Satellite remote sensing of aerosol vertical distribution: A critical review and future directions

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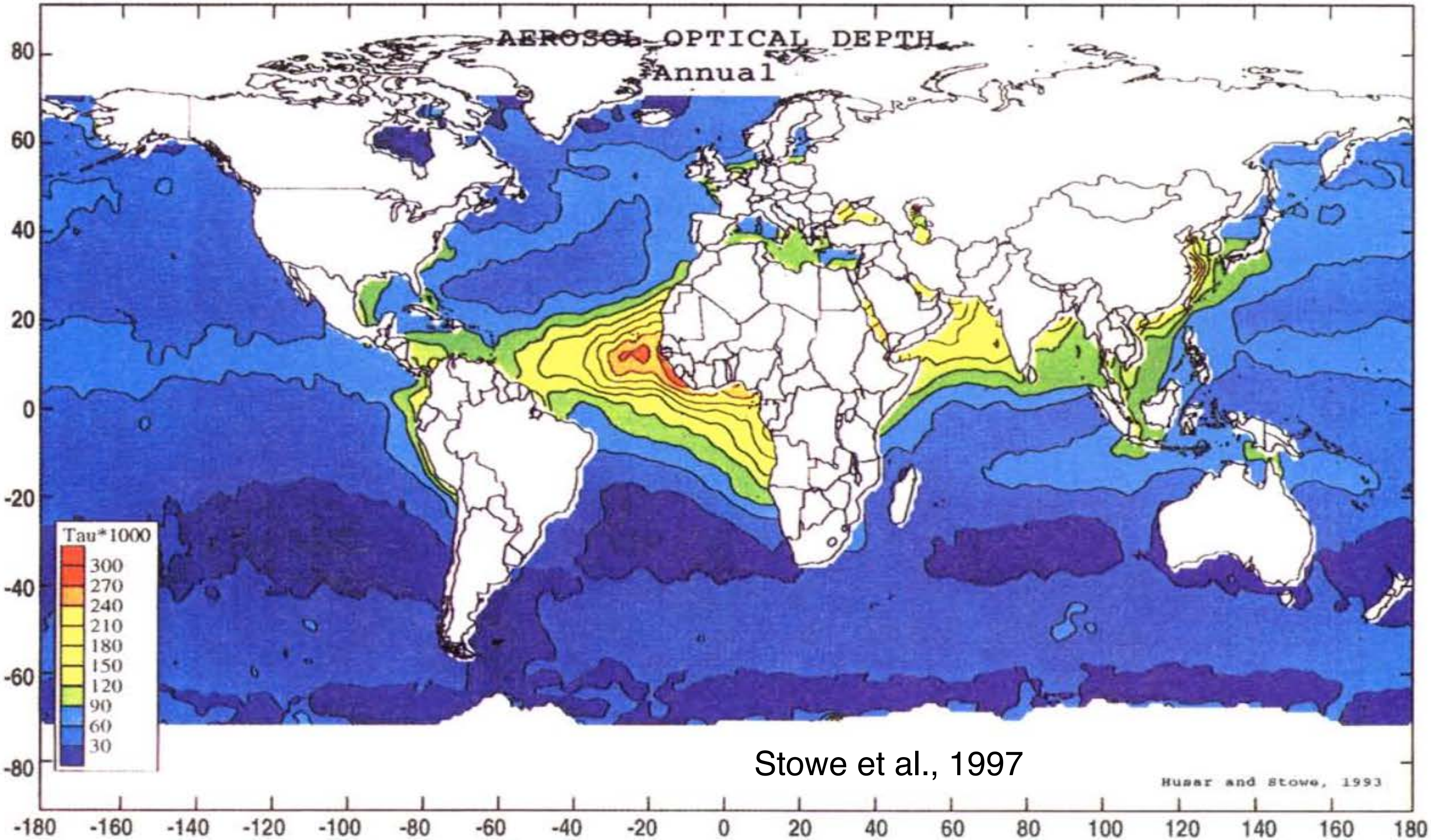
Outline

- Background & Acknowledgements
- Importance
- Uncertainties
- Overview of techniques
- Thoughts for future directions

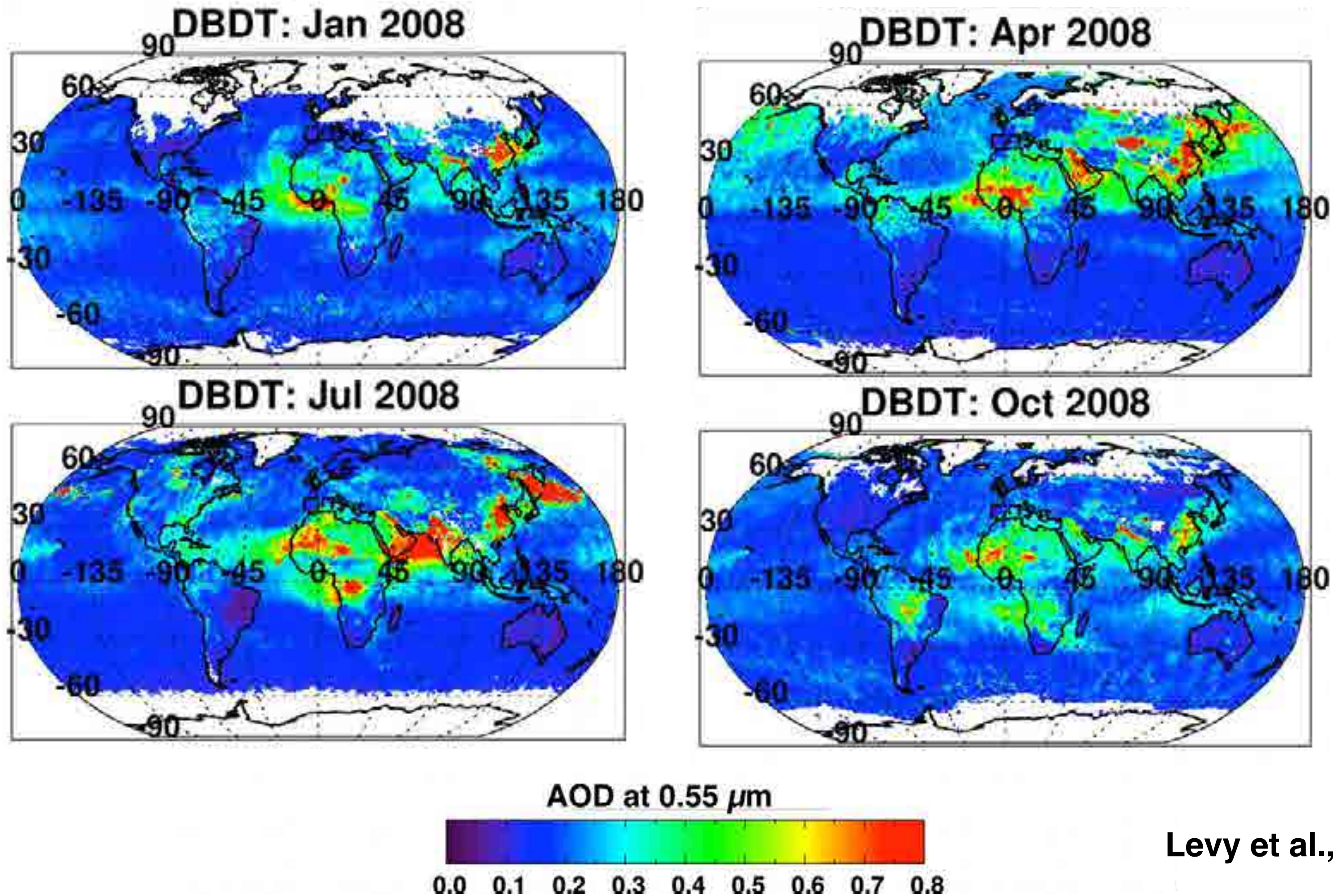
24 yrs ago: AOD from AVHRR



Stowe et al., 1997

Plate 2. Mean distribution of τ^{A}_{SAT1} at 0.5 μm for 2 years prior to the eruption of Mount Pinatubo.

MODIS Collect-6 AOD @ 550 nm



Levy et al., 2013

Validation of AOD

Stowe et al., 1997

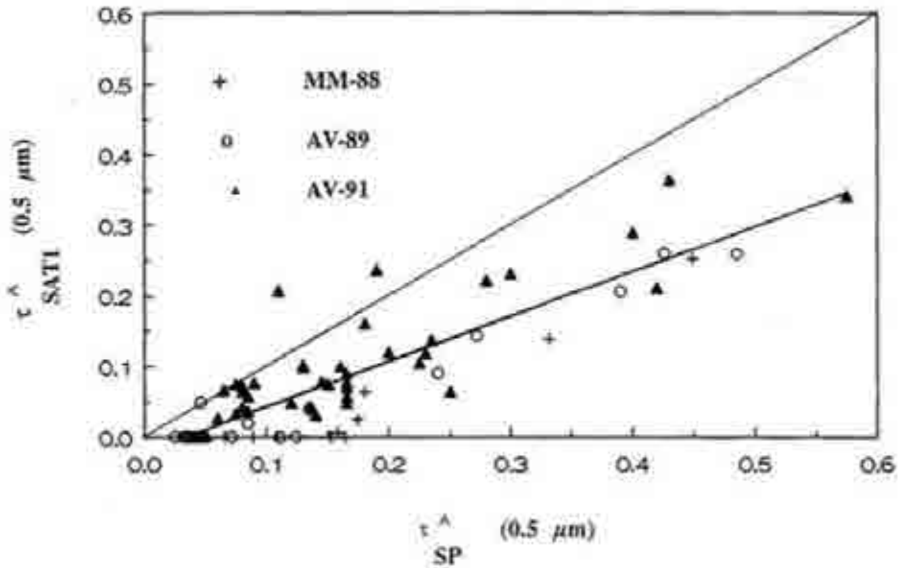
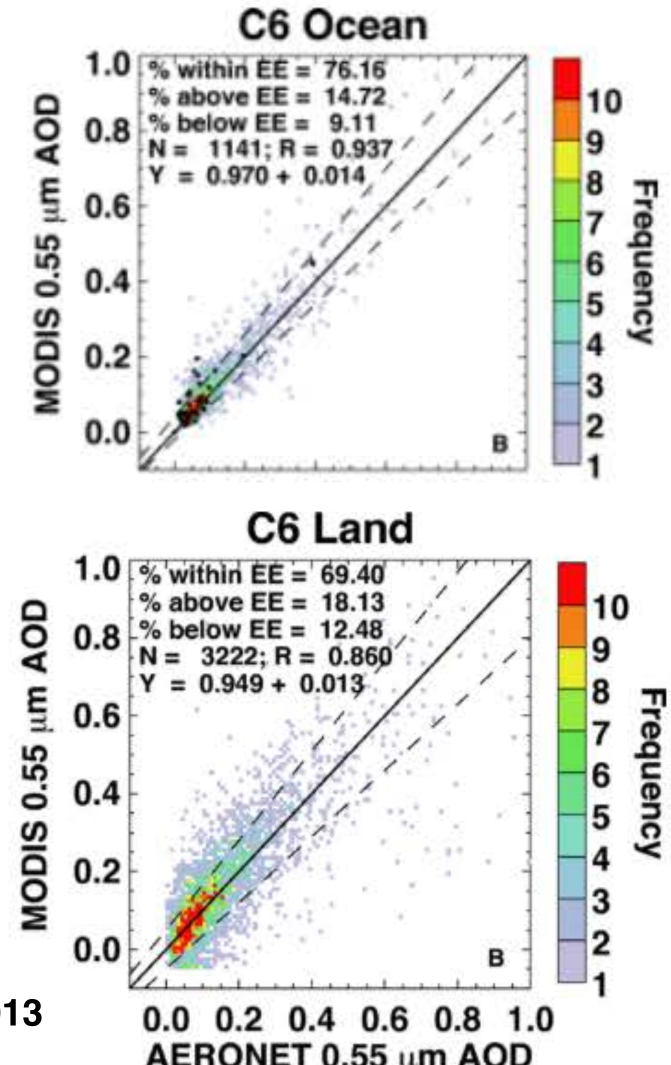


Figure 2. Regression of $\hat{\tau}_{SAT1}$ against Sun-photometer aerosol optical thickness at 0.5-μm wavelength.



Levy et al., 2013

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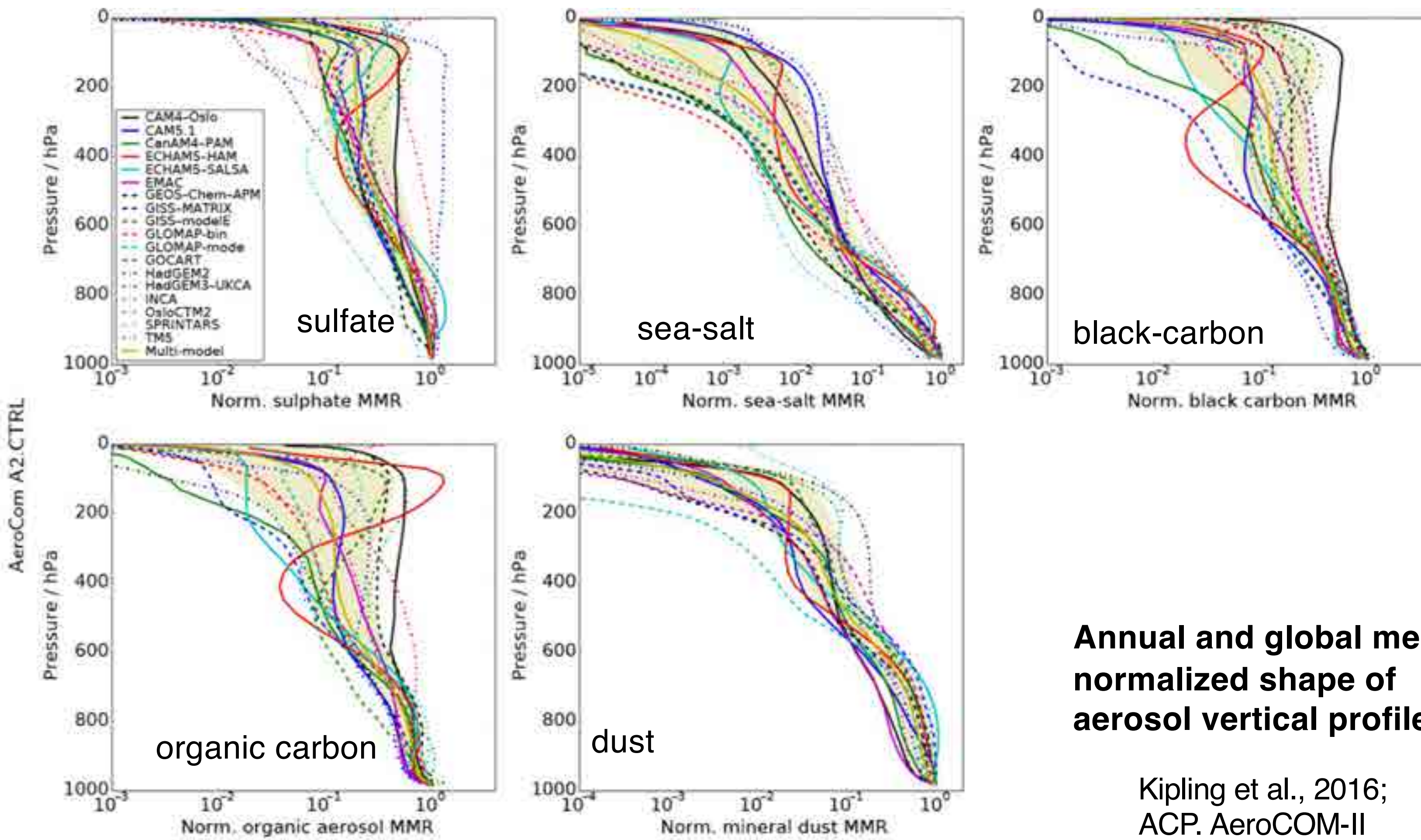
Importance of aerosol vertical distribution

- Monitoring surface air quality from space
- Aerosol direct and indirect effects on climate
- Aerosol effects on atmospheric chemistry & gas retrievals
- Long-range transport and biosphere-atmosphere interactions
- Air quality & climate forecast
- …

