Retrieval of Aerosol Parameters from Hyperspectral Satellite Data

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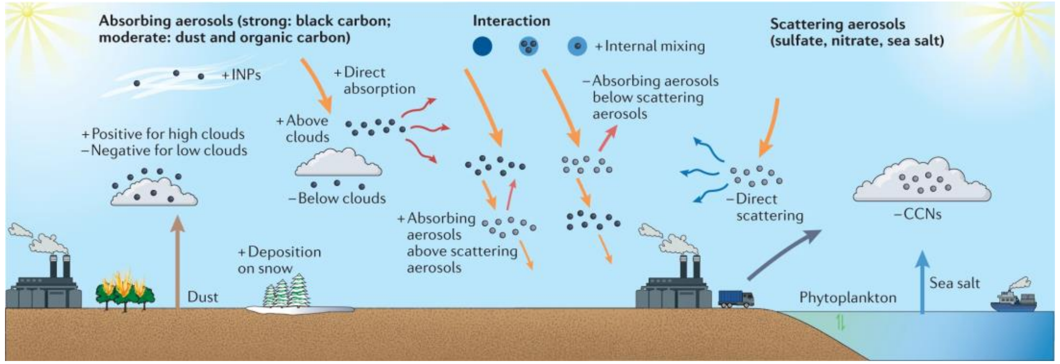
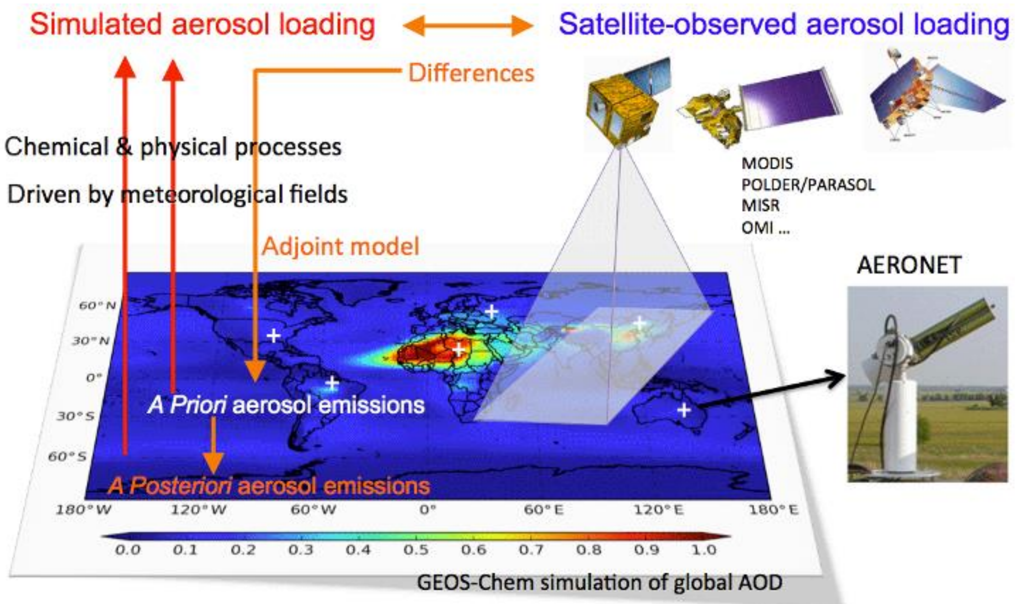
Background

- **Impact of aerosols in atmosphere on**
  - Surface radiation and temperature
  - Clouds and precipitation
  - Boundary layer and air pollution
- **Requires spatiotemporal information on**
  - Horizontal distribution of aerosols
  - Vertical distribution of aerosols
- **Detection of aerosols**
  - Ground-based
  - Satellite- and airborne-based
  - Model simulation



Radiative forcing of aerosols (source: Li et al., 2022)



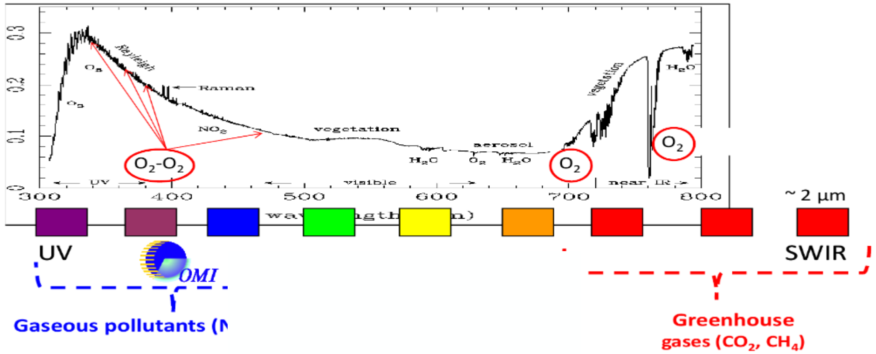
Observation and simulation of aerosols(source: Chen et al., 2019)

Background

- **Hyperspectral satellite**
  - **AAI - Absorption characteristics**
  - **AOD - Concentration**
  - **ALH - Vertical information**
- **Data**
  - **Near-Infrared (O_2A band, ~760 nm)**
  - **Visible (O_2B band, ~690 nm)**
  - **UV-Visible (O_2-O_2 bands, 340, 360, 380, 440, 477 nm)**
- **Algorithm for new generation hyperspectral satellites**
  - **TROPOMI/S5P (Launched in October 2017)**
  - **OMS/FY-3F (Launched in August 2023)**

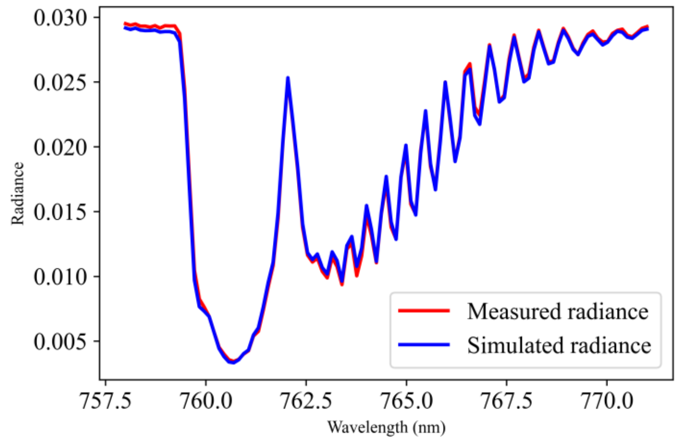
Hyperspectral satellite sensors used for atmospheric composition detection

