Applications of EPIC AOCH for climate and air quality studies

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Previous Work and Motivations

- **Algorithm Development**
  - EPIC retrieval of aerosol optical centroid height (AOCH) over dark surfaces
  - Xu et al., 2017, GRL; Xu et al., 2019, AMT

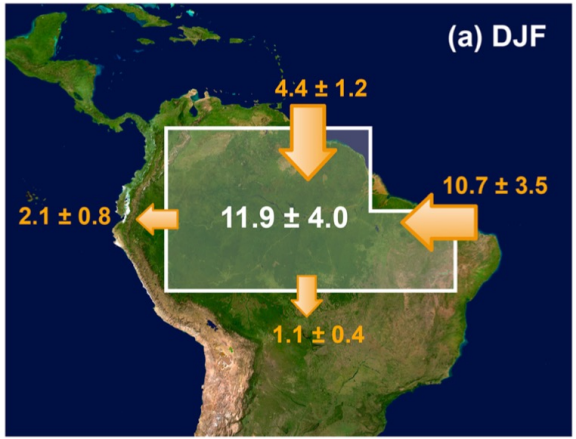
- **Application of EPIC's data for Climate Studies**
  - Aerosol vertical distribution affects the radiative forcing of aerosols
  - Large uncertainties of aerosol vertical distribution in current climate models

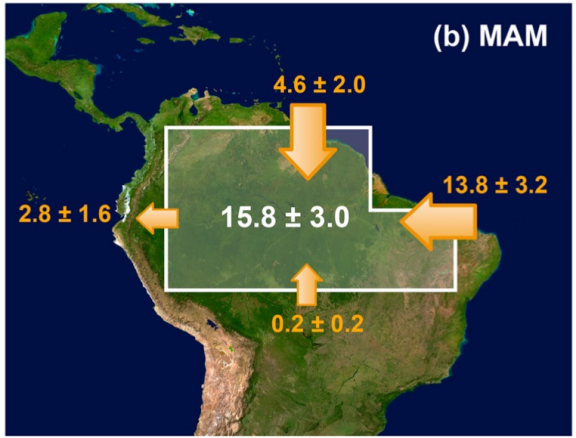
- **Application of EPIC's data for Air quality Studies**
  - Diurnal variation of aerosol layer height is needed for better surface air quality forecasting

Importance of Saharan dust transport

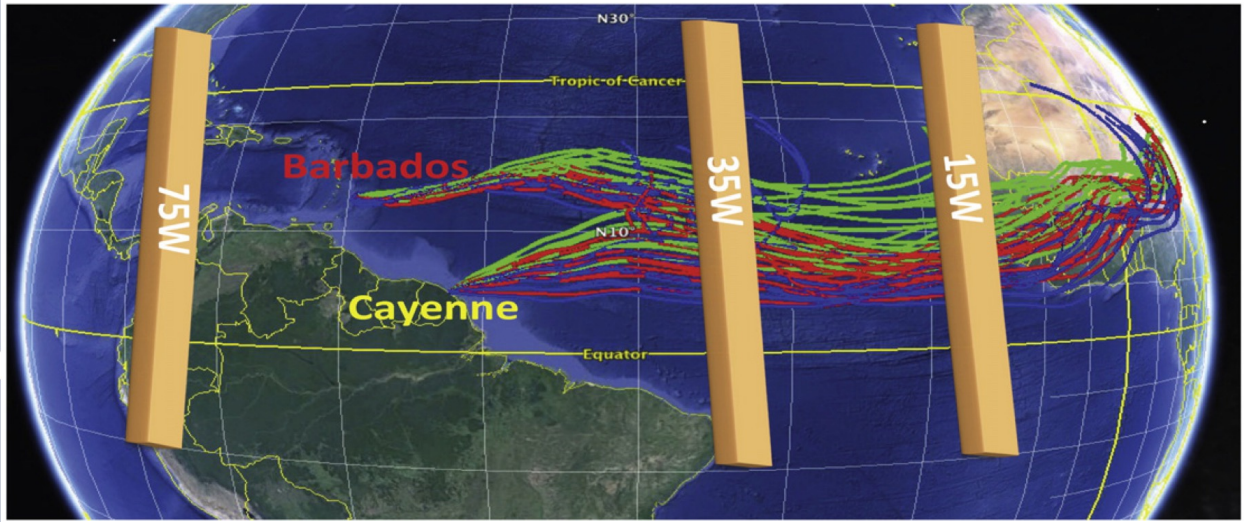
vertical distribution

Transboundary mass flux: $-\int_0^{10km} m(z)U_{CLR}(z)Ldz$





All numbers are in Tg

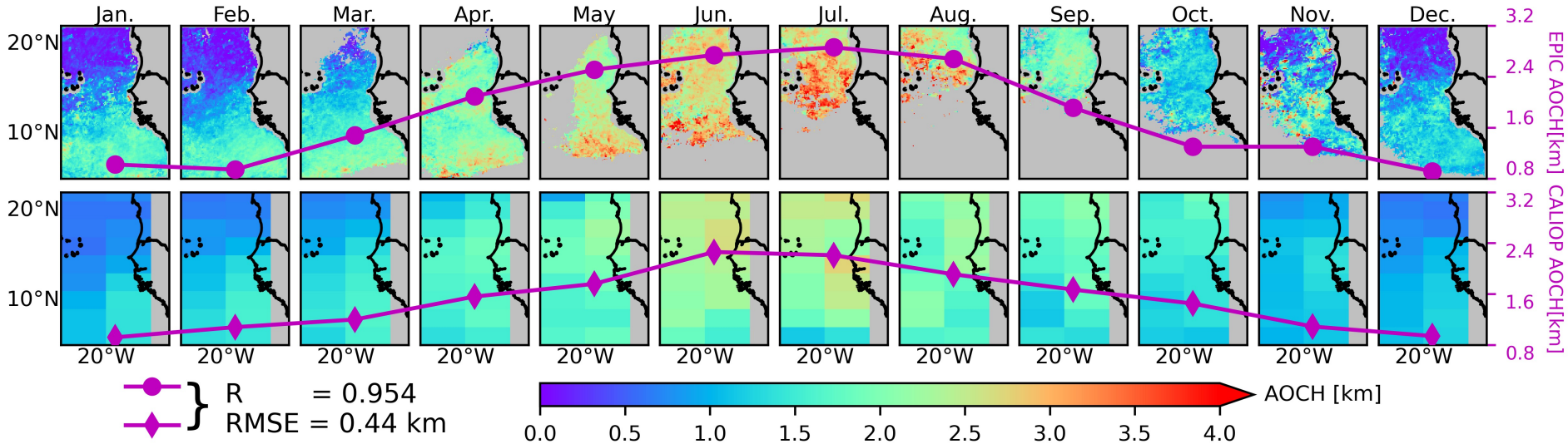


1) Fertilization source for Amazon forest
2) Impact on ice cloud formation and lase rate
3) Air quality effect

Hongbin Yu et al., GRL, 2015; RSE, 2015.

EPIC vs. CALIOP

Aerosol Optical Centroid Height (AOCH)



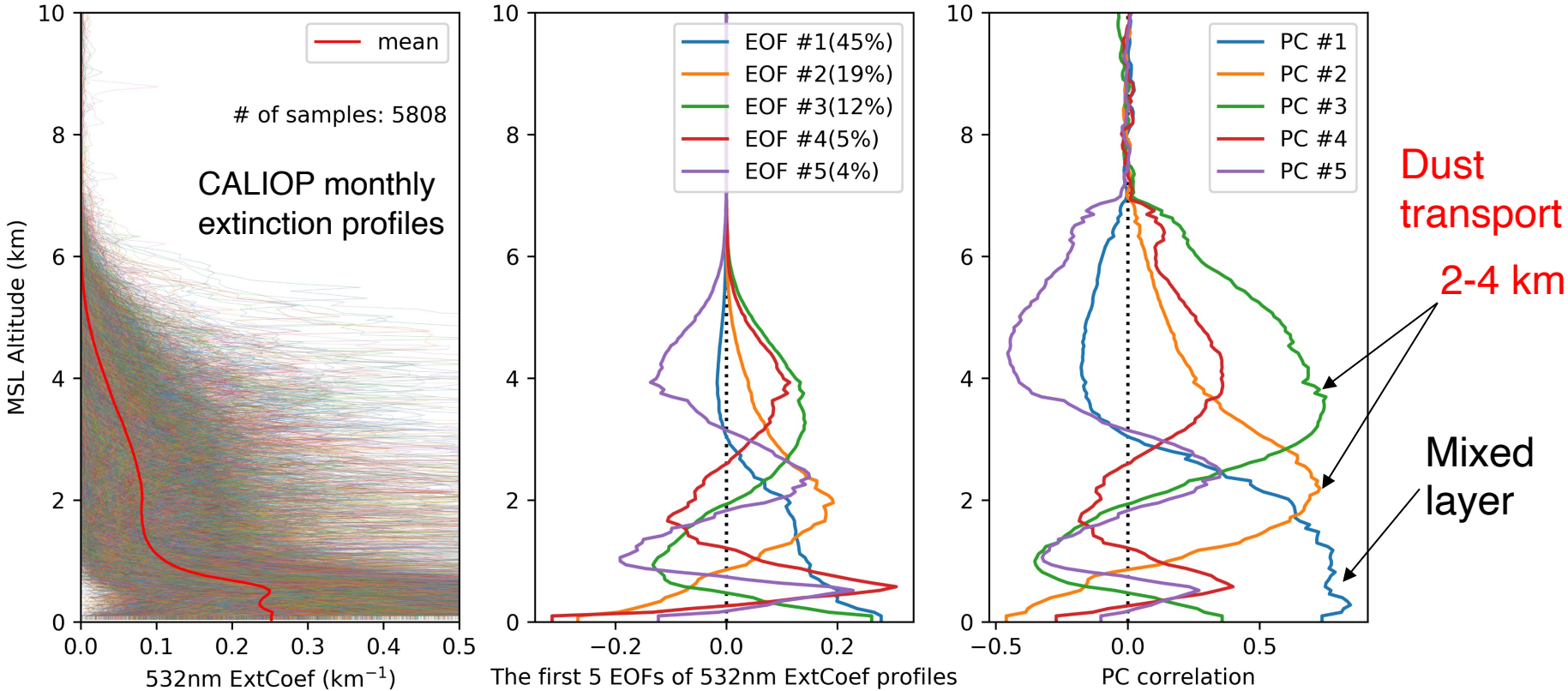
Top : EPIC retrieval: 2015.06-2019.06, at ~10 km resolution

Bottom : CALIOP level3: 2006.06-2019.06, at 2.5° x 5° resolution

Peak at summer, lowest at winter

Major variation modes of dust vertical profiles

PCA of Sahara dust profiles over Atlantic Ocean (Daytime)