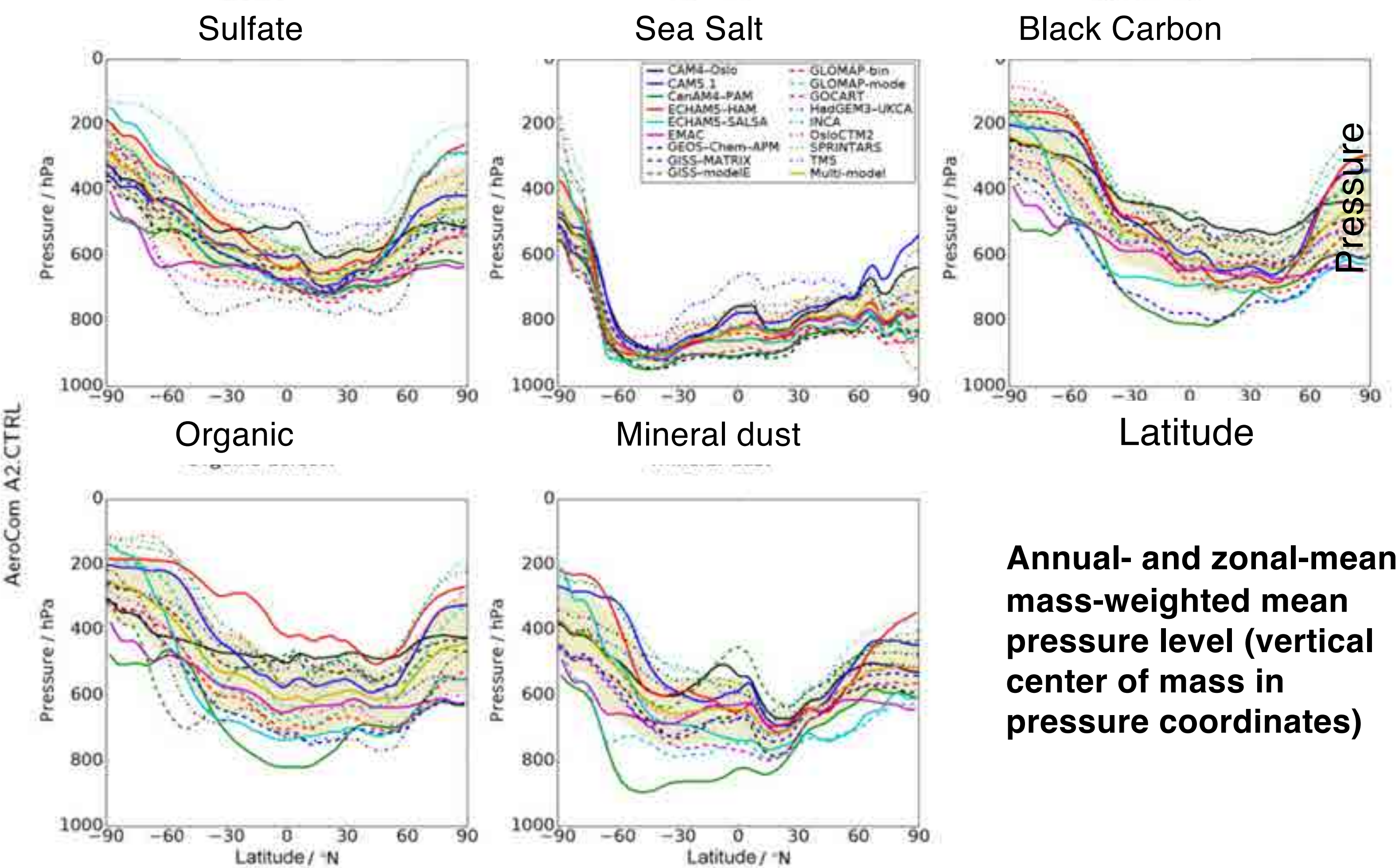
Large uncertainty in aerosol vertical profile (1)



Annual and global mean normalized shape of aerosol vertical profile

Kipling et al., 2016; ACP. AeroCOM-II

Large uncertainty in aerosol vertical profile (2)

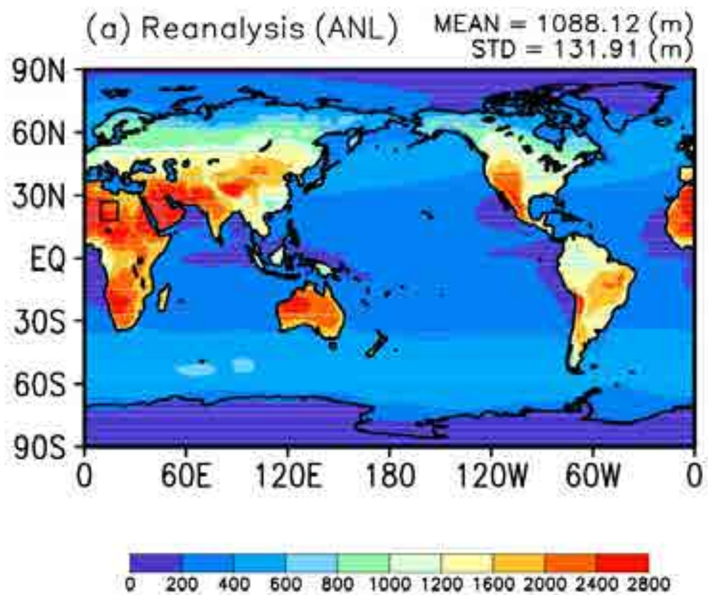


Annual- and zonal-mean mass-weighted mean pressure level (vertical center of mass in pressure coordinates)

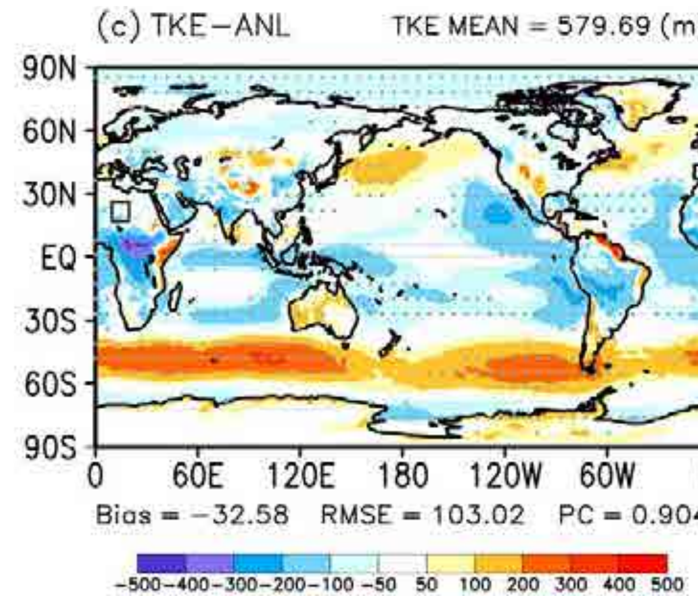
Modeled PBLH itself is elusive in some ways

Definition of PBLH; PBL scheme; …

PBLH diurnal amplitude



Annual-mean PBLH difference



Shin et al., 2018.

- No observation data for evaluation of global PBLH
- Three re-analysis datasets are used as the baseline
- Inconsistent diurnal variation and definition of PBLH among different models

Different techniques for sensing AVD from space

Diurnal variation
Global converge

Active

-*Lida*r such as CALIOP and CATS

Passive

- *Limb/ occultation* : SAGE, OMPS
- *Stereo photogrammetry* : ATSR, MISR
- *UV, Deep Blue + Polarization* : OMI, TROPOMI, POLDER/PARASOL
- *Oxygen absorption spectroscopy:* POLDER and MERIS, OMI, TROPOMI, SCIAMACHY; EPIC/DSCOVR, GEMS
- *Infrared:* dust and smoke, MODIS, VIIRS, AIRS…

Active + Passive: OMI/OMPS, MODIS/VIIRS, and CALIOP

Elastic backscatter lidar technique
(532 nm, polar-orbiting at 700 km ABS)

$$P(r) = E_0 \frac{cA}{2r^2}\left[\frac{3}{8\pi}\beta_m(r) + \frac{p_a(\pi,r)}{4\pi}\beta_a(r)\right] e^{-2\int_0^r \beta_e(r')dr'} + \overset{\text{M. sca.}}{M(r)} + \overset{\text{bkgrd.}}{b}$$

Pros

- Details: profiling of aerosol backscattering
- Simplicity: assumption of one unknown, lidar ratio, to derive extinction
- Maturity: demonstrated by CALIPSO and CATS mission already
- Robust: to answer if aerosol layer is above PBLH (mixing layer height)
- All time: day and night

Cons

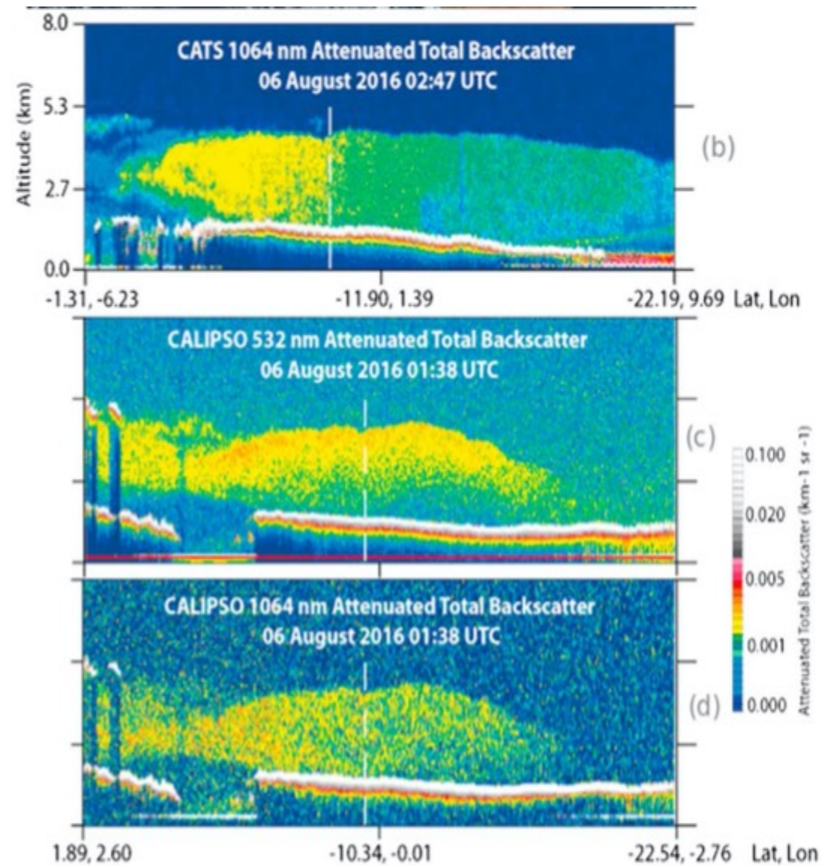
- Narrow: very limited spatial converge; 0.2% of global surface area in 16 days
- Attenuation: lose the signal for moderate-to-thick aerosol layer or low AOD loading
- Less accurate in daytime

Multiple-wavelength lidar with depolarization

More Pros

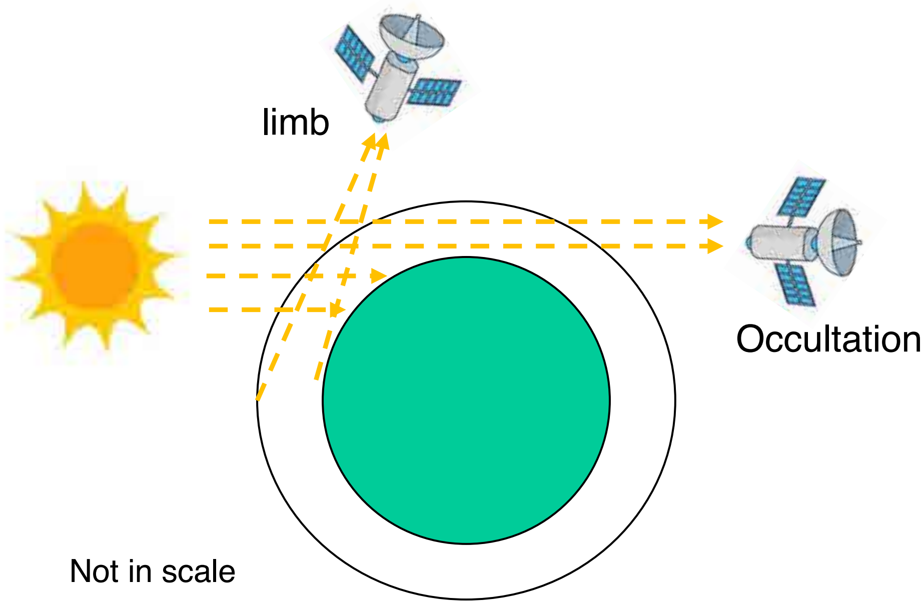
- Particle shape:
  - non-spherical vs. spherical
- More constraints:
  - particle size
- More in-depth penetration:
  - possible to probe columnar AOD up to 5 at 1062 nm at night

There are more advanced and complex ones such as HSRL that directly measures aerosol attenuation and backscatter.



Rajapakshe et al., 2017

Limb/Occultation Technique



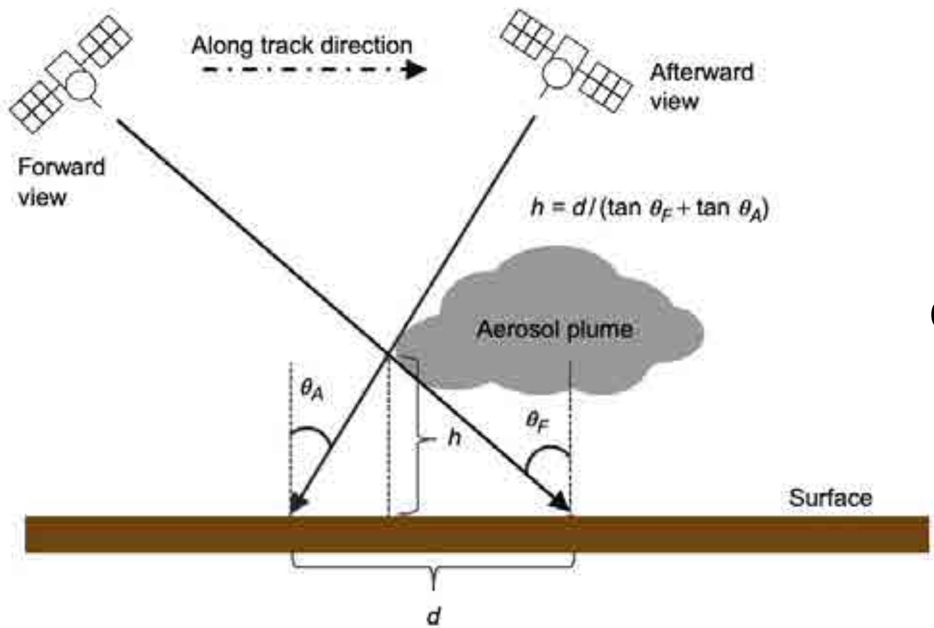
Pros

- Upper troposphere and low stratosphere (UTLS)
- Relatively accurate for occultation technique

Cons

- Data is very sparse for occultation technique
- Uncertainty gets larger at lower altitude
- No information for lower troposphere
- Need to assume particle properties for limb technique
- Earth curvature effect

Stereo photogrammetry



Xu et al., 2018

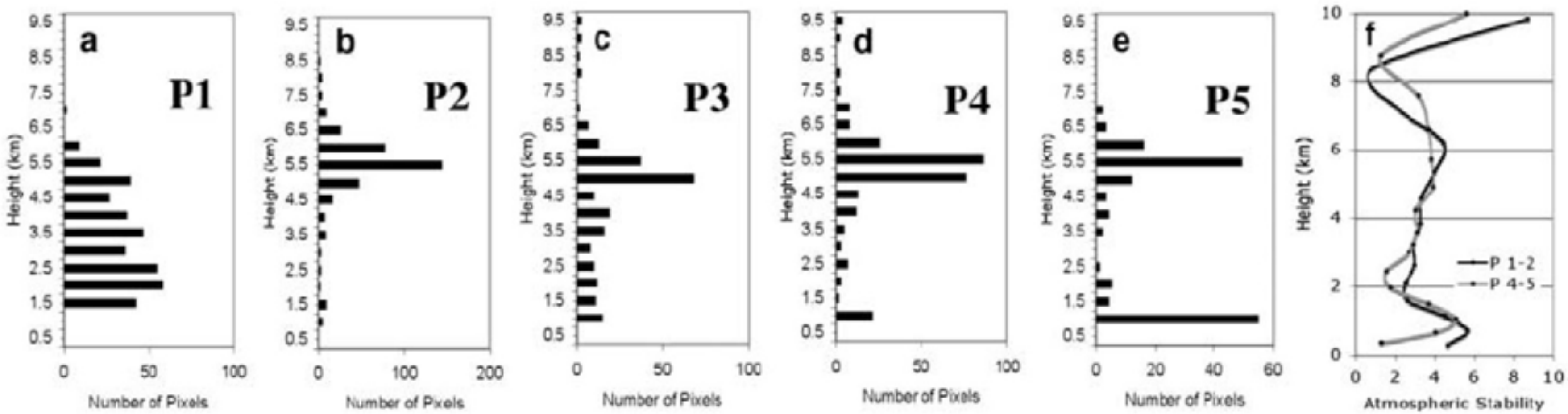
Pros

- Simplicity; 1 band & >2 angles
- No need of a priori on particle properties; pure geometry
- Accurate (depending on pixel resolution and georeferencing accuracy)
- Air motion vector (AMV) is retrieved as a by-product