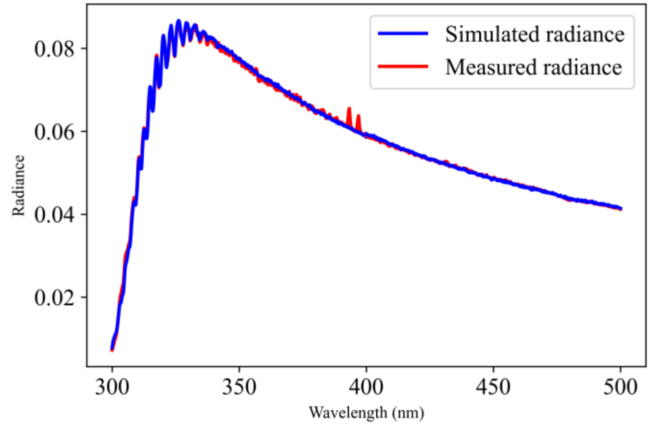
Instrument	Spectral Range (nm)	Spatial resolution (km×km)	Swath (km)	Overpass time	Operational
GOME	240-790	320 x 40	960	10:30	1995-2011
SCIAMACHY	240-2400	30 x 215	1000	10:00	2002-2012
OMI	270-500	13 x 24	2600	13:30	2004-present
GOME-2	240-790	80 x 40	1920	9:30	2007-present
OMPS-nadir	290-1000	10 x 10	2800	13:30	2011-present
TROPOMI	270-495 710-775 2305-2385	7 x 3.5 7 x 28 (UV1) 7 x 7 (SWIR)	2600	13:30	2017-present
EMI	240-710	13 x 48	2500	13:30	2018-present
EMI2	240-710	13 x 24	2500	13:30	2022-present
OMS-nadir	250-300 300-500	21 x 28 7 x 7	2900	10:30	August 2023 (Planned)



Method-Radiative Transfer Model

- **Acceleration algorithms:**
  - **Discrete ordinate method with matrix exponential (Doicu and Trauttmann, 2009)**
  - **False discrete ordinate, K-distribution, PCA, Forward-adjoint methods, etc.**
- **Gas absorption**
  - **O_2A Band: O_2**
  - **O_2-O_2 Bands: O_2-O_2, O_3, NO_2, H_2O**
- **Surface properties**
  - **Lambertian surface**
  - **BRDF function**
- **Aerosol**





Method-Radiative Transfer Model

Aerosol Layer

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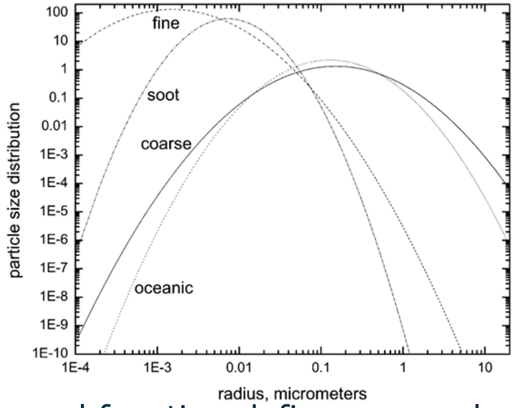
Aerosol Model

- **Micro-physical properties**
  - **Aerosol components**
  - **Shape**
  - **Particle distribution**
  - **Refractive index**
- **Optical properperites**
  - **Absorption coefficient** $\overline{C}_{ext}$
  - **Scattering coefficient** $\overline{C}_{sct}$
  - **Expantion coefficient of pahse fucntion** $\overline{\chi}_n$

Particle size distribution function of aerosol componets（Source: Hess et al., 1998）

Component	r_0, µm	σ
Sea salt (accumulation mode)	0.209	2.03
Sea salt (coarse mode)	1.75	2.03
Desert dust (nucleation mode)	0.07	1.95
Desert dust (accumulation mode)	0.39	2.0
Desert dust (coarse mode)	1.9	2.15
Water-insoluble aerosol	0.471	2.51
Water-soluble aerosol	0.0212	2.24
Soot aerosol	0.0118	2.0

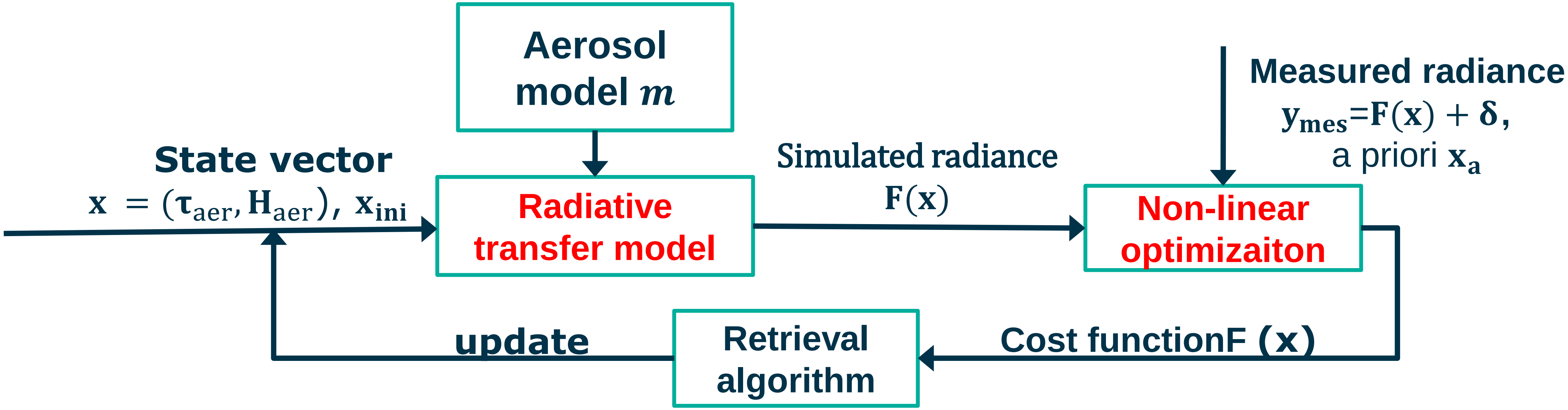


Lognormal function defines aerosol particle size distribution.
（Source: Hess et al., 1998）

For an aerosol model containing n aerosol components, its optical property parameters are calculated using the optical properties of each component and their volume mixing ratios w_i (either fixed values or defined during retrieval).

optica properties of aerosol component i $\overline{C}_{ext}^{(i)}, \overline{C}_{sct}^{(i)}, \overline{\chi}_n^{(i)}, w_i$ —external mixing→ optical properties of aerosol model $C_{ext}^{aer}, \omega_{aer}, \chi_n^{aer}$

Physical retrieval algorithm

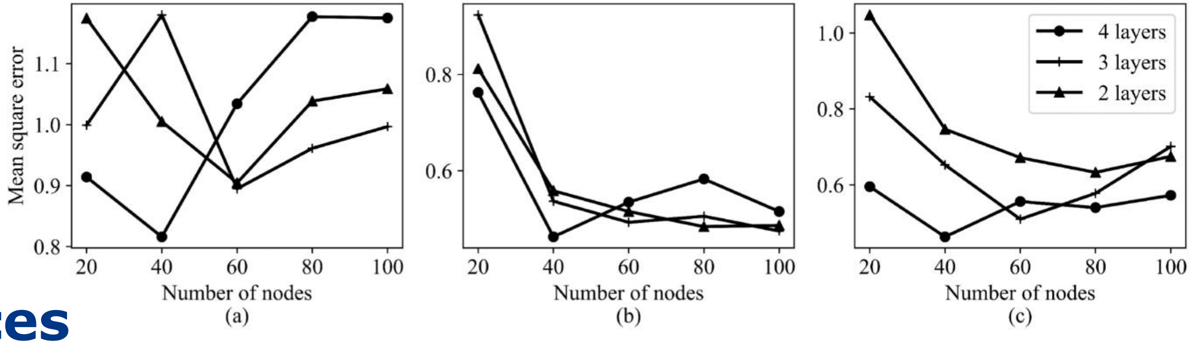


Neural Network Algorithms

Three physics-based NN retrieval algorithms (Rao et al., 2022b)

