Monitoring of Air Pollution From Space by GOSAT, GOSAT-2 and Himawari-8

Atmospheric Science and Land-Use/Cover Change
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***Makiko Hashimoto**[1], Shi Chong[1],
Mayumi Yoshida[1], Maki Kikuchi[1], Takashi M. Nagao[2],
and Teruyuki Nakajima[1]

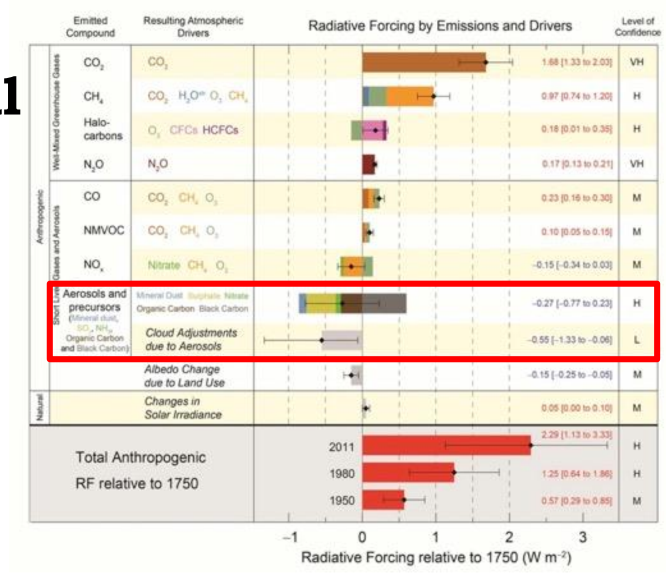
[1] Japan Aerospace Exploration Agency (JAXA) Japan
[2] The University of Tokyo, Japan

Introduction

Significance in aerosol monitoring from space

Uncertainty factors in modeling for global warming prediction (IPCC AR5, 2013)

- Uncertainty in direct radiative forcing : ± 0.5 W/m^2 (IPCC AR5, 2013)
- Black Carbon (BC) has the third largest radiative forcing after CO_2 and CH_4
- Indirect effect is difficult to estimate yet



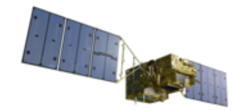
IPCC AR5 SPM (2013)

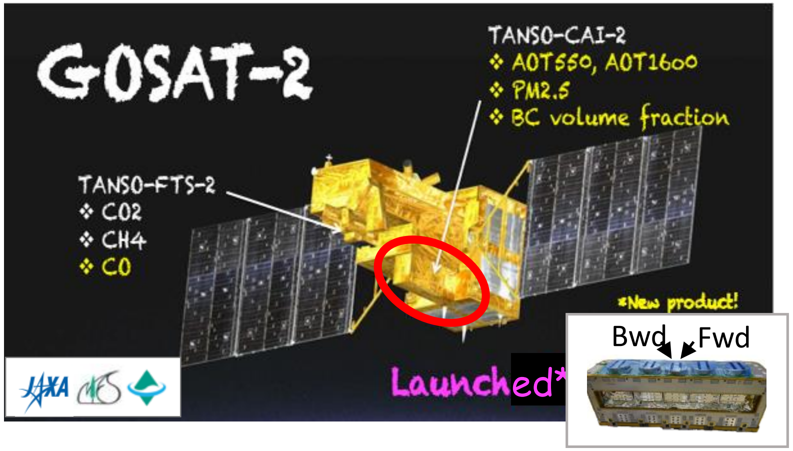
Air pollution is a cause of Health Hazards

- Fine particulate matter "PM2.5" continues to spread worldwide, and about 7 million people die every year from lung cancer and respiratory diseases. (WHO, 2018)
- Transboundary air pollution, related to health hazards
- To prevent health hazards and global worming, various international efforts are being made.
  - The Paris Agreement, Climate Clean Air Coalition (CCAC), Sustainable Development Goals (SDGs).

GOSAT-2/TANCO-CAI-2

GOSAT-2 (Greenhouse Gases Observing Satellite 2)

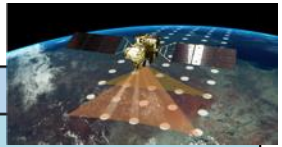




- Successor to GOSAT (2009~)
- Launched on October 29, 2018.
- Polar-orbiting, 6 day cycle
- Local EQ crossing time: 13:00+0:15
- Two sensors:
  - FTS-2 : For Green house gases
  - CAI-2 : For Cloud and Aerosol (Imager)

GOSAT-2/CAI-2 specification

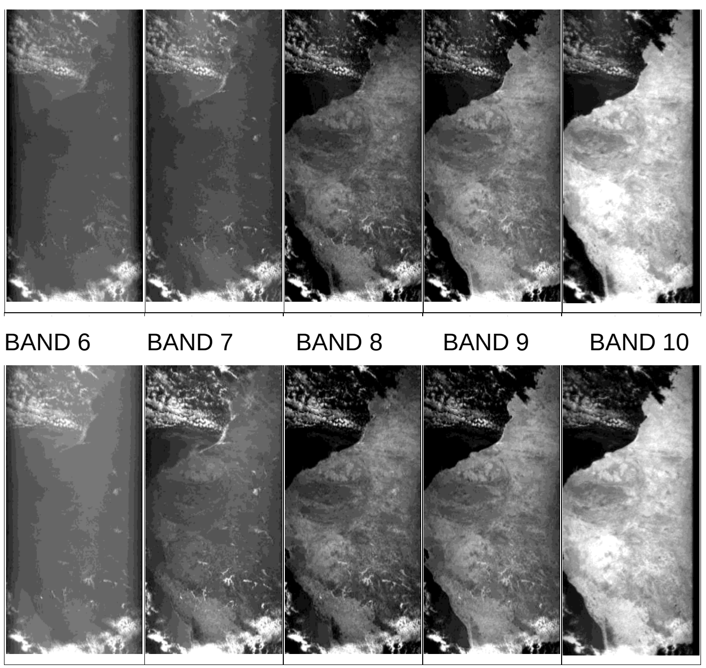
- Two UV bands : 340nm and 380nm with IFOV 460m
- Forward and Backward viewing to avoid Sun glint region



Cloud and Aerosol Imager - 2 (TANSO-CAI-2)										
Items	Specifications									
Band	1	2	3	4	5	6	7	8	9	10
Center wavelength [nm]	339	441	672	865	1630	377	546	672	865	1630
Line of sight [deg]	+20					-20				
IFOV [km]	0.46				1	0.46				1
Swath [km]	920									