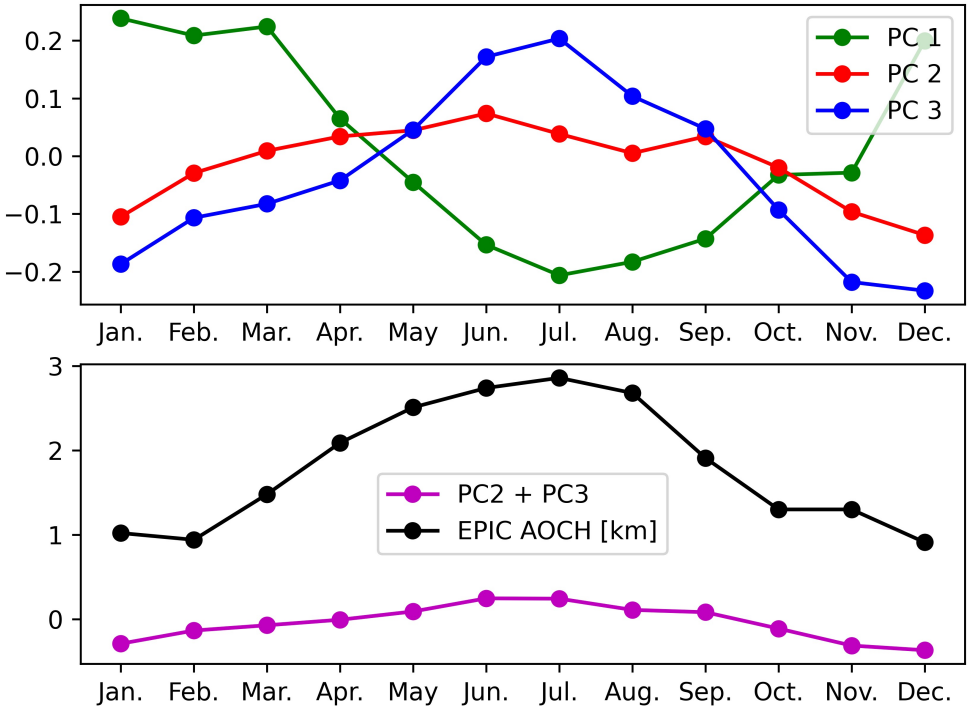


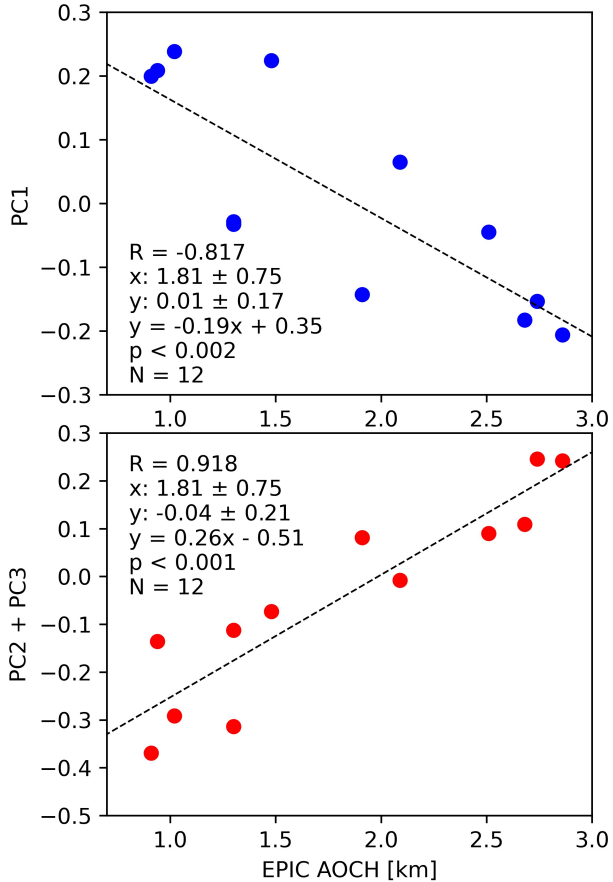
5 major modes explain ~85% variance in the vertical

First 3 modes: boundary layer and mid-troposphere explain ~76% variance

EPIC AOCH retrieval can explain the change of dust transport mode as seen by CALIOP

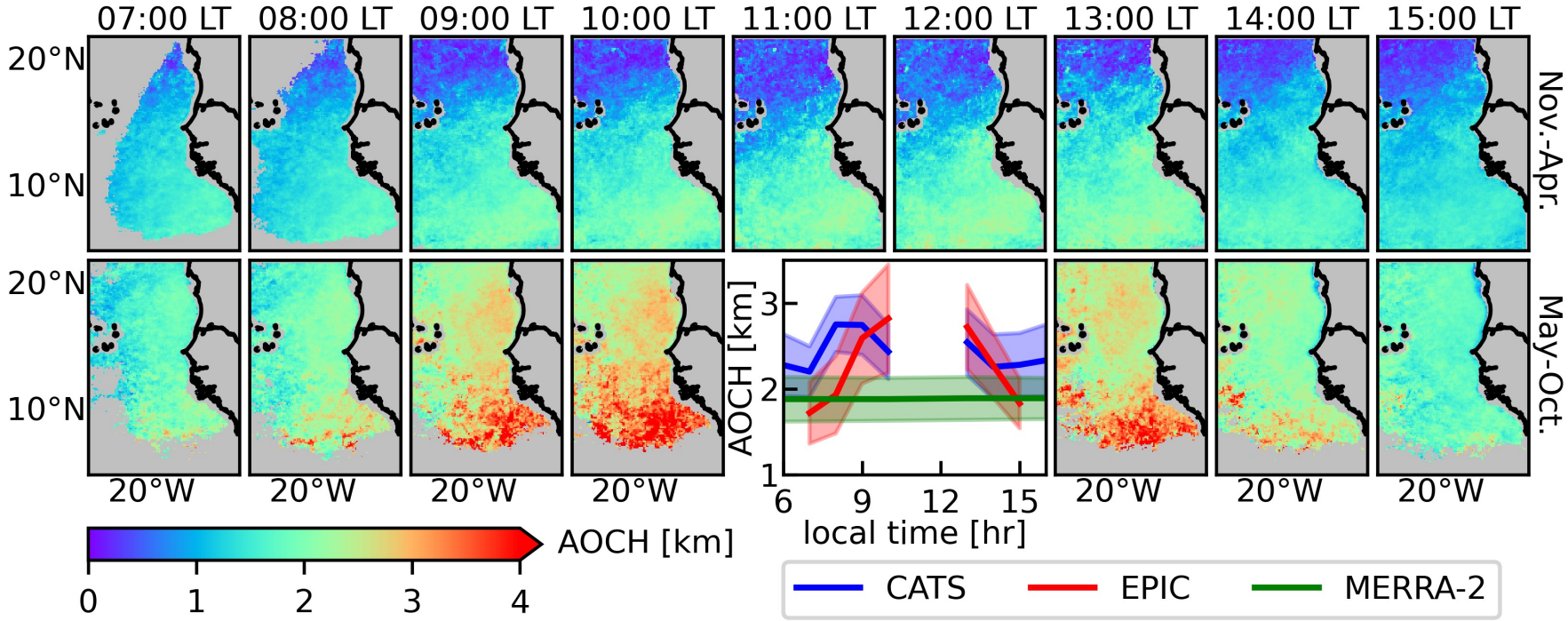
PC1: **Weights** of mixed layer variation
PC2 & PC3: **Weights** of dust transport





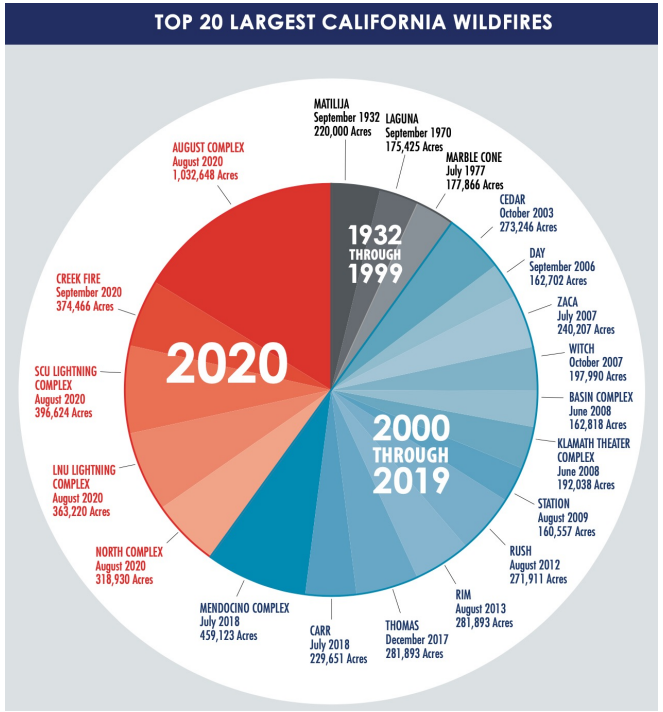
AOCH increase is driven by change of dust plumes
(and relatively decreasing role of boundary layer process)

EPIC's uniqueness:
Hourly climatology of Saharan dust height
EPIC v.s. CATS v.s. MERRA-2

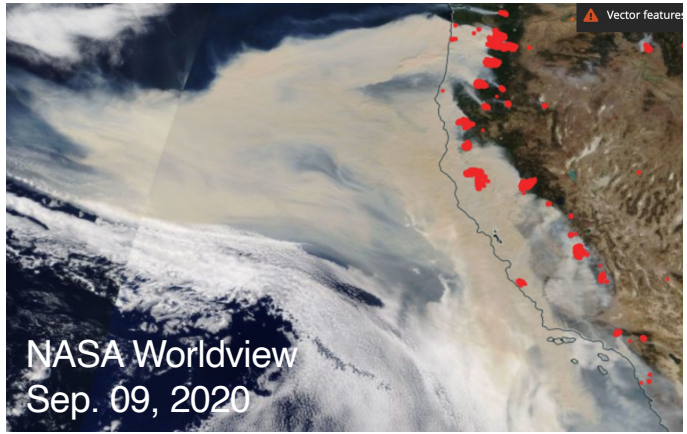


Both EPIC and CAT agree that high height around noon; Low at early morning & late afternoon
MERRA-2 shows little variation.