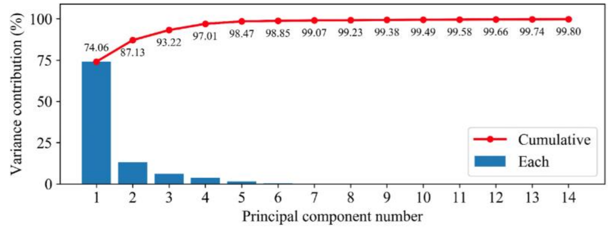
- **NN for Forward Operator**

$$\mathbf{x} = \begin{bmatrix} [\tau, H]^T \\ [\theta_0, \theta, \Delta\varphi, H_s, A_s]^T \end{bmatrix} \longmapsto \mathbf{y} = [I(\lambda_k)]_{k=1}^{N_\lambda}$$



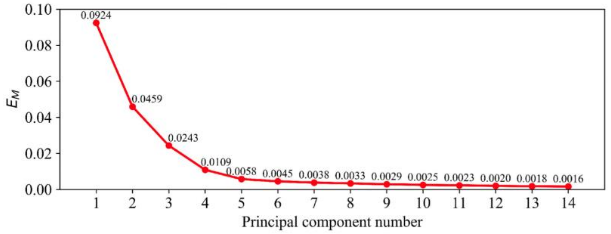
- **NN for Inverse Operator with Radiances**

$$\mathbf{x} = \begin{bmatrix} [I(\lambda_{mk}^r) + \delta_{mk}]_{k=1}^{N_{m\lambda}} \\ [\theta_0, \theta, \Delta\varphi, H_s, A_s]^T \end{bmatrix} \longmapsto \mathbf{y} = [\tau, H]^T$$



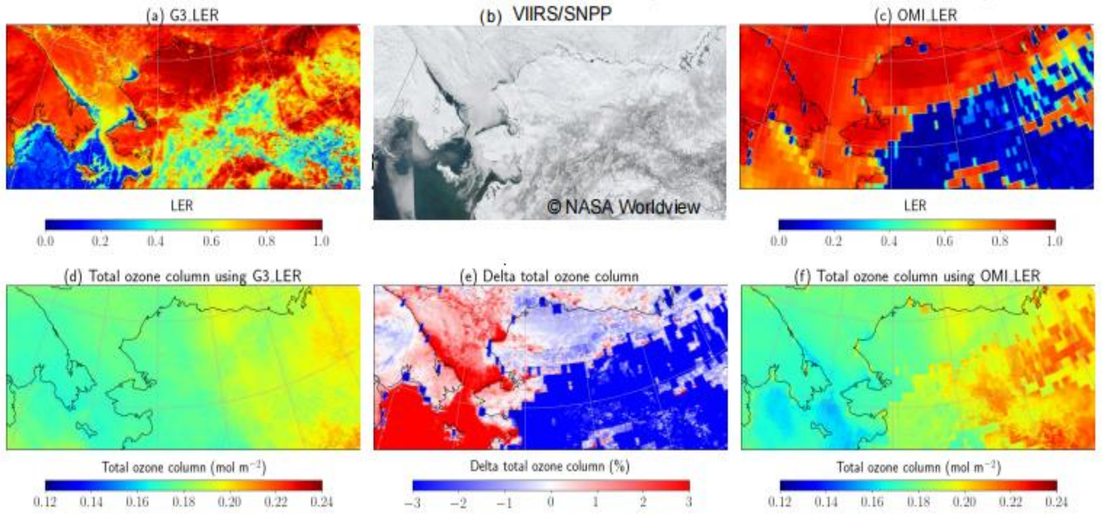
- **NN for Inverse Operator with PCA**

$$\widehat{\mathbf{i}}_m^\delta = \mathbf{U}_M^T(\mathbf{i}_m^\delta - \langle \mathbf{i}_m \rangle) = \widehat{\mathbf{i}}_m + \widehat{\boldsymbol{\delta}}_m$$



Results-Aerosol Retrieval in the Near-Infrared Band

Retrieveal in O_2A band



LER comparison with OMI over snow/ice area (Loyola, Xu, et al., 2020)

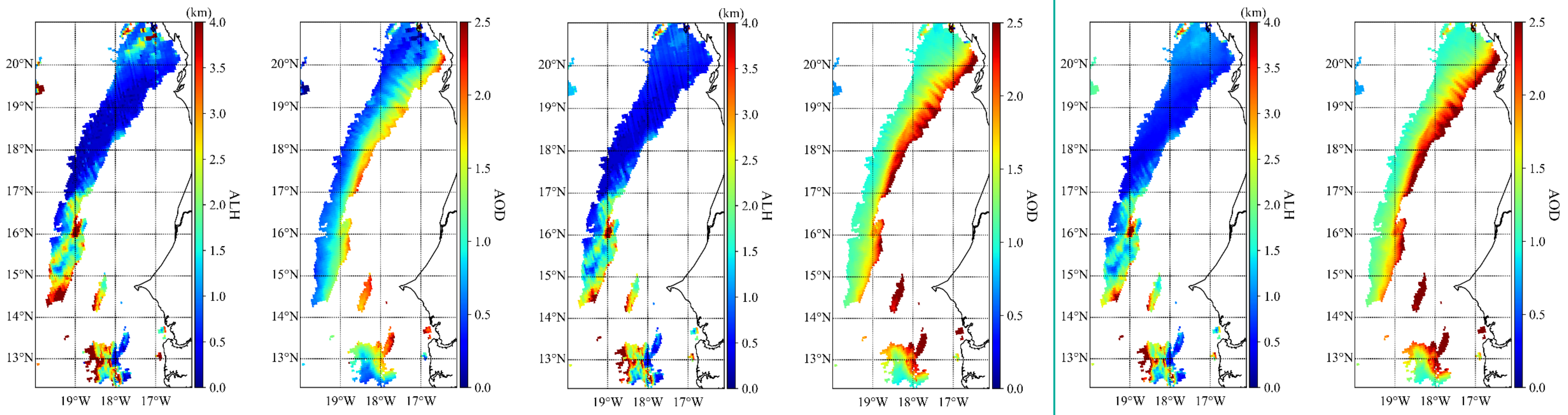
Retrieval of Aerosol Properties

- O_2A band (758-771 nm):
- AOD & ALH
- Cloud-free or low-cloud conditions
- Aerosol layer configuration
  - Elevated layer
- Aerosol model
  - MODABS (MODIS Dark Target Algorithm)
- Surface properties
  - Real-time geometric observation conditions for surface albedo products (GE_LER, geometry-dependent effective Lambertian equivalent reflectivity)

Physical retrieval in O_2A band

Retrieving aerosol properties in O_2A band using TROPOMI/S5P (Rao et al., 2021, 2022a)

- Comparison with Operational Products (provided by KNMI) (Saraha, 2020-06-06)



