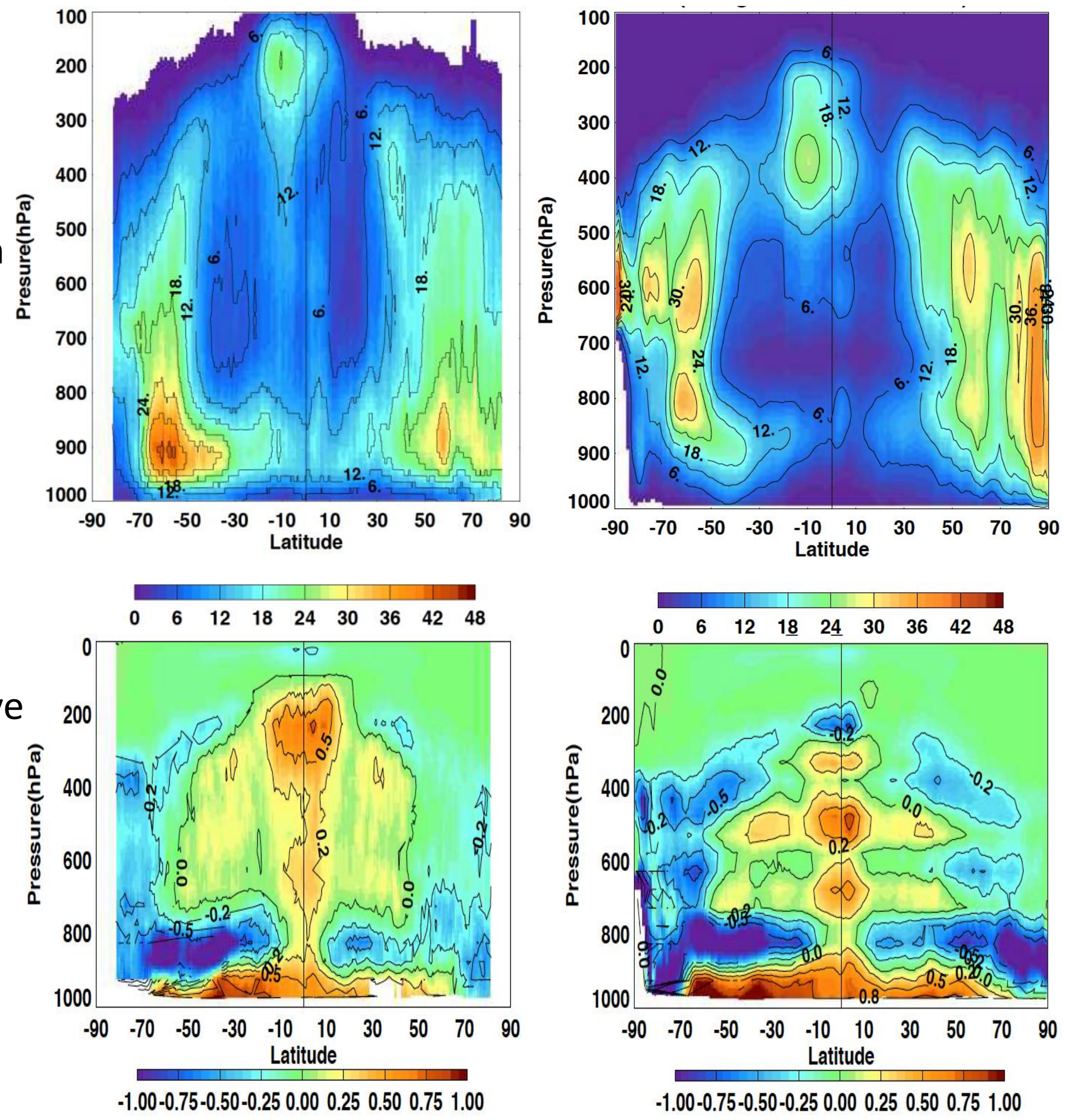


Our first true view of cloud vertical distribution

CALIOP-CloudSat | MODIS + GEO

Vertical Cloud Fraction

Cloud Radiative Effect (K/day)