Importance of smokes from wildfires



California Department of Forestry and Fire Protection, *2020 Fire Siege*
https://www.fire.ca.gov/media/hsviuuv3/cal-fire-2020-fire-siege.pdf



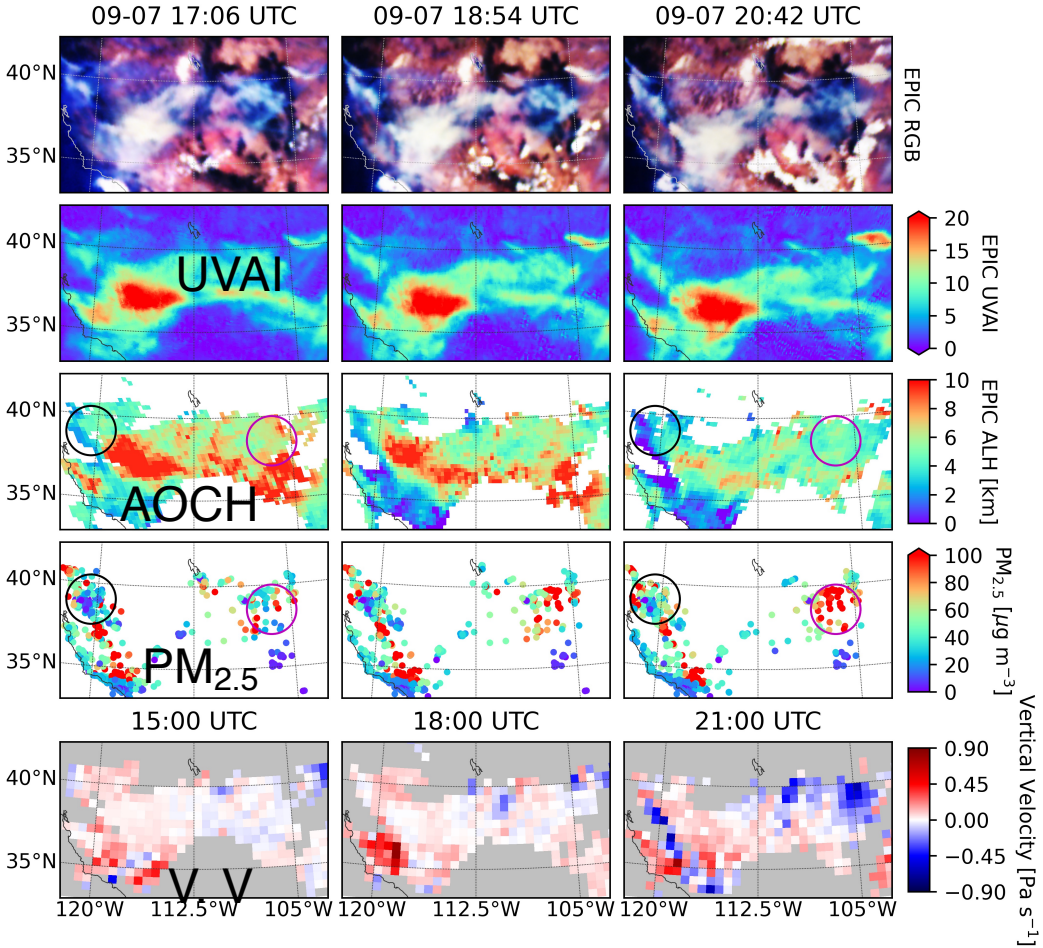
(1) Degrade surface air quality
(2) Affect Earth's energy budget

How high are these smoke layers?!

Val Martin et al., ACP, 2013
Zarzycki et al., GRL, 2010

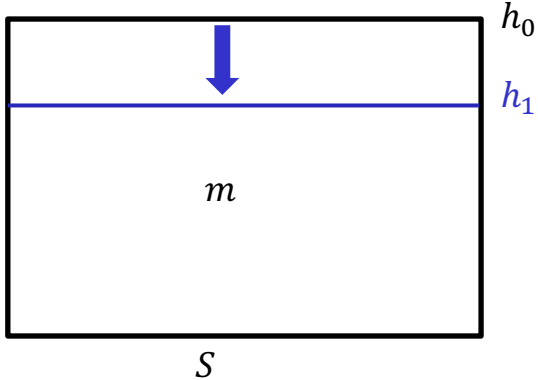
Hourly mapping of smoke height

- Algorithm Revisions
  - vicarious calibration based on TROPOMI data
  - adjust cloud mask so that thick smokes would not be misclassified as clouds
  - Lu et al., 2021, FRS, in review
- Descending smoke heights lead to increasing $PM_{2.5}$
- Positive vertical pressure velocity indicates descending air motion



Smoke vertical velocity and variation of $PM_{2.5}$: a box model

box model



Assume total mass of $PM_{2.5}$ is constant in the "box".

$$c = \frac{m}{Sh}$$

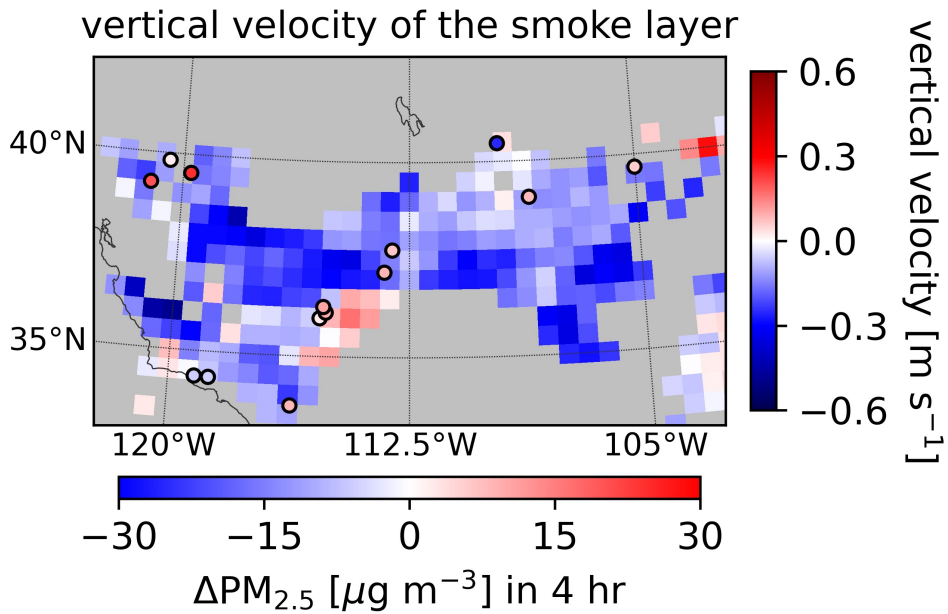
$$dc = d\left(\frac{m}{Sh}\right) = \frac{Sh\,dm - m\,d(Sh)}{S^2h^2} = \frac{-m\,dh}{Sh^2} = \frac{-c\,dh}{h}$$

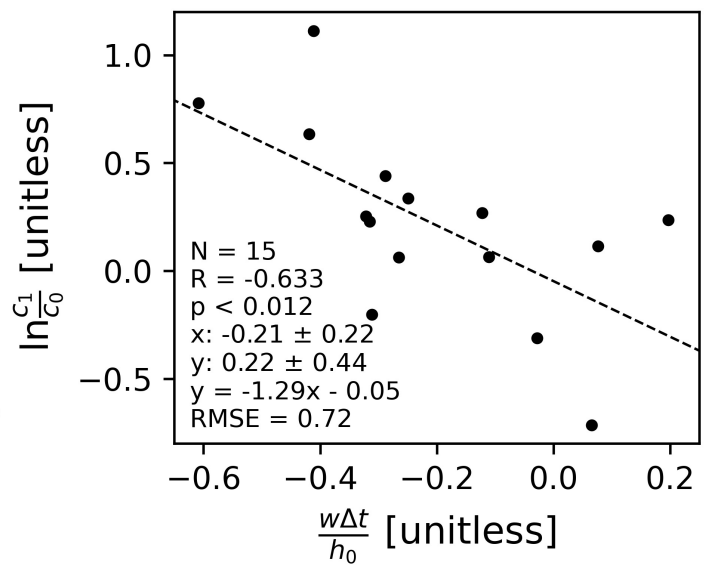
$$\frac{dc}{c} = -\frac{w\,dt}{h}$$

$$\ln\frac{c_1}{c_0} \approx -\frac{w(t_1 - t_0)}{h_0}$$

- m: total mass of $PM_{2.5}$, assumed to be constant;
- S: bottom area of the box;
- h_0 (h_1): smoke height at time t_0 (t_1);
- c_0 (c_1): mass concentration of $PM_{2.5}$ at time t_0 (t_1);
- w: vertical velocity of smoke layer.

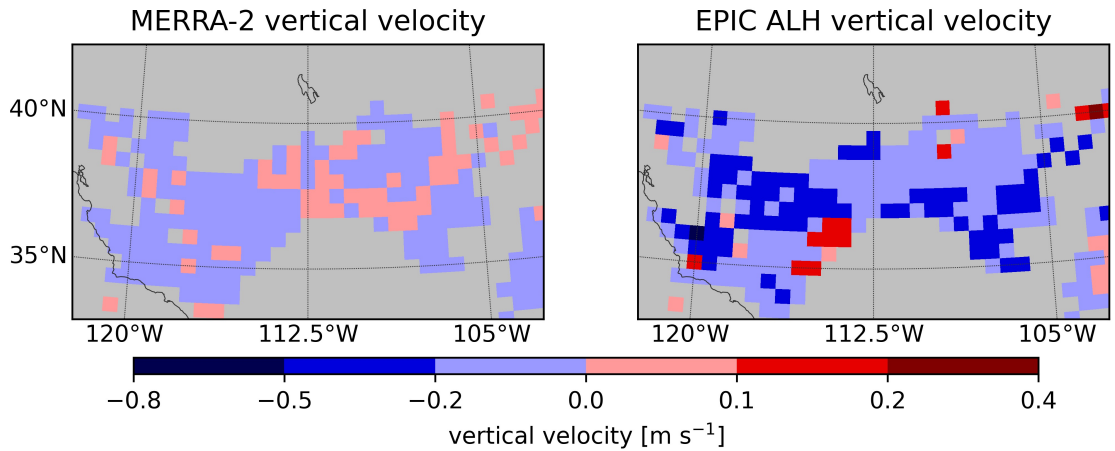
Smoke vertical velocity and variation of $PM_{2.5}$: a box model

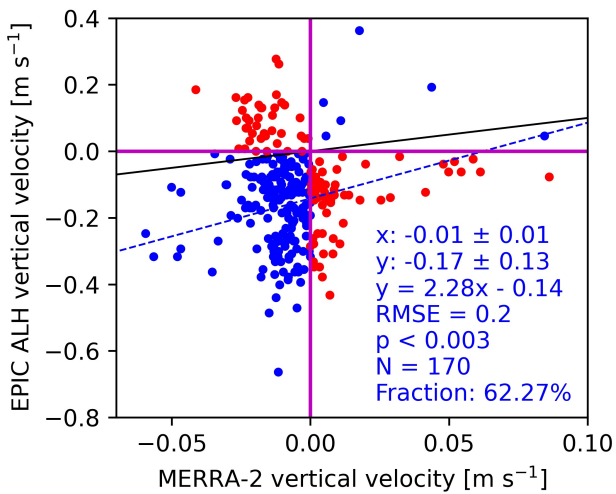




Improve hourly $PM_{2.5}$ estimation by integrating diurnal aerosol layer height

vertical velocity between EPIC v.s. MERRA-2





- Vertical velocity is very difficult to measure and model
- Both EPIC retrieval and MERRA-2 data show the descending motion dominates.
- 62.3% of total samples are in the same motion direction for EPIC and MERRA-2.