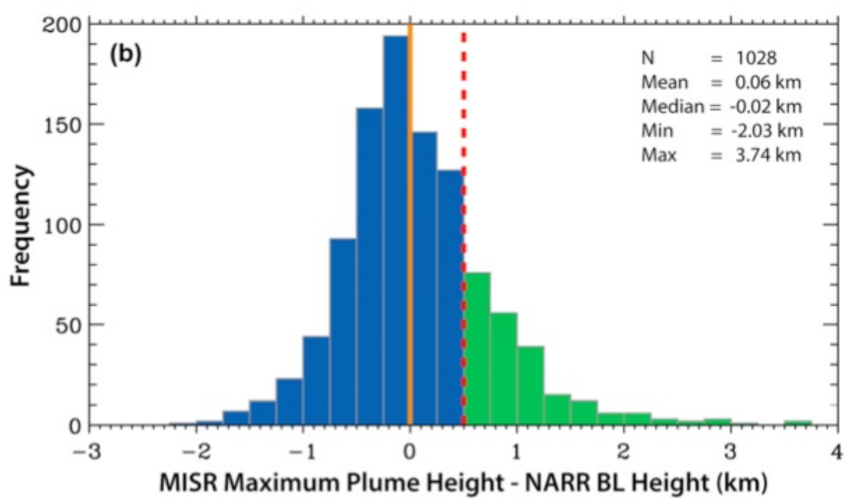
Cons

- Uncertainty subject to the wind-induced parallax displacement, especially in direction along the track
- Requires texturally rich features. (not for well-mixed plumes)
- Not for optically moderate or thin plumes that are transparent to reflect surface features

MISR-based smoke plume height



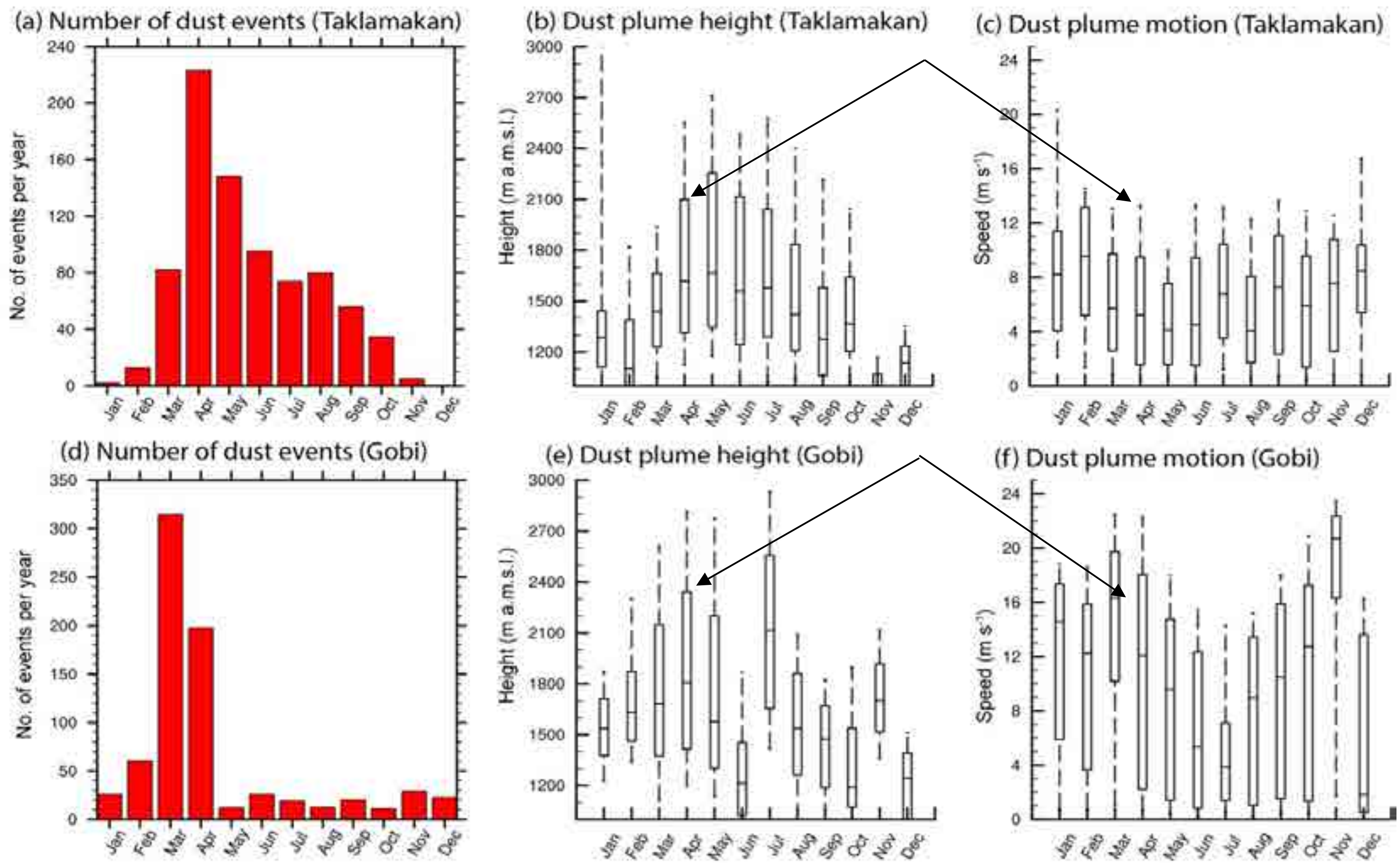
Kahn et al., 2007



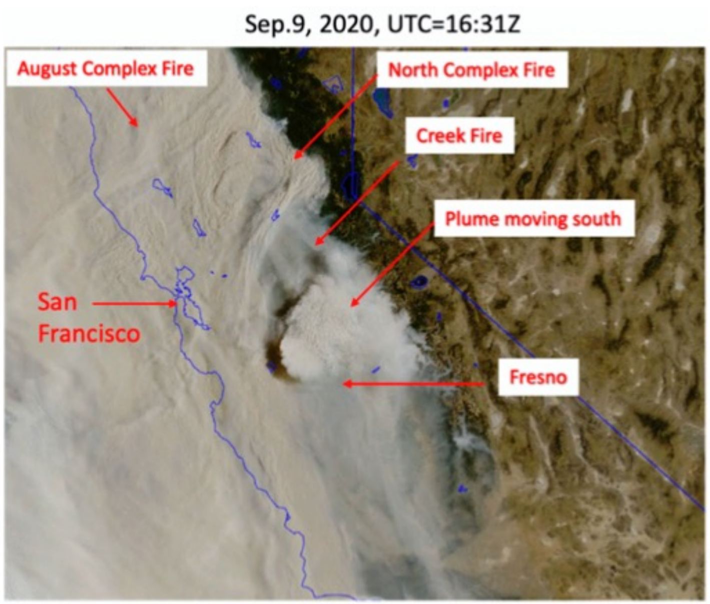
Peterson et al., 2014

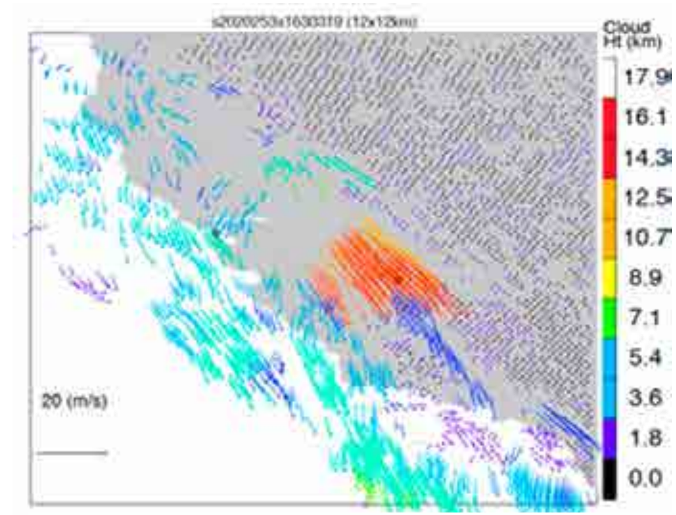
MISR-based analysis of dust plume motion and dust plume height at the dust source region

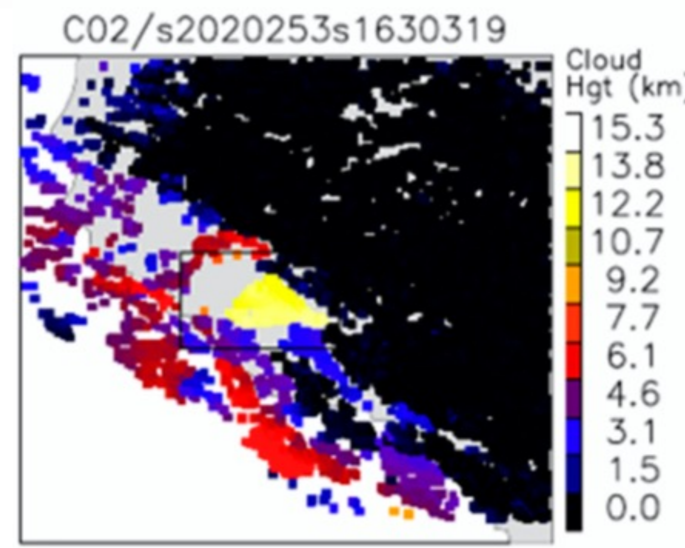
Yu et al., 2019



GEO + GEO



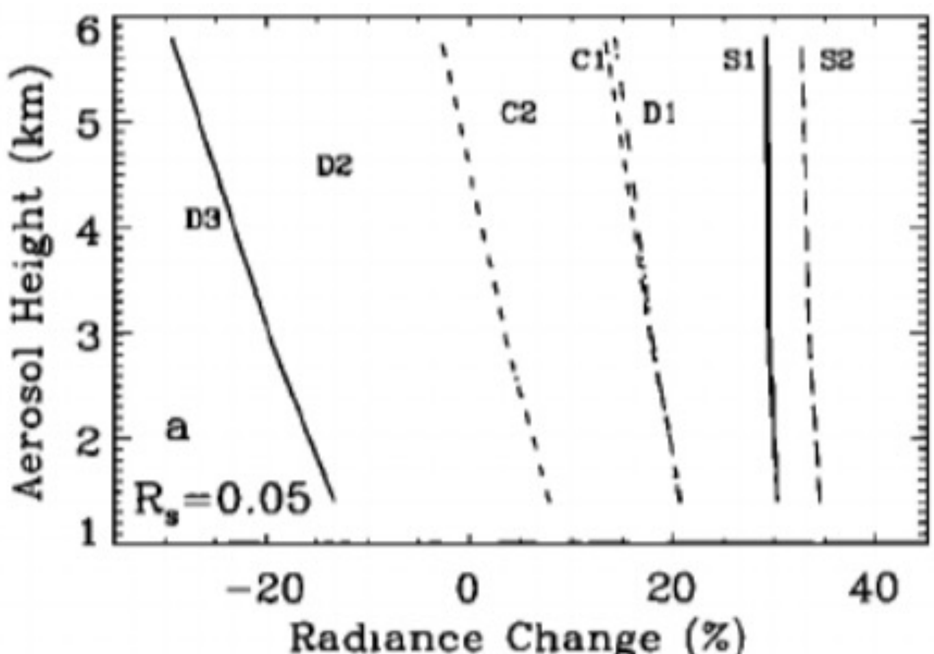




- Minimize the error otherwise possibly in the LEO in the along-track direction
- Has the potential in high temporal frequency
- Other ‘cons’ remain

Carr et al. (2020)

UV, Deep Blue



380 nm

Torres et al., 1998

Pros

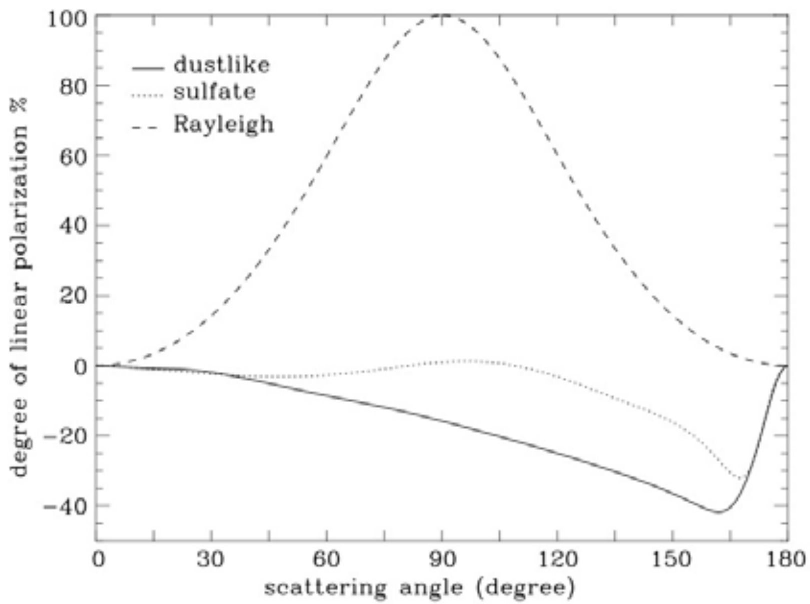
- Rayleigh scattering can be computed accurately
- Less uncertainty in low boundary conditions
- Sensitive to absorption and height

Cons

- Not for non-absorbing aerosols
- Need a priori of aerosol absorption and AOD.

No routine product yet; case demonstration so far. Often AOD are retrieved from MODIS/VIIRS and then used as inputs for SSA and Height retrieval.

UV, Deep Blue + Polarization



Zeng et al., 2008

Pros

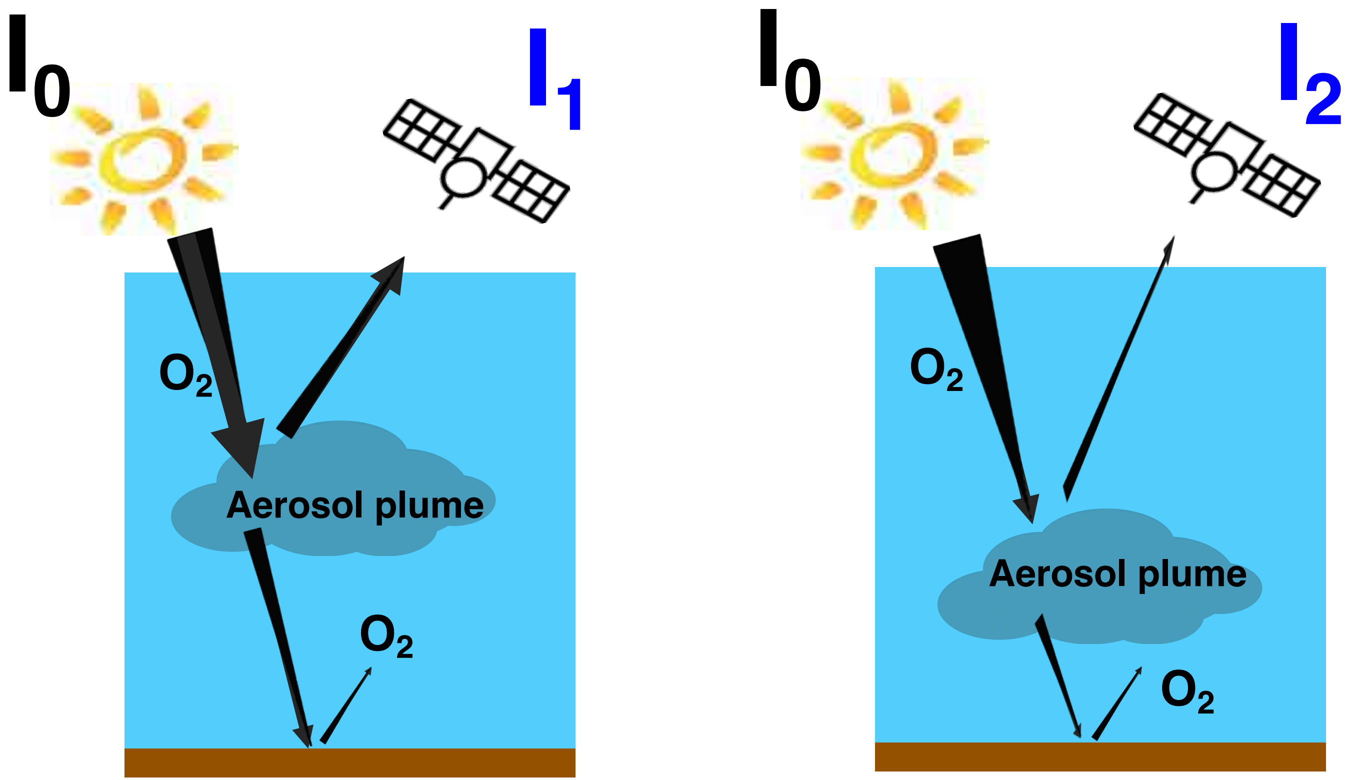
- Less sensitivity to aerosol absorption
- For all types of aerosols
- Surface reflectance is low
- Rayleigh scattering can be computed accurately