(Kato et al. 2019)

- Cloud climatologies from passive sensors are ‘top-heavy’
  - Passive sensors only view tops of deep clouds
  - View of lower clouds blocked by upper clouds

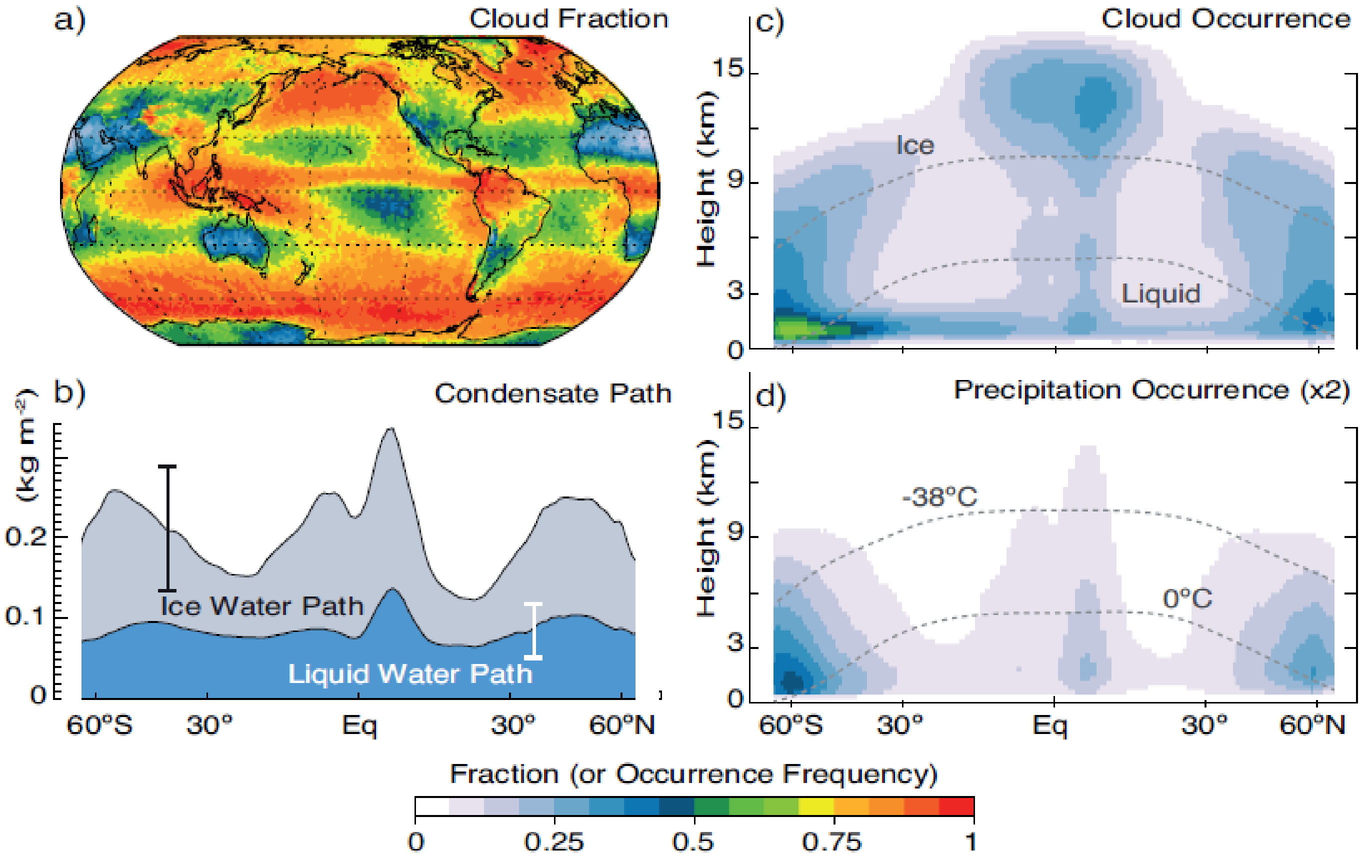
- This leads to large errors in estimates of atmospheric heating from clouds
- Important for coupling of clouds and atmospheric circulation