MODABS, GE_LER

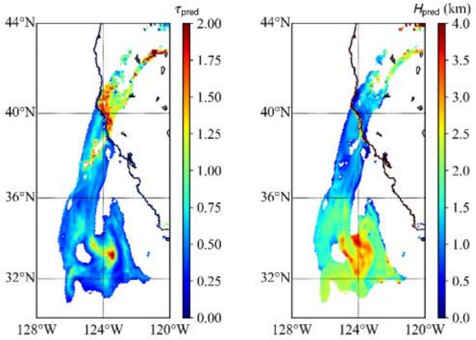
KNMI Configuration

Operational product（KNMI）

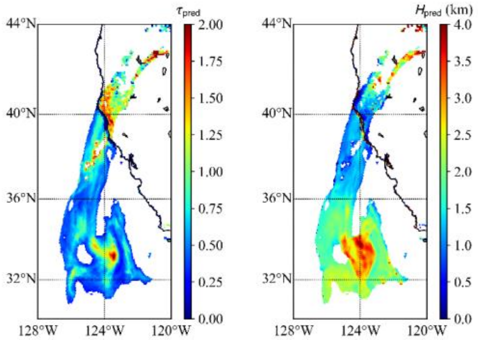
Results-Aerosol Retrieval in the Near-Infrared Band

Neural Network Algorithms

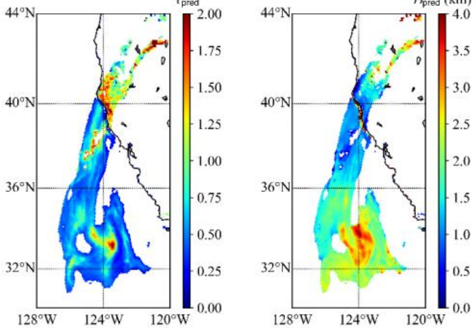
- Retrieval results using TROPOMI Data（California, 2017-12-12） （ Rao et al., 2022b）



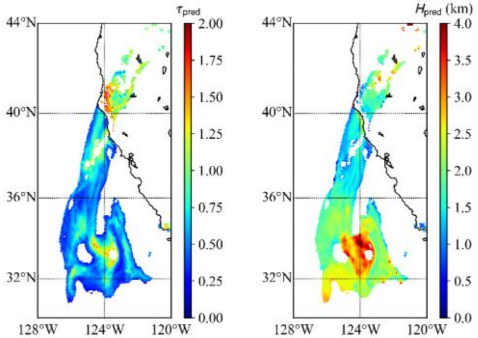
NN for Inverse Operator with Radiances



NN for Forward Operator



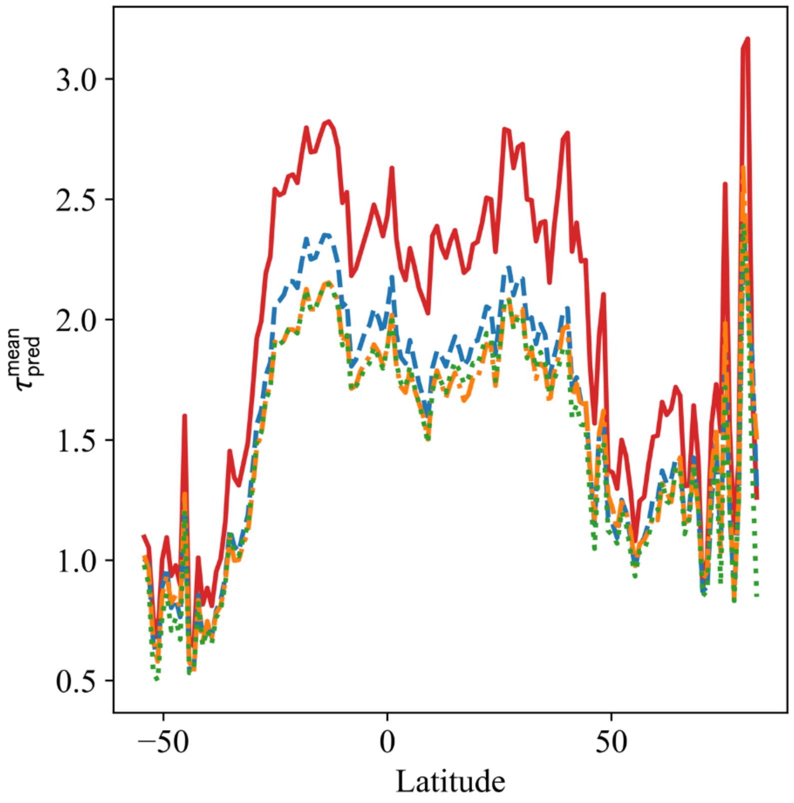
NN for Inverse Operator with PCAs of Radiances