Cons

- Need good constraints of AOD and particle size (and to some degree shape)
- Complexity

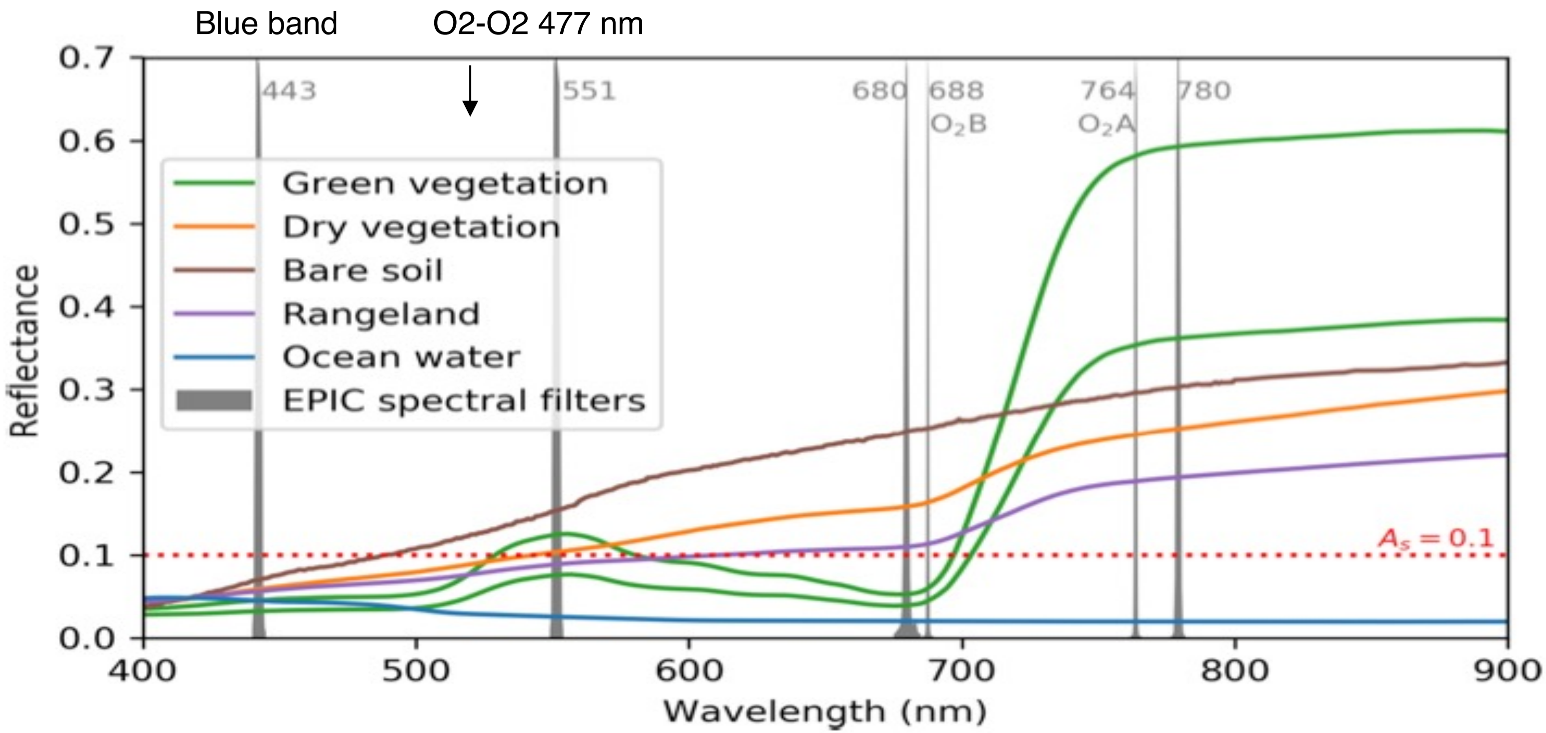
Research product exists via GRASP POLDER/PARASOL; but the product has not been assessed with real data.

Oxygen absorption spectroscopy



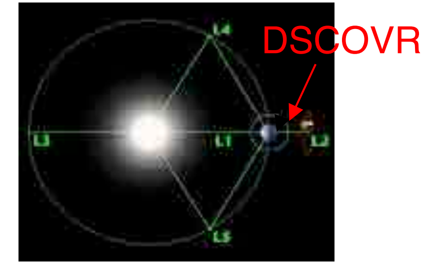
$I_1 > I_2$

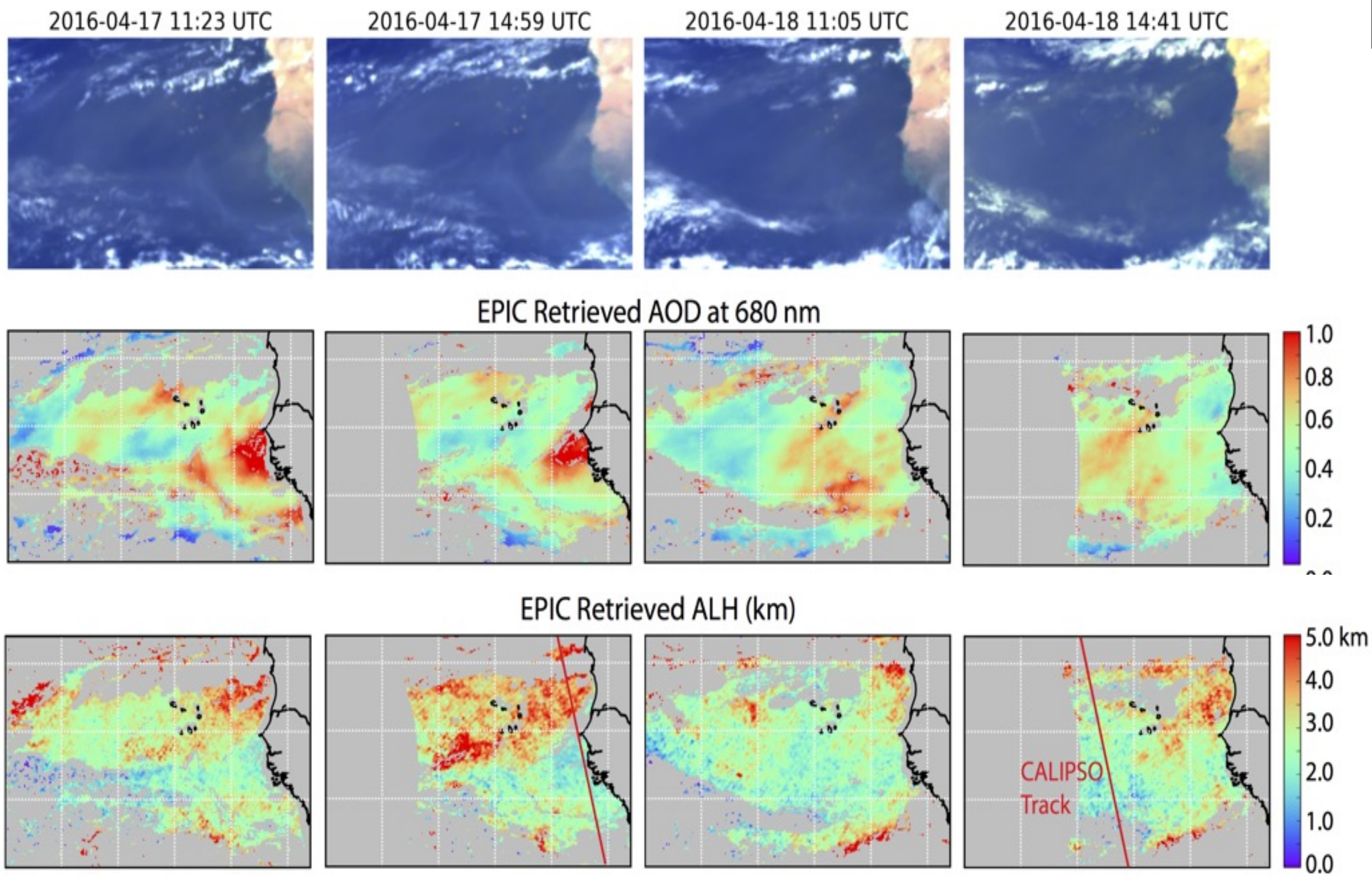
Oxygen absorption bands vs. surface reflectance spectra



O2 B-band has moderate absorption, stronger than O2-O2 at 477 nm and weaker than O2 A. O2 B-band also has very low surface reflectance, comparable if not lower than blue bands, due to Chlorophyll-a absorption.

Retrieval of diurnal variation AOD from EPIC's O_2 A and B bands



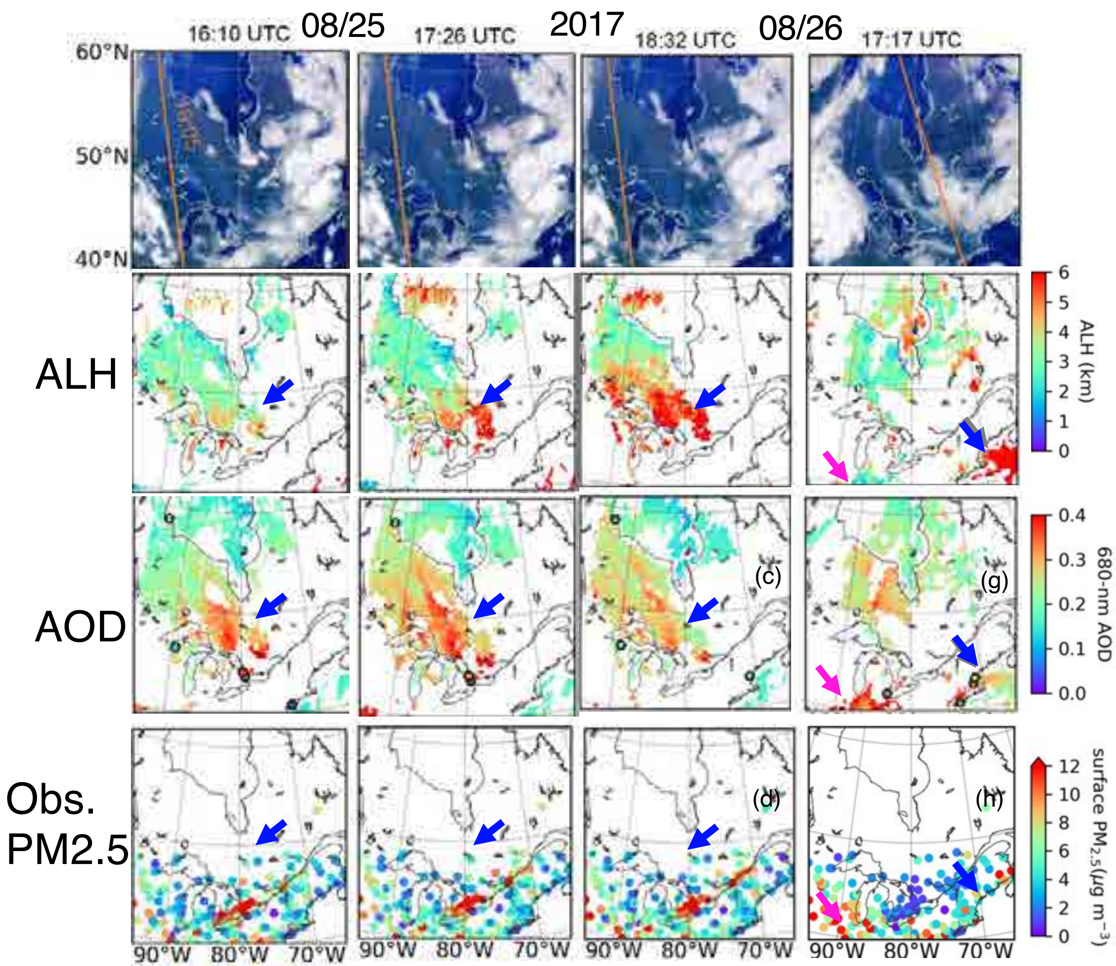


- AOD field clearly indicates mass continuity; high close to the source, and low in downwind.

- ALH shows no relationship with AOD

- ALH varies 1 – 5 km.

Implication to surface PM2.5 Air Quality Assessment



Location later affected by high AOD and descending layer of smoke

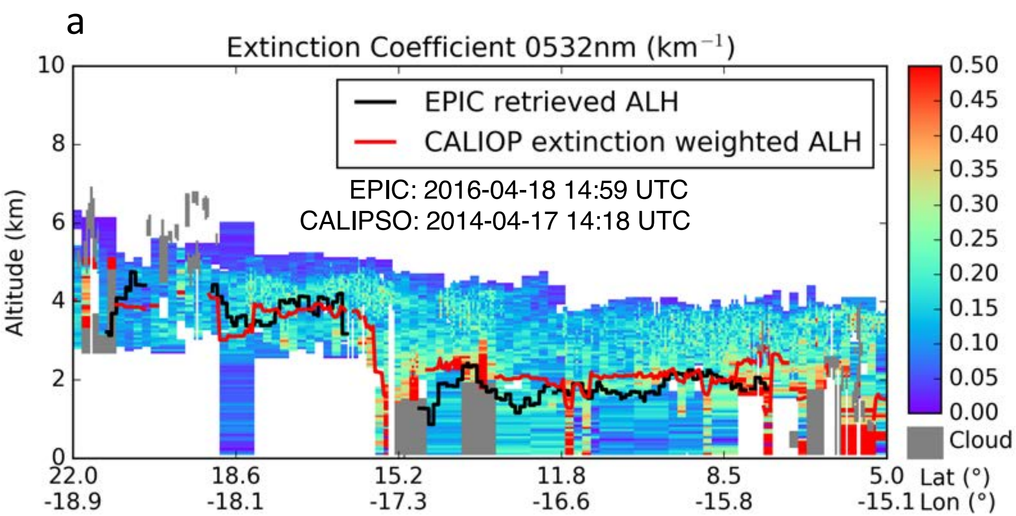
High surface PM2.5

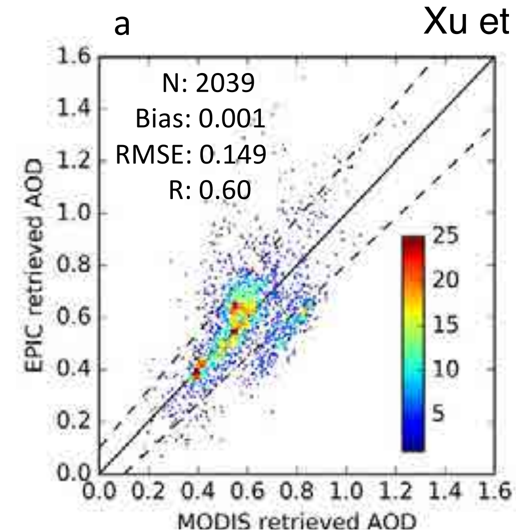
Location later affected by high AOD and lofted layer of smoke