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 is now on orbit!
… ATLID first light in a few weeks

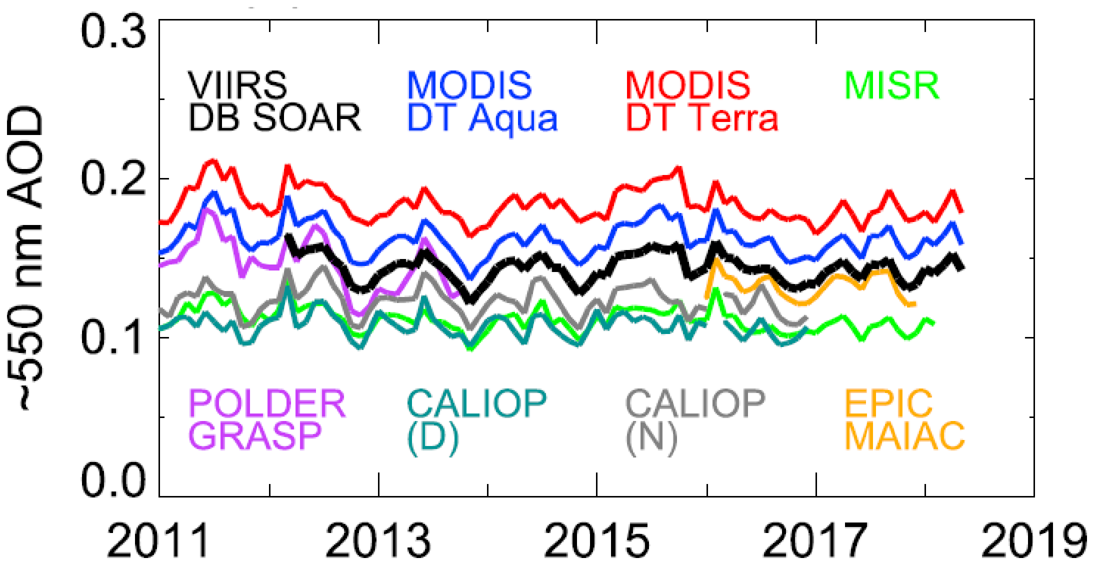
What's left to do?

Aerosols

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

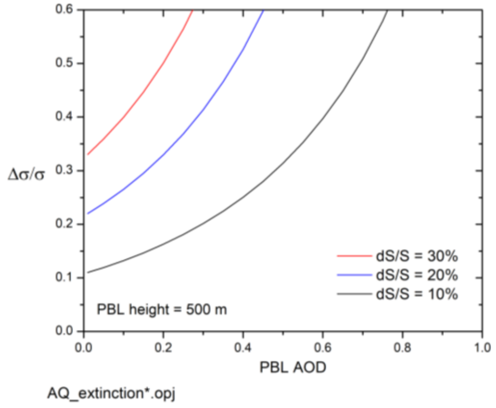
- Quantify climate forcing of aerosols
- Improve representation of aerosol in models