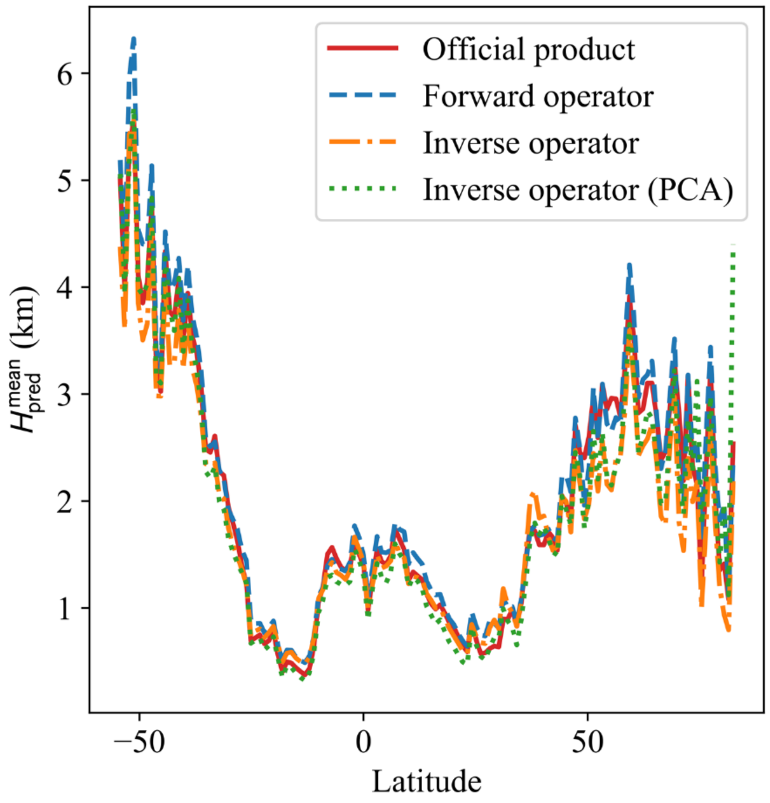


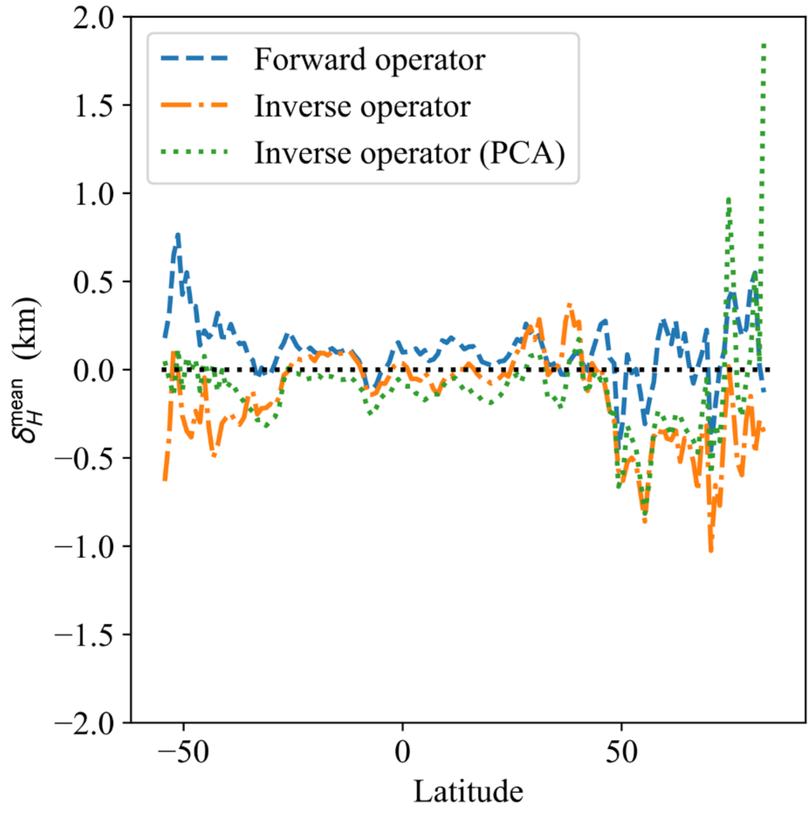
Operational Product

Neural Network Algorithms

- Retrieval results using TROPOMI Data: Three NN algorithms vs. KNMI official product (2019 full year) (Rao et al., 2022b)

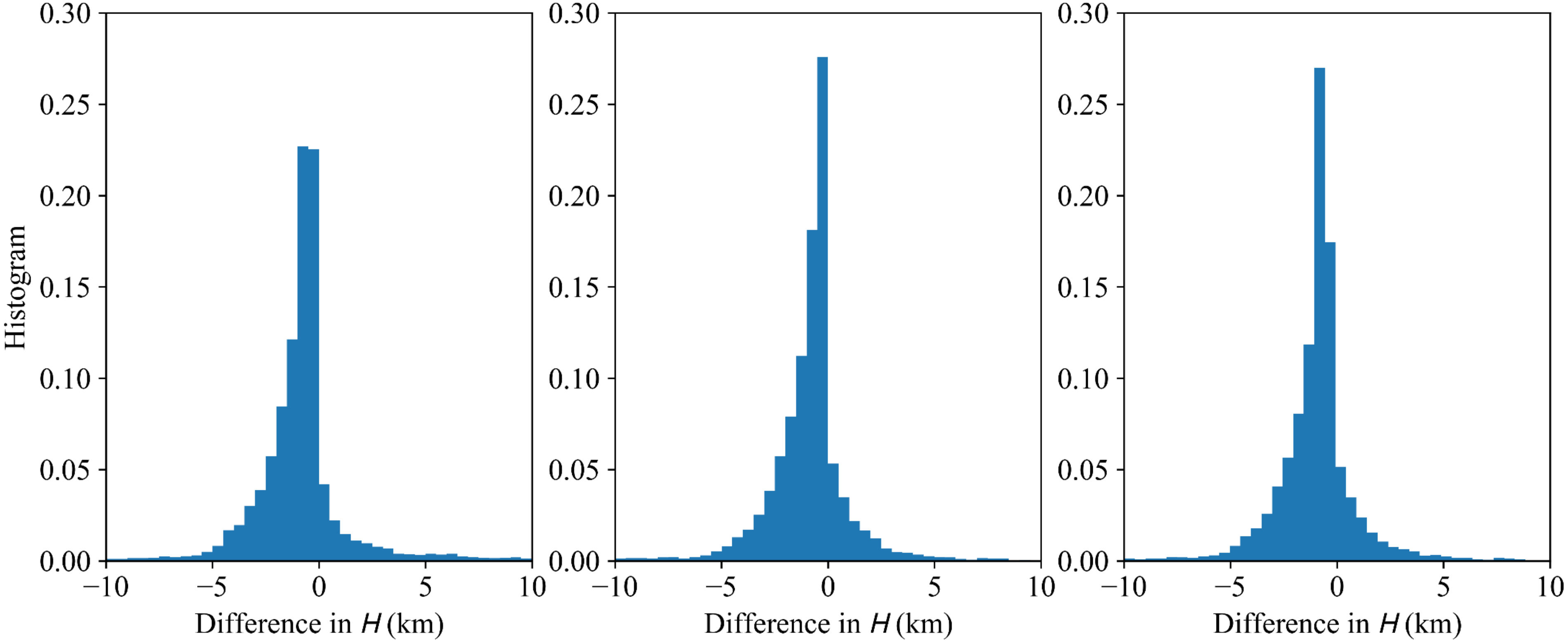






Neural Network Algorithms

- TROPOMI layer height retrieval vs. CALIPSO layer height product (Full Year 2019) (Rao et al., 2022b)

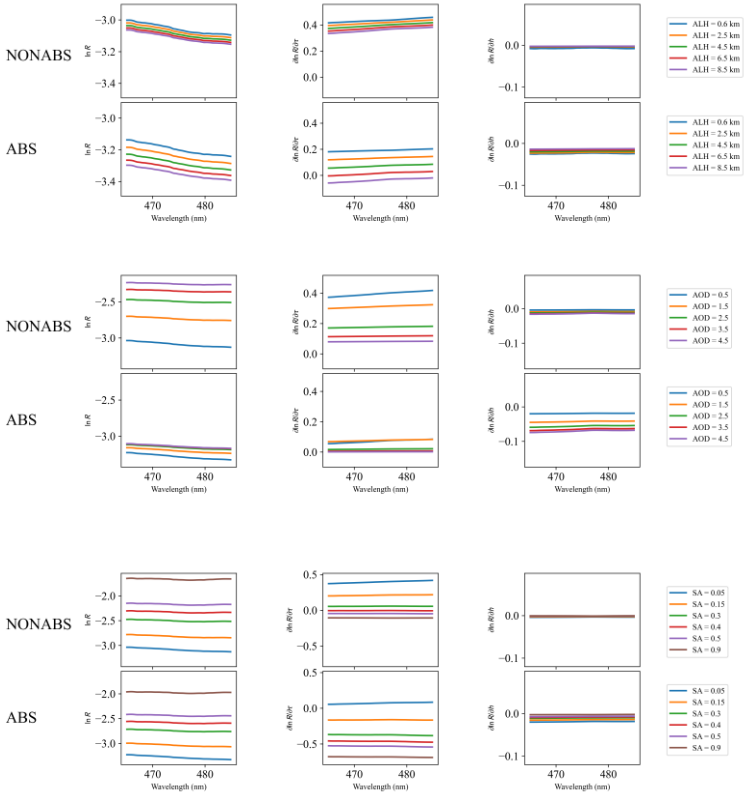


(a) (b) (c)

