# TEMPO Aerosols and Clouds

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TEMPO Science Team Meeting, August 2020

# Outline

- **Introduction: aerosols/clouds in TEMPO STM**

- **Aerosol data/science uniquely enabled by TEMPO**
  1) hourly retrieval of aerosol absorption
  2) hourly retrieval of spectral AOD and surface reflectance
  3) hourly retrieval of aerosol centroid layer height

- **Cloud data/science uniquely enabled by TEMPO**
  – hourly retrieval of cloud optical centroid pressure from O2-O2 band

- **TEMPO applications and synergy with other sensors**
  1) surface networks, AOD-PM2.5 relationship
  2) with GOES-16 and GOES-17
  3) with TROPOMI, GMES, Sentinel-4 (S4), Sentinel-5 (S5), …
  4) with MODIS, MISR, VIIRS, MAIA

# Importance of aerosols and clouds

- **Aerosols are omnipresent,**
  - affect retrieval of gases
  - partially and collectively reflect emissions of various gases
  - Integrated part of TEMPO objectives for AQ forecast & process studies
  - Integrated part of TEMPO objectives for climate forcing studies

- **Clouds are present 60%-70% of time,**
  - Affect life cycle of gases and aerosols
  - Key source of uncertainty for aerosol retrievals
  - Integrated part of TEMPO objectives for climate forcing studies

Table D.1-1 in TEMPO proposal

| TEMPO Science Goals | TEMPO Objectives |
|---|---|
| Characterize the temporal and spatial variations of emissions important for AQ and climate; observe continental inflow and outflow of pollution. 1,2,5,6,7,8,9 | Collect simultaneous high temporal and spatial resolution measurements of pollutants over Greater North America. |
| Understand how processes determine AQ over range of time and space scales. 1,2,5,6,7,8 | Measure the major elements in tropospheric $O_3$ chemistry & aerosol cycles. |
| Characterize the effect of episodic events, e.g. volcanic eruptions, wild fires and dust outbreaks, on AQ. 1,2,6,8 | Observe aerosols & gases for quantifying and tracking evolution of pollution. |
| Determine how observations from space can improve AQ forecasts and assessments for societal benefit. 3,4,5,7,8,9 | Integrate observations from TEMPO and other platforms into models to improve representation of processes. |
| Understand how air pollution drives climate forcing and how climate change affects AQ on a continental scale. 4,5,6,8 | Determine the instantaneous radiative forcings associated with $O_3$, aerosols & clouds on the continental scale. |

# Aerosol data/science uniquely enabled by TEMPO
## (1) hourly retrieval of aerosol absorption

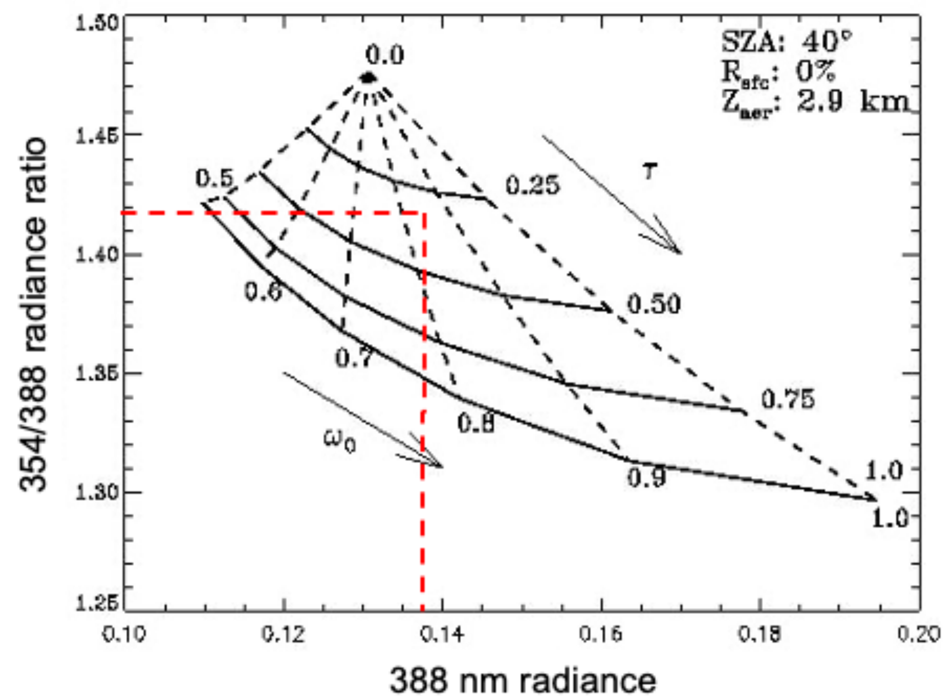
**Operational product led by O. Torres**

- UV Aerosol Index,
- AOD and SSA (388 nm) using 354 and 388 nm measurements
- Heritage Algorithms : OMAERUV (Aura-OMI) & TropOMAER (S5P-TROPOMI)
- Status: ready at launch

**Sciences**

- Tracking smoke/dust plumes including in cloudy conditions
- Process understanding of aerosol particle evolution in the atmosphere
- Aerosol radiative absorption

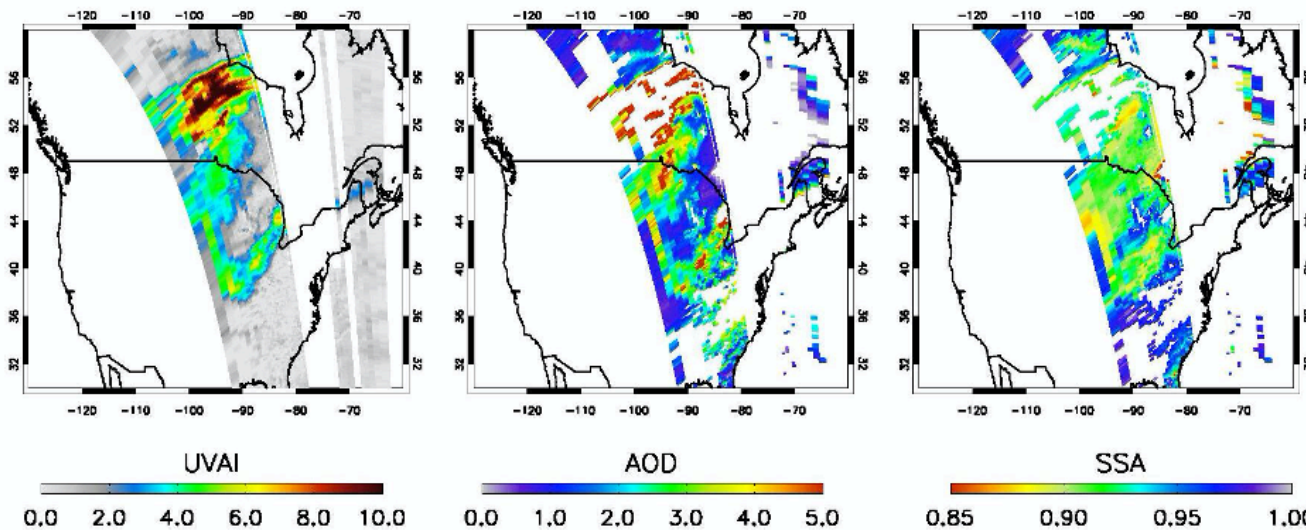
**Near UV Inversion Scheme**



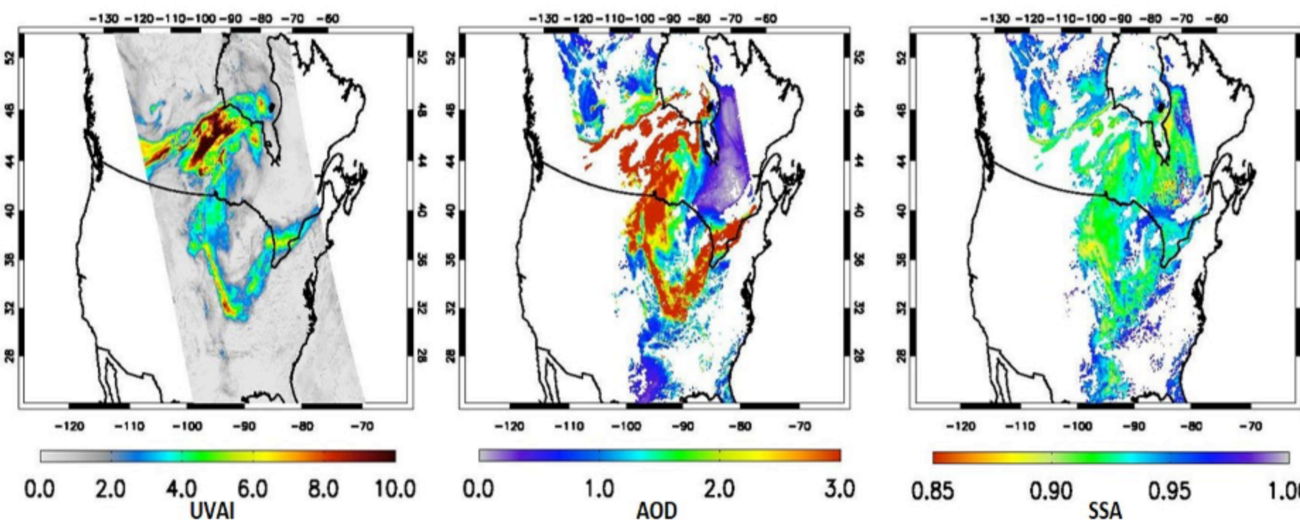

*For a given aerosol type and layer height, satellite measured radiances at 354 and 388 nm are associated with a set of AOD and SSA values.*

**From OMI (13x24 km at nadir) .....**

**August 18, 2018 wildfires**




**To TROPOMI ( 7x3.5km nadir) and TEMPO (~ 2x5 km)**



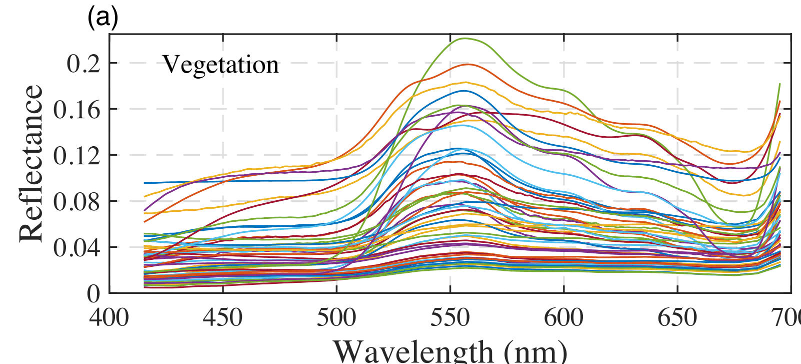
# Aerosol data/science uniquely enabled by TEMPO
## (2) hourly retrieval of spectral AOD and surface reflectance

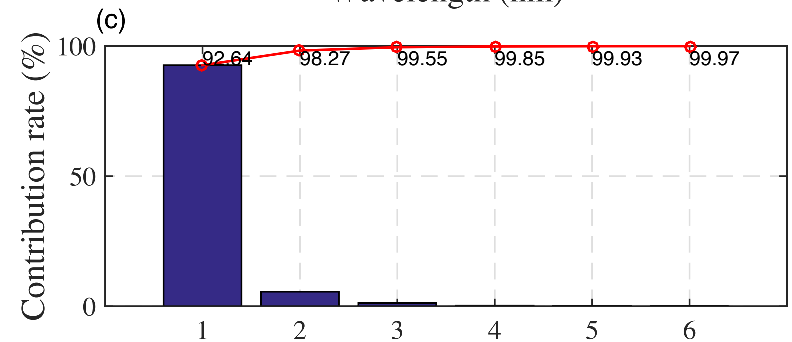
**Research algorithm led by U. Iowa**

- Simultaneous retrieval of spectral AOD, AOD fine-mode fraction, and surface reflectance
- New algorithm developed under support of GEO-CAPE, GEO-TASO, and TEMPO
- Status: prototype tested with KORUS-AQ data; continuing with GCAS data;

**Sciences**

- Hourly analysis of aerosol size
- Process understanding of aerosol particle evolution in the atmosphere
- Improve estimates of aerosol radiative forcing