Red: *New channels and changed parts from CAI*

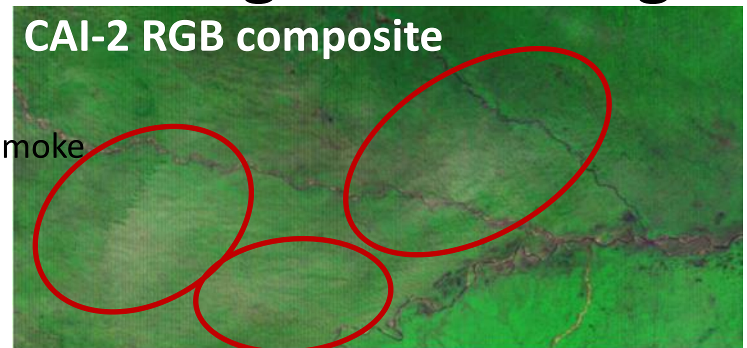
Observed image of CAI-2 each band on Nov. 26, 2018

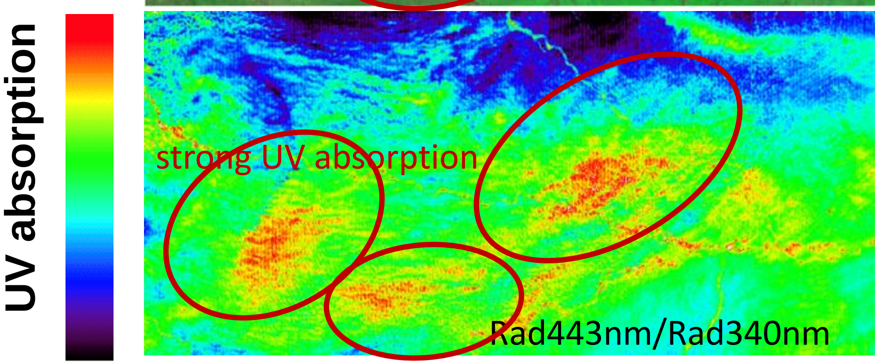


Absorptive aerosol signals in two UV bands of CAI-2

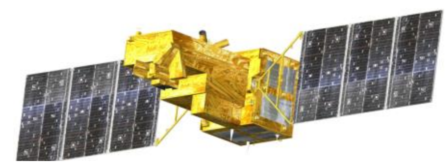
Stubble burning in Indo-Gangetic Plain

Streaky smoke



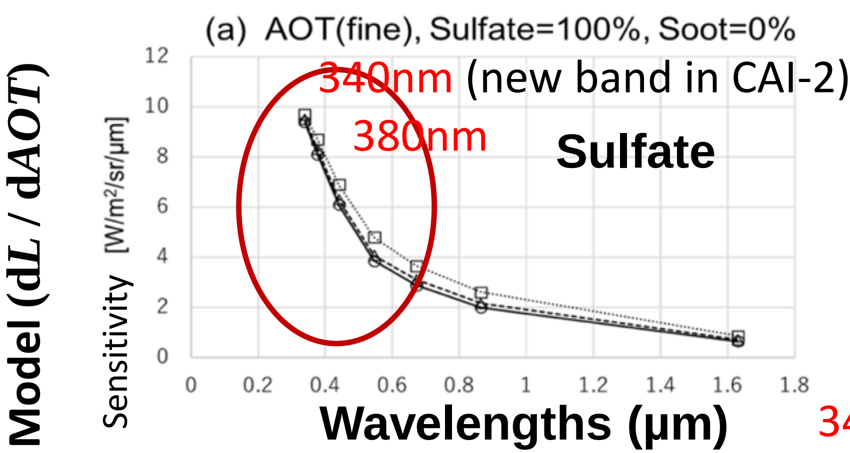


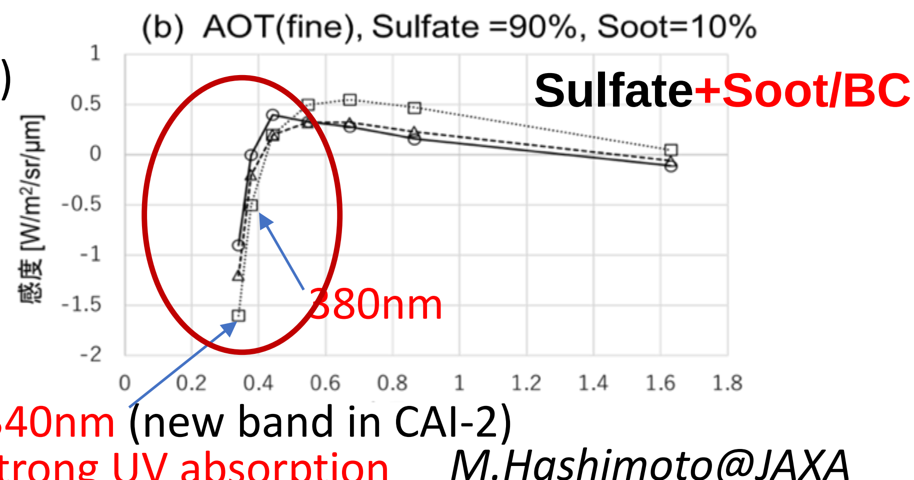
340, 380nm
w IFOV 460m



GOSAT-2/CAI-2

RT model: Rstar (T. Nakajima)





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What is GOSAT-2/TANCO-CAI-2 target?

- □ **Cloud detection for Green house gas retrieval using FTS-2**

- □ **Monitoring Air pollution**

Target:

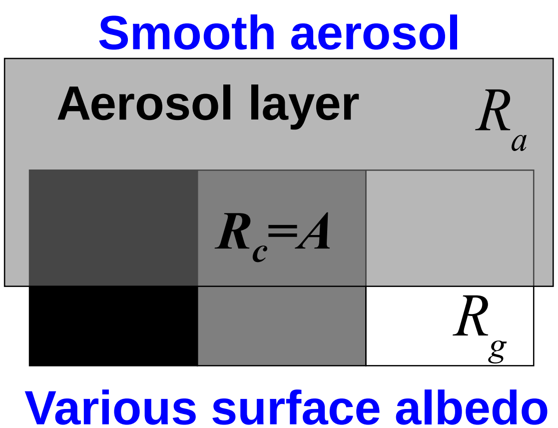
- Aerosol optical thickness(AOT)
- Ångström exponent(AE)
- BC volume ratio
- Estimation of PM2.5.