Low surface PM2.5

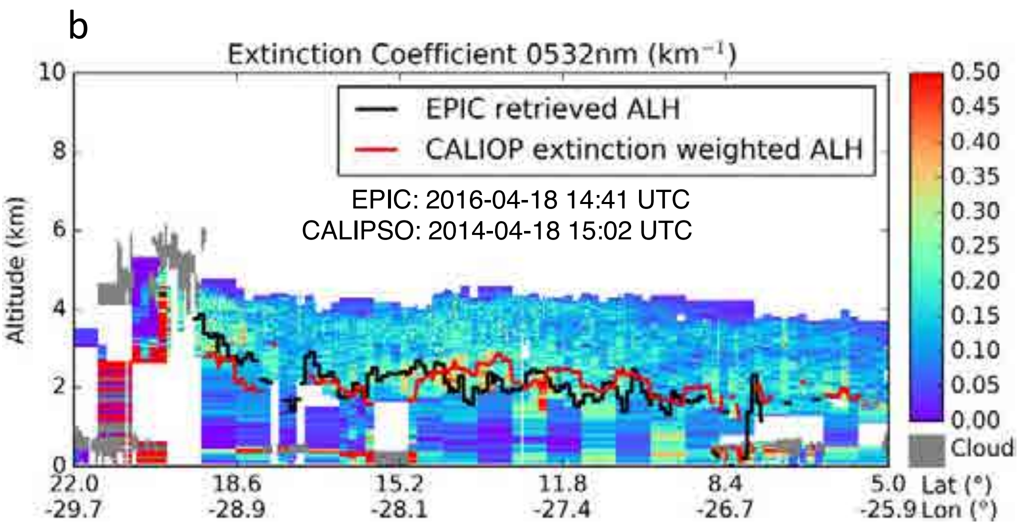
Validation with MODIS and CALIOP data

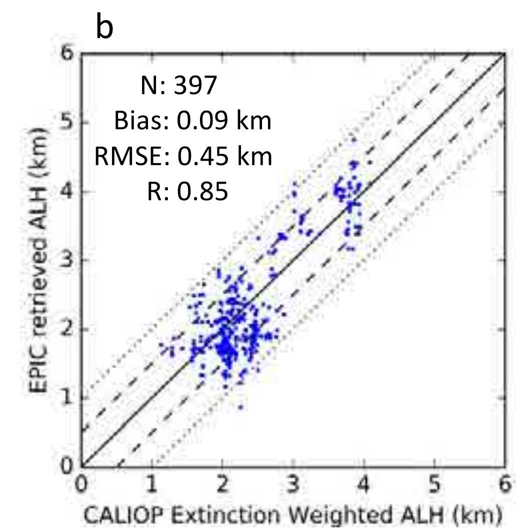
Xu et al., 2019, AMT



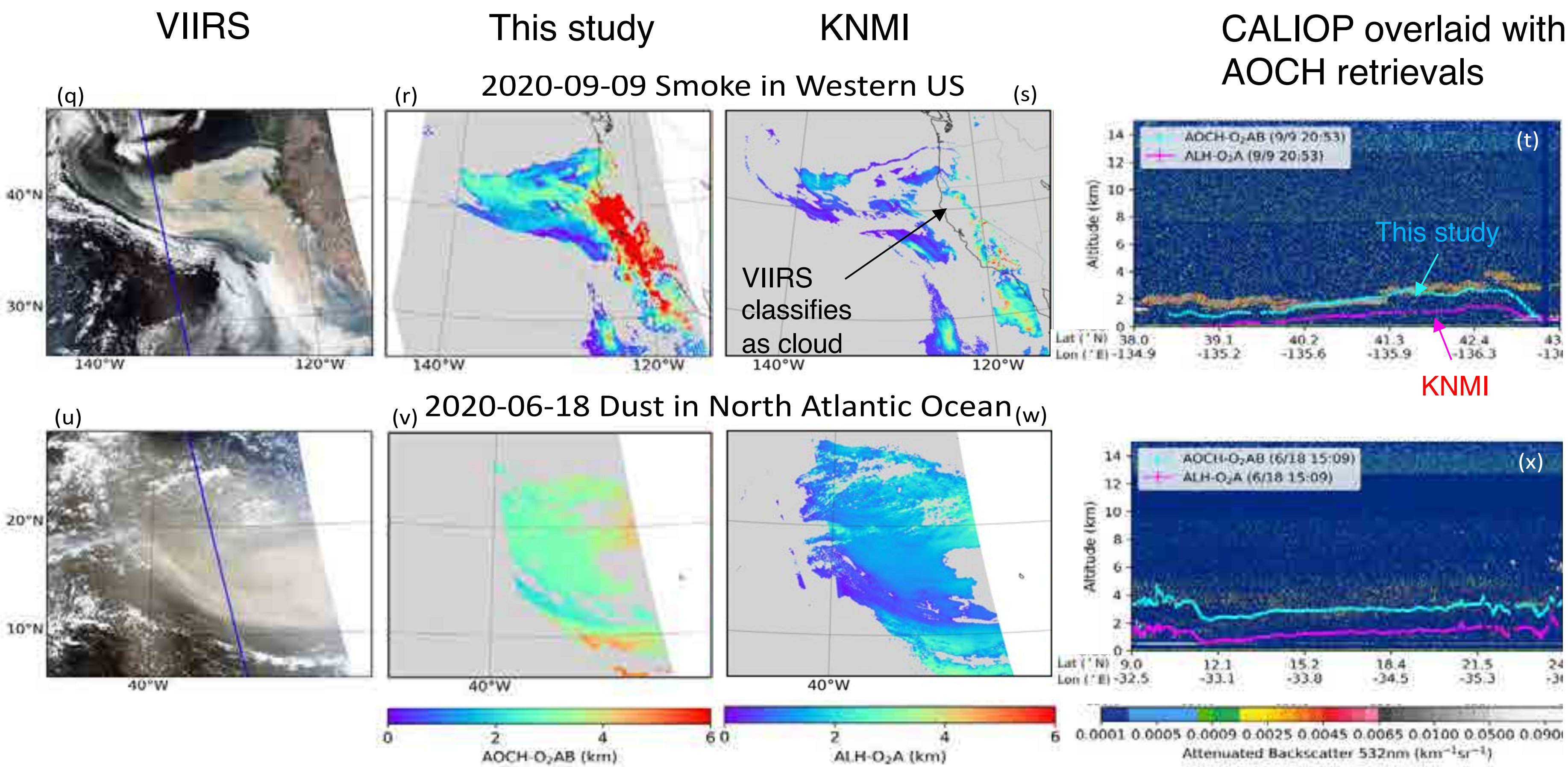


$$\mathrm{AOCH_{CALIOP}} = \frac{\sum_{i=1}^{n} \beta_{\mathrm{ext},i}\, Z_i}{\sum_{i=1}^{n} \beta_{\mathrm{ext},i}}$$





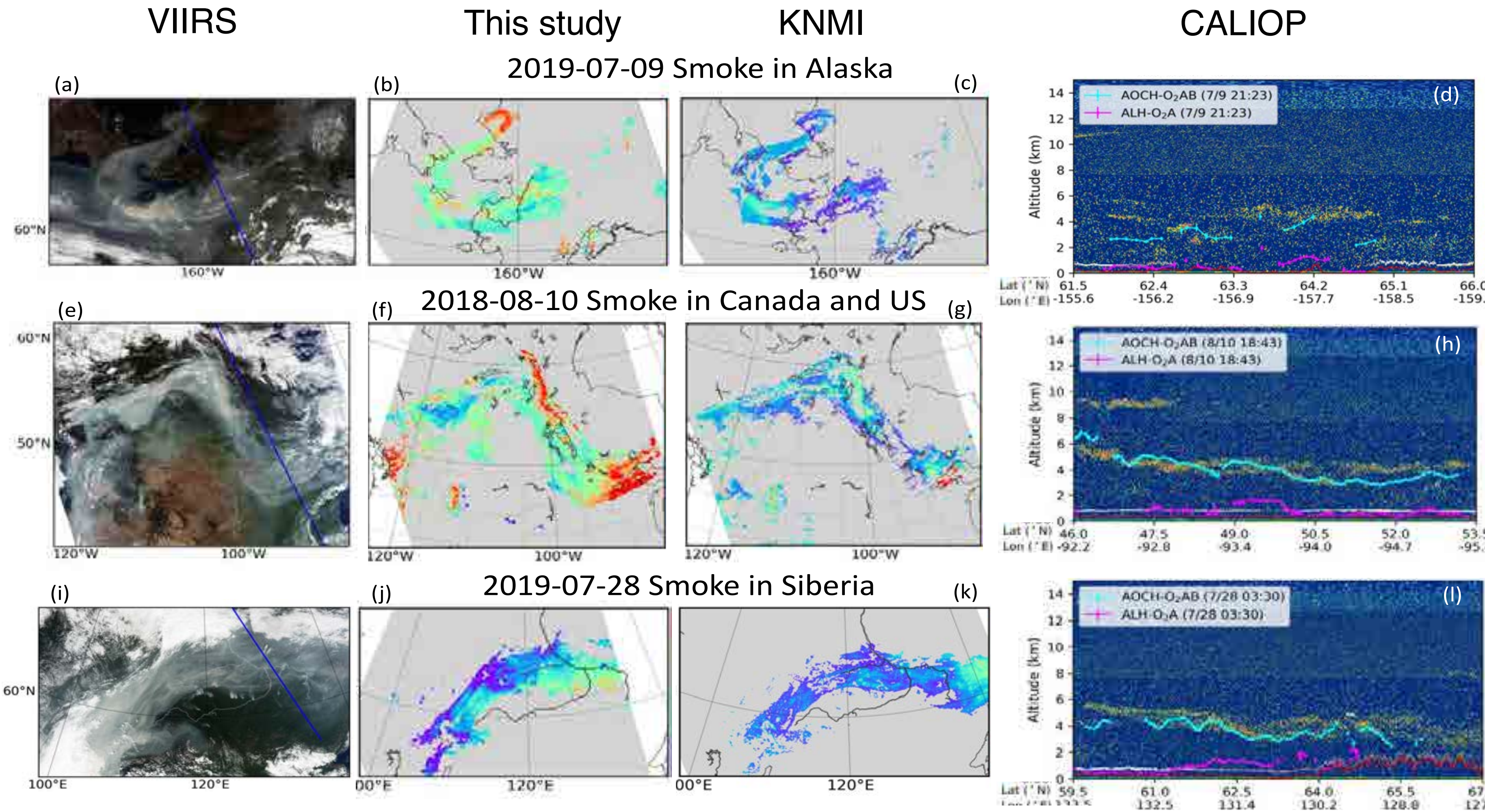
Enabled by TROPOMI



Algorithms using channels similar as EPIC.

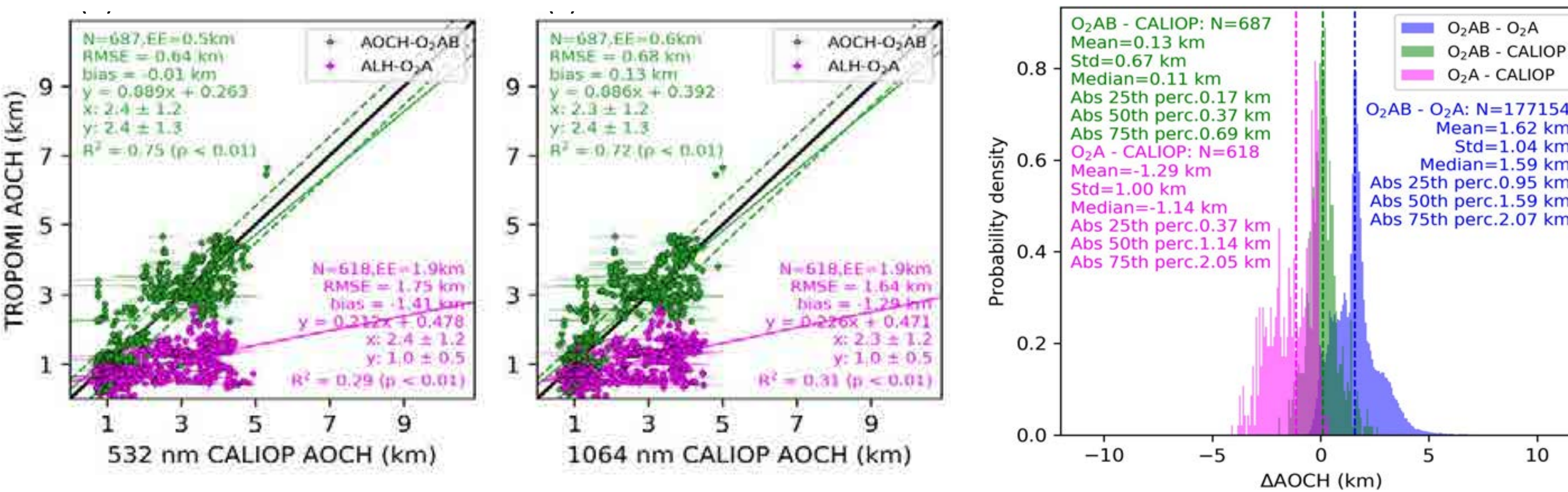
Chen et al., 2021, RSE, In review.
Don't cite or quote

More demonstration



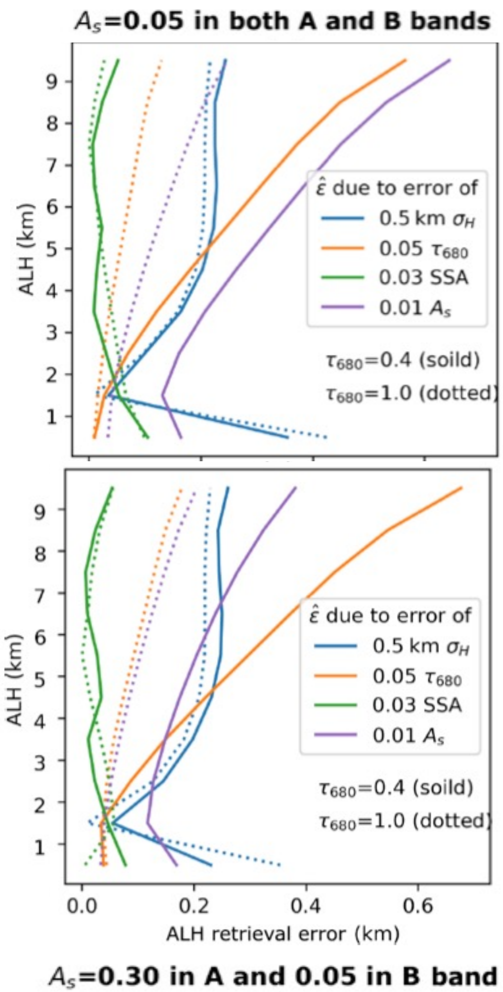
Chen et al., 2021, RSE, In review. Don't cite or quote

Validation



- TROPOMI operational ALH product based on O2 A-band has 1.5 km low bias (Nanda et al., 2020)
- This study using O2 A- and B-bands has mean bias of nearly zero in AOCH.

Oxygen absorption spectroscopy



Pros

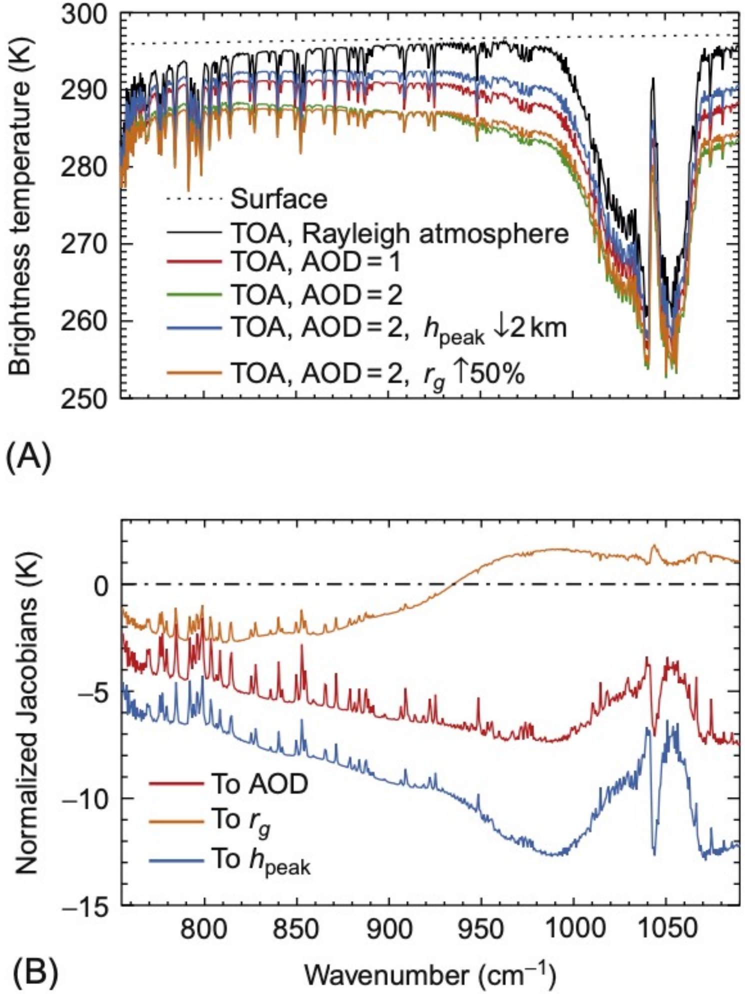
- Surface reflectance is low in O2 B and O2-O2
- Has sensitivity in low, middle and upper troposphere.
- Work well for from source to downwind region
- Sensitive to both scattering and absorption aerosols
- Aerosol optical properties have less uncertainties (as compared to that in UV)
- Simplicity and robustness (the ratio between absorption and continuum bands can be well attributed to the aerosol height)
- Less sensitivity to aerosol absorption

Cons

- Subject to the shape of aerosol profile, but that is true for all passive techniques
- Subject to the surface reflectance (with a note that in O2 B-band, the reflectance is low).