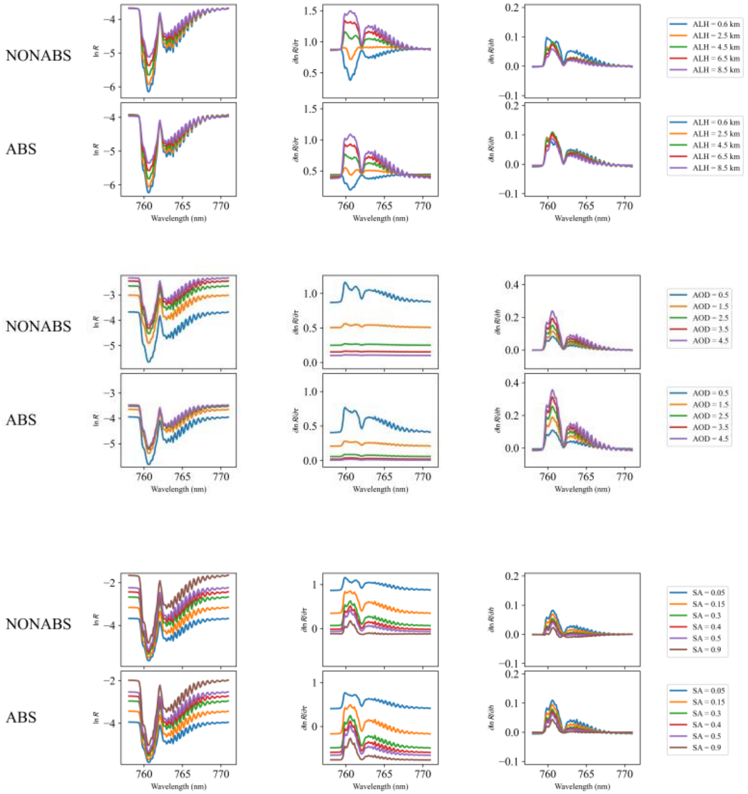
Forward Operator | Inverse Operator | Inverse Operator (PCA)

Sensitivity Analysis (477 nm vs. O_2A band)

477 nm



O_2A band

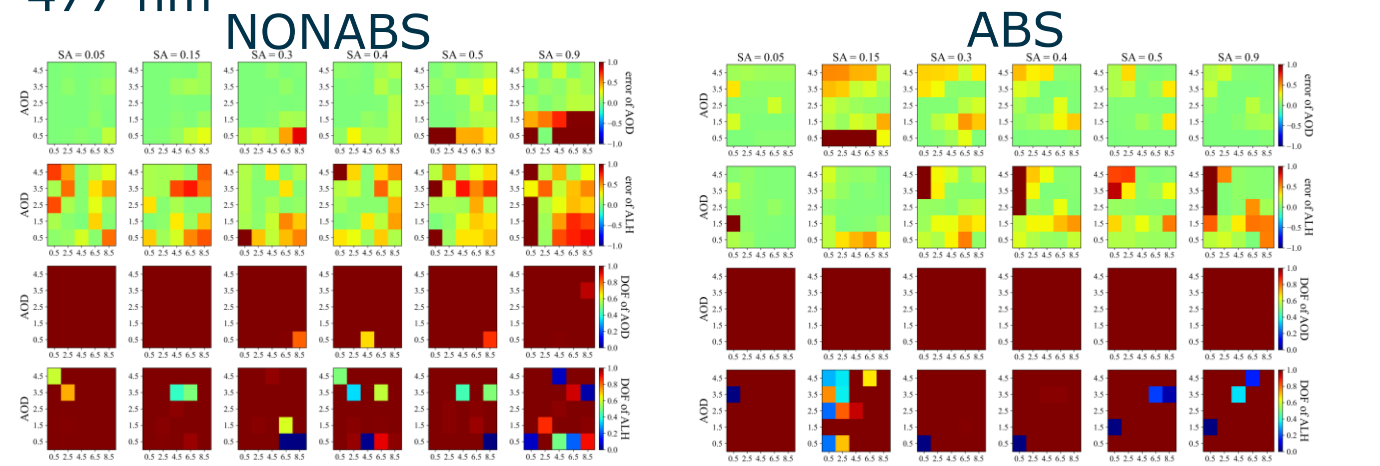


Retrieval around 477 nm:

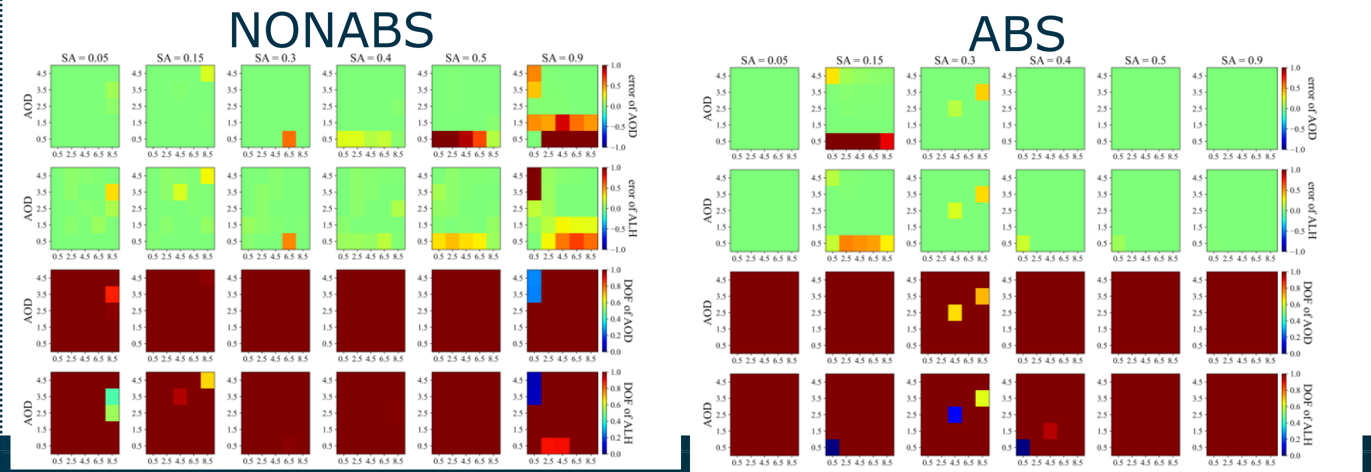
1. harder to separate contribution of AOD and ALH.
2. more sensitive to the aerosol model when retrieving ALH.
3. more challenging for non-absorbing aerosols when retrieving ALH.
4. more challenging for absorbing aerosols when retrieving AOD.