→ Need to know aerosols in urban area, which is a source region of air pollution such as PM2.5

Development of aerosol retrieval algorithm

Multi-Wavelength and Multi-Pixel Method (MWPM)

- Problems: pixel-by-pixel retrieval methods in urban areas: AOT retrieval is difficult in bright surface fields, SSA is also difficult in dark surfaces.
- ***MWPM: Advantage in the simultaneous estimation of AOT and SSA over land (Hashimoto & Nakajima, JGR'17)***



$$R_1 = R_{a,1} + R_{g,1} \approx A_{g,1} + \tau \cdot [c_1 \cdot \omega P(\Theta) - c_2 \cdot A_{g,1}]$$

$$R_2 = R_{a,2} + R_{g,2} \approx A_{g,2} + \tau \cdot [c_1 \cdot \omega P(\Theta) - c_2 \cdot A_{g,2}]$$

$\vdots$

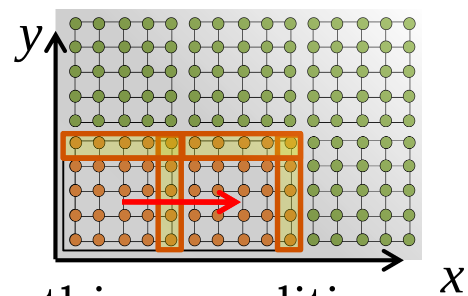
=0 (Independent of AOT*)

simultaneous equations difference in the surface reflectance $\rightarrow$ $R = f(u) + e$

R: Reflectance, t_l : AOT, w_l : SSA,

$P_l(\Theta)$: Phase function, $\lambda = \{\lambda_i, i = 1, N_{band}\}$

$u = \{t_{550,fine}, t_{550,coarse}, w, \{A_g\}_l\}_x$



☐Optimal Estimation theory: MAP(Rodgers, 2000)&Smoothing condition

MAP method (Rodgers, 2000) | Smoothing condition

Cost function $\phi = \phi_{MAP} + \phi_{PT} = \left(R - f(u)\right)^T S_e^{-1} \left(R - f(u)\right) + \left(u - u_a\right)^T S_a^{-1} \left(u - u_a\right) + \sum_k \gamma_k \left(u_{bk} + D_k u\right)^2$

©: smoothing parameter

$$u_{k+1} = u_k + \left[\left(K_k^T S_e^{-1} K_k + S_a^{-1}\right) + \sum_k g_k H_k\right]^{-1} \cdot \left[K_k^T S_e^{-1}\left(R - f(u)\right) - S_a^{-1}\left(u - u_a\right) - \sum_k g_k \left(H_k u + D_k^T u_b\right)\right]$$

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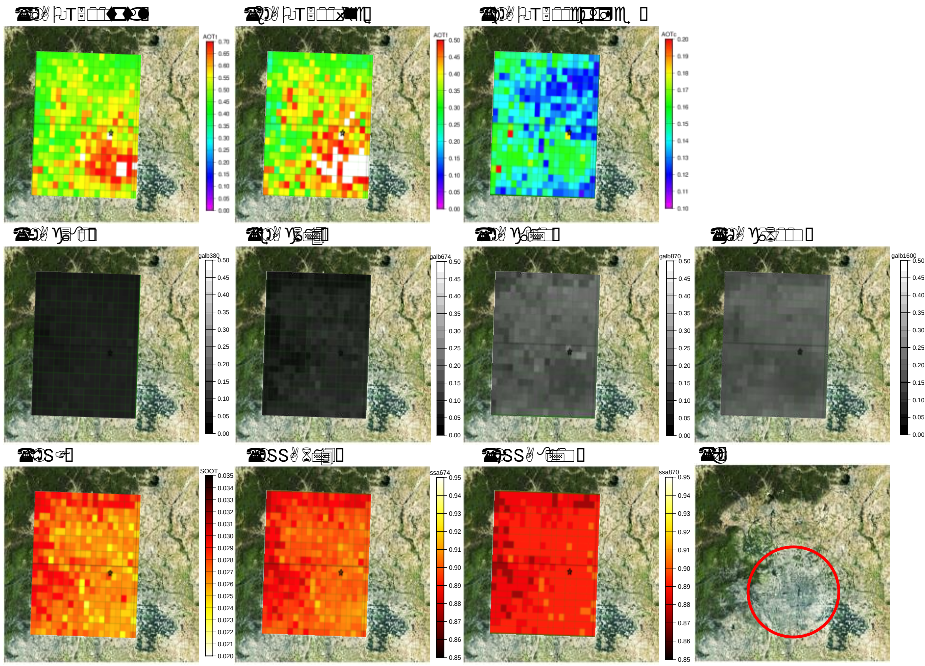
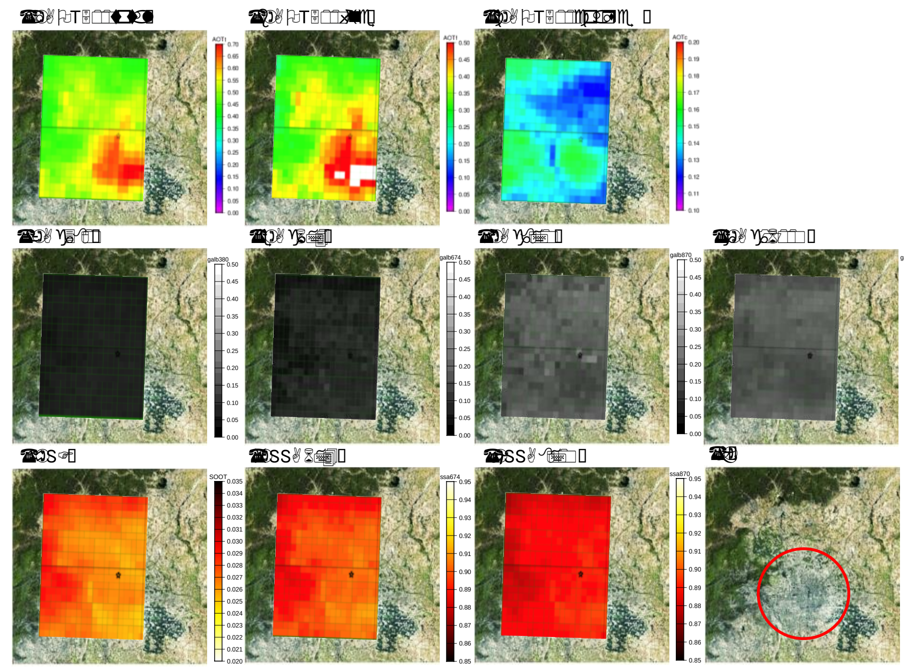
Comparison between PBP and MWPM

In Beijing

Pixel-By-Pixel (PBP)



Multi-pixel (MWPM)



pixel-by-pixel, γ=**0** (Left) and MWPM analysis, γ=**1** (Right) . October 5, 2009 around Beijing
The noise between pixels is reduced.

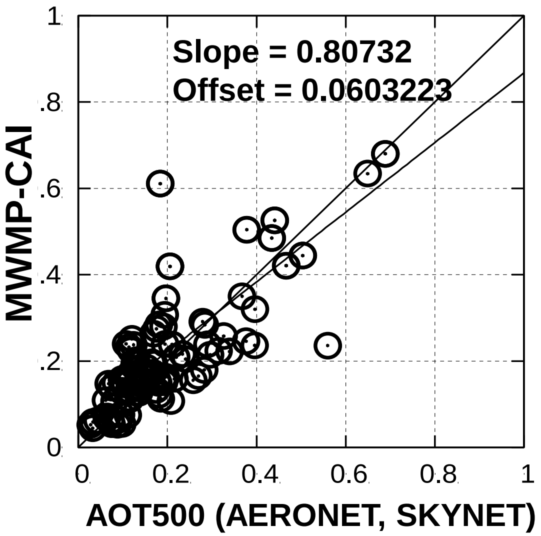
- AOT, PBP: 0.751(0.065), MWPM: 0.634 (0.027), AERONET : 0.649
  ( ) : RMSE calculated by the nearest nine pixels.