Xu et al., 2019

Infrared Techniques



Pros

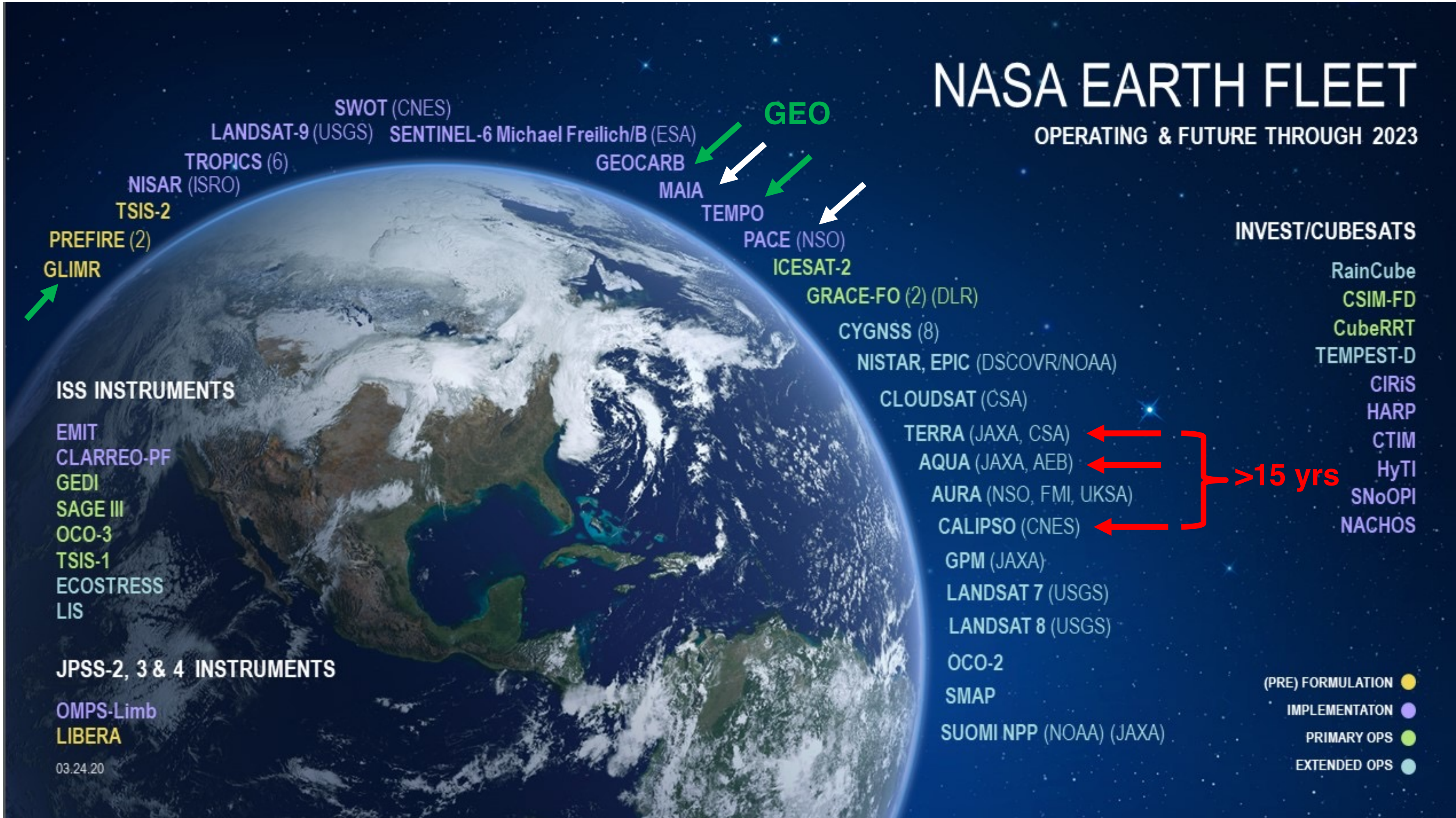
- Works both at day and night
- Good temporal converge (from GEO)

Cons

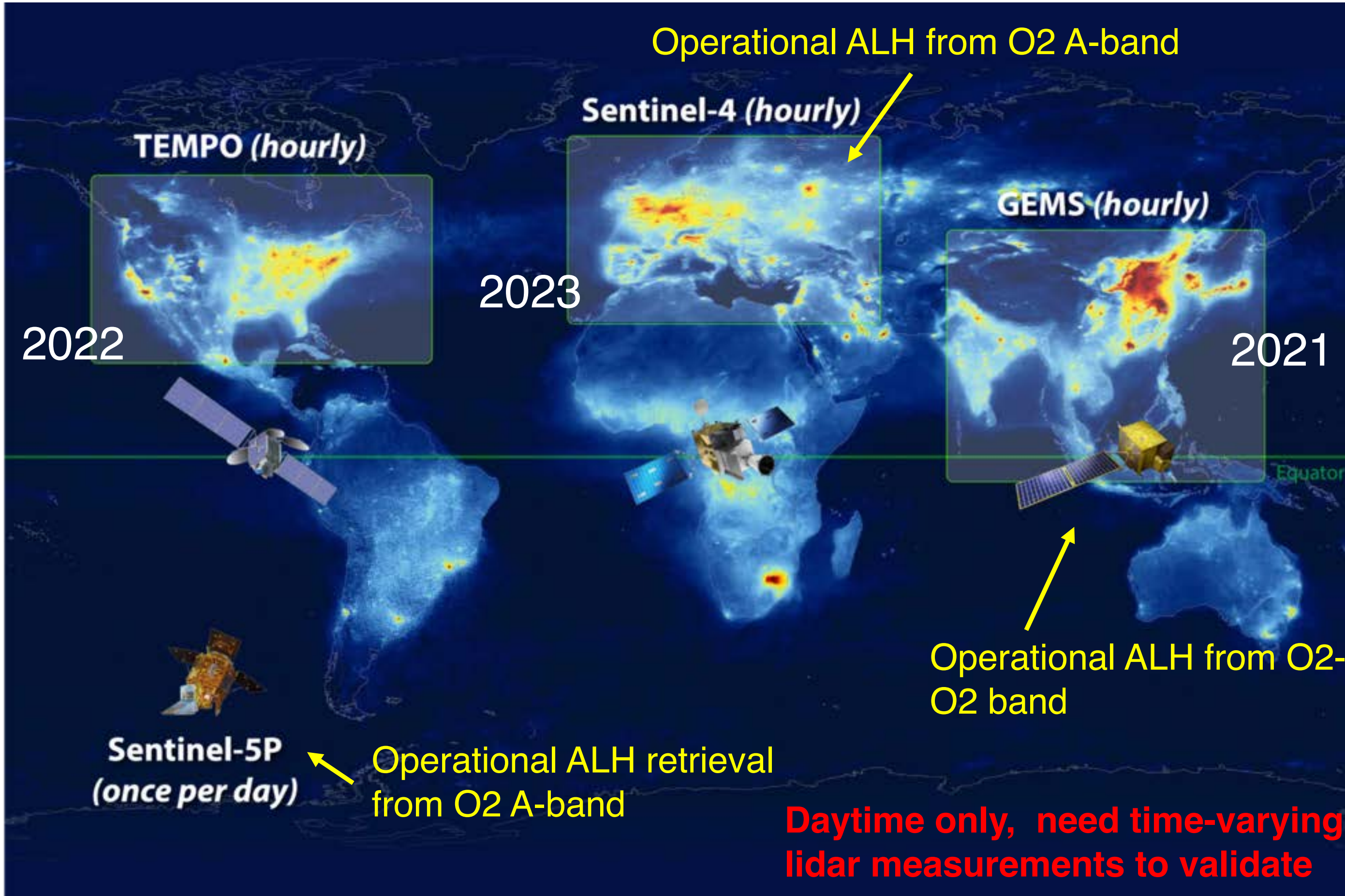
- Subject to the uncertainties in temperature profile and surface temperature
- Subject to water vapor and gas absorption
- Best for dust particles (and to some degree, thick smoke particles at the source region)
- Subject to the uncertainties of aerosol absorption that is not well constrained in the infrared spectrum, and particle size

Xu et al., 2018

Thoughts for future directions



GEO constellation for atmospheric composition

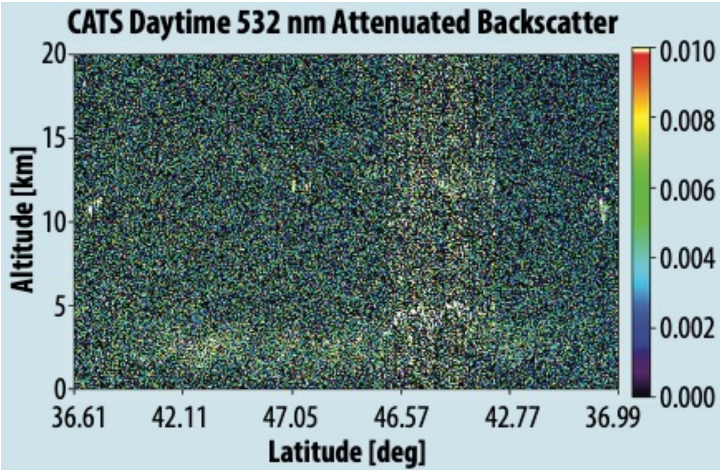


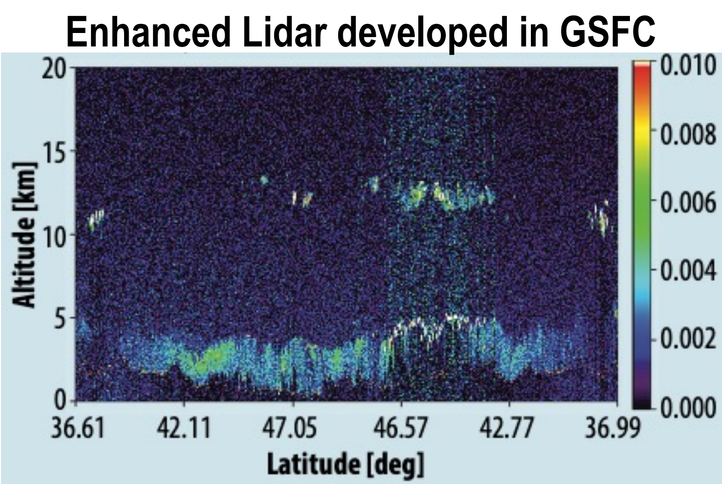
Geostationary and Extended Orbits (GEO-XO)

https://www.nesdis.noaa.gov/GEO-XO

Now in formulation

Requirements & recommendations of a SmallSat Mission





do we wait before A-CCP in 2028 (or later)?

- A pathfinder to A-CCP -> emergent
- Fill in the data gap of aerosol vertical profile with unprecedented spatial coverage → combine active and passive techniques
- Time-varying measurements to sample the diurnal cycle in the vertical to complement the horizonal observation from GEO -> inclined LEO
- Low risk and low cost -> excellent heritage
- Near real time for societal benefits -> data latency < 6 hours

Synthetic data based on newly developed (smaller and enhanced) lidar in GSFC; Courtesy: J. Yorks

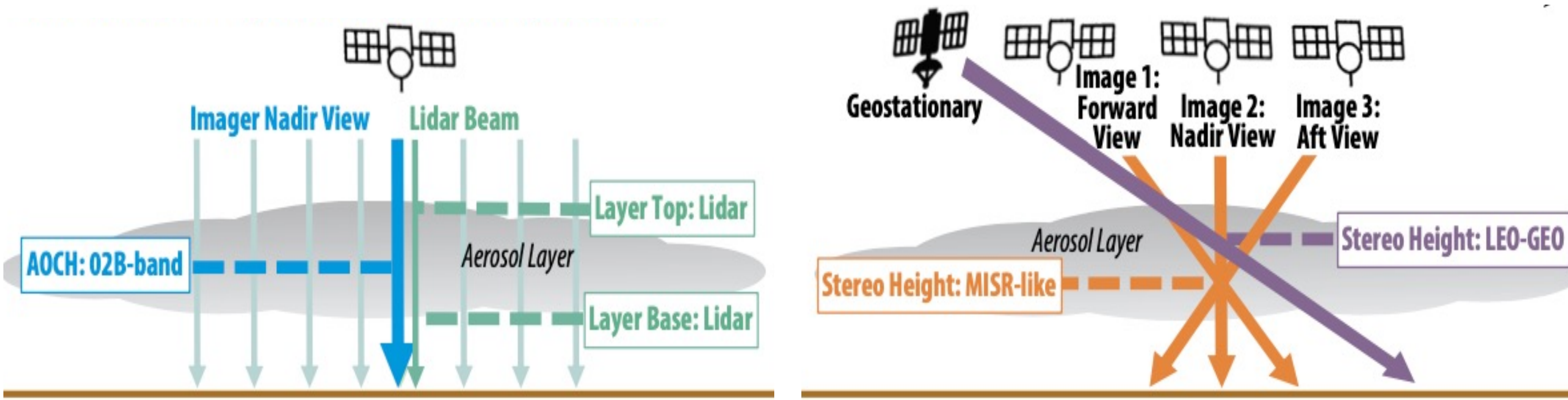
Payloads

- **An elastic (Mie) backscatter lidar**
  - Measure both backscatter and depolarization at 532 nm and 1064 nm (heritage from CALIOP and CATS)
  - Enhanced SNR due to inclined LEO (altitude of ~450 km)

- **A multi-angle view imager with a minimum of 3 bands and 3 angles**
  - Three angles (forward, backward and nadir) for stereo-height mapping
  - Three wavelengths (blue, 670 nm and 688 nm O2 B-band) for plume height mapping

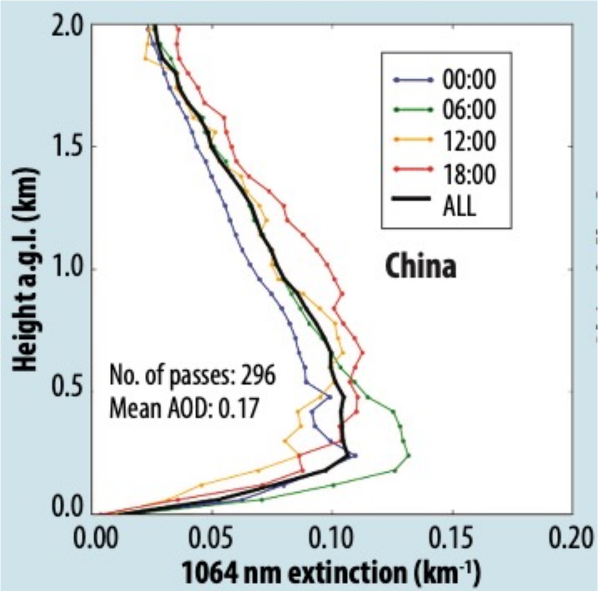
- **Synergistic use of GEO data**
  - Enhance retrieval of stereo height (to minimize the uncertainties from impact of along-the-track motion)

Four techniques together to provide unprecedented characterization of aerosol vertical distribution

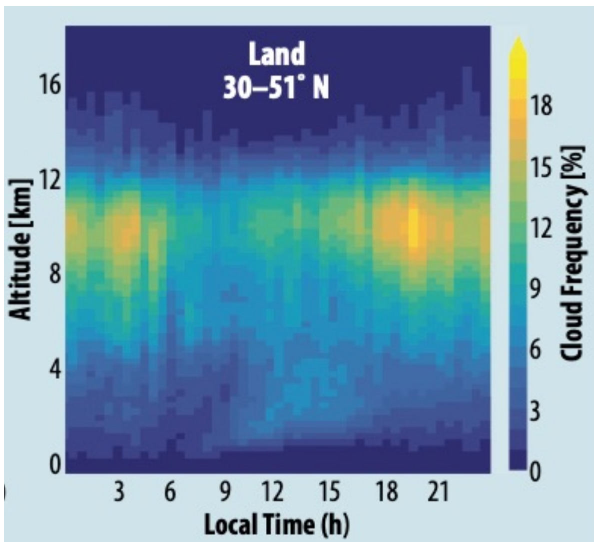


- Accuracy: lidar data can help correct localized bias in imager-based height data
- Spatially: imager-based AOCH and stereo height data help expand lidar data
- Temporally: time varying, around-the-clock measurements

- Multiple-angle + O2 B-band further helps the retrieval in the downwind region.
  Chen et al., 2021, in review.