Sensitivity Analysis (477 nm vs. O_2A band)

477 nm



O_2A band

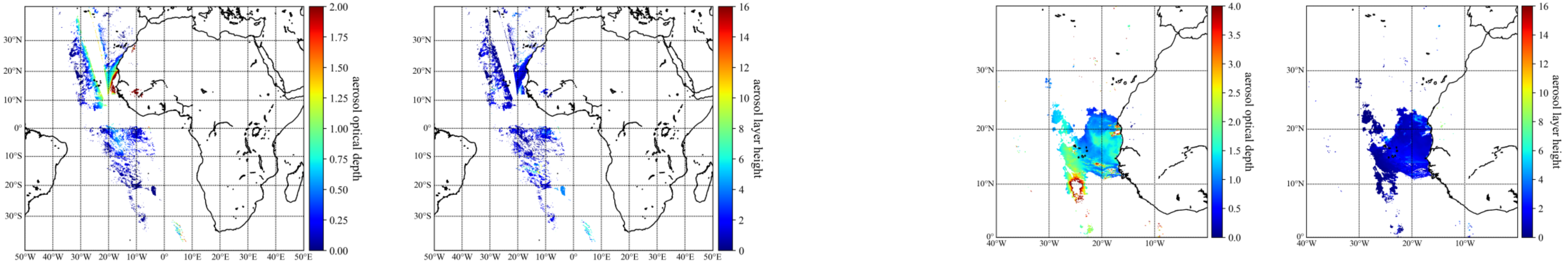


1. Errors in AOD are smaller than errors in ALH;
2. Errors in AOD for NONABS are smaller than those for ABS;
3. Over dark surfaces, errors in ALH retrievals for ABS are smaller than those for MODABS. However, over surfaces with a surface albedo of 0.15, the degrees of freedom (DOF) for ALH for ABS are less than 1, and ALH is less than 4.5 km;
4. Erros are smaller and DOF are overally larger for retrieval in O_2A band.

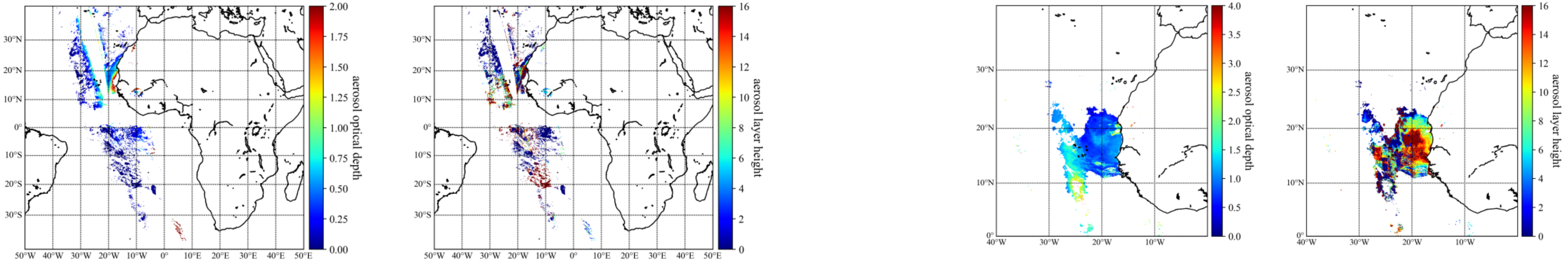
Results-Retrieval in the Ultraviolet-visible Band