- Multi-pixel method is good for aerosol retrieval over Urban region

Aerosol retrieval over land using GOSAT/CAI

GOSAT/CAI: 380, 674, 869, 1600nm

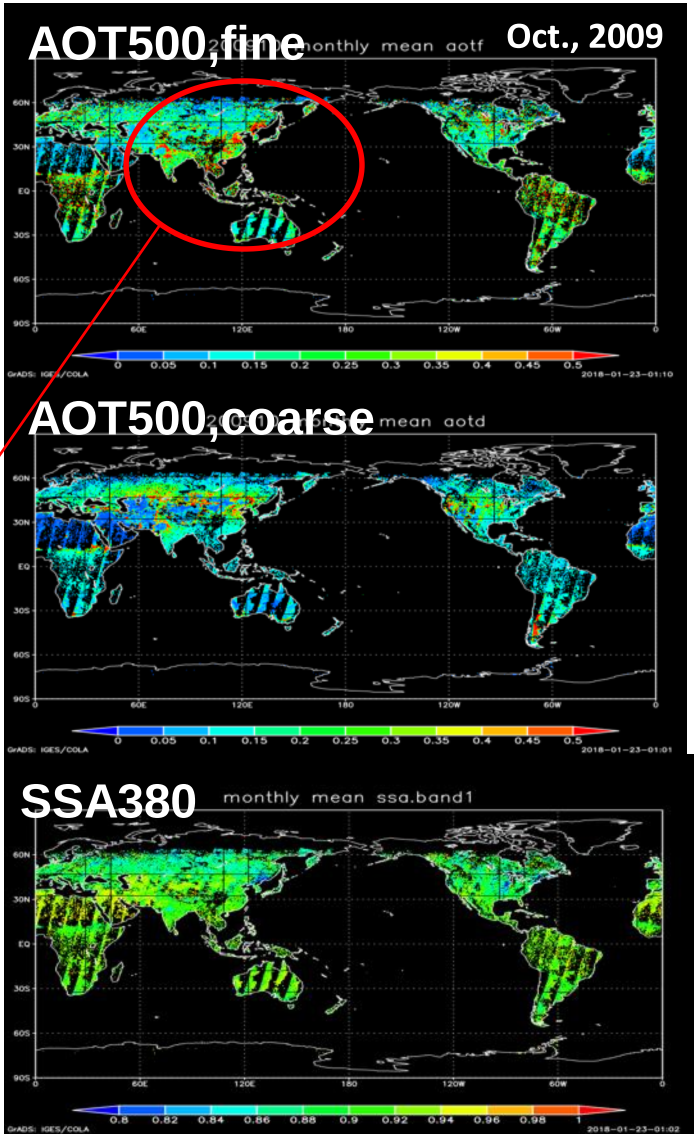
July to December in 2009 Over ***urban region***



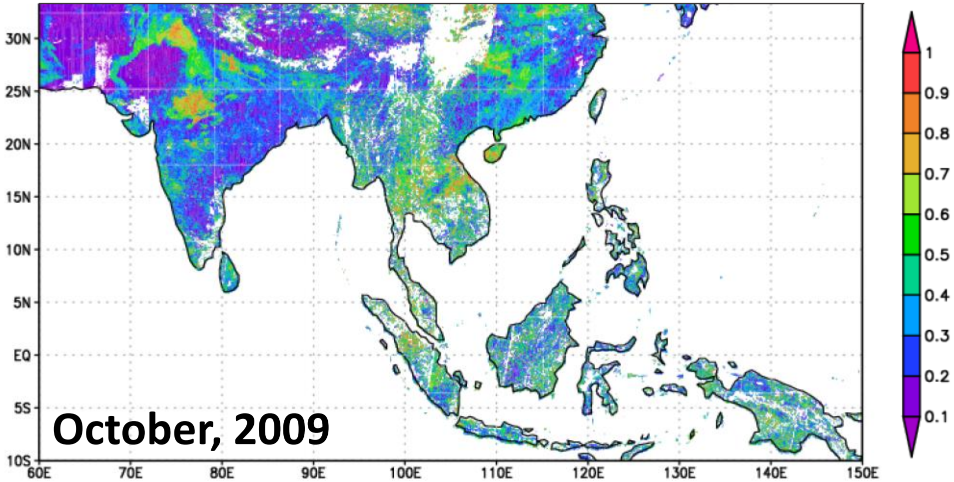
← Total AOT
Fine + Coarse

RMSE=0.077
cf. CAI-2 criteria
(RMS_AOT@550nm < 0.1)

Monthly mean aerosol properties



Monthly mean **AOT (fine particle) corresponding to PM2.5**



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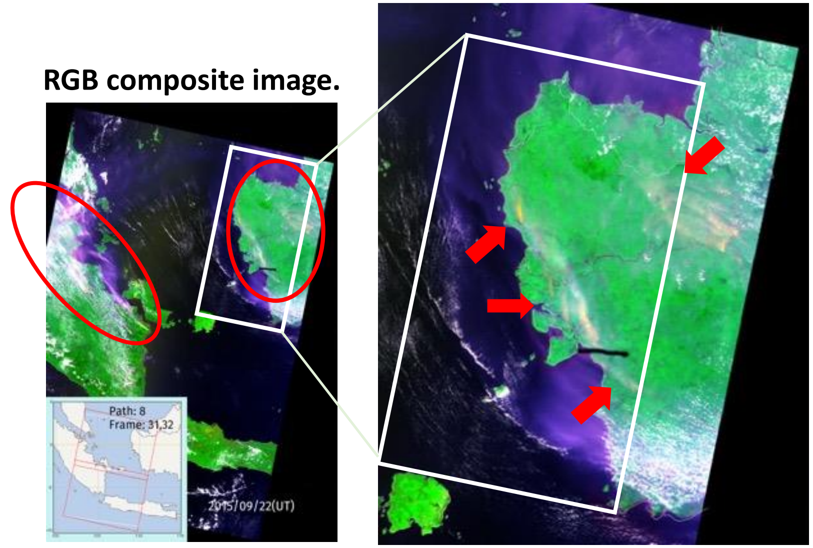
Forest Fire Smoke Case of GOSAT/CAI

GOSAT/CAI: 380, 674, 869, 1600nm

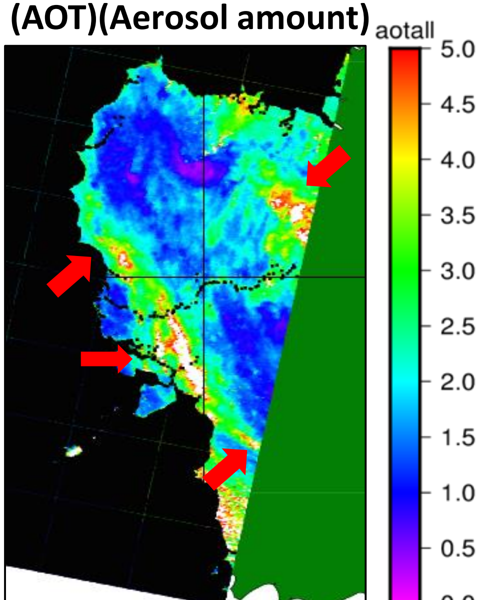
- **September 22, 2015**
- **Smoke from forest fires (Smoke is distinguished from clouds by 380nm)**
- 1.5km × 1.5km

RGB composite image.