Lee et al., 2019



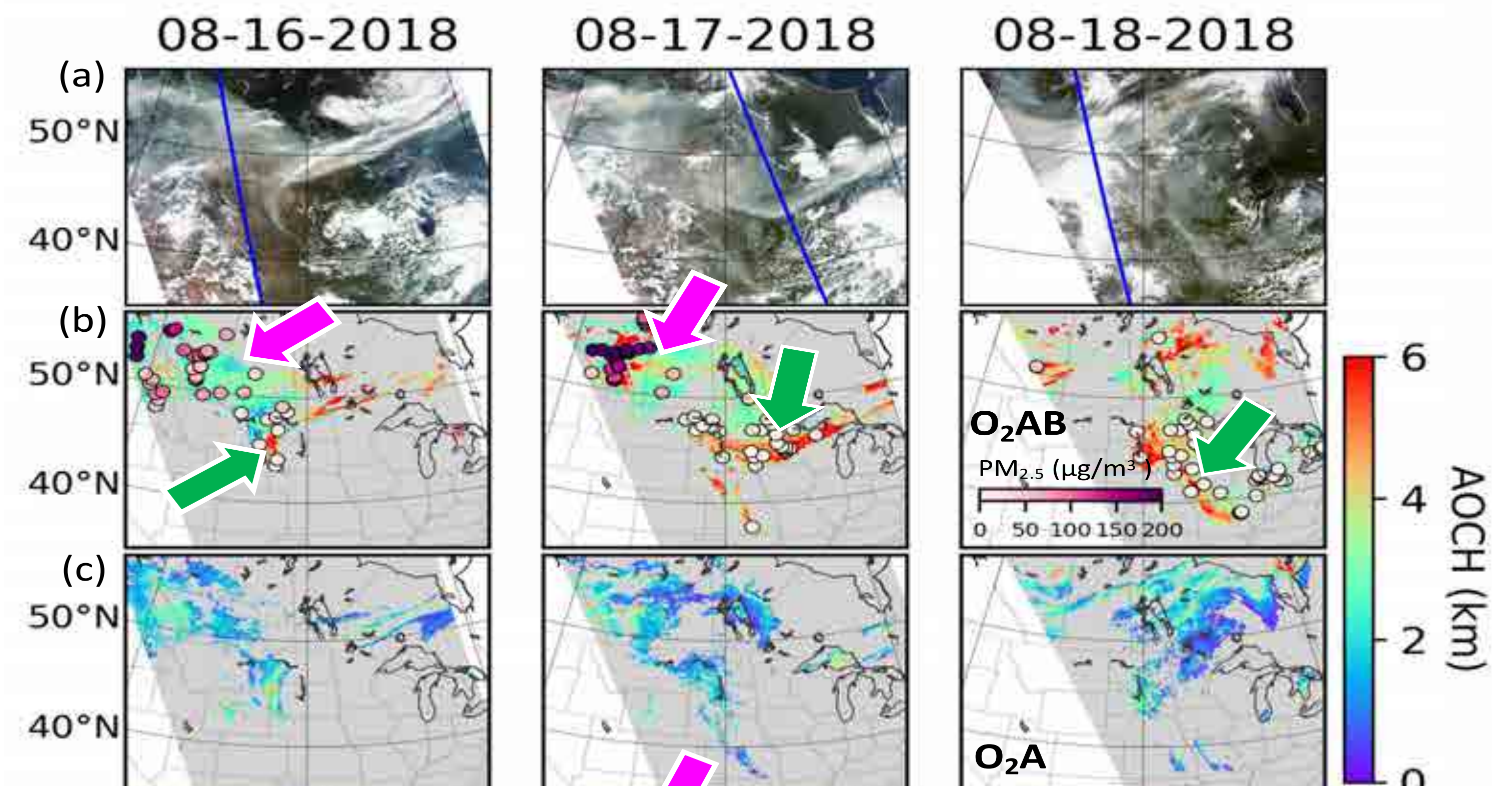
Y. Yorks

Co-benefits

- Cirrus cloud optical properties and forcing
- Characterization of low-level cloud heights
- Surface PM2.5 and air quality studies (complementary to MAIA and GEO constellation for atmospheric chemistry)
- Upper Troposphere and Lower Stratosphere (UTLS) studies
- Climate studies for smoke and dust injections and long-range transport
- Operational short-term forecast of aerosol transport
- Boundary layer research
- …

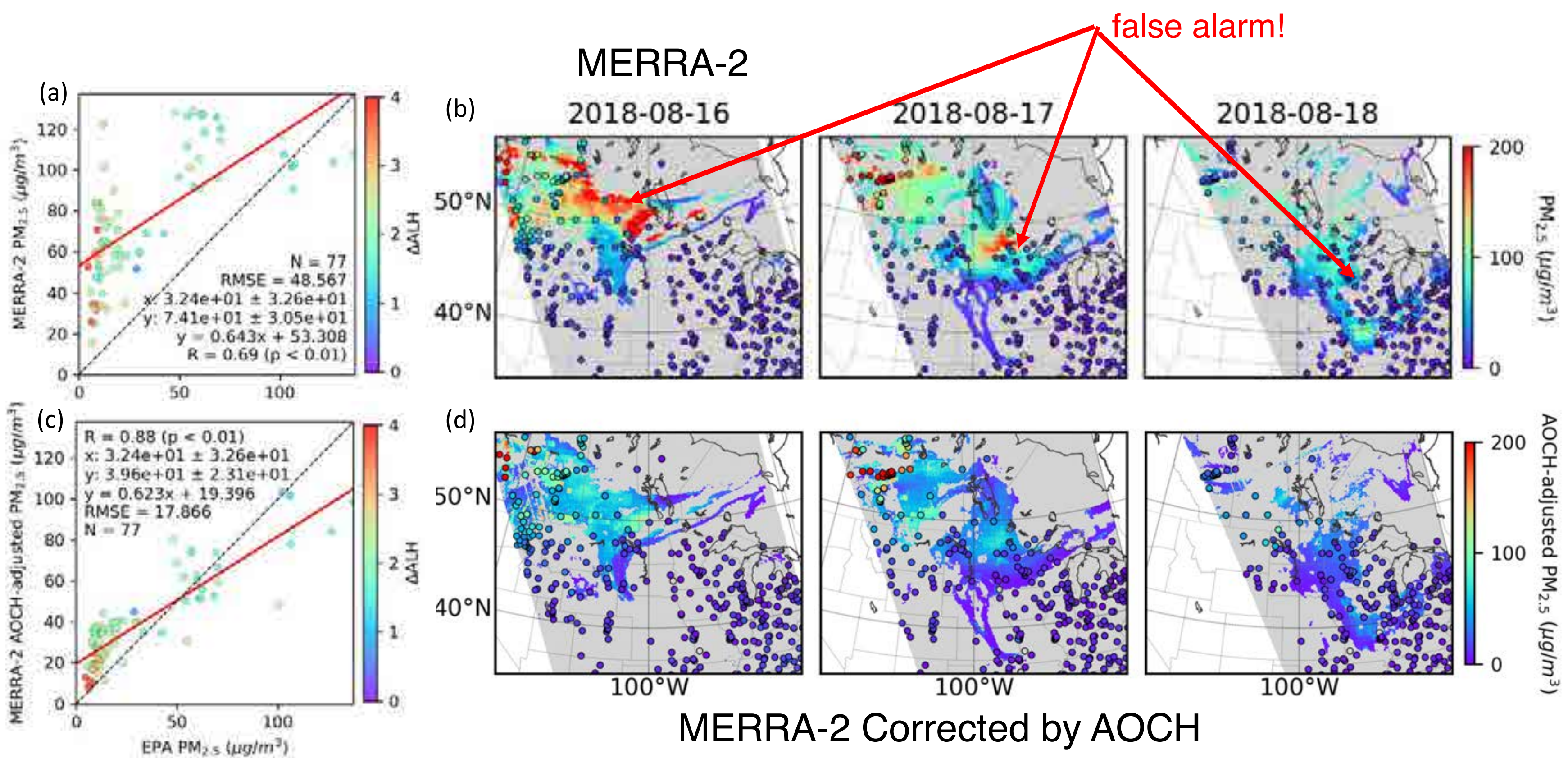
Demonstration for societal benefits

- Air quality forecast is needed by the state/local communities to make advisories/decisions for mitigating public exposure to air pollution.
- Aerosol layer height is one of the most needed information air quality mangers wants (based on HAQST group discussion on air quality forecast in smoke conditions).



Improvement on prediction and analysis

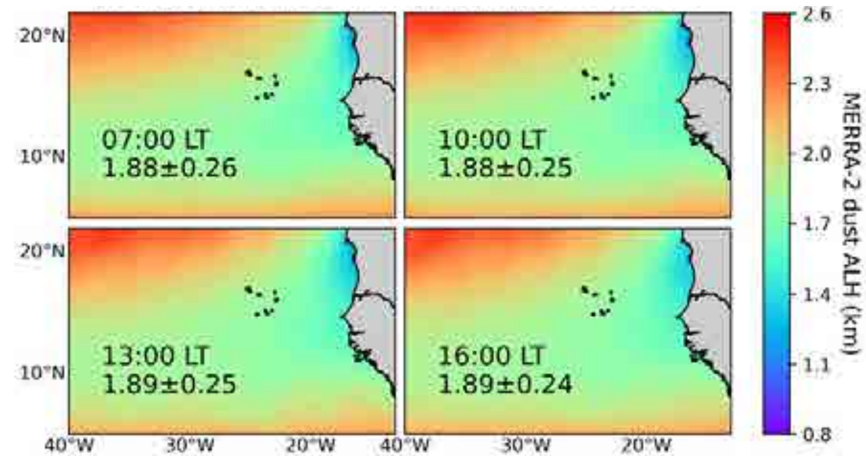
- While the measurements of AOCH at fire source region helps, equally and perhaps even more important is the AOCH at the downwind, where the smoke has a far reaching effect.
- This underscores the importance to combine multiple-angle and O2 absorption band to achieve spatial converge and use lidar for details, bias correction, and <u>information at night</u>.



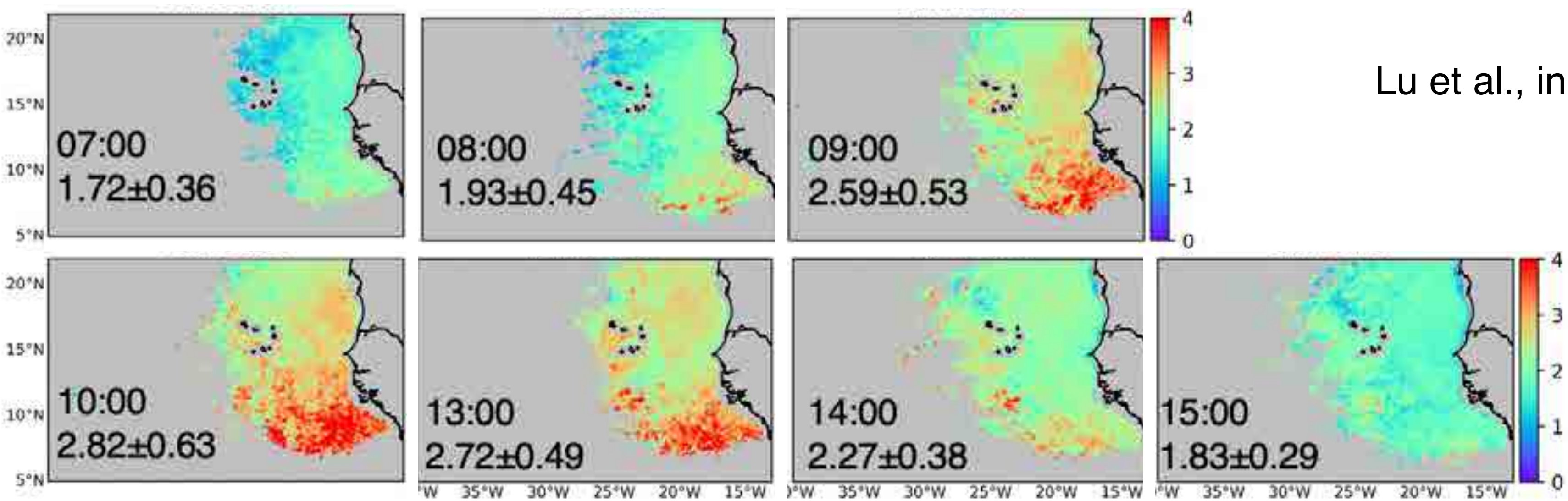
Diurnal variations

MERRA-2 clearly has deficiency to describe the diurnal variation of dust layer height seen by EPIC

MERRA-2



EPIC-based, dust AOCH at each hour
Multi-yr mean of 2015-2019 in May - Oct



Lu et al., in prep.

Summary & Outlook

- **A brief review** is given on the satellite remote sensing of aerosol vertical distribution
- **A SmallSat mission** is emergently needed to measure the diurnal variation of aerosol vertical distribution with unpresented spatial coverage and NRT capability
  - Avoiding data gap in Program of Record of aerosol vertical profiles
  - Serving as a pathfinder for future A–CPP and other mission(s)
  - Enhancing the GEO constellation for atmospheric composition
  - Providing complementary information to MAIA, PACE and JPSS
- **Recommendations**
  - Inclined LEO orbit, elastic lidar + multiple-angle view imager (with blue and O2 B-band as a mimimum)
  - Field campaigns, surface network, and modeling should be part of the mission
  - GEMS (Asia) and TROPOMI (Europe) have operational product of aerosol height product. As a community, we need to **act now**!

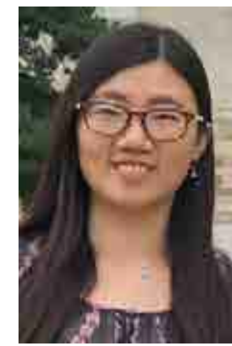
Thank you.

MURI

GEO-XO

Xiaoguang Xu
UMBC

Xu, X., J. Wang, Y. Wang, and A. Kokhanovsky (2018), Passive remote sensing of aerosol height.https://doi.org/10.1016/B978-0-12-810437-8.00001-3