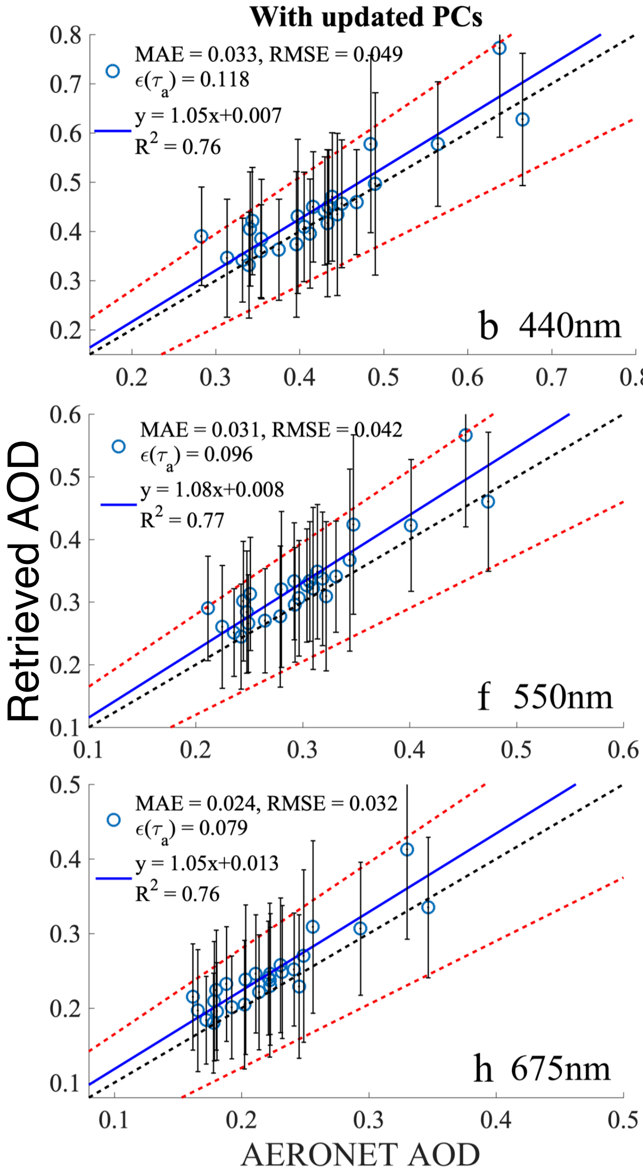

*The variation of surface spectral reflectance is characterized by PCs, enabling retrieval aerosol & weights of PCs at the same time.*

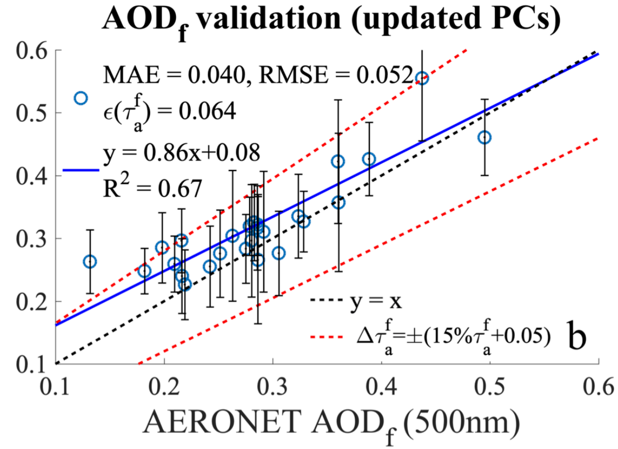
**An algorithm for hyperspectral remote sensing of aerosols**

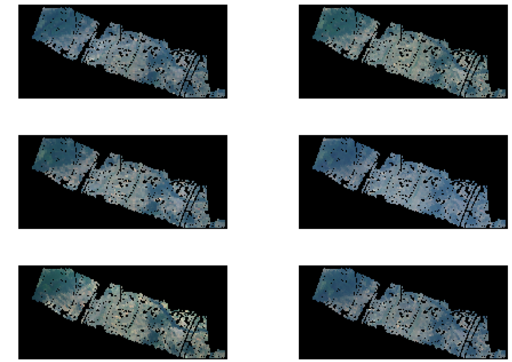
1. Development of theoretical framework, *JQSRT,* 2016.
2. Information content analysis for aerosol parameters and principal components of surface spectra, *JQSRT*. 2017.
3. Application to the GEO-TASO data in KORUS-AQ field campaign, *JQSRT*. 2020.

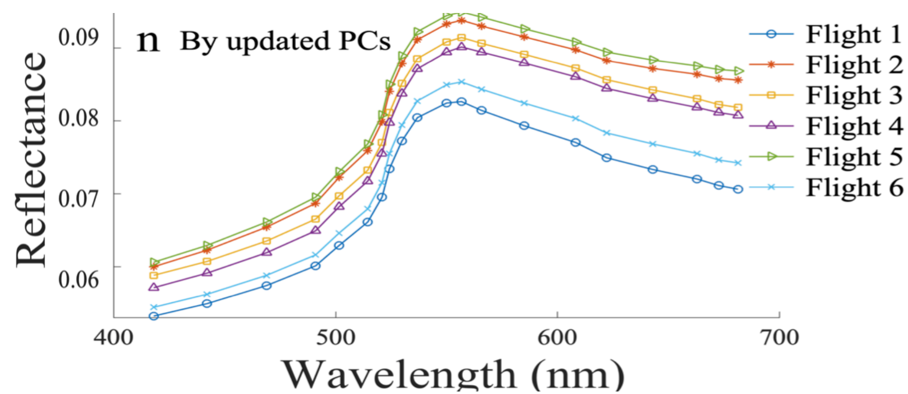
# Results in KORUS-AQ

In collaboration with
Scott Janz @ GSFC NASA
James Leitch @ Ball



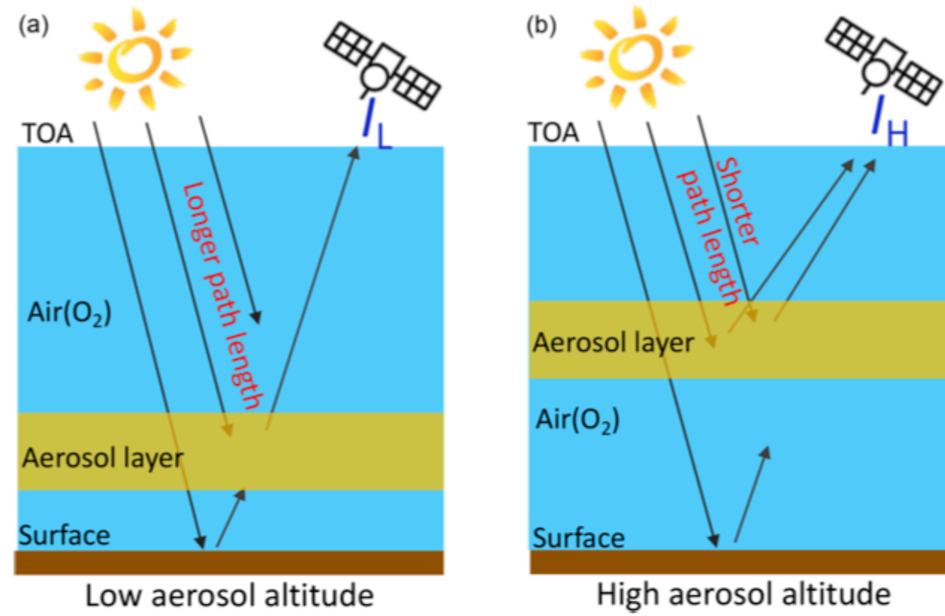



Hou et al., *JQSRT*, 2020.

# Aerosol data/science uniquely enabled by TEMPO
## (3) hourly retrieval of aerosol centroid layer height

**Research algorithm, U. Iowa & GSFC**

- Retrieval of aerosol layer height (ALH) using O2 B-band.
- Heritage: EPIC/DSCOVR
- Status: prototype tested with TROPOMI data.



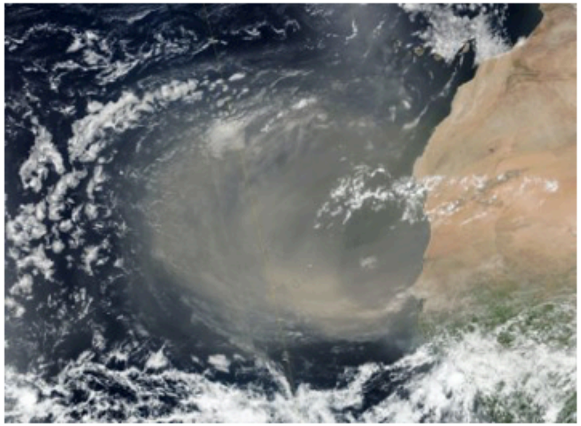

**Sciences**

- Mesoscale 3D view of aerosol movement Process understanding of aerosol injection and vertical transport in the atmosphere
- Improved estimate of surface PM2.5

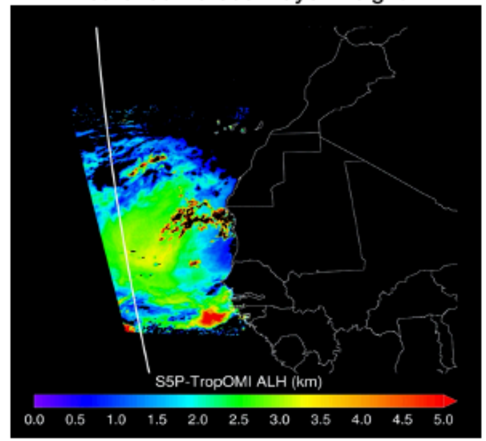
Xu, X., J. Wang, et al., Detecting layer height of smoke aerosols over vegetated land and water surfaces via oxygen absorption bands: Hourly results from EPIC/DSCOVR satellite in deep space, *Atmospheric Measurements and Techniques*, 2, 3269–3288, 2019, 2019.
Xu, X., J. Wang, et al., Passive remote sensing of altitude and optical depth of dust plumes using the oxygen A and B bands: First results from EPIC/DSCOVR at Lagrange-1 point, *Geophys. Res. Lett.*, 44, 7544-7554, 2017.