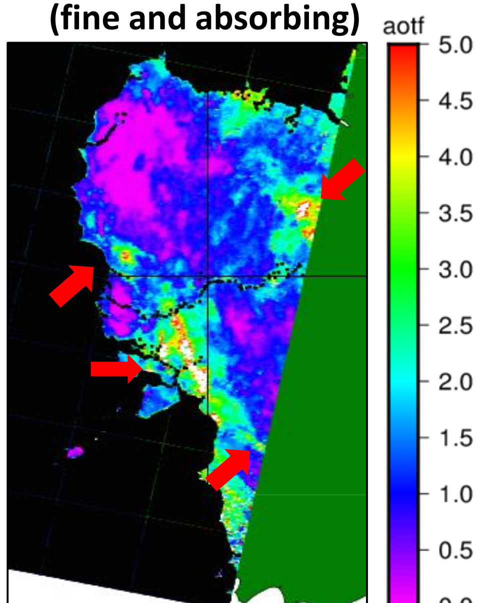


(Original data provided by JAXA/NIES/MOE) **September 22nd, 2015**

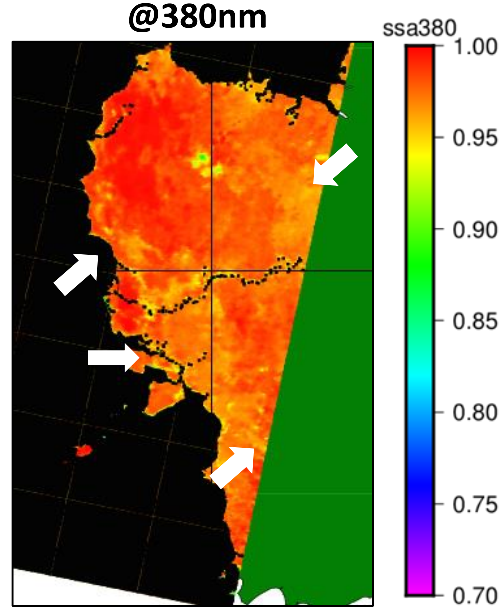
Aerosol optical thickness (AOT)(Aerosol amount)



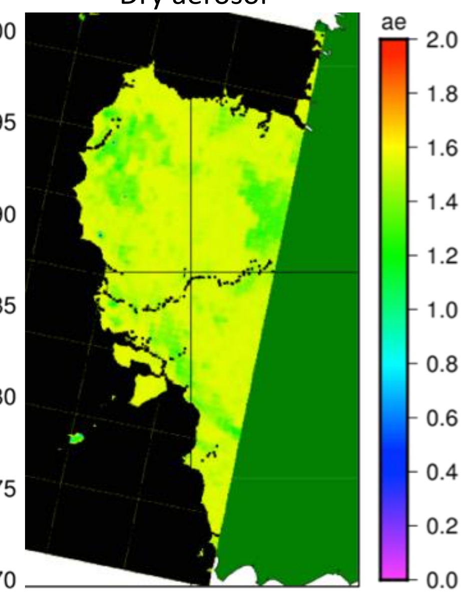
AOT (fine and absorbing)



SSA @380nm



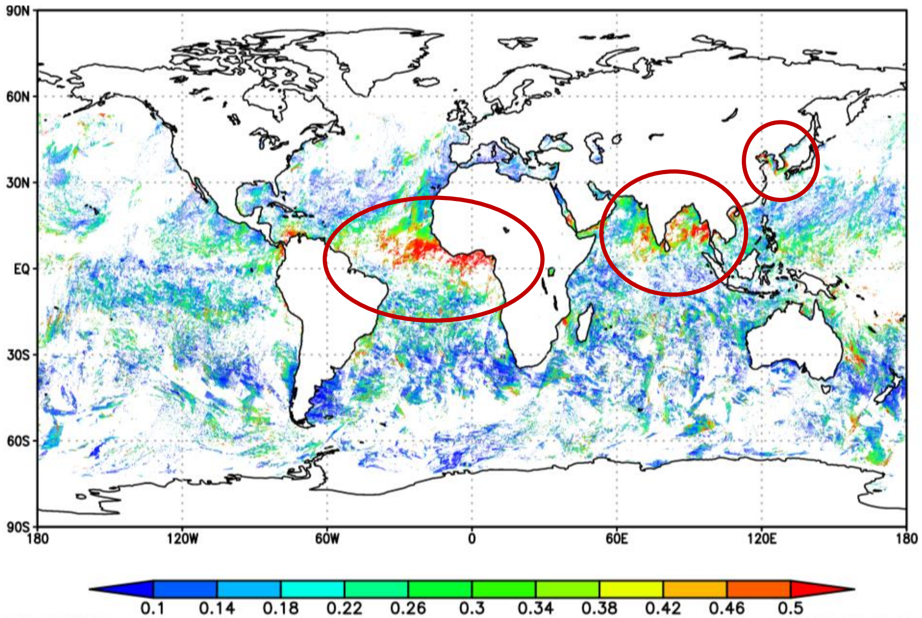
AE
Dry aerosol



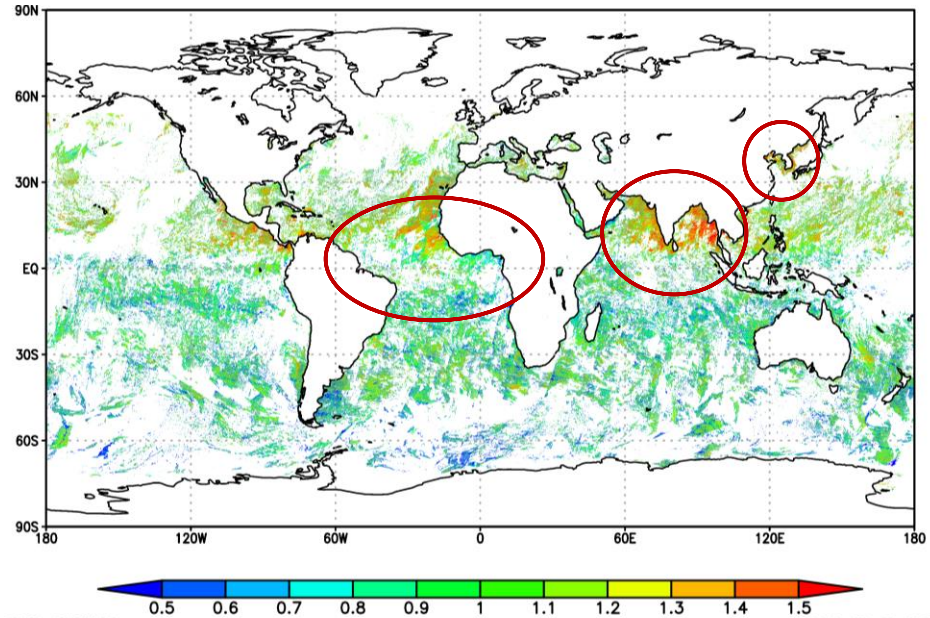
Preliminary results of aerosol properties by CAI-2