Global AOD from Observations

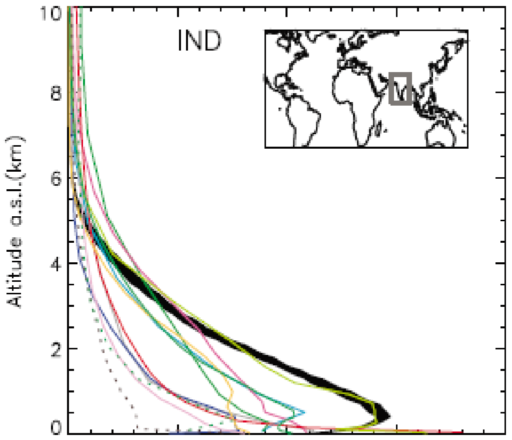


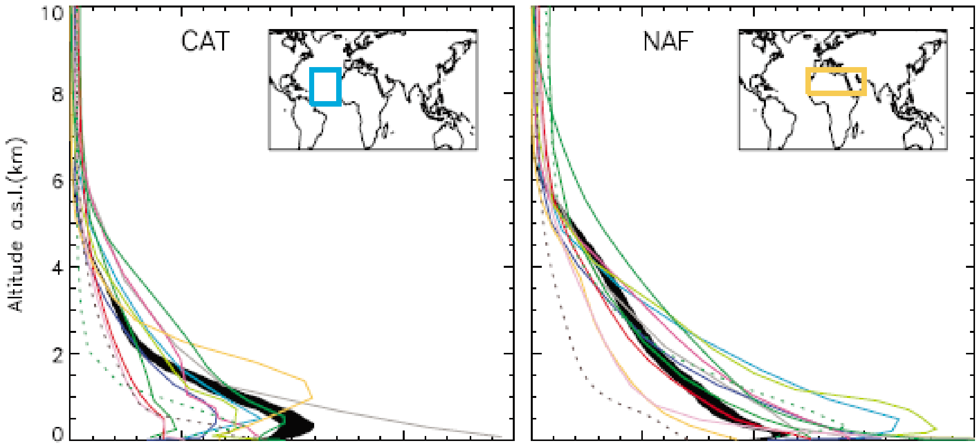
(Sayer et al. 2018)

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



Model Comparisons





(Koffi et al. 2012)

… 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

References

- Brient, F., T. Schneider, Z. Tan, S. Bony, X. Qu, A. Hall, 2015: Shallowness of tropical low clouds as a predictor of climate models' response to warming. Clim. Dyn. doi:10.1007/s00382-015-2846-0
- Chepfer, H., V. Noel, D. Winker and M. Chiriaco, 2014: "Where and when will we observe cloud changes due to climate warming?", *Geophys. Res. Lett.*, **41**, 8387–8395, https://doi.org/10.1002/2014GL061792.
- di Michele, S., T. McNally, P. Bauer, and I. Genkova, 2013: "Quality Assessment of Cloud-Top Height Estimates From Satellite IR Radiances Using the CALIPSO Lidar", *IEEE Trans. Geosci. Remote Sens.*, **51**, 2454–2464, https://doi.org/10.1109/TGRS.2012.2210721.
- Garnier A., J. Pelon, P. Dubuisson, M. Faivre, O. Chomette, N. Pascal and D. P. Kratz, 2012: "Retrieval of cloud properties using CALIPSO Imaging Infrared Radiometer. Part I: effective emissivity and optical depth", *J. Appl. Meteor. Climatol.*, **51**, 1407–1425, https://doi.org/10.1175/JAMC-D-11-0220.1.
- Holz, R., S. Ackerman, F. Nagle, R. Frey, S. Dutcher, R. Kuehn, M. Vaughan, and B. Baum. 2008: "Global MODIS Detection and Height Evaluation Using CALIOP", *J. Geophys. Res.*, **113**, D00A19, https://doi.org/10.1029/2008JD009837.
- Holz, R. E., S. Platnick, K. Meyer, M. Vaughan, A. Heidinger, P. Yang, G. Wind, S. Dutcher, S. Ackerman, N. Amarasinghe, F. Nagle and C. Wang, 2016: "Resolving ice cloud optical thickness biases between CALIOP and MODIS using infrared retrievals", *Atmos. Chem. Phys.*, **16**, 5075–5090, https://doi.org/10.5194/acp-16-5075-2016.
- Kar, J., K.-P. Lee, M. A. Vaughan, J. L. Tackett, C. R. Trepte, D. M. Winker, P. L. Lucker and B. J. Getzewich, 2019: "CALIPSO Level 3 Stratospheric Aerosol Product: Version 1.00 Algorithm Description and Initial Assessment", *Atmos. Meas. Tech.*, **12**, 6173–6191, https://doi.org/10.5194/amt-12-6173-2019.
- Kato, S., F. G. Rose, S. H. Ham, D. A. Rutan, A. Radkevich, T. E. Caldwell, S. Sun-Mack, W. F. Miller and Y. Chen, 2019: "Radiative Heating Rates Computed with Clouds Derived from Satellite-based Passive and Active Sensors and their Effects on Generation of Available Potential Energy", *J. Geophys. Res. Atmos.*, **124**, 1720–1740, https://doi.org/10.1029/2018JD028878.