Summary

EPIC data is uniquely positioned for:

- **Climate studies of diurnal variation of aerosol layer height climatology**
  - DSCOVR/EPIC can help provide monthly climatology of dust plume height with a much finer spatial resolution than CALIOP.
  - DSCOVR/EPIC can uniquely provide the hourly climatology of Saharan dust height.

- **Air quality studies to estimate surface PM2.5 and characterize smoke vertical transport**
  - Hourly variation of smoke height retrieved from DSCOVR/EPIC could be quantitatively linked to the diurnal variation of surface $PM_{2.5}$ through a simple box model.

AGU PUBLICATIONS

Geophysical Research Letters 2017

RESEARCH LETTER

10.1002/2017GL073939

44, 7544–7554

Key Points:

- Algorithm to retrieve dust optical depth and centroid height using the O_2 A and B bands is developed
- First retrieval results of dust optical depth and altitude from EPIC/DSCOVR are shown in good agreement with the counterparts from MODIS and CALIPSO
- Passive remote sensing of aerosol height multiple times within a day is demonstrated with EPIC and discussed for future studies

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

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Acknowledgments

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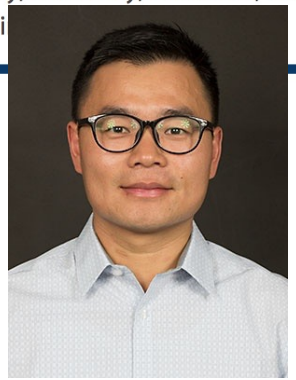
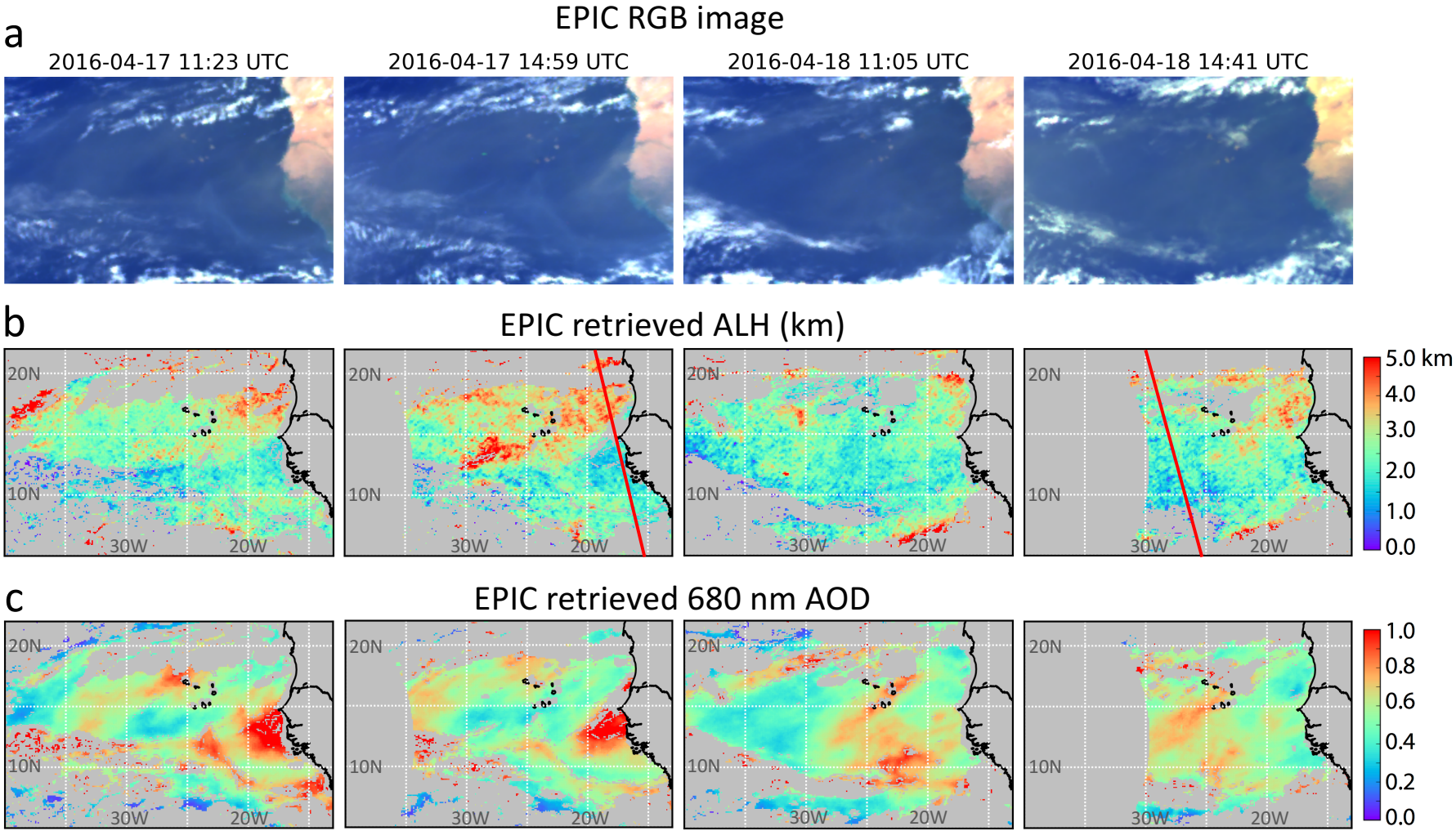


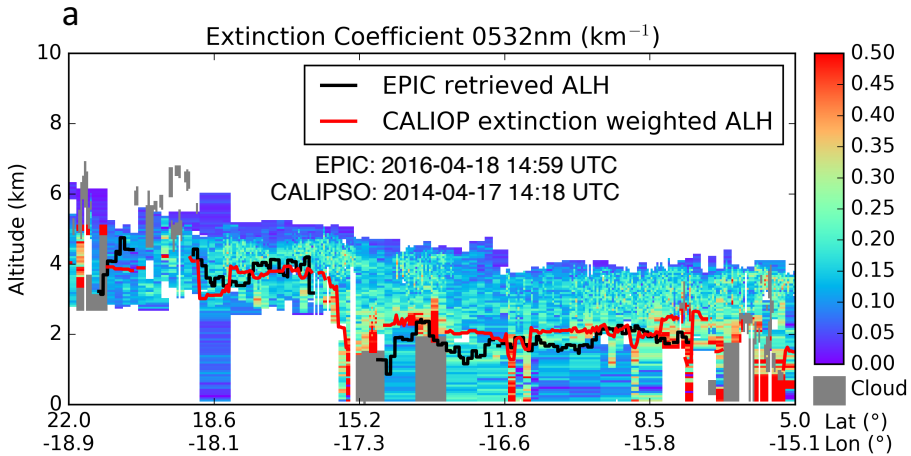
Xiaoguang Xu, UMBC

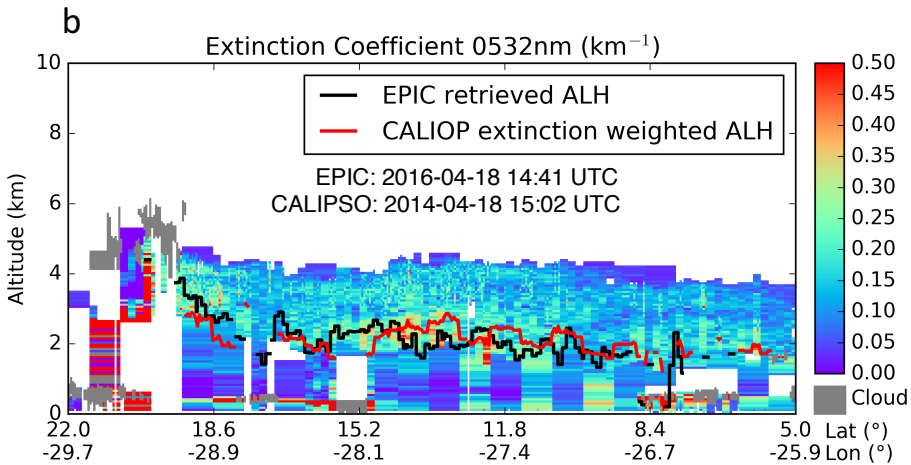
Retrieval of plume height and AOD

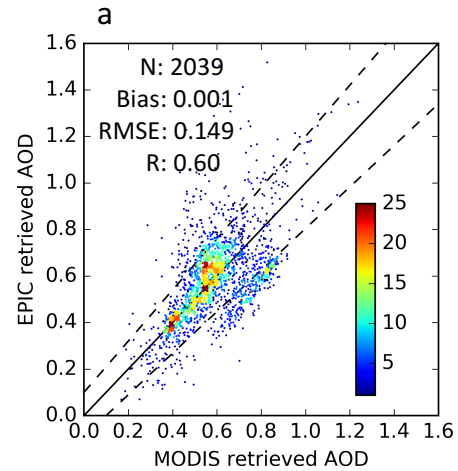


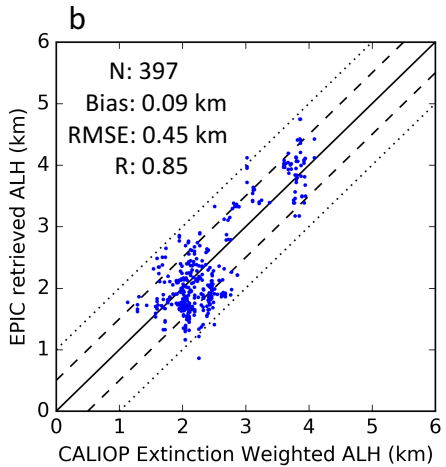
Validation with MODIS and CALIOP data

Xu et al., 2017, GRL









Atmos. Meas. Tech., 12, 3269–3288, 2019
https://doi.org/10.5194/amt-12-3269-2019
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Atmospheric Measurement Techniques
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Journal highlight article

Detecting layer height of smoke aerosols over vegetated land and water surfaces via oxygen absorption bands: hourly results from EPIC/DSCOVR in deep space