# Simultaneous Retrieval of ALH and AOD from O2B bands (680 vs. 688 nm)

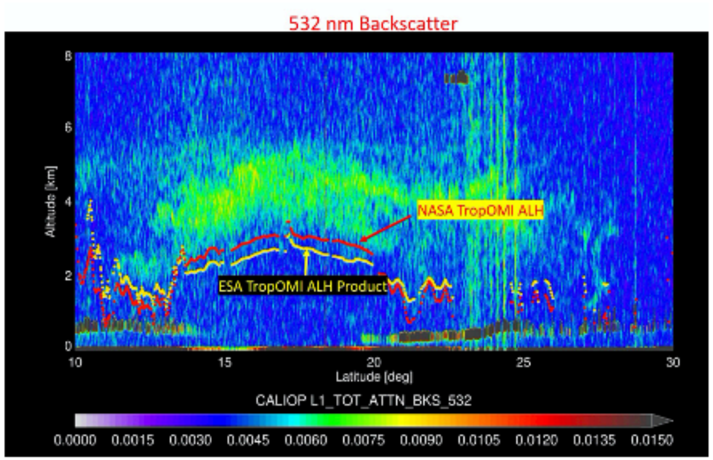
S-NPP/VIIRS July 31, 2018



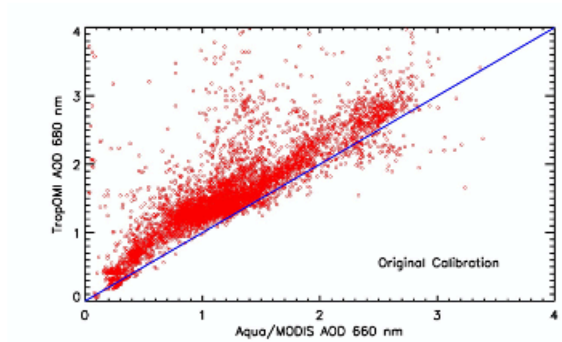
Retrieved Aerosol Layer Height




Courtesy:
O. Torres



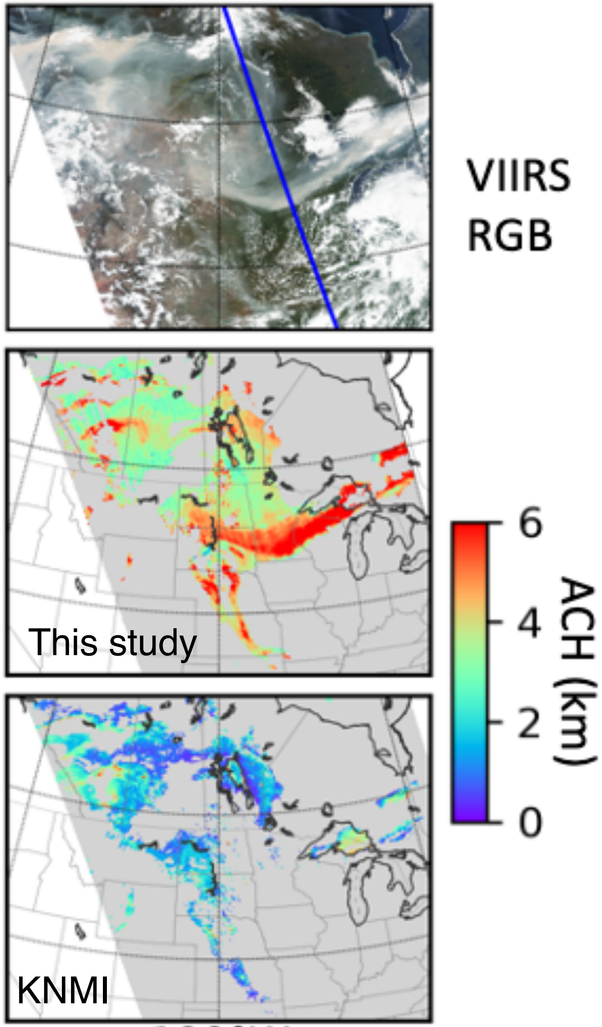

Comparison to CALIOP and KNMI O2A Retrieval



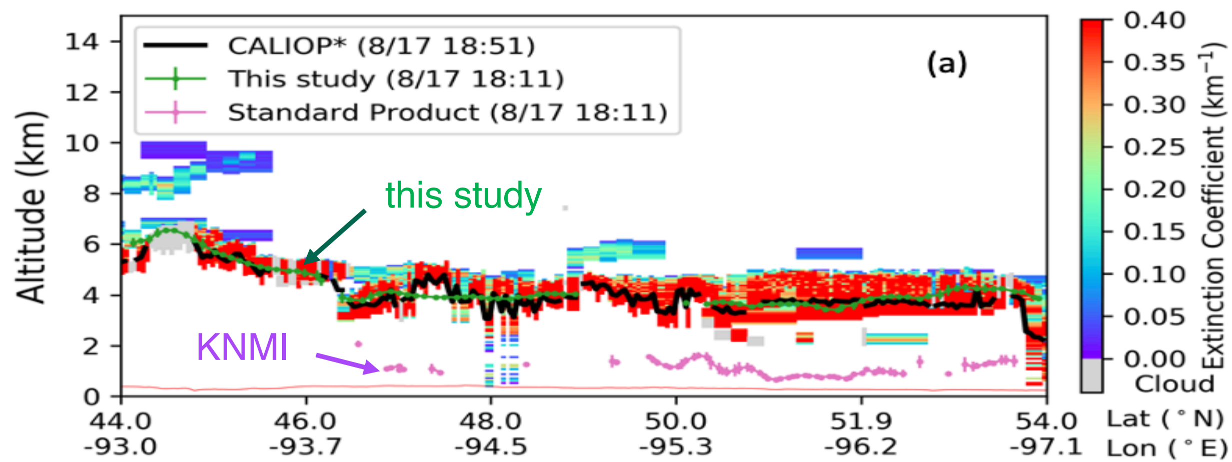

Tropomi 680 nm AOD vs MODIS 660 nm AOD

# Retrieval of ACH and AOD from blue & $O_2$ B bands over land

for details, see Xi Chen's poster




$$\mathrm{ACH}_{\mathrm{CALIOP}} = \frac{\sum_{i=1}^{n} \beta_{\mathrm{ext},i}\, z_i}{\sum_{i=1}^{n} \beta_{\mathrm{ext},i}}$$




- TROPOMI *operational* retrieval of ALH with $O_2$ A band has a negative bias of 1-2 km, and this bias increases with surface albedo (Nanda et al., 2020, AMT).
- Land surface reflectance at $O_2$ B band and blue band are much lower than in that in $O_2$ A band, which favor the retrieval of ALH.

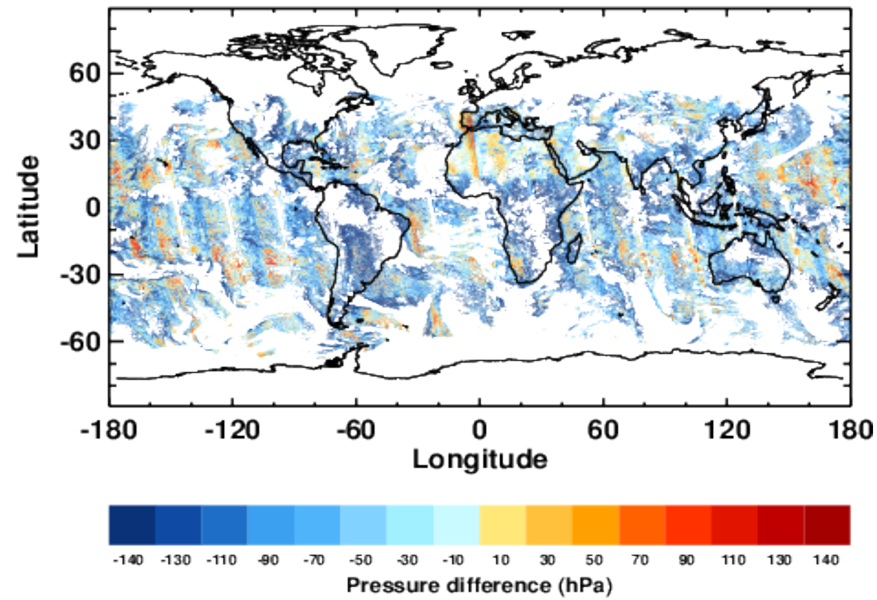
# Cloud data/science uniquely enabled by TEMPO

## cloud optical centroid pressure retrieval from $O_2$-$O_2$ band

Courtesy: Alexander (Sasha) Vasilko & Joanna Joiner

- An advanced spectral fitting algorithm for retrieving $O_2$-$O_2$ slant column densities (Vasilkov et al., 2018)
  - Use of the temperature-dependent $O_2$-$O_2$ cross sections
  - Removal of $O_3$, $NO_2$, and $H_2O$ absorption based on estimates of their slant column densities (SCDs) from independent algorithms
  - Account for specifics of surface reflectivity
- ***Hourly*** **cloud optical centroid pressure** (OCP) retrieved from the $O_2$-$O_2$ SCD (using LUTs with the DOAS-type approach); **cloud fraction**, etc.
- Status: adaptation for TEMPO geometry may need additional nodes of the LUTs

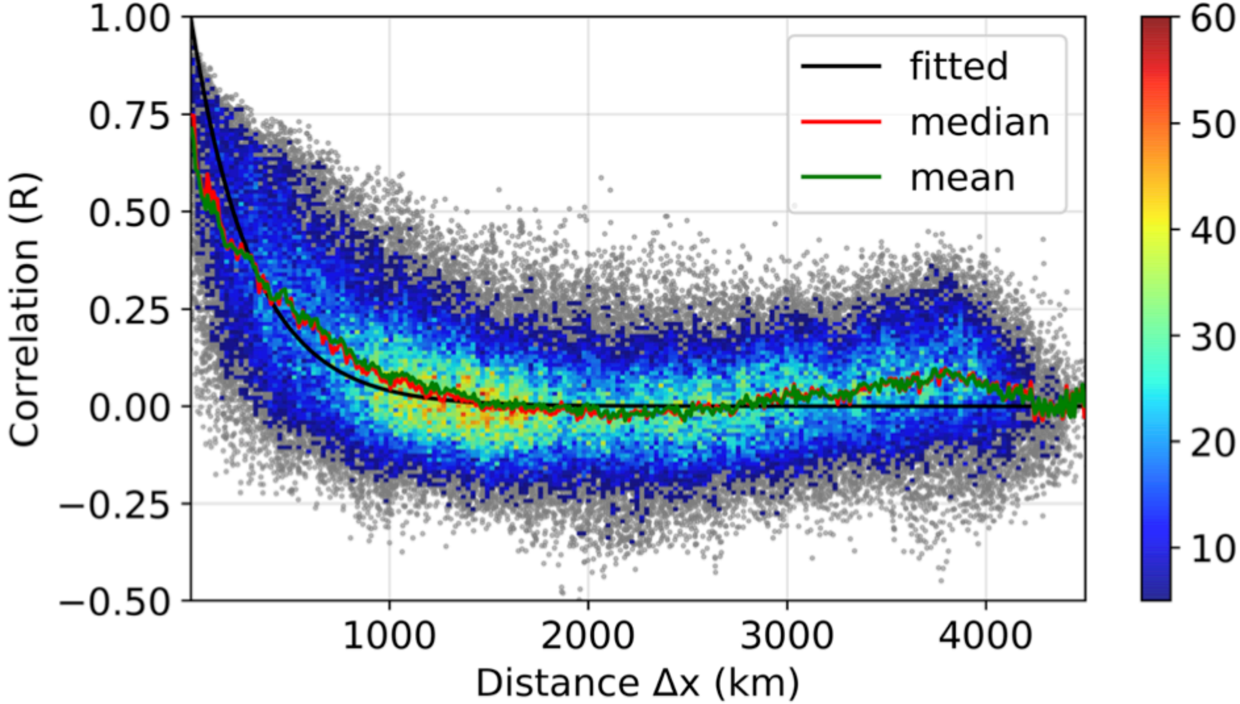
Nov. 13, 2006




$P_{scene}$ - $P_{surface}$

# TEMPO applications and synergy with other sensors
## (1) importance of surface networks, AOD-$PM_{2.5}$ relationship,

$PM_{2.5}$ spatial auto-correlation in U.S.




**Huanxin (Jessie) Zhang**

Zhang et al., 2020, JGR

Improving Surface $PM_{2.5}$ Forecasts in the United States Using an Ensemble of Chemical Transport Model Outputs: 1. Bias Correction With Surface Observations in Nonrural Areas, *J. Geophy. Res. – Atmos.*, 125(14), e2019JD032293, 2020.

# Diurnal variations of AOD and PM2.5 – what should we expect from geostationary satellite observations for air quality

Mian Chin[1], Qian Tan[2], Alex Coy[3], Tianle Yuan[1,4], Hongbin Yu[1]

[1]NASA Goddard Space Flight Center [2]Bay Area Environmental Research Institute [3]Now at Cornell University [4]University of Maryland Baltimore County

# Background

- Monitoring air quality from space has played a key role in our understanding of the status and trends of air pollution. The geostationary satellite data bring the possibility of getting hourly air quality
- Challenges: the AOD-$PM_{2.5}$ relationship is not constant but depends on many factors including
  - aerosol vertical profile (e.g., aerosol fraction in the PBL) – affecting $PM_{2.5}$ levels
  - chemical composition, size distribution – affecting $PM_{2.5}$ and AOD
  - relative humidity or water vapor amount – affecting AOD
  - Mesoscale and synoptic scale meteorology