CAI-2 FWD or BWD data. February 10 – 15, 2019. Global Aerosol over ocean

AOT (fine particle)

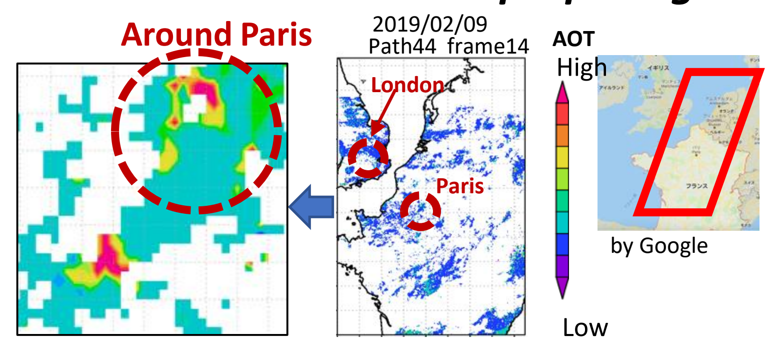


Ångström exponent



- High fine aerosols around *the Gulf of Guinea, Bay of Bengal and Arabian Sea* and *East China.*
- The fine aerosol over ocean is a kind of continent-derived aerosol.
- As you can see the Ångstrom exponent result, fine aerosols, which is corresponding to PM2.5 dominate in the Arabian Sea and Bay of Bengal.

Aerosol over Land. Now preparing



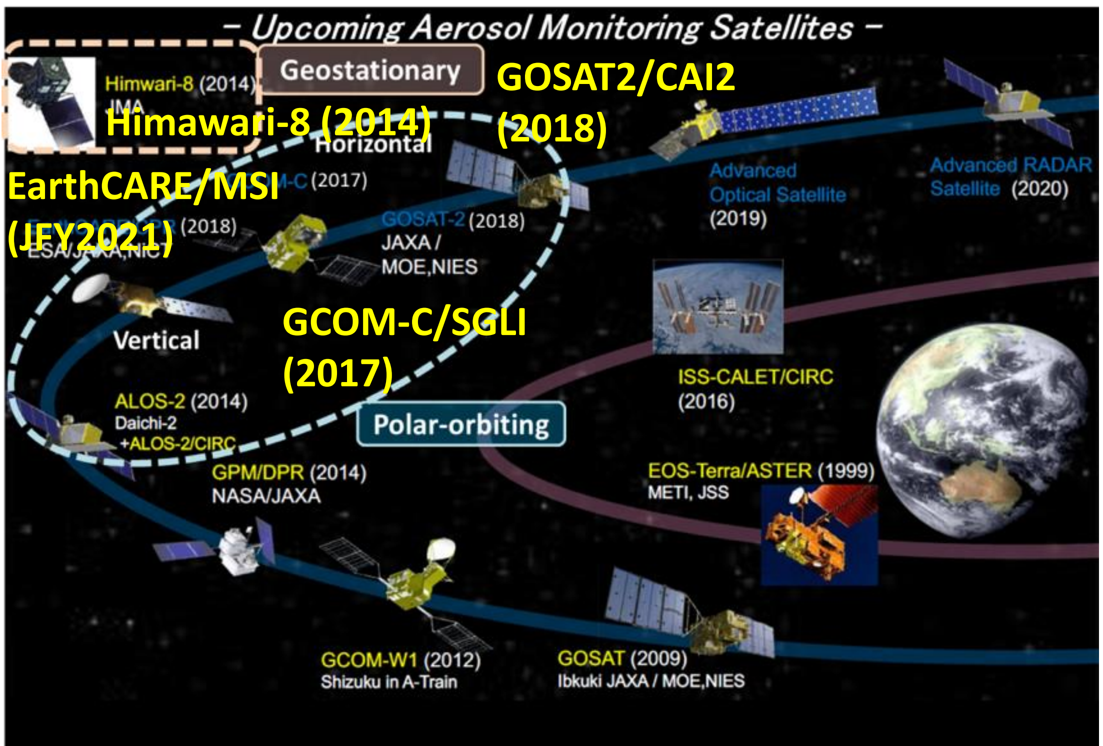
(By ***Shi@JAXA***, ***Hashimoto@JAXA***, *Nakajima@JAXA, Tamaru@RESTEC, Kataoka@RESTEC*)

Aerosol monitoring in JAXA

<u>ONE of our goal.</u>

- Produce synergistic global aerosol data set
  - using **<u>JAXA Polar-orbiting</u>** and **<u>geostationary</u>** satellites
  - Provided in near real time
- Collaborate with Modeling group, NIES, MRI, Kyushu Univ. etc.

Current and Upcoming Aerosol Monitoring Satellite



Target sensors

<u>Geostationary:</u>
Himawari-8/AHI, GOES-R, Meteosat
<u>Polar-orbiting:</u>
Aqua,Terra/MODIS, GCOM-C/SGLI, GOSAT2/CAI2, EarthCARE/MSI

Aerosol monitoring using LEO and GEO: Himawari-8

Himwari-8/AHI characteristics

CH	λ(nm)	IFOV (m)
1	471	1000
2	510	
3	639	500
4	857	1000
5	1610	
6	2257	
7	3885	2000
8	6243	
9	6941	
10	7347	
11	8592	
12	9637	
13	10407	
14	11240	
15	12381	
16	13311	