Retrieval results using TROPOMI data（~477 nm）

TROPOMI offical product（O_2A）



Retrieval result（~477nm）

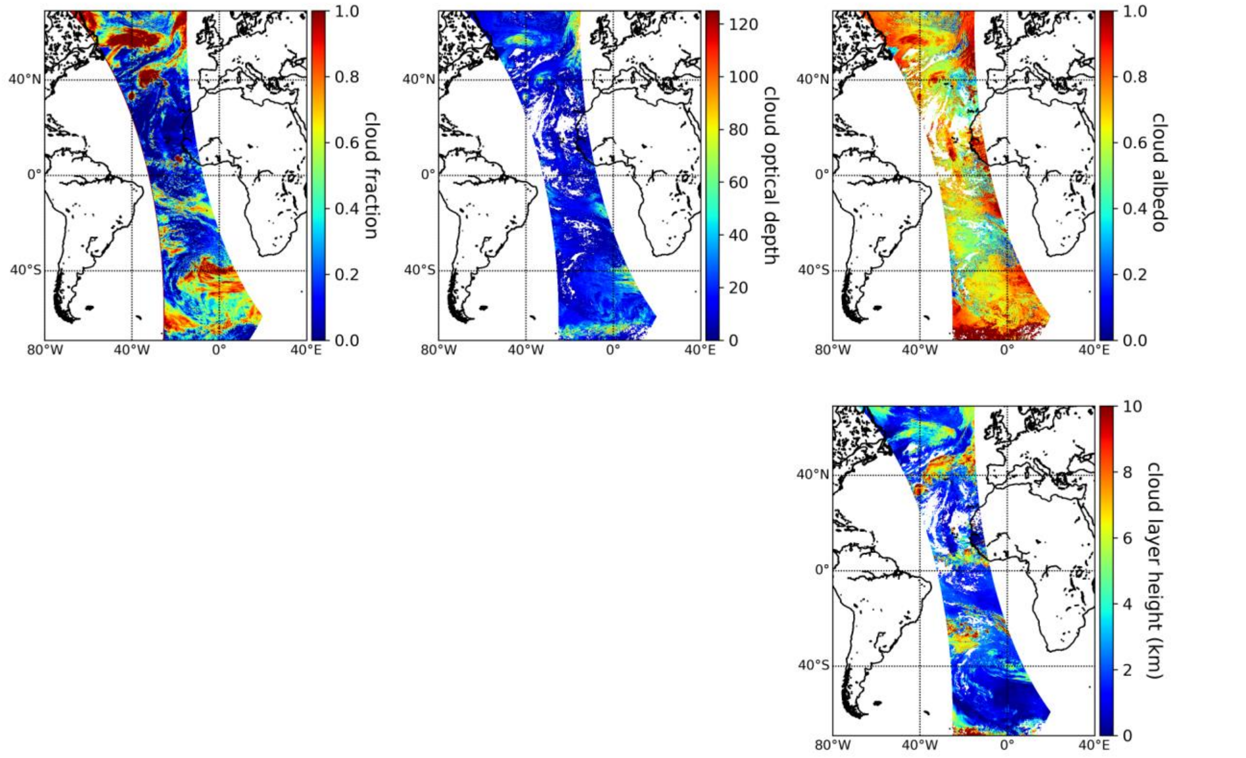


2020-6-6 **2018-09-15**

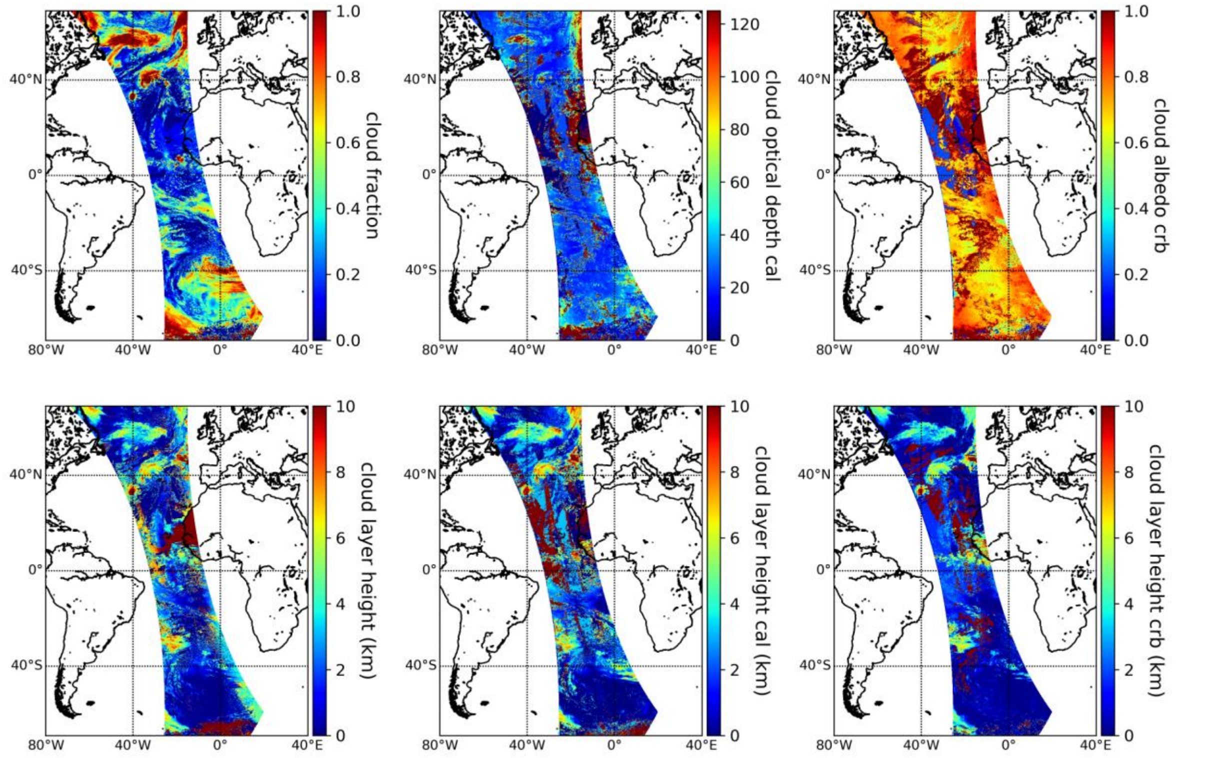
Results-Retrieval in the Ultraviolet-visible Band

Retrieval of clouds （~477 nm）， 2018-09-15

TROPOMI Official Product （O_2A）



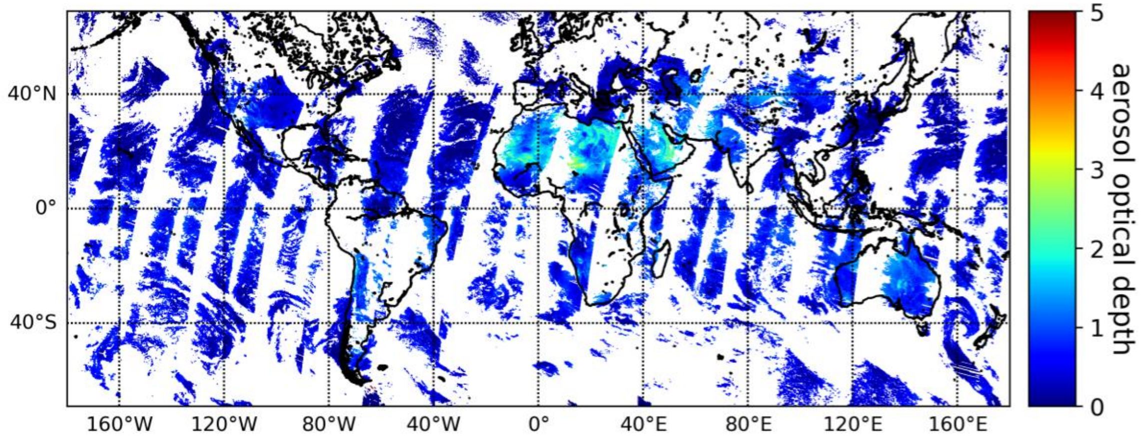
Retrieval results （O_2-O_2, ~477nm）

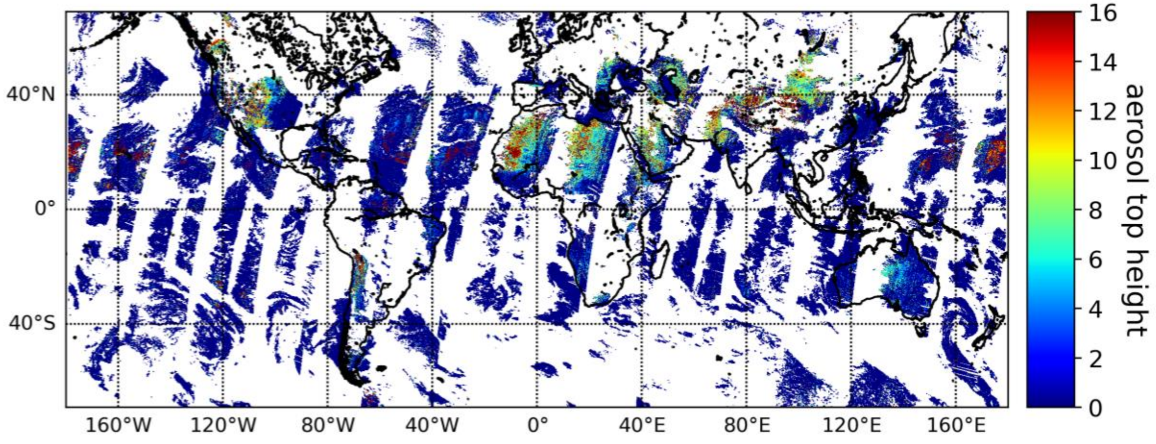


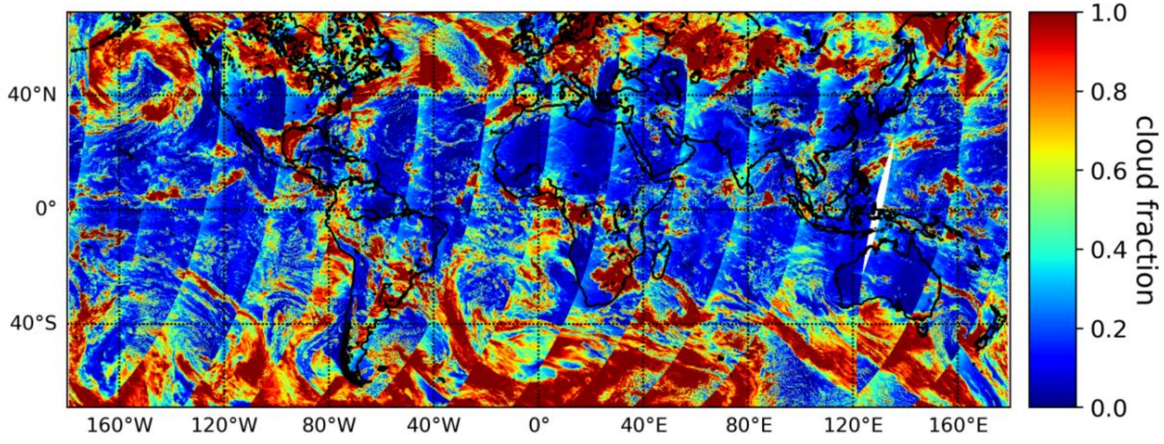
Results-Retrieval in the Ultraviolet-visible Band

Retrieval results using OMS data（2023-10-31）

Aerosol retrieval







Summary and Outlook

Summary

- Developed aerosol physical retrieval algorithms
- Developed neural network algorithm
- Applied to O_2A and O_2-O_2 bands of TROPOMI and OMS

Outlook

- Optimize retrieval algorithm using multi-band or multi-source satellite data
- Validate retrievals in O_2-O_2 band

Thanks!