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U. Iowa

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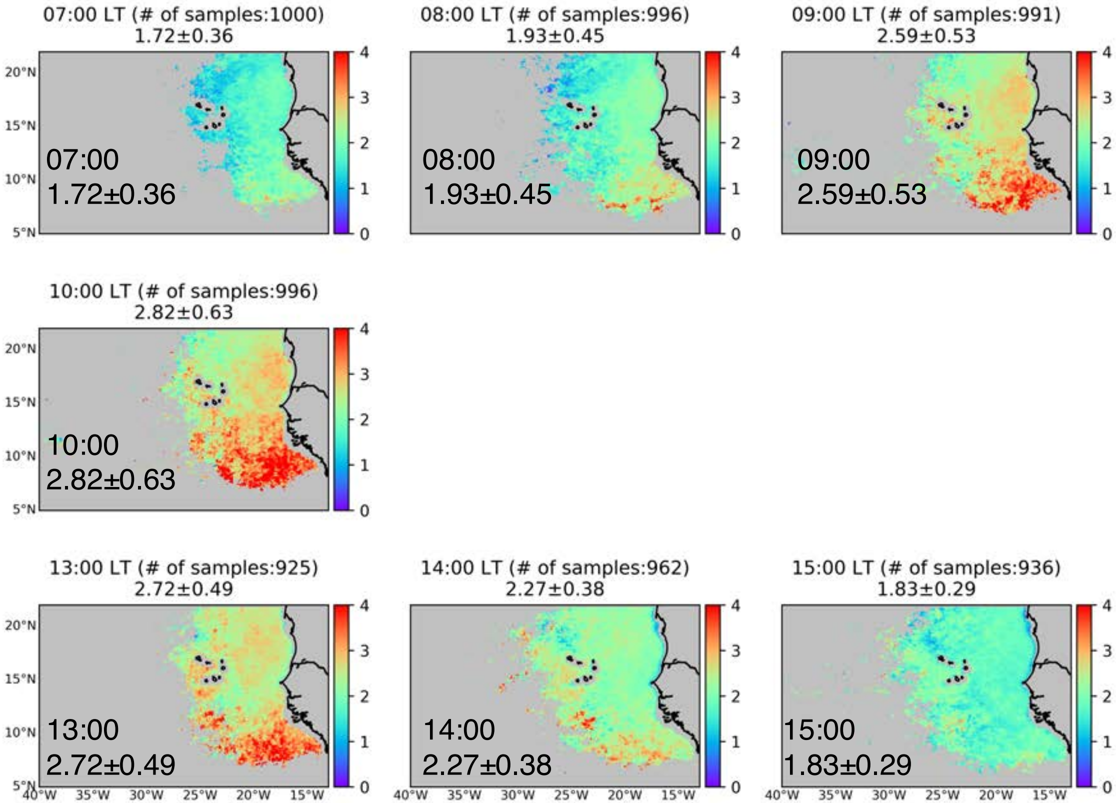
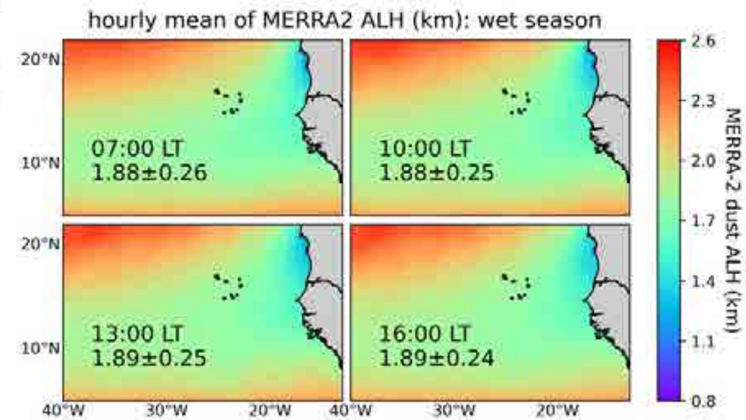
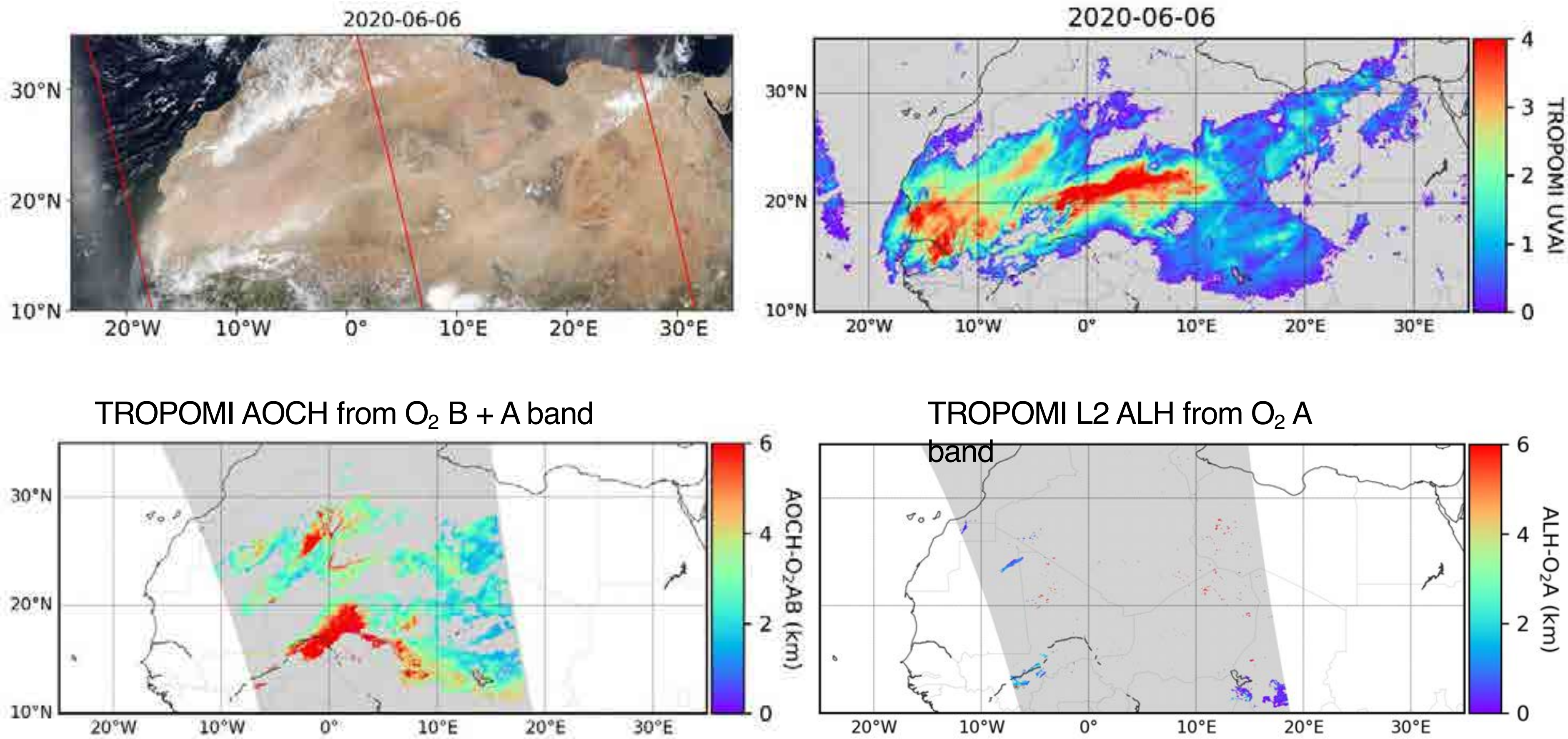

07:00 LT (# of samples:1000)
1.72±0.36
07:00
1.72±0.36
08:00 LT (# of samples:996)
1.93±0.45
08:00
1.93±0.45
09:00 LT (# of samples:991)
2.59±0.53
09:00
2.59±0.53
10:00 LT (# of samples:996)
2.82±0.63
10:00
2.82±0.63
13:00 LT (# of samples:925)
2.72±0.49
13:00
2.72±0.49
14:00 LT (# of samples:962)
2.27±0.38
14:00
2.27±0.38
15:00 LT (# of samples:936)
1.83±0.29
15:00
1.83±0.29
20°N
15°N
10°N
5°N
40°W
35°W
30°W
25°W
20°W
15°W
0
1
2
3
4


hourly mean of MERRA2 ALH (km): wet season
07:00 LT
1.88±0.26
10:00 LT
1.88±0.25
13:00 LT
1.89±0.25
16:00 LT
1.89±0.24
20°N
10°N
40°W
30°W
20°W
MERRA-2 dust ALH (km)
0.8
1.1
1.4
1.7
2.0
2.3
2.6

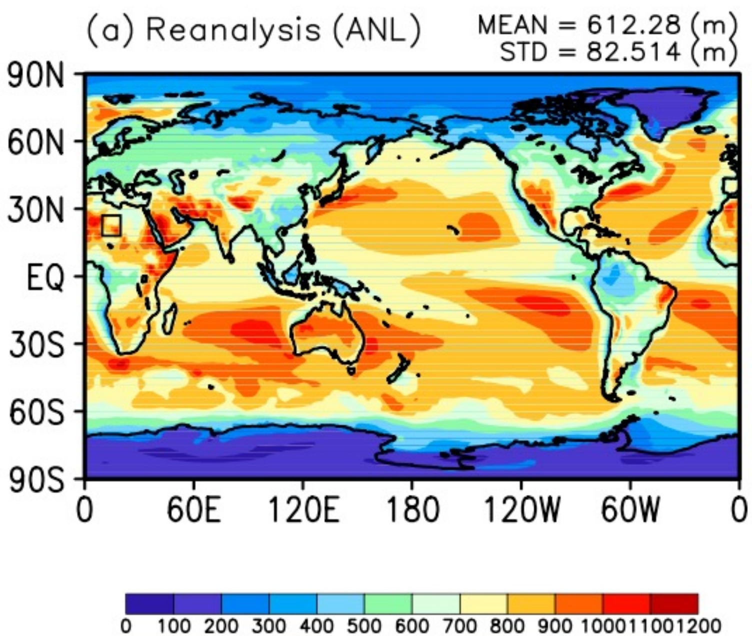


2020-06-06
2020-06-06
TROPOMI UVAI
TROPOMI AOCH from O$_2$ B + A band
AOCH-O$_2$AB (km)
TROPOMI L2 ALH from O$_2$ A band
ALH-O$_2$A (km)

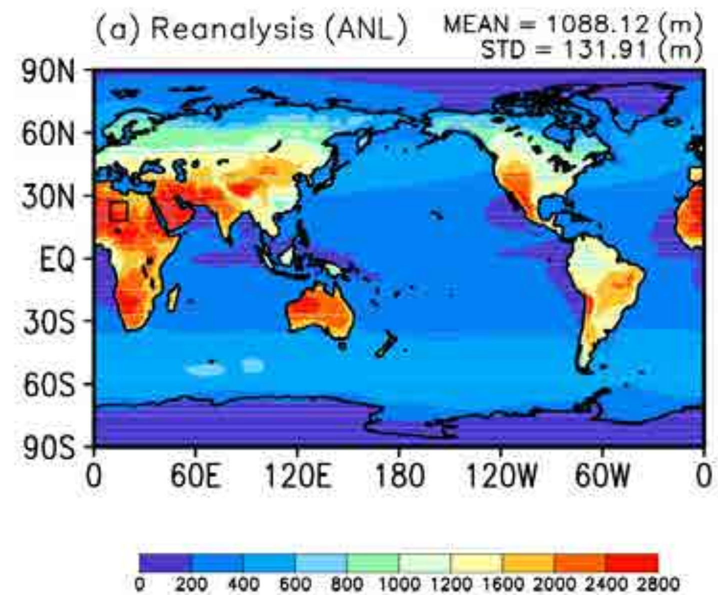
Modeled PBLH itself is elusive in some ways

Definition of PBLH; PBL scheme; …

PBLH mean from three re-analysis



PBLH diurnal amplitude



Shin et al., 2018.

A rising trajectory of geostationary satellites for air pollution

GEMS 02/18/2020;
TEMPO & Sentinel-4,
2022/23

GEO-XO
2030?

Kim et al., 2020
Chance et al., 2019
Zoogman et al, 2017

Fishman et al., 2012

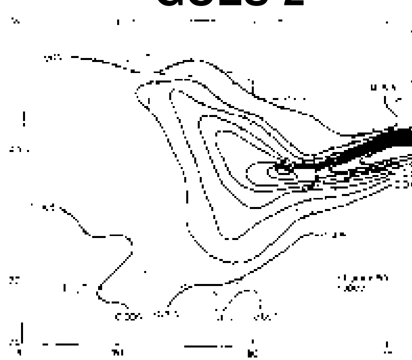
Lahoz et al., 2012

Imager → Spectrometer

Schmit et al., 2017

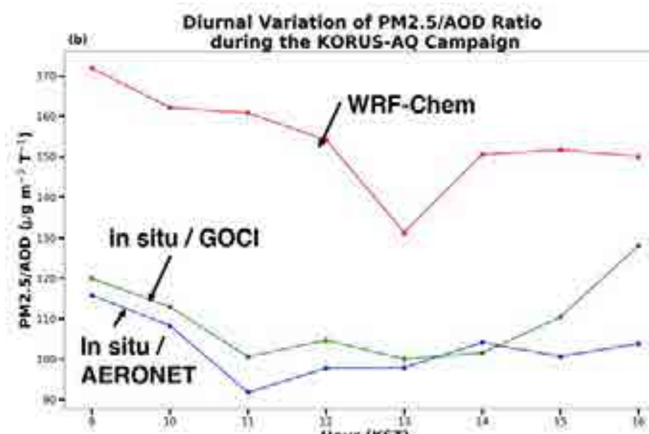
Lee et al., 2010. RSE
6 visible
2 NIR

GOES-2



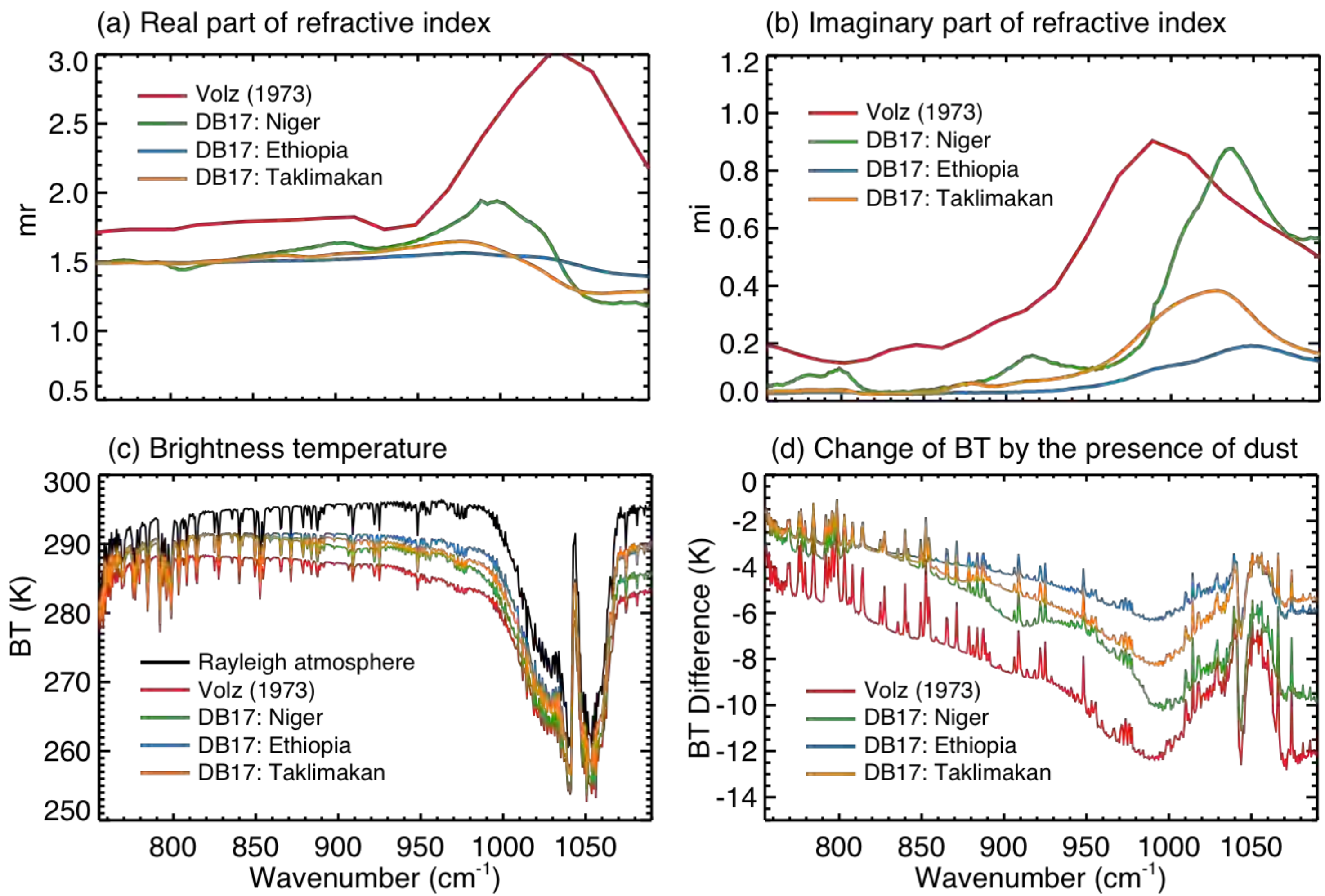
MSG, 8/28/2002
12 channels
2 visible

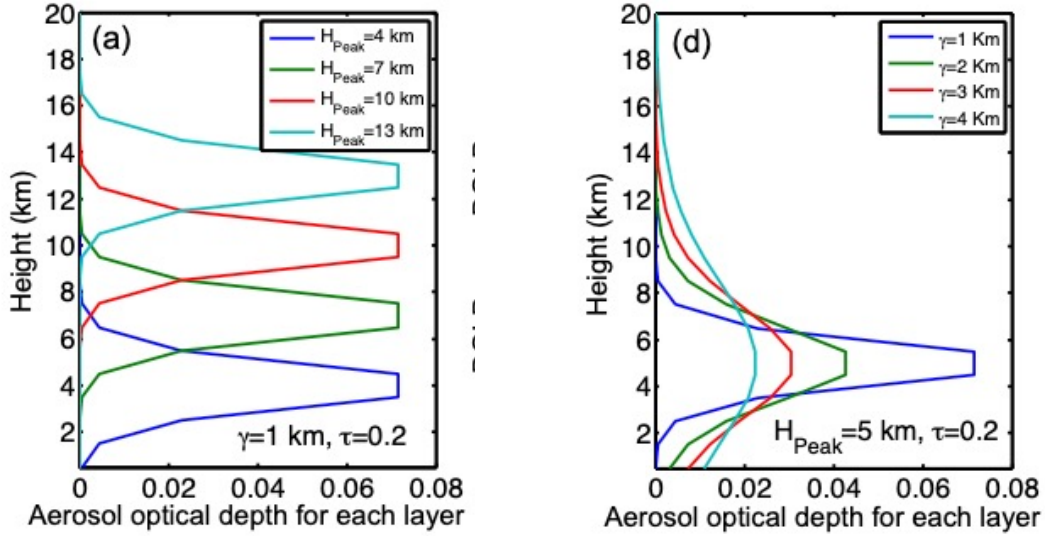
Fraser et a., 1984, AE



→ Lennartson et al., 2018, ACP

Impacts on dust refractive index uncertainty on the infrared spectra





$$\tau_{\mathrm{A}}(z) = K \frac{\exp(-\gamma|z - z_{\mathrm{peak}}|)}{[1 + \exp(-\gamma|z - z_{\mathrm{peak}}|)]^2} \tag{32}$$

where K is a constant related to τ_{a0}, γ is related to half-width constant σ by $\gamma = \ln(3 + \sqrt{8})/\sigma$, and z_{peak} is the height having peak loading.