Xiaoguang Xu[1,2], Jun Wang[1], Yi Wang[1], Jing Zeng[1], Omar Torres[3], Jeffrey S. Reid[4], Steven D. Miller[5], J. Vanderlei Martins[2], and Lorraine A. Remer[2]

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[5]Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado 80523, USA

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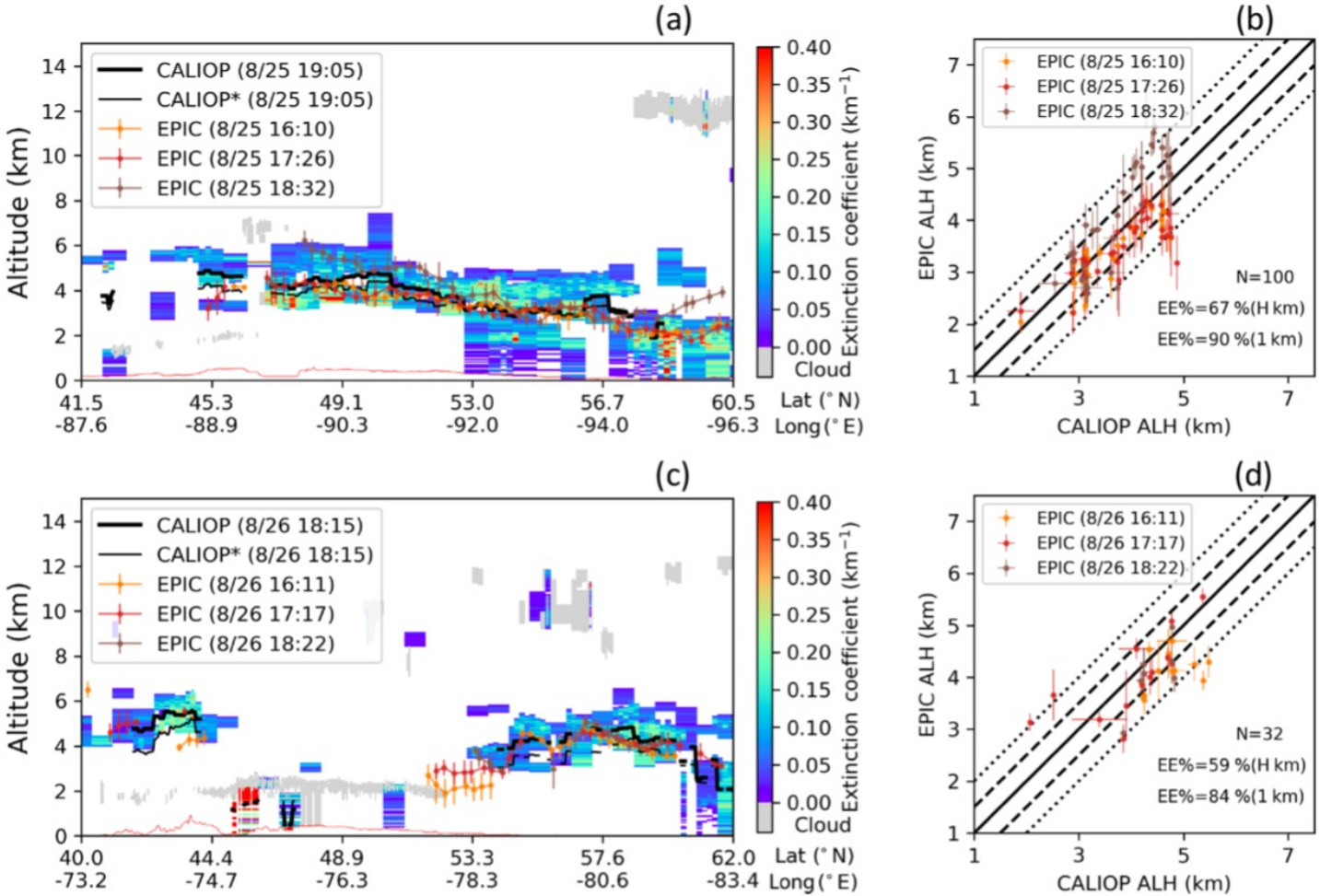
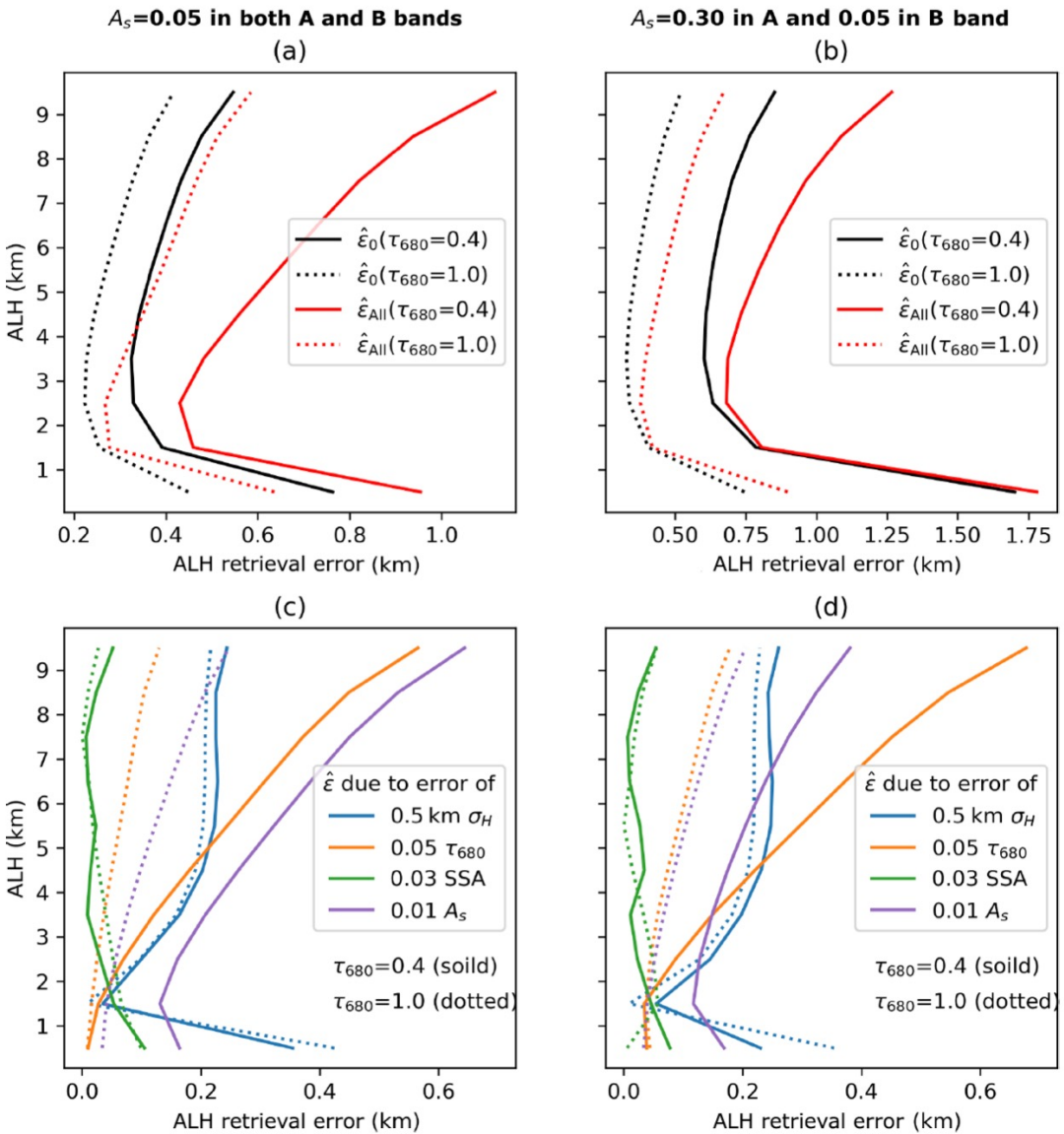
Xiaoguang Xu
UMBC

EPIC ALH vs. CALIOP extinction profile



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

Xu et al., 2019, AMT
AMT highlight article



A brief summary

EPIC O2 A & B bands are unique to constrain diurnal variation of smoke and dust plumes over dark (ocean and land) surfaces.

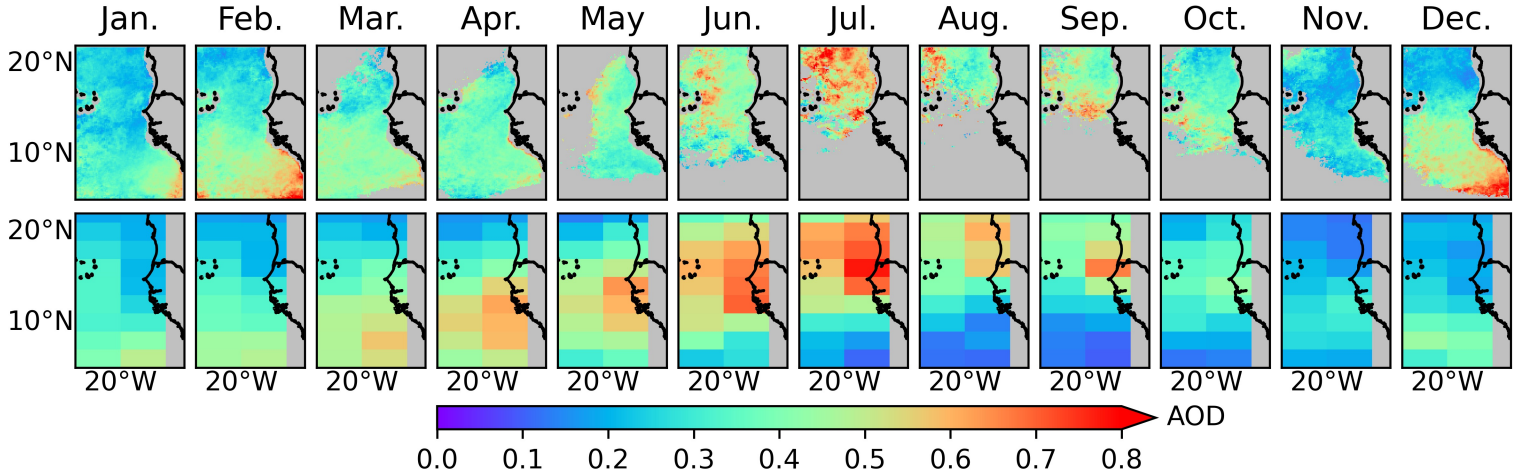
Instantaneous retrieval errors:

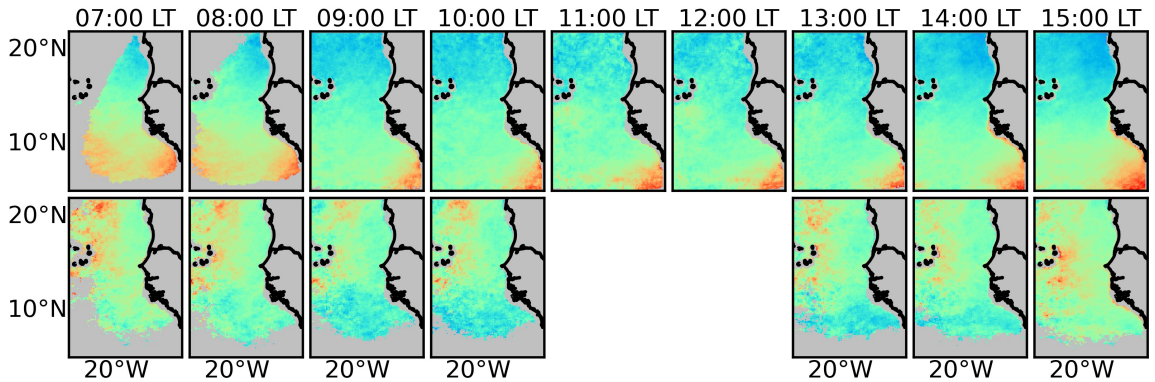
1) Higher over bright surfaces
2) Higher for low AODs
3) Smaller to mid-troposphere aerosol layer height

Comparison with CALIOP show overall error is ~0.5 km.