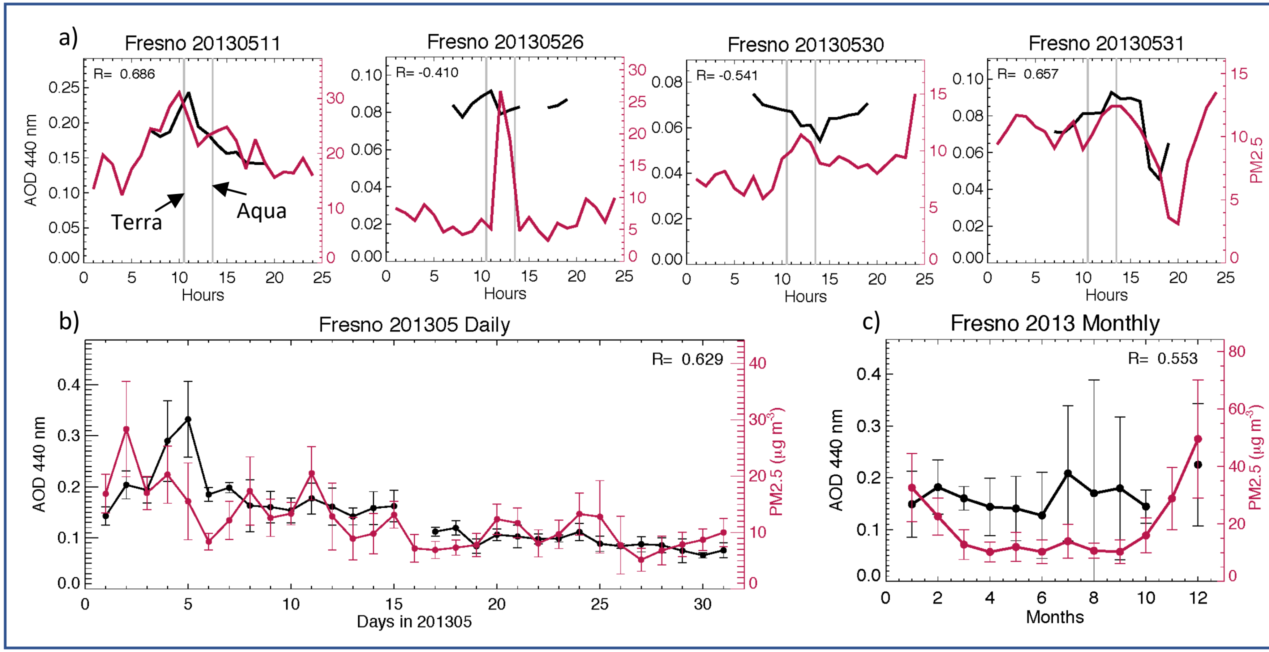
# Fresno 2013 as an example: Collocated AERONET AOD and EPA $PM_{2.5}$

19% of the days in 2013 the hourly AOD and $PM_{2.5}$ are correlated at $R \geq 0.7$ and 31% of the days they are negatively correlated

a) Examples of daytime hourly variations of AOD and $PM_{2.5}$ in four different days in May 2013

b) Daily mean AOD and $PM_{2.5}$ in May 2013

c) Monthly mean AOD and $PM_{2.5}$ in 2013

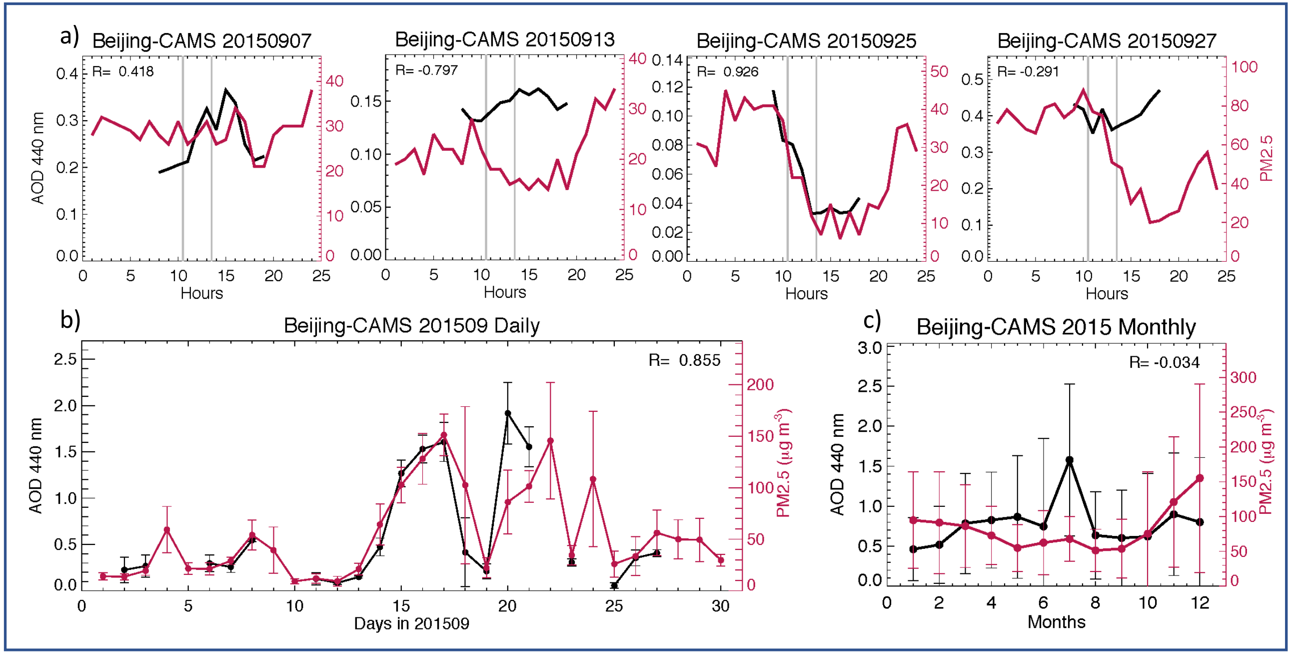



- AOD-$PM_{2.5}$ often have different variability on diurnal timescale
- AOD-$PM_{2.5}$ are better correlated on daily scale in the sub-seasonal time domain
- AOD-$PM_{2.5}$ ratios change significantly with seasons

# Beijing 2015 as an example: Collocated AERONET AOD and surface $PM_{2.5}$

36% of the days in 2013 the hourly AOD and $PM_{2.5}$ are correlated at $R \geq 0.7$ and 25 % of the days they are negatively correlated

a) Examples of daytime hourly variations of AOD and $PM_{2.5}$ in four different days in September 2015
b) Daily mean AOD and $PM_{2.5}$ in September 2015
c) Monthly mean AOD and $PM_{2.5}$ in 2015

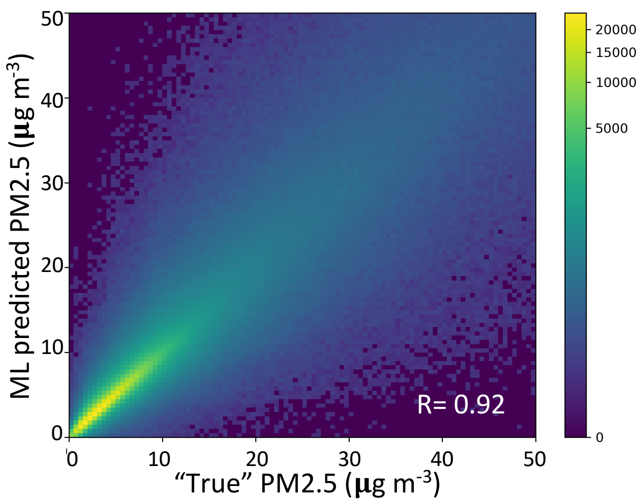



**Recommendations:**

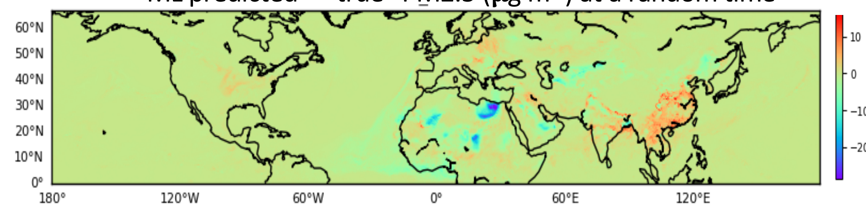
1) Including diurnal variations of PBL height, RH or column water vapor, and effective aerosol layer height (can be obtained from satellite and ground stations) in deriving PM2.5 from TEMPO or GOES AOD data
2) Including aerosol composition and/or particle size and aerosol vertical profiles (can be estimated from limited observations, or from credible models or reanalysis)

# Using a physically-based machine learning model to retrieve $PM_{2.5}$ from AOD: Preliminary experiment with GEOS simulation as a test

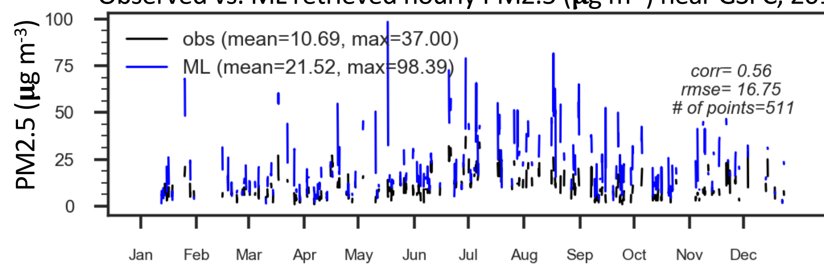
- GEOS/GOCART output at 3-hourly, 0.5° horizontal resolution over the globe for the entire year of 2012
- Randomly select $2x10^7$ data points as training dataset including variables of AOD, $PM_{2.5}$, PBL height, column water vapor, and aerosol vertical extinction profiles (surface to tropopause), and $6x10^6$ independent data points to retrieve $PM_{2.5}$ from AOD




ML predicted – “true” PM2.5 (µg m-3) at a random time




Observed vs. ML retrieved hourly PM2.5 (µg m-3) near GSFC, 2012




ML overestimates $PM_{2.5}$ in polluted areas but underestimates that in dust dominated areas, mostly likely due to no consideration of aerosol composition and/or size distribution in training

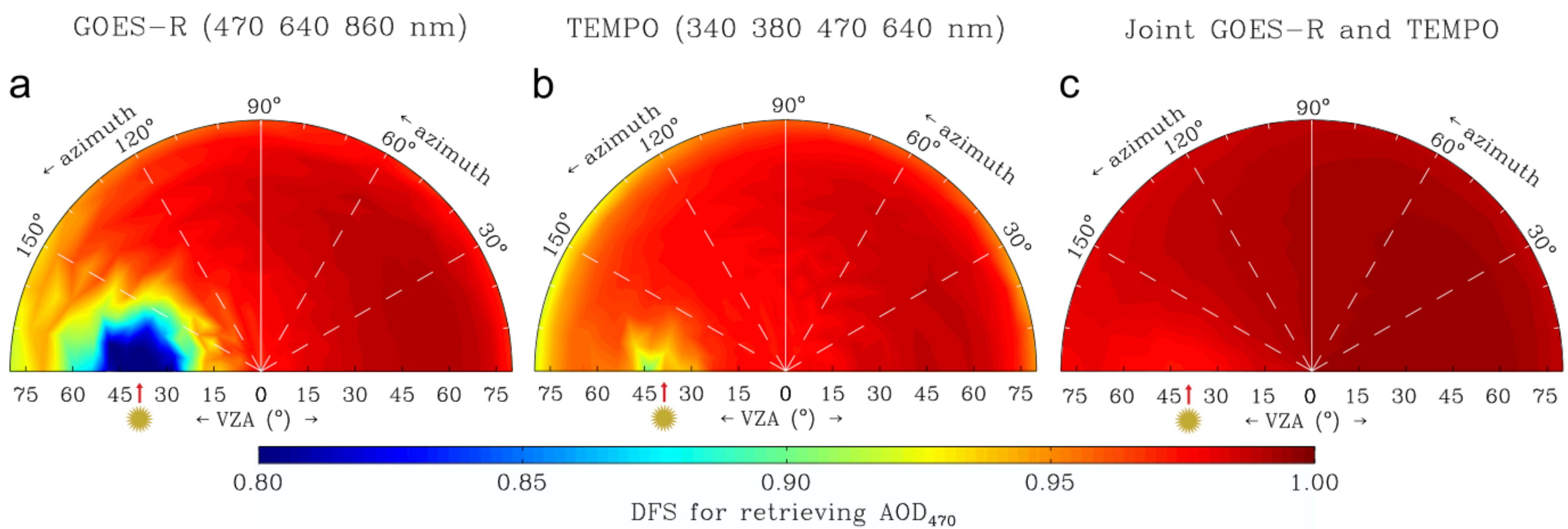
Using the above ML to retrieve $PM_{2.5}$ from AERONET AOD and compared to EPA observations shows an overestimation

(Preliminary study by Tianle Yuan, NASA GSFC)