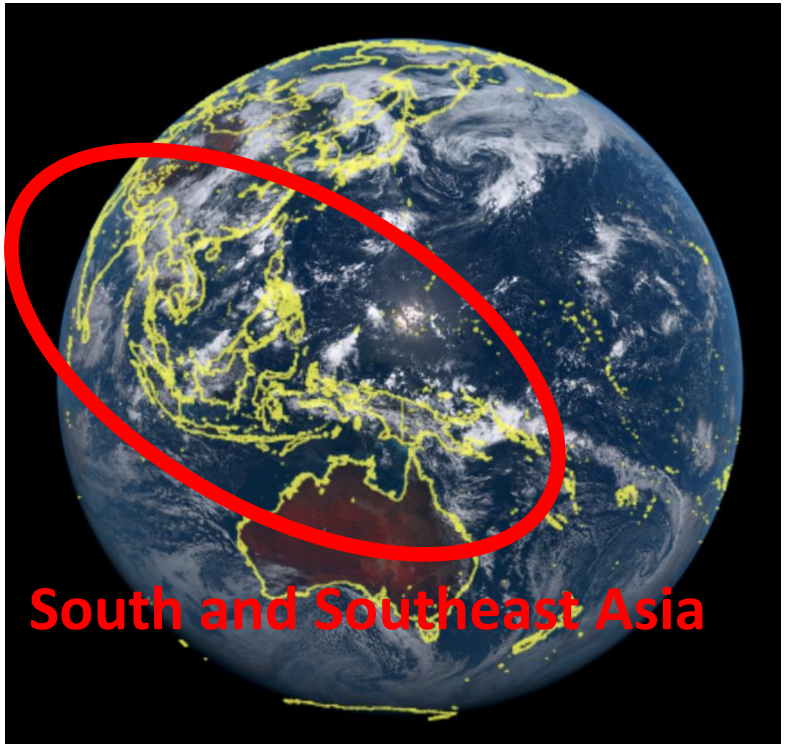
Aerosol retrieval

High temporal resolutions

Himawari-8 Full disk observation

16 bands in Visible-Infrared

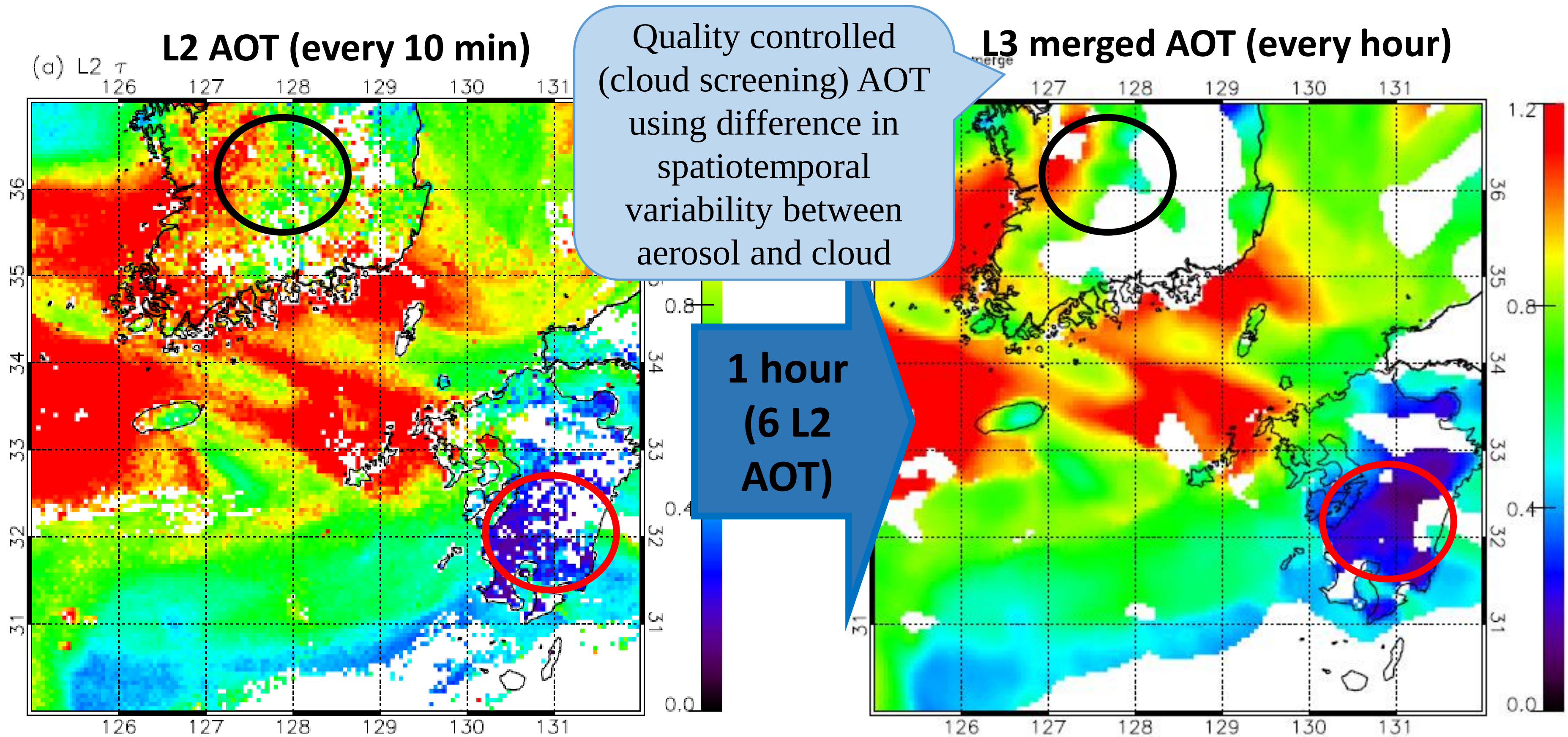
10 minutes interval



Himawari Real-time@NICT
https://himawari8.nict.go.jp

Retrieval Results (Himawar-8/AHI)

16 JST 27 Apr. 2018 : continental air pollutant transported to Kyusyu

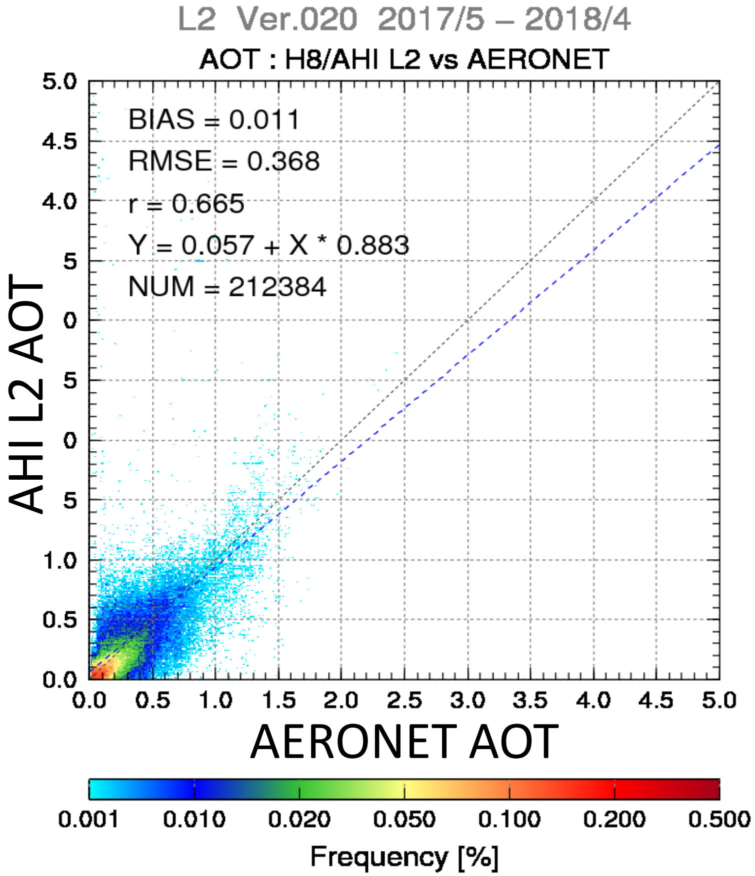


Yoshida et al., 2018 *Kikuchi et al., 2018*

- The high and nearly continuous AOT over land and ocean are estimated
- High AOT caused by local noise or insufficient cloud screening was eliminated and interpolated smoothly in L3