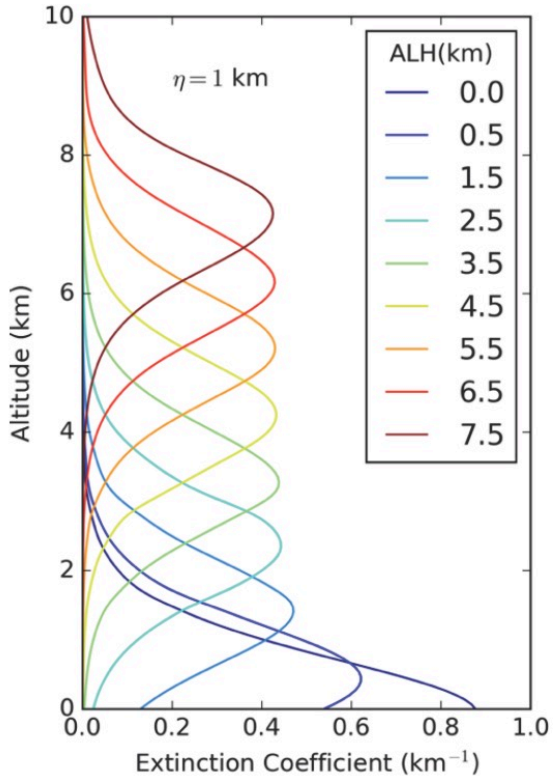
Xu et al., AMT, 2019.

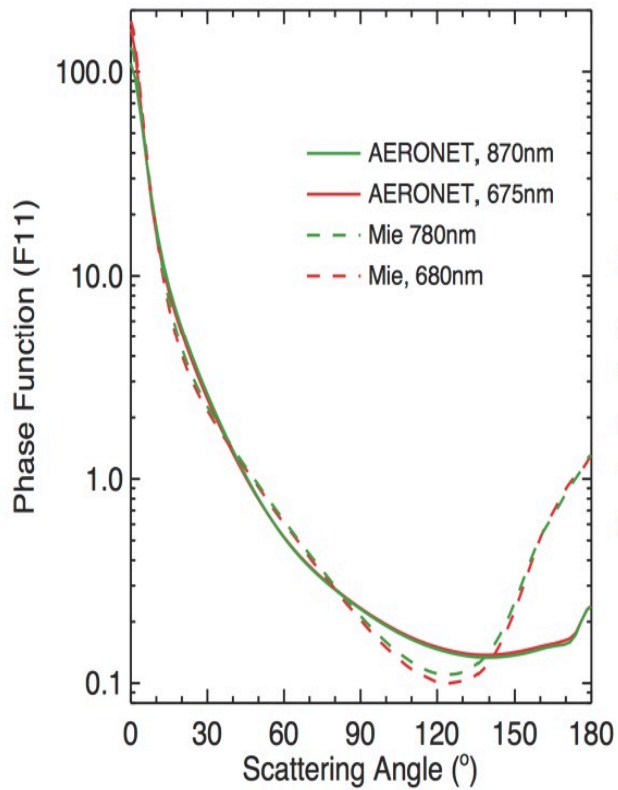
EPIC vs. CALIOP
AOD

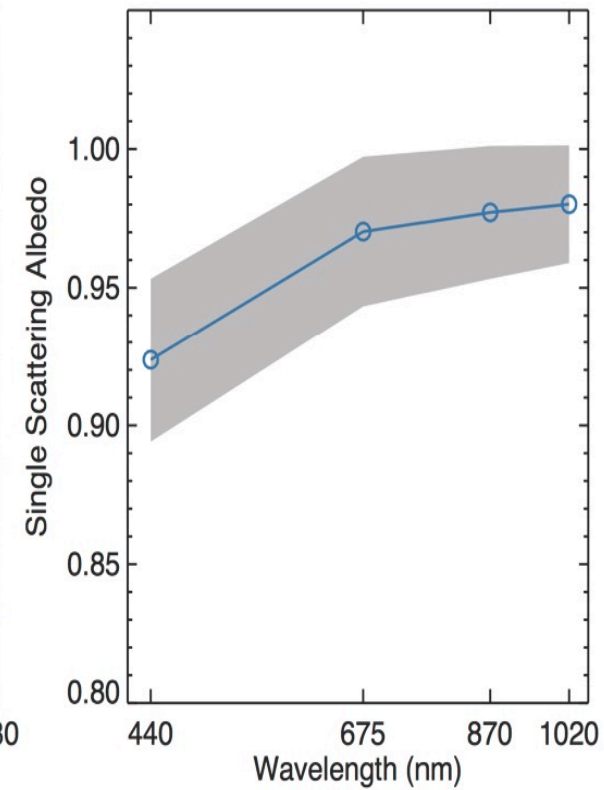




Aerosol Properties



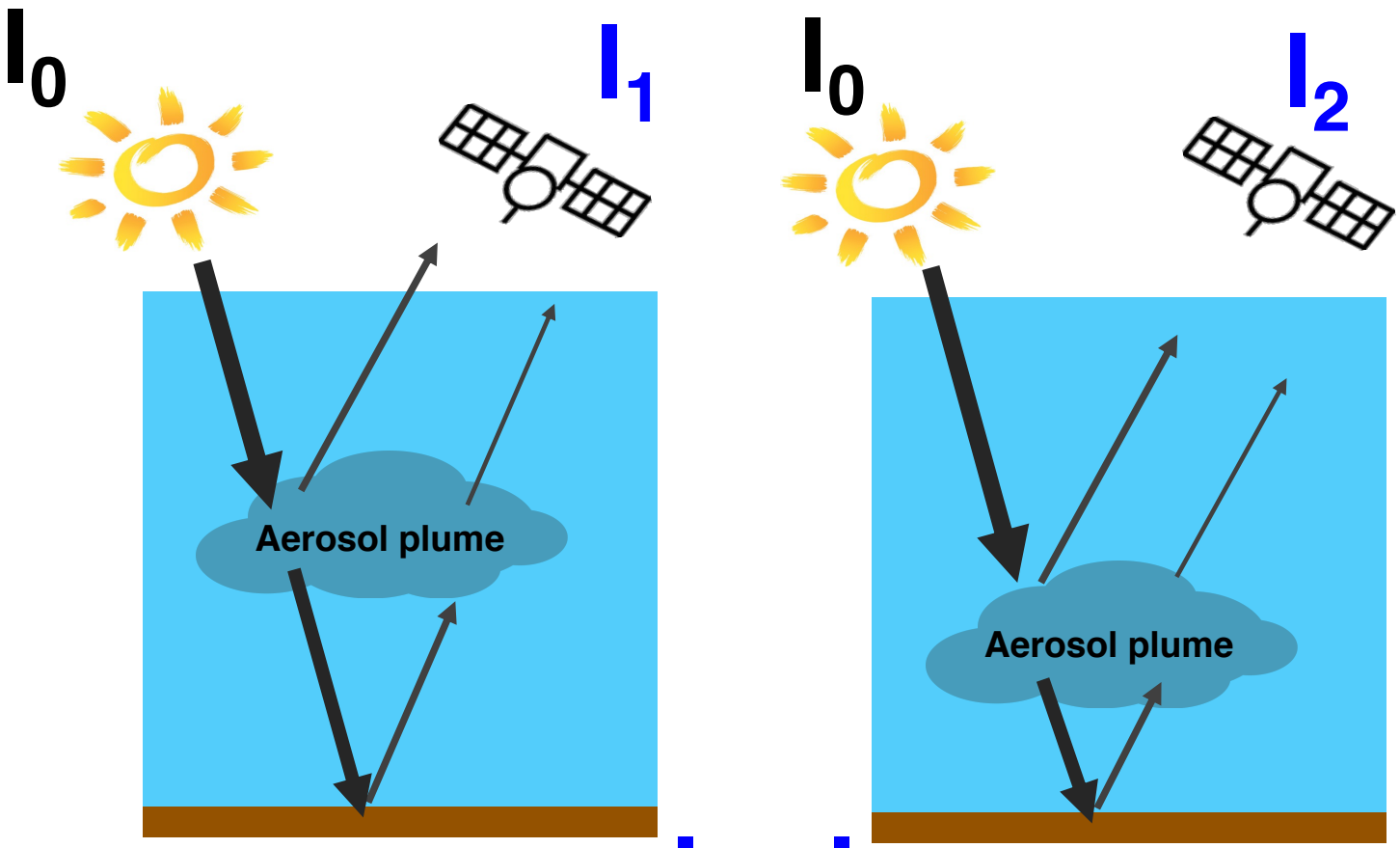




$$\tau_A(z) = C\,\frac{\exp\left(-h\left|z-H_{\text{peak}}\right|\right)}{\left[1+\exp\left(-h\left|z-H_{\text{peak}}\right|\right)\right]^2}$$