# TEMPO applications and synergy with other sensors
## (2) with GOES-16, GOES-17, and AQ applications

**Synergy between GOES and TEMPO algorithms**

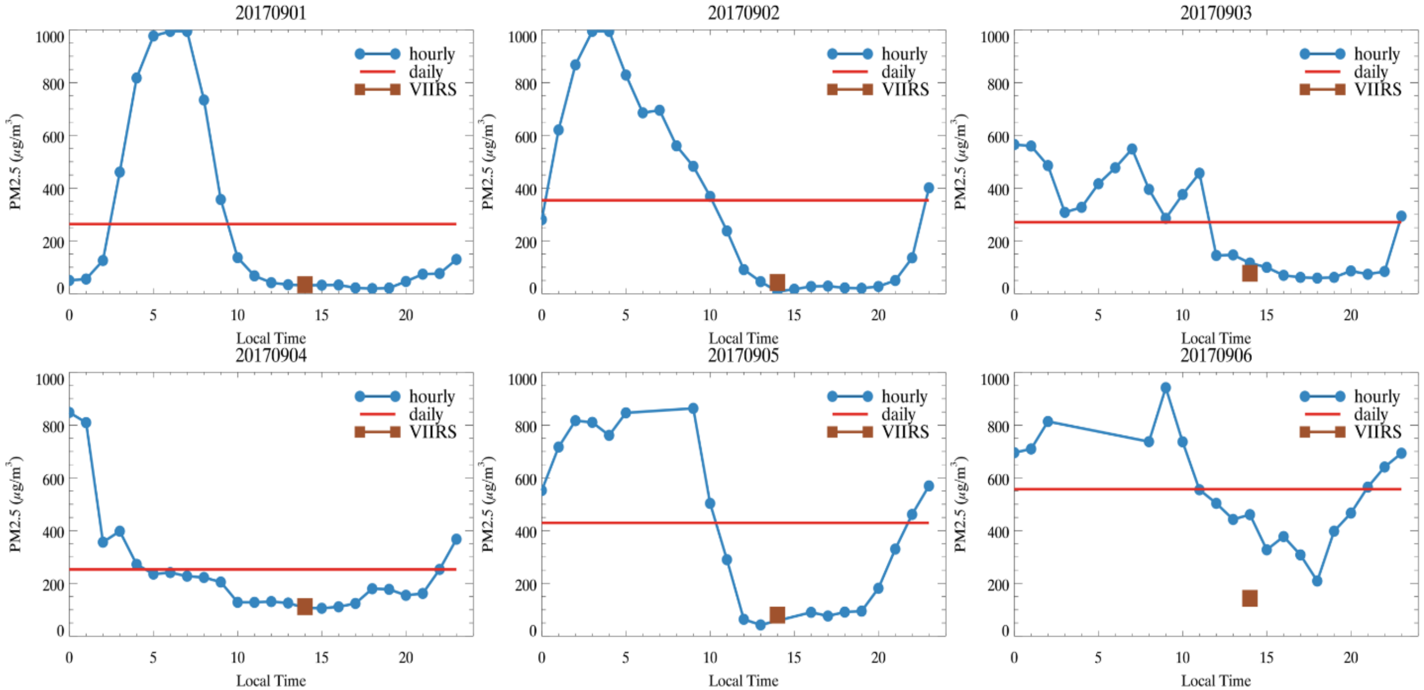
- Cloud screening and sub-pixel cloud
- Spectral properties of aerosols and surfaces
- Multiple angle characterization of aerosol properties
- Retrieval of aerosol layer height, enabling OMI+MODIS type of algorithm for air quality applications




DFS for AOD are increased by TEMPO+GOES, especially near the exact backscattering angle.
Wang et al., JQSRT, 2014.

# Temporally Resolved AOD for PM2.5

To estimate PM2.5 concentrations of the air we breathe, we need temporally resolved AOD measurements




**Courtesy: S. Kondragunta**

# Suite of Aerosol Products from Imager/Spectrometer Synergy

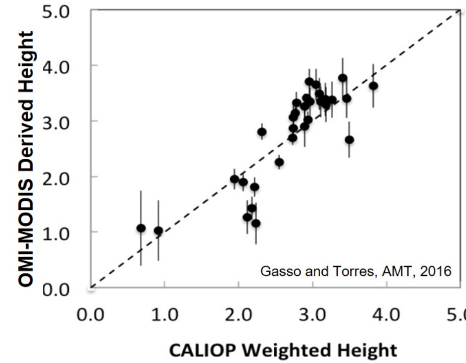
**Spectrometer L1B radiances**

| **Imager Pixel Resolution** |
| --- |
| 2.2 um reflectance |
| 4-level cloud mask |
| Visible AOD |

| **Spectrometer Pixel Resolution** |
| --- |
| 2.2 um reflectance |
| 4-level cloud mask |
| UV AOD |

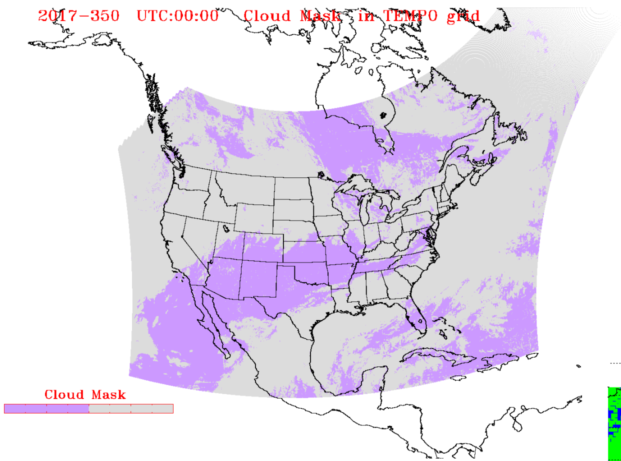
**NASA UV Aerosol Algorithm**

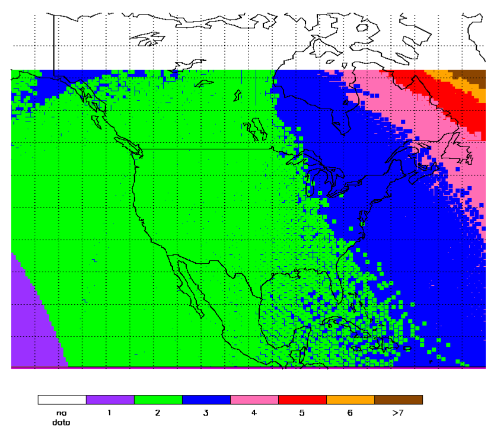
| | | | |
| --- | --- | --- | --- |
| **Aerosol Optical Depth** | **Single Scattering Albedo** | **Aerosol type** | **Aerosol layer height** |




**Courtesy: S. Kondragunta**

# Requirements for Synergy

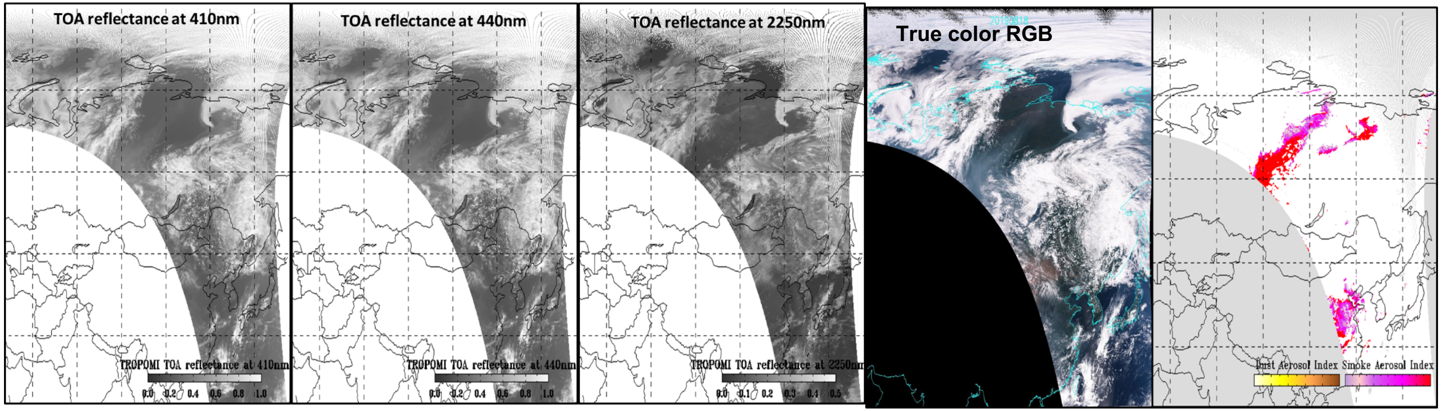



- Orbital location of satellites carrying the imagers and spectrometers important
  - ✓ Longitudinal separation of 30° or less is desired
  - ✓ GOES-R (16) at 75.2°W and TEMPO at 100°W
    - ➢ Two to six 500m ABI pixels fall into each TEMPO pixel depending on whether the region of interest in near-nadir or off-nadir

**Courtesy: S. Kondragunta**

# Synergy Experiment




- GOES-R/TEMPO Synergy tested with S5P TROPOMI/SNPP VIIRS
- G2A AMI/G2B GEMS gives an opportunity to test the synergy from a geostationary orbit

$$AAI = -100\left[\log_{10}\left(\frac{R_{0.41}}{R_{0.44}}\right) - \log_{10}\left(\frac{R'_{0.41}}{R'_{0.44}}\right)\right]$$

$$DSDI = -10\log_{10}\left(\frac{R_{0.41}}{R_{2.2}}\right)$$

**Courtesy: S. Kondragunta**

# TEMPO applications and synergy with other sensors
## (3) with TROPOMI, GEMS, Sentinel-4 (S4), Sentinel-5 (S5), …

**Use TROPOMI as a 'bridge' to bring together intercomparisons of aerosols/clouds products among different algorithms/sensors**

- Aerosol centroid layer heights
  - GEMS O4 technique
  - TROPOMI/S5 O2 A-band *spectral fitting* technique
  - TEMPO O2 B-band *band-intensity* fitting technique
- Cloud centroid pressure
  - TROPOMI O4 technique
  - TEMPO O4 technique
  - GEMS O4 technique
  - Cloud fraction
- UV aerosol product
- AOD product

  …

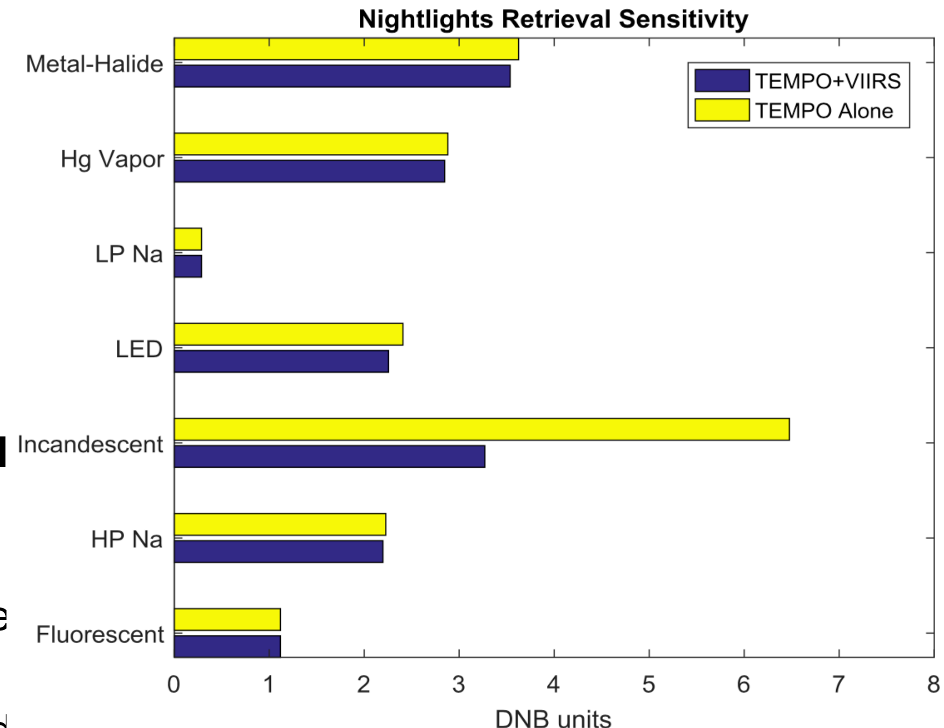
# TEMPO applications and synergy with other sensors
## (4) with MODIS, MISR, VIIRS, MAIA, …

**TMEPO intercomaprsion with**

- MISR aerosol/cloud stereo height
- MODIS/VIIRS cloud top height, cloud fraction, ….
- MISR/MAIA AOD, fine-mode AOD, …
- Surface reflectance

**Synergy with VIIRS for nighttime AOD and nighttime light pollution studies**

- VIIRS + TEMPO have the potential to characterize the surface light bulb type and spectral intensity
- VIIRS + TEMPO may lead to improved retrieval of nighttime AOD and fire confusion efficiency




Carr et al., JRSL, 2017.