Validation (AHI vs AERONET)

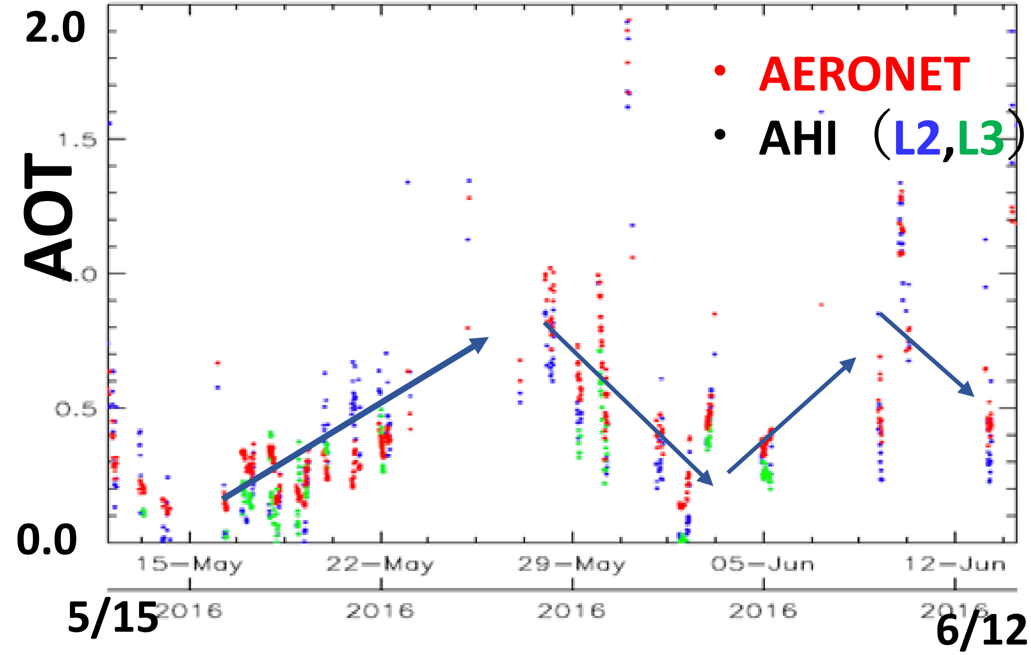
Frequency distributions
: 1 year, all AERONET site



- AHI AOT is generally consistent with AERONET

Time variation

Baeksa in Korea



L2: snapshot retrievals every 10 min
L3: cloud screening data using 1hour data

- AHI AOT successfully represent the time variation of AERONET

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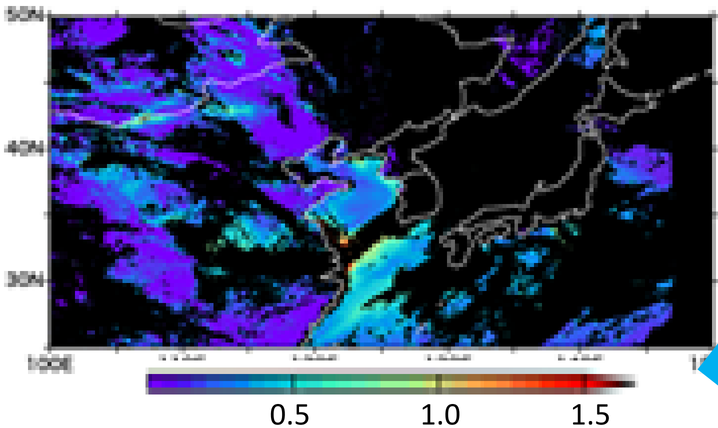
MRI Aerosol Assimilation

A case of yellow sand day (April 16, 2015)

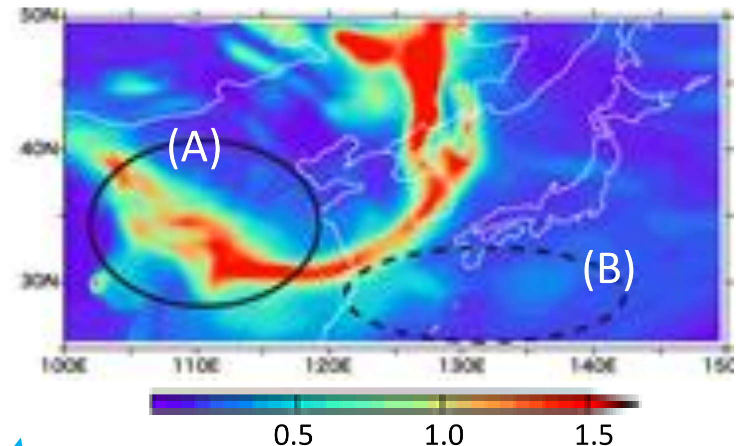
Retrieved AOT from Himawari-8



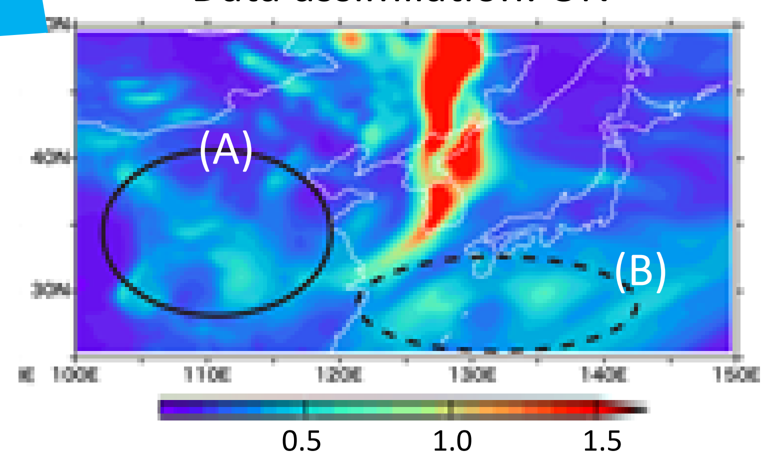
Data assimilation

Model Simulated AOT

Data assimilation: OFF



Data assimilation: ON