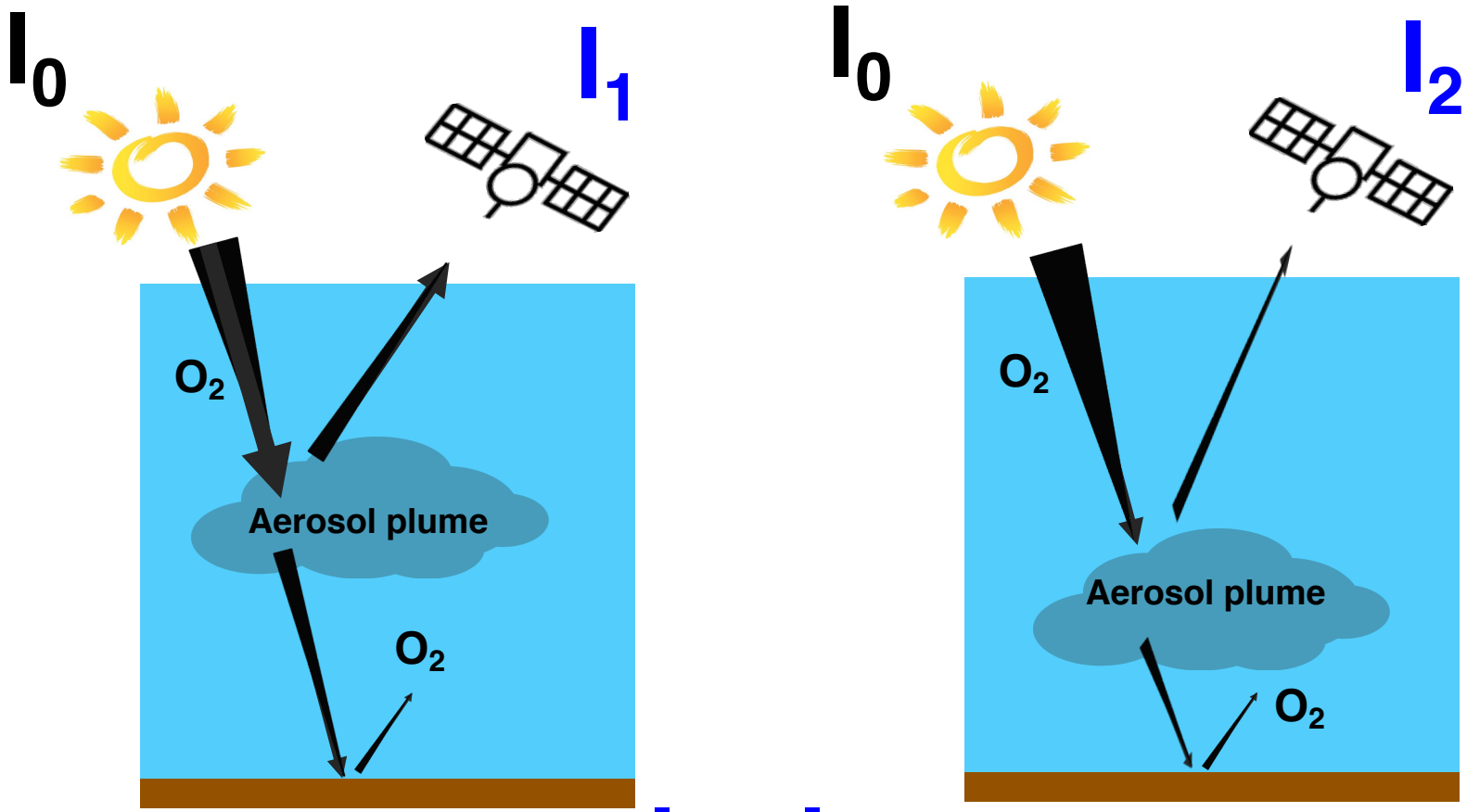
$$\eta = \frac{\ln\left(3+\sqrt{8}\right)}{h}$$

At atmospheric window channels:



$$I_1 = I_2$$

At O2 absorption band:



$I_1 > I_2$

Aim 1: EOF modes of aerosol profiles from PCA

$\boldsymbol{X}_0$ ➡ $\boldsymbol{X} = \boldsymbol{X}_0 - \overline{\boldsymbol{X}}$

n x m anomaly (n x m)

eigenvector, i.e., EOF

➡ $\boldsymbol{C} = \frac{1}{m-1}\boldsymbol{X}\boldsymbol{X}^{\mathrm{T}} = \boldsymbol{E}\boldsymbol{\Lambda}\boldsymbol{E}^{\mathrm{T}}$

covariance (n x n) eigen decomposition (sort eigenvalues)

➡ $\boldsymbol{P} = \boldsymbol{X}^{\mathrm{T}}\boldsymbol{E}$

principal components (m x n)

➡ $\boldsymbol{X} = \boldsymbol{E}\boldsymbol{P}^{\mathrm{T}}$

reconstruction

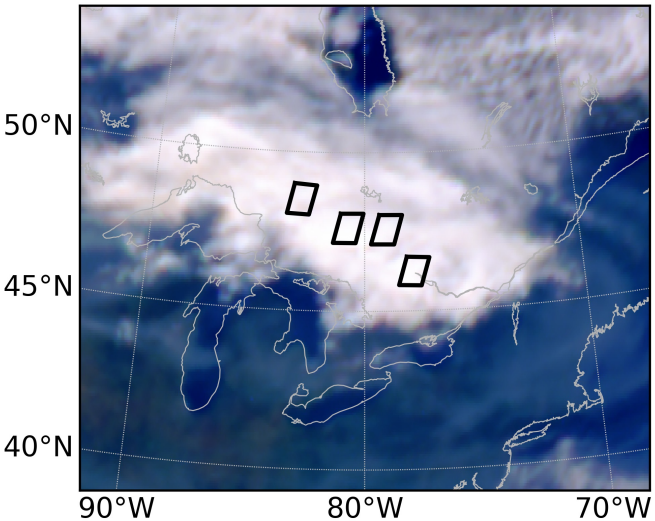
➡ $\boldsymbol{x}_i = \sum_{j=1}^{n} p_{ij}\boldsymbol{e}_j$

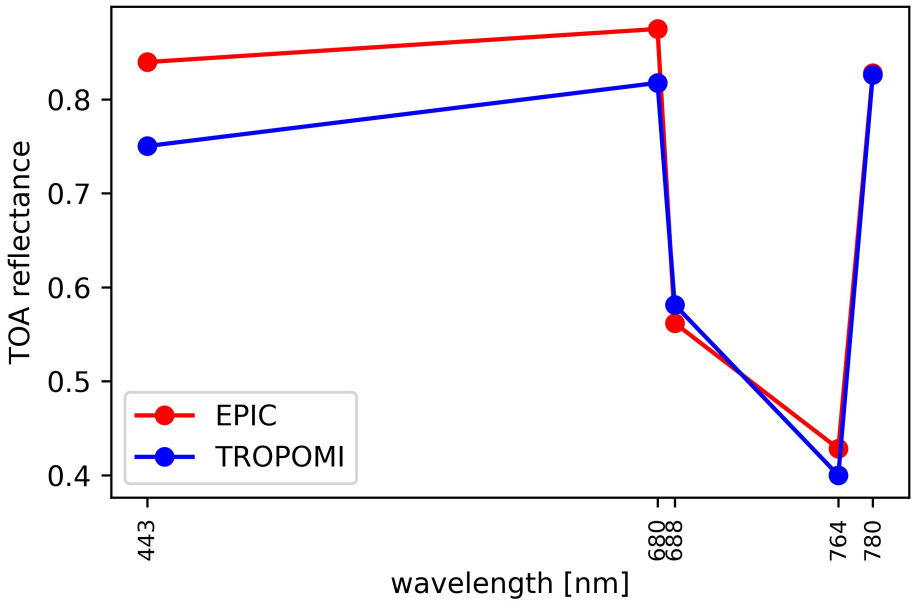
Vicarious calibration of EPIC based on TROPOMI data

- EPIC instrument does not have on-board calibration.
- The official after-launch calibration of EPIC measurements has not been updated since 2017 (https://epic.gsfc.nasa.gov).

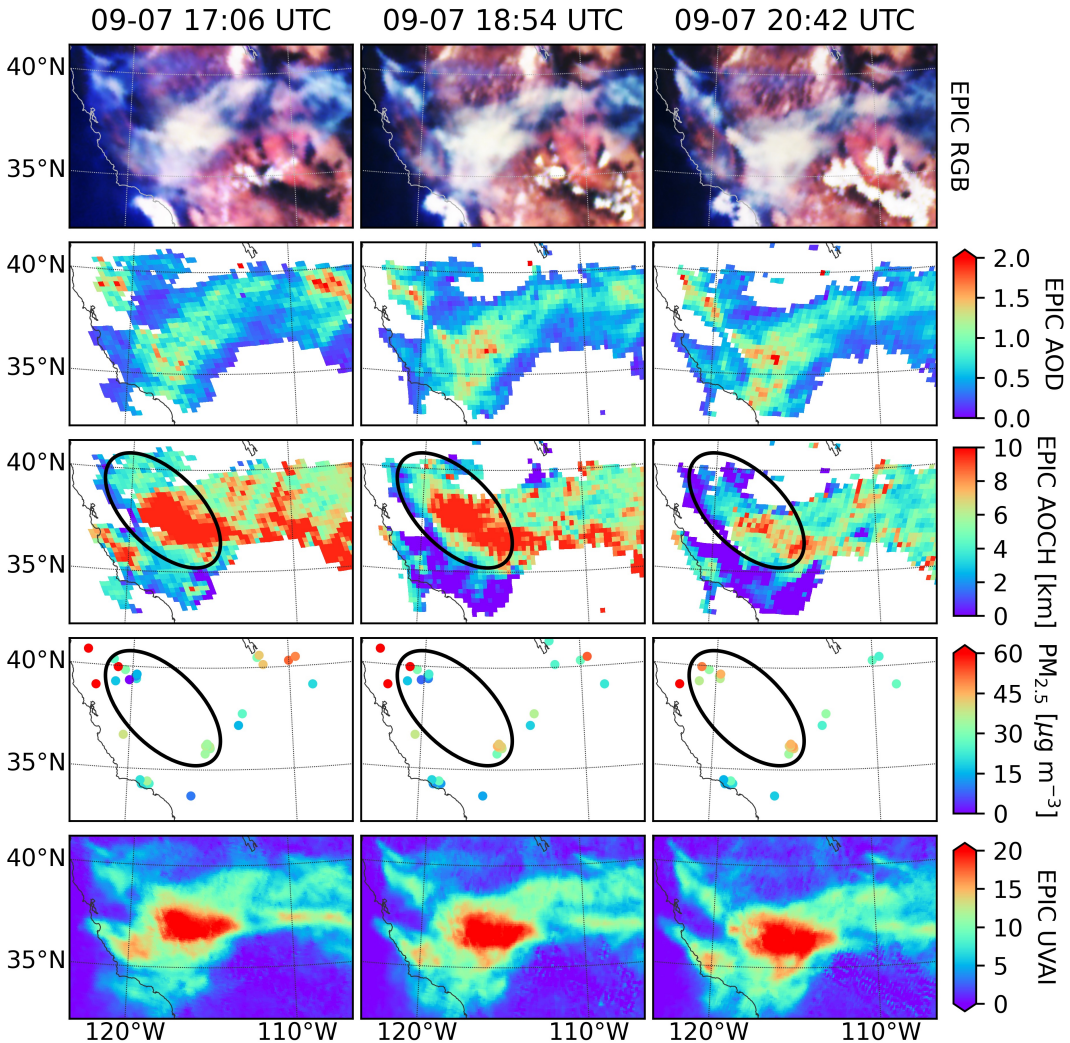
Geogdzhayev and Marshak (2018), Atmos. Meas. Tech. 11(1), 359-368