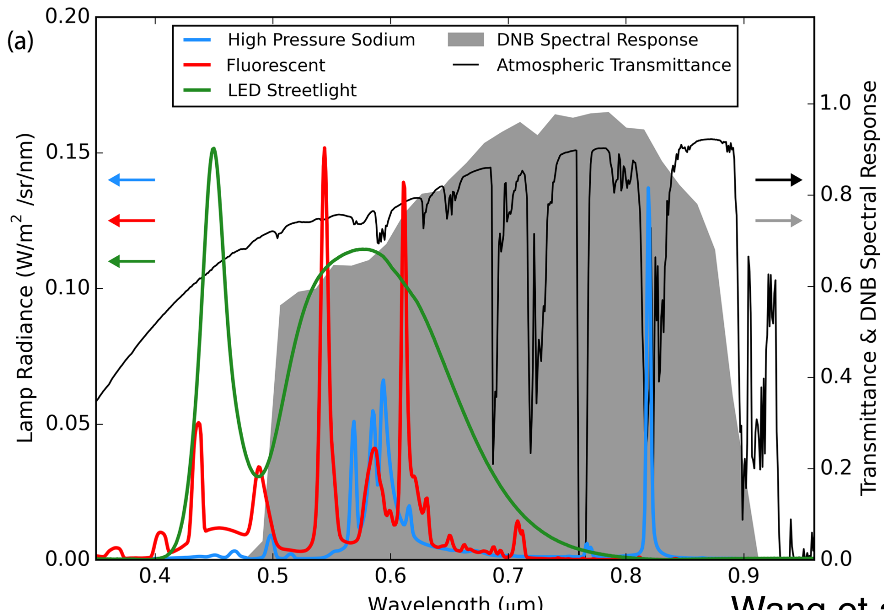
# Nighttime AOD and $PM_{2.5}$ mapping
## for details, see Meng Zhou's poster

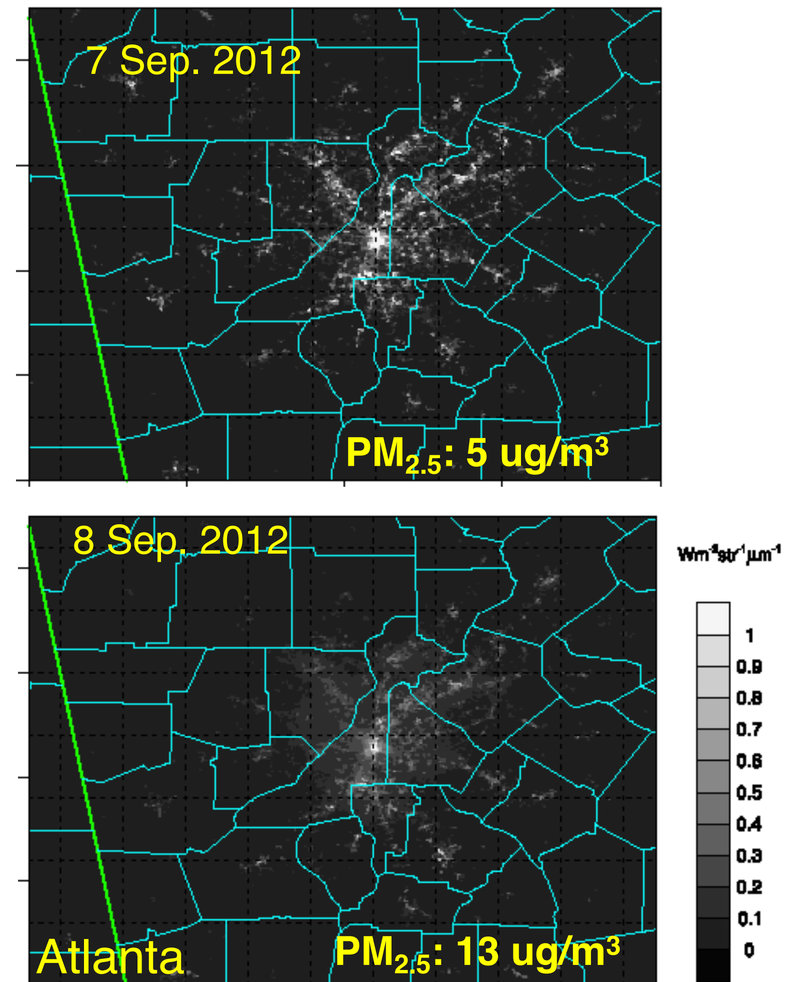
**Needs:**

- NAAQS requires 24-hr averages.
- Nighttime AOD data enriches model evaluation and data assimilation & forecast

**TEMPO + VIIRS**

- TEMPO: derive urban light spectra
- VIIRS: retrieve AOD and derive surface PM2.5

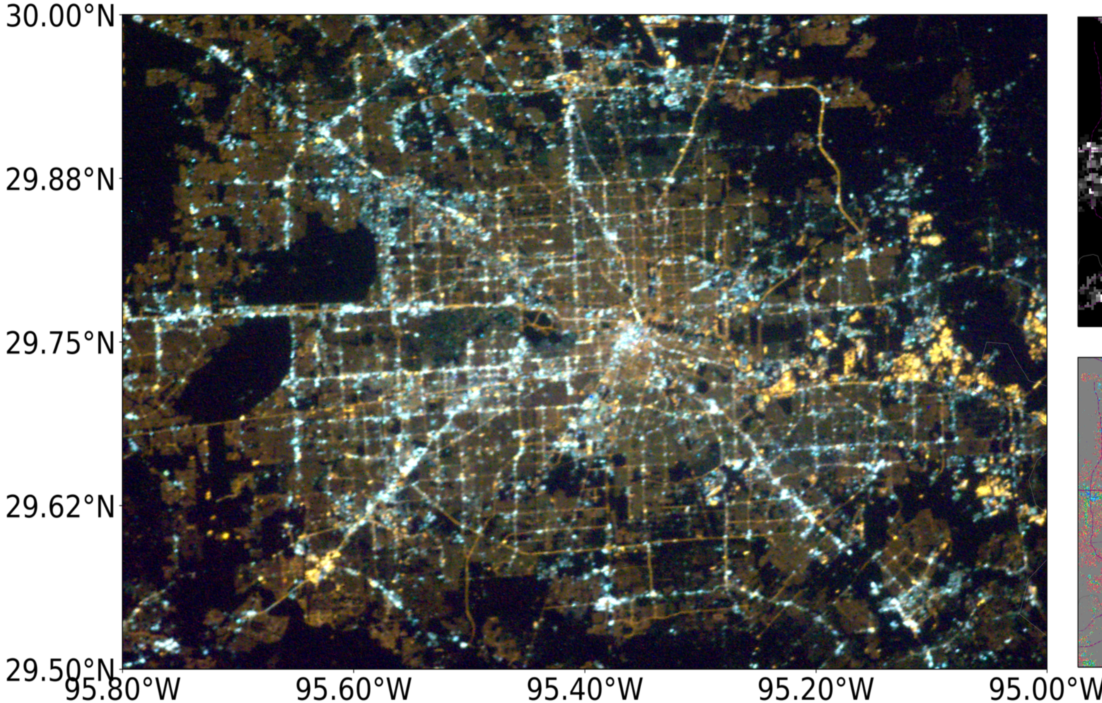


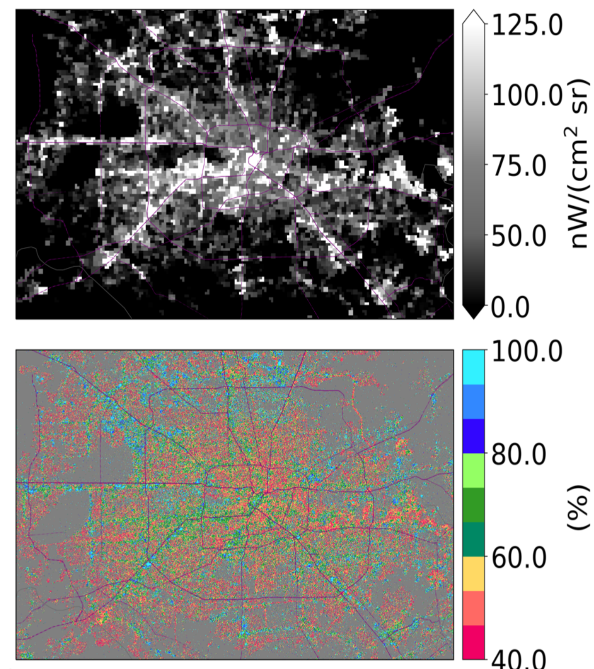




Wang et al., AE, 2016

# TMEPO+VIIRS have the potential to advance surveillance of light pollution and studies of light pollution on public health

- 99% U.S. population live with light-polluted activities skies (Falchi et al., Sci. Adv., 2016)
- Light pollution leads to circadian disruption & sleep deficiencies, affecting human health.
- Photoreceptor cells critical to circadian regulation in human eyes peaks at blue wavelength




VIIRS DNB

ISS Green/Red

ISS nighttime image over Houston on 9 Aug. 2014

# Summary

- *Daytime hourly* retrieval of aerosol absorption, spectral AOD and surface reflectance, as well as *aerosol centroid layer height*, which can advance AQ forecast and climate forcing studies (a key component of TEMPO STM).

- *Daytime hourly* retrieval of cloud centroid pressure and cloud fraction.

- *Strong synergy* with other sensors and surface networks to characterize AOD, fine-mode AOD, aerosol/cloud layer height.

- *New nighttime* observations to explore surface light pollution, AOD and surface $PM_{2.5}$ air quality, fires, ….

- *Many exciting products can be on the way provided  there are resources support*

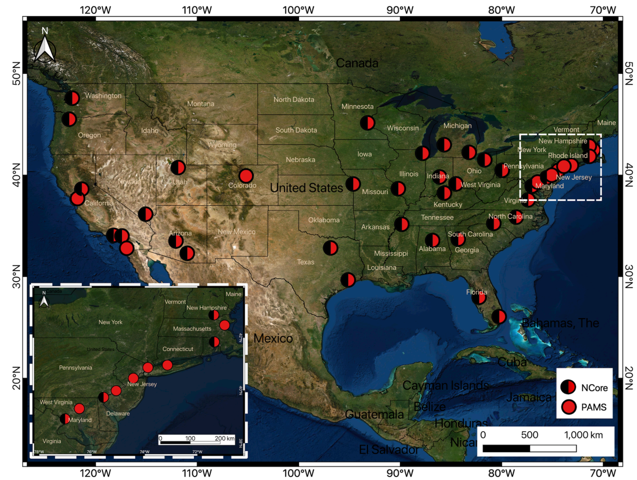
- An emergent era for aerosol layer height retrieval also calls for validation planning with surface networks of ceilometer/lidar and space-borne lidar (especially after CALIOP).