References

- Koffi, B., M. Schulz, F.-M. Bréon, J. Griesfeller, D. M. Winker, Y. Balkanski, S. Bauer, T. Berntsen, M. Chin, W. D. Collins, F. Dentener, T. Diehl, R. C. Easter, S. J. Ghan, P. A. Ginoux, S. Gong, L. W. Horowitz, T. Iversen, A. Kirkevag, D. M. Koch, M. Krol, G. Myhre, P. Stier, and T. Takemura, 2012: "Application of the CALIOP Layer Product to evaluate the vertical distribution of aerosols estimated by global models: Part 1. AeroCom phase I results", *J. Geophys. Res.*, **117**, D10201, https://doi.org/10.1029/2011JD016858.
- Liu, Z., A. Omar, M. Vaughan, J. Hair, C. Kittaka, Y. Hu, K. Powell, C. Trepte, D. Winker, C. Hostetler, R. Ferrare, and R. Pierce, 2008: "CALIPSO lidar observations of the optical properties of Saharan dust: A case study of long-range transport", *J. Geophys. Res.*, **113**, D07207, https://doi.org/10.1029/2007JD008878.
- Oikawa, E., T. Nakajima and D. Winker, 2018: "An evaluation of the shortwave direct aerosol radiative forcing using CALIOP and MODIS observations", *J. Geophys. Res. Atmos.*, **123**, 1211–1233, https://doi.org/10.1002/2017JD027247.
- Sayer, A. M., N. C. Hsu, J. L. Woogyung, V. Kim, O. Dubovik, S. T. Dutcher, D. Huang, P. Litvinov, A. I. Lyapustin, J. L. Tackett and D. M. Winker, 2018: "Validation of SOAR VIIRS over-water aerosol retrievals, and context within the global satellite aerosol data record", *J. Geophys. Res. Atmos.*, **123**, 13,496–13,526, https://doi.org/10.1029/2018JD029465.
- Stephens, G., D. Winker, J. Pelon, C. Trepte, D. Vane, C. Yuhas, T. L'Ecuyer and M. Lebsock, 2018: "CloudSat and CALIPSO within the A-Train: Ten years of actively observing the Earth system", *B. Am. Meteorol. Soc.*, **99**, 583–603, https://doi.org/10.1175/BAMS-D-16-0324.1.
- Textor, C., M. Schulz, S. Guibert, S. Kinne, Y. Balkanski, and co-authors, 2006: Analysis and quantification of the diversities of aerosol life cycles within AeroCom. Atmos. Chem. Phys. 6, 1777-1813. https://www.atmos-chem-phys.net/6/1777/2006/
- Vaillant de Guélis, T., H. Chepfer, R. Guzman, M. Bonazzola, D. M. Winker and V. Noel, 2018: "Space lidar observations constrain longwave cloud feedback", *Sci. Rep.*, **8**, 16570, https://doi.org/10.1038/s41598-018-34943-1.