EPIC true color image
2020-09-15 18:36 UTC

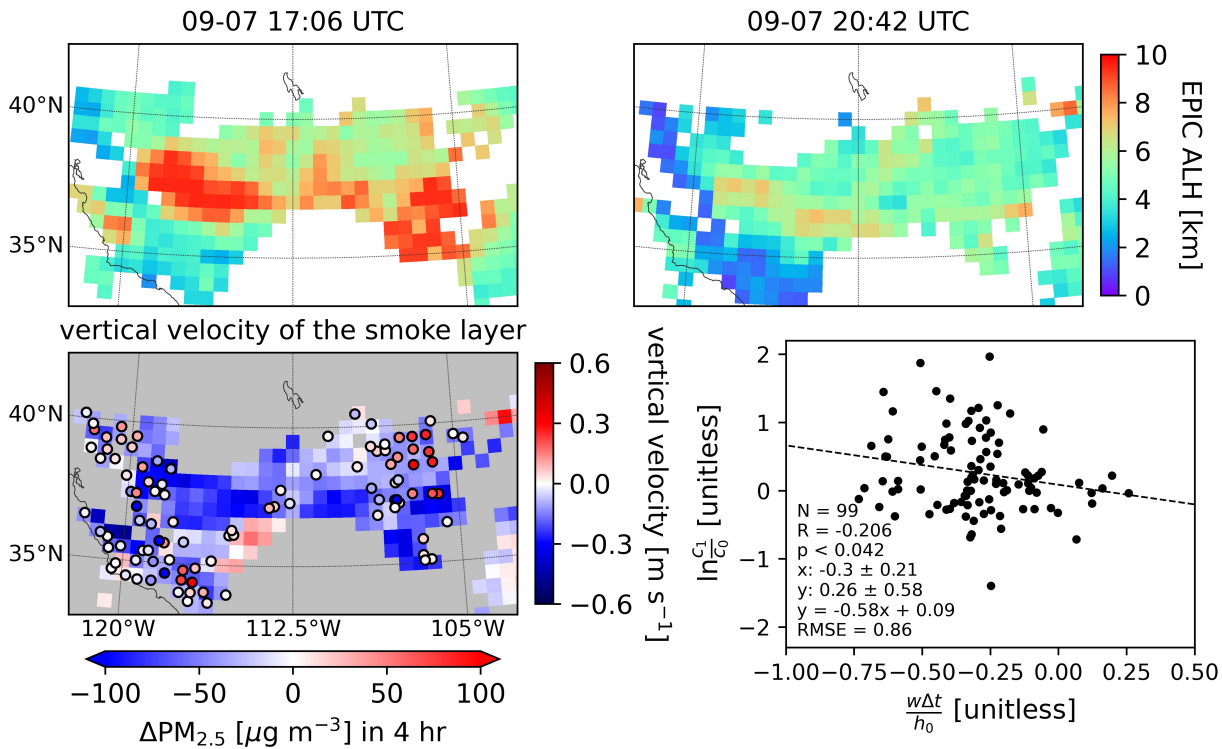




EPIC reflectance at 443, 680, 688 nm are scaled by **-10.6%**, **-6.6%** and **3%**, respectively.

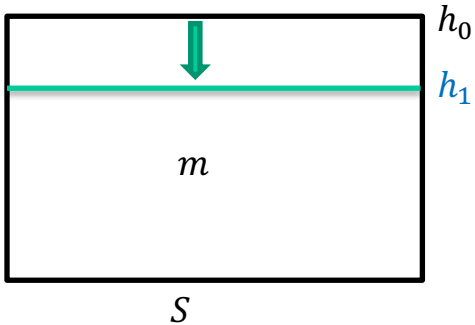

09-07 17:06 UTC
09-07 18:54 UTC
09-07 20:42 UTC
40°N
35°N
120°W
110°W
EPIC RGB
EPIC AOD
2.0
1.5
1.0
0.5
0.0
EPIC AOCH [km]
10
8
6
4
2
0
PM2.5 [μg m−3]
60
45
30
15
0
EPIC UVAI
20
15
10
5
0

EPA + Purpleair



Consider the change of total mass of $PM_{2.5}$

box model



$$c = \frac{m}{Sh}$$

$$dc = d\left(\frac{m}{Sh}\right) = \frac{Sh\,dm - m\,d(Sh)}{S^2h^2} = \frac{dm}{Sh} - \frac{m\,dh}{Sh^2} = \frac{dm}{Sh} - \frac{c\,dh}{h}$$

$$\frac{dc}{c} = \frac{dm}{cSh} - \frac{w\,dt}{h} = \frac{dm}{m} - \frac{w\,dt}{h}$$

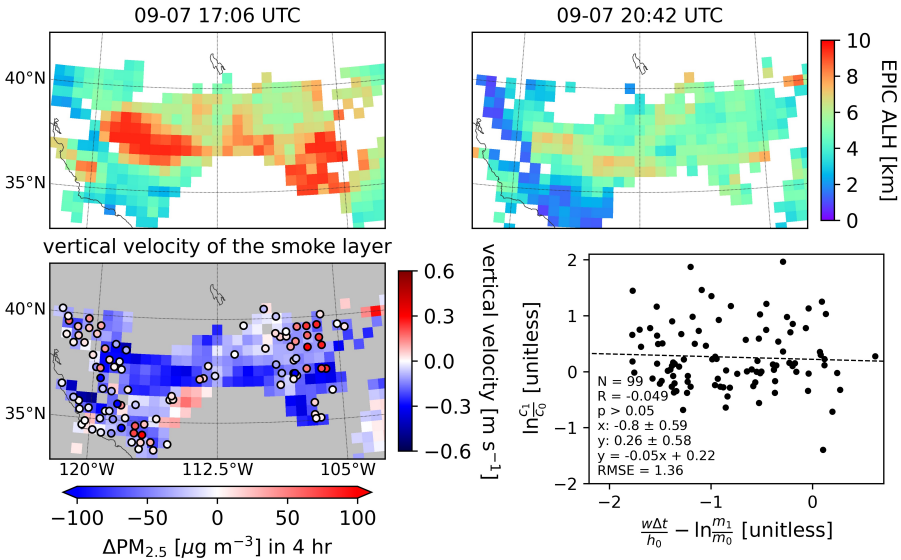
$$\ln\frac{c_1}{c_0} \approx \ln\frac{m_1}{m_0} - \frac{w(t_1 - t_0)}{h_0} = \ln\frac{\tau_1}{\tau_0} - \frac{w(t_1 - t_0)}{h_0}$$

Assume $\frac{m_1}{m_0} = \frac{\tau_1}{\tau_0}$

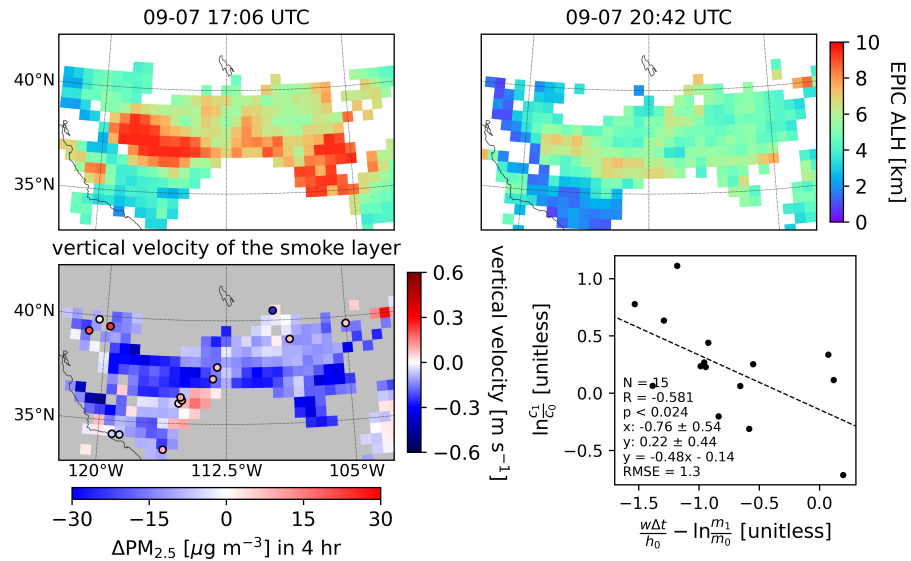
- m: total mass of $PM_{2.5}$, assumed to be constant;
- S: bottom area of the box;
- h_0 (h_1): smoke height at time t_0 (t_1);
- c_0 (c_1): mass concentration of $PM_{2.5}$ at time t_0 (t_1);
- τ_0 (τ_1): EPIC AOD at time t_0 (t_1);
- w: vertical velocity of smoke layer.

Consider the change of total mass of $PM_{2.5}$

EPA + Purpleair $PM_{2.5}$ data



EPA $PM_{2.5}$ data only



Vertical geometric velocity from MERRA-2

$$V_{\mathrm{MERRA-2}} = \frac{\Delta h}{\Delta t} = -\frac{\Delta P}{\rho g \Delta t} = -\frac{\omega}{\rho g}$$

$V_{\mathrm{MERRA-2}}$ is MERRA-2 vertical geometric velocity; Δh and ΔP are the change in the geometric altitude and pressure level of the smoke layer respectively during the time interval Δt; g is the gravity acceleration (9.81 m/s^2); ρ is the air density that is linearly interpolated from MERRA-2 data to the altitude of smoke layer at 18:00 UTC for each grid cell and ω is the MERRA-2 vertical pressure velocity from the same linear interpolation as for air density.

Linear interpolation of air density

$$\rho = \frac{\rho_2(h - h_1) + \rho_1(h_2 - h)}{h_2 - h_1}$$

h is smoke layer height at 18:00 UTC for a specific grid cell; h_1 is the highest altitude of the model layer that is lower than h; h_2 is the lowest altitude of the model layer that is higher than h; ρ_1 and ρ_2 are the air density at the model layers with the altitudes of h_1 and h_2 respectively. The smoke layer height at 18:00 UTC is obtained from linear interpolation using EPIC ALH retrieval at 17:06 and 20:42 UTC.