# Ceilometer Network

Courtesy: James Szykman
Vanessa Caicedo
Ruben Delgado

- Research Collaboration between EPA, University of Maryland, Baltimore County (UMBC), Maryland Department of the Environment (MDE), and NASA - [https://alg.umbc.edu/ceilometer-network/](https://alg.umbc.edu/ceilometer-network/)

- Objectives:
  - Maximize the science and applications value of ceilometer measurements at EPA Photochemical Assessment Monitoring Station Network
  - Allow for ceilometers at non-PAMS sites to become part of a larger network
  - Development and application of standardized retrieval algorithms for heterogeneous network
    - Caicedo et al. (2020) "An automated common algorithm for planetary boundary layer retrievals using aerosol lidars in support of the U.S. EPA Photochemical Assessment Monitoring Stations Program"
  - Development of data archive for ceilometer backscatter profiles and associated geophysical data products – mixing layer heights/aerosol layers heights/cloud based heights
  - PAMS/Ncore sites contains a suite of trace gases and aerosols, subset of sites with Pandoras
  - Used to support model development and evaluation and EPA exceptional events analysis
  - Collaboration with MPLNet to extend use of data through WMO
  - Operational by June 2021

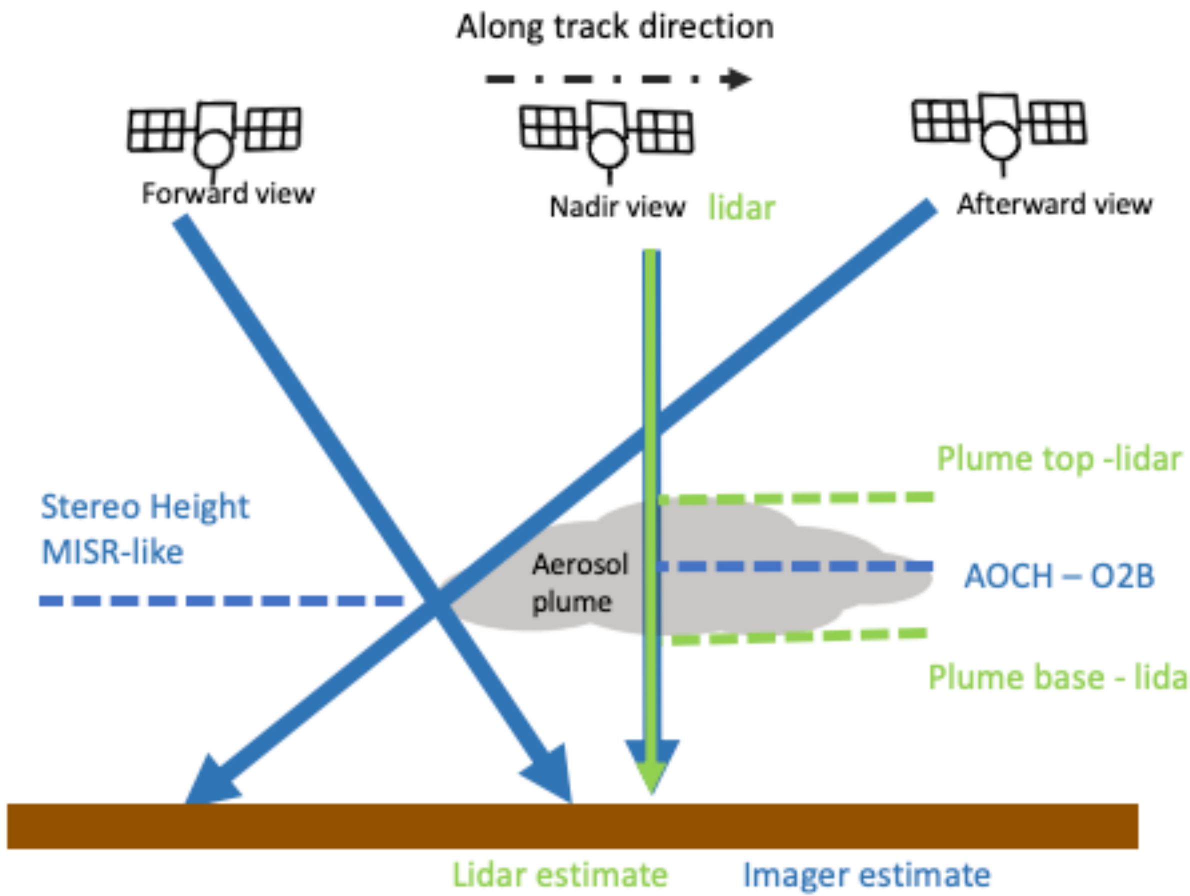



PAMS sites with requirement for hourly MLH

# Thank you !

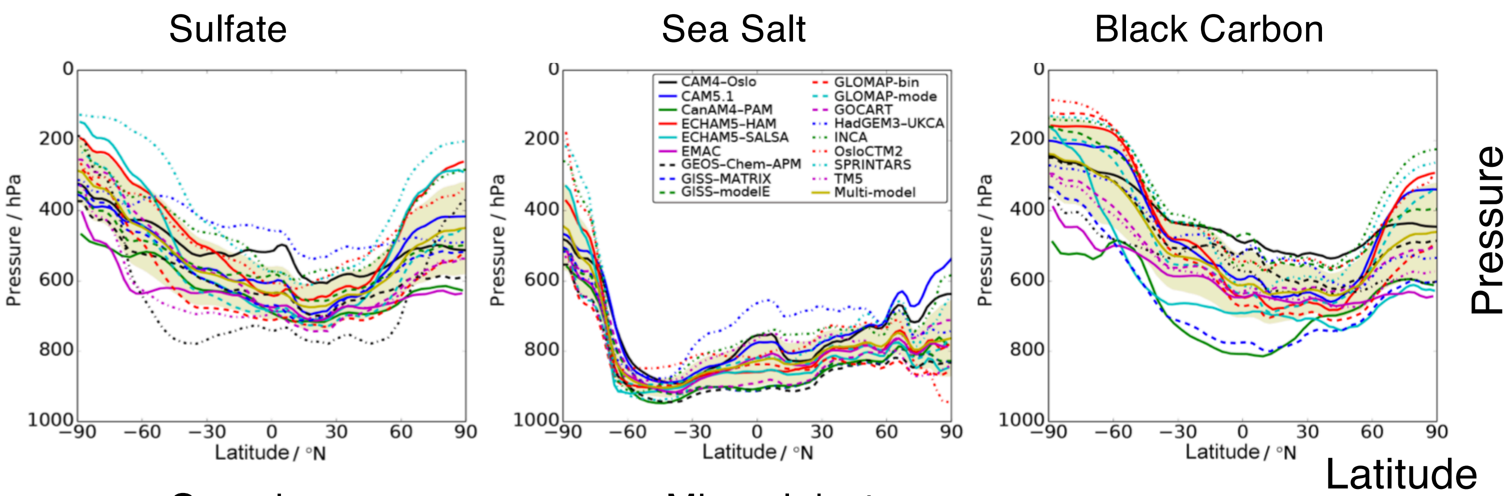
TEMPO, GEO-CAPE, ACMAP, KORUS-AQ, Applied sciences

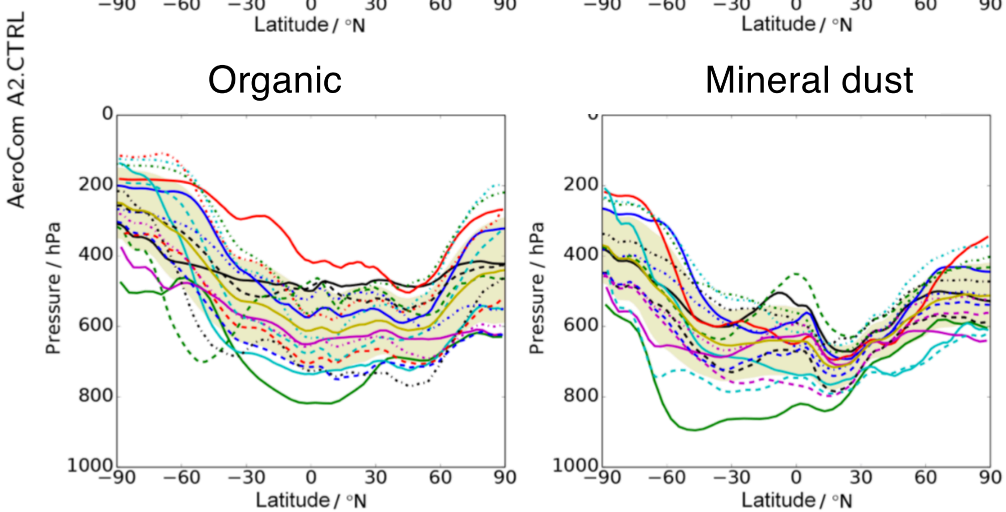
# Backup slides



Along track direction
Forward view
Nadir view
lidar
Afterward view
Plume top -lidar
Stereo Height
MISR-like
Aerosol
plume
AOCH – O2B
Plume base - lidar
Lidar estimate
Imager estimate

# Large uncertainty in aerosol vertical profile

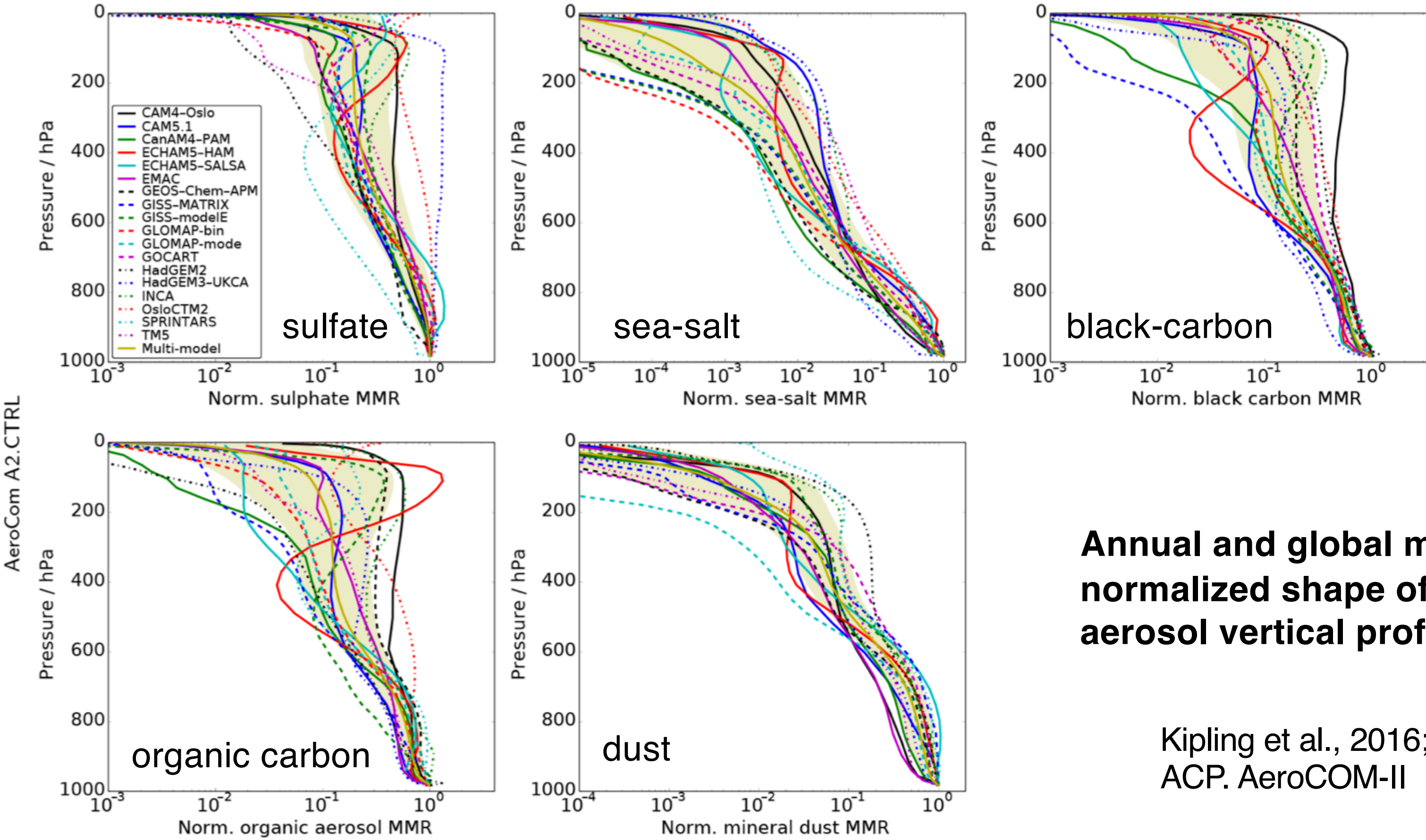



**Annual- and zonal-mean mass-weighted mean pressure level (vertical center of mass in pressure coordinates)**

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

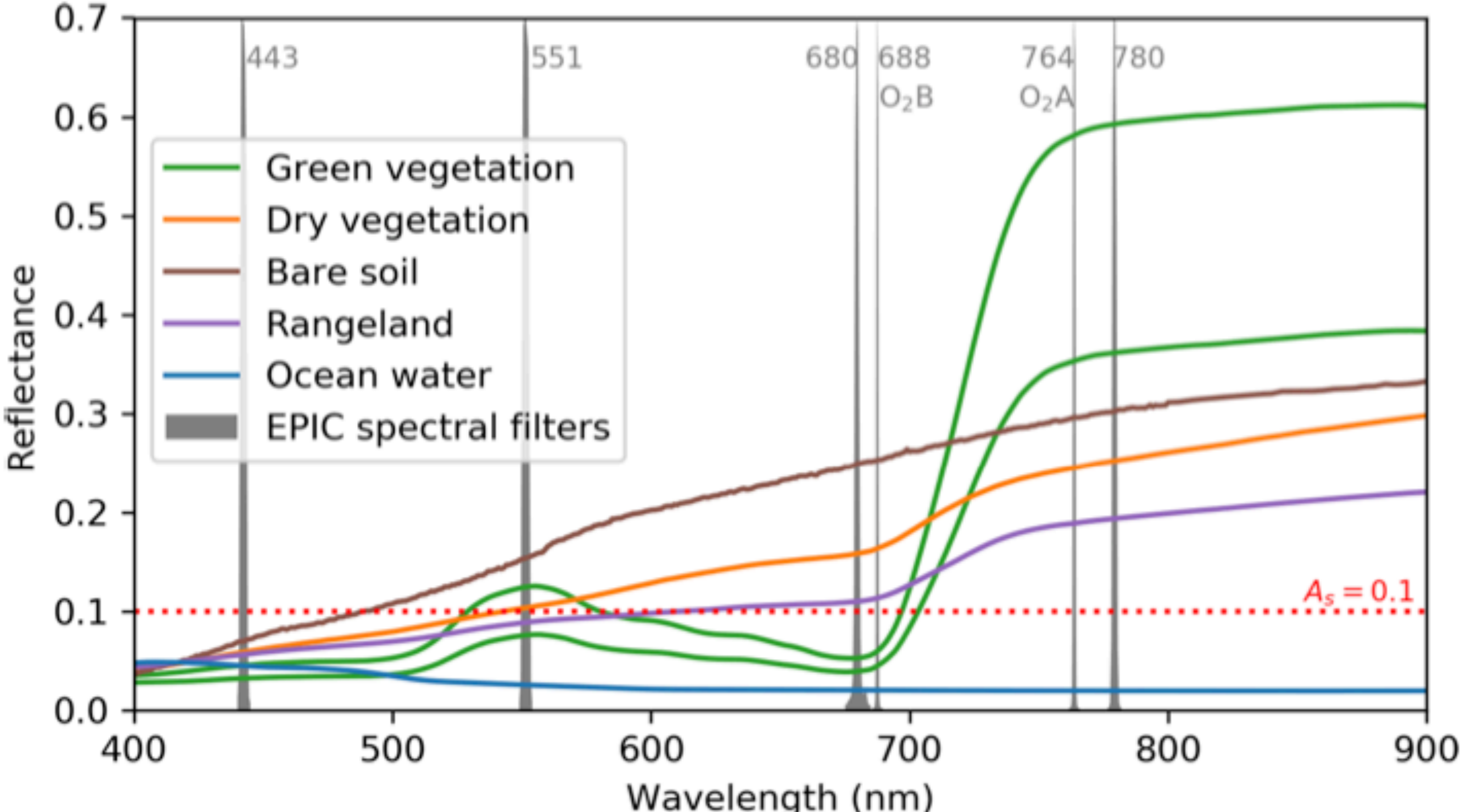
# Large uncertainty in our modeling of aerosol vertical profile highly relevant to climate and air quality prediction



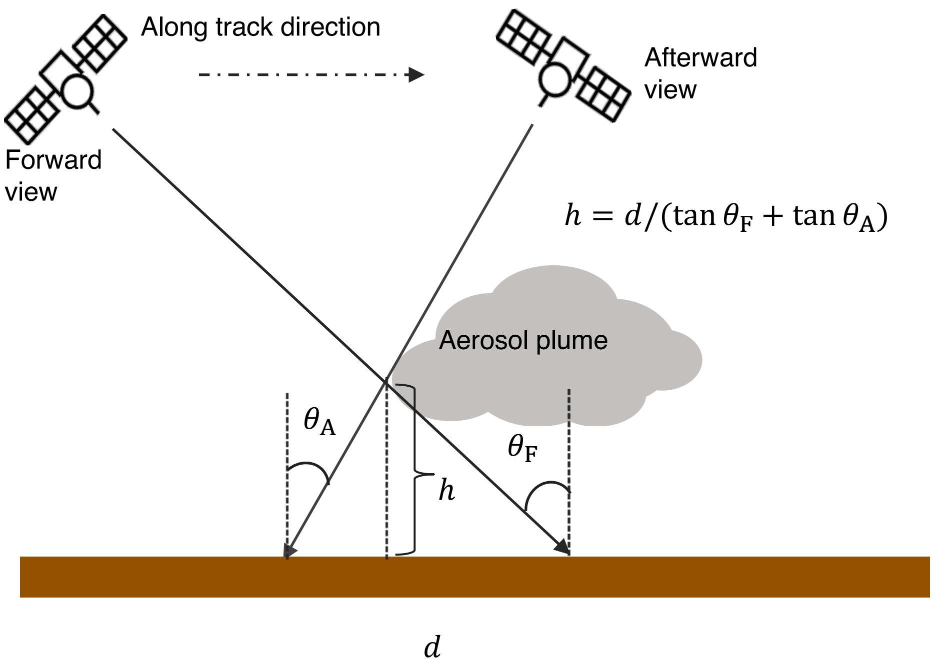

Uncertainty in free troposphere and UTLS is the very large; but this part of the atmosphere is also where lidar is best at for observing.

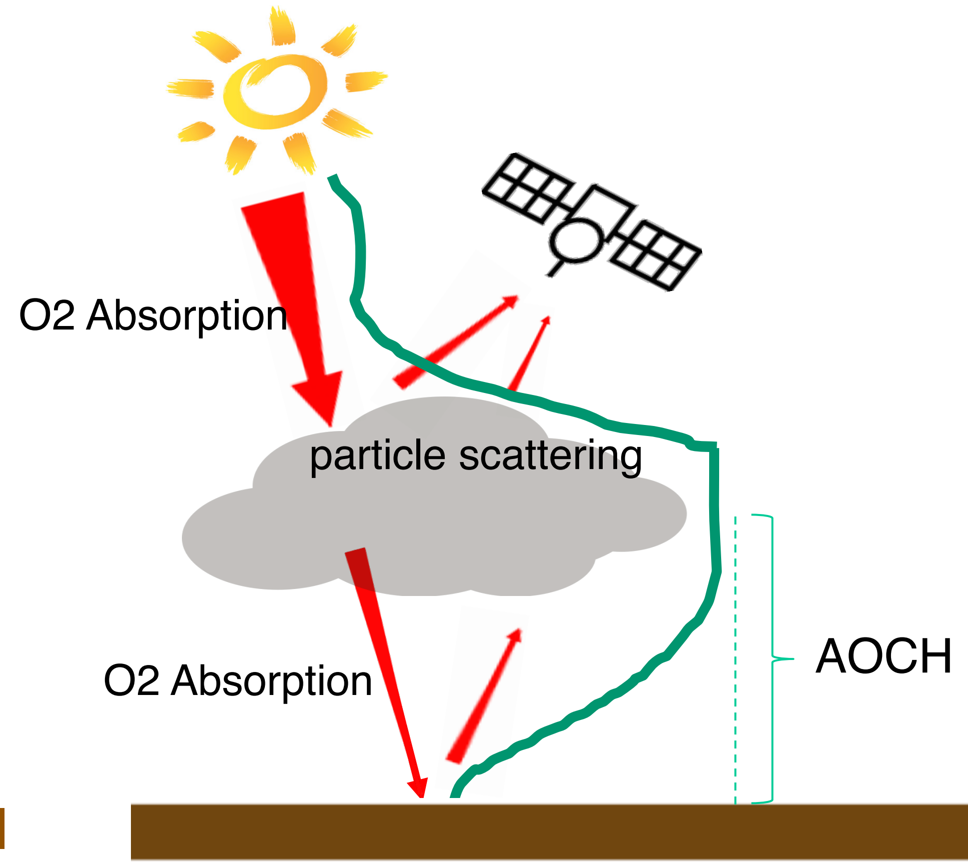
**Annual and global mean normalized shape of aerosol vertical profile**

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




Xu, Wang, et al., 2019


Along track direction
Afterward
view
Forward
view
$h = d/(\tan\theta_F + \tan\theta_A)$
Aerosol plume
$\theta_A$
$\theta_F$
$h$
$d$


O2 Absorption
particle scattering
O2 Absorption
AOCH

# TEMPO, GEO-TASO, and GCAS

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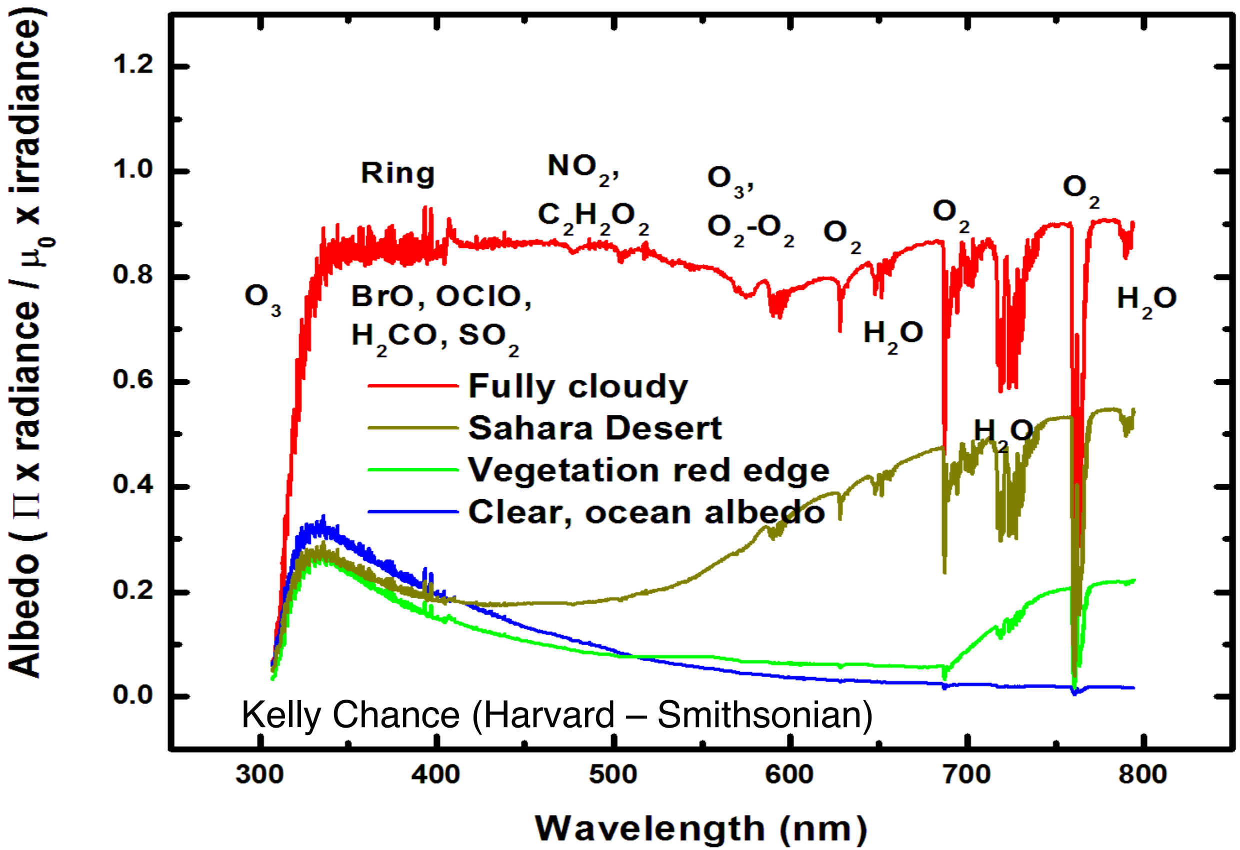
I---- TEMPO -----I I-------- -TEMPO -------I




**TEMPO**
**290–490 nm 540–740 nm**
**λ sampling: 0.2 nm**
**resolution/FWHM: 0.57 nm**

**GEO-TASO**
**290-400 nm 415-695 nm**
**λ sampling: 0.14/0.28 nm**
**Resolution/FWHM: ~0.4nm/ 0.8 nm**

**GCAS**
**300-490 nm, 480-900 nm**
**λ sampling: 0.2/0.8 nm**
**Resolution/FWHM: 0.6/2.8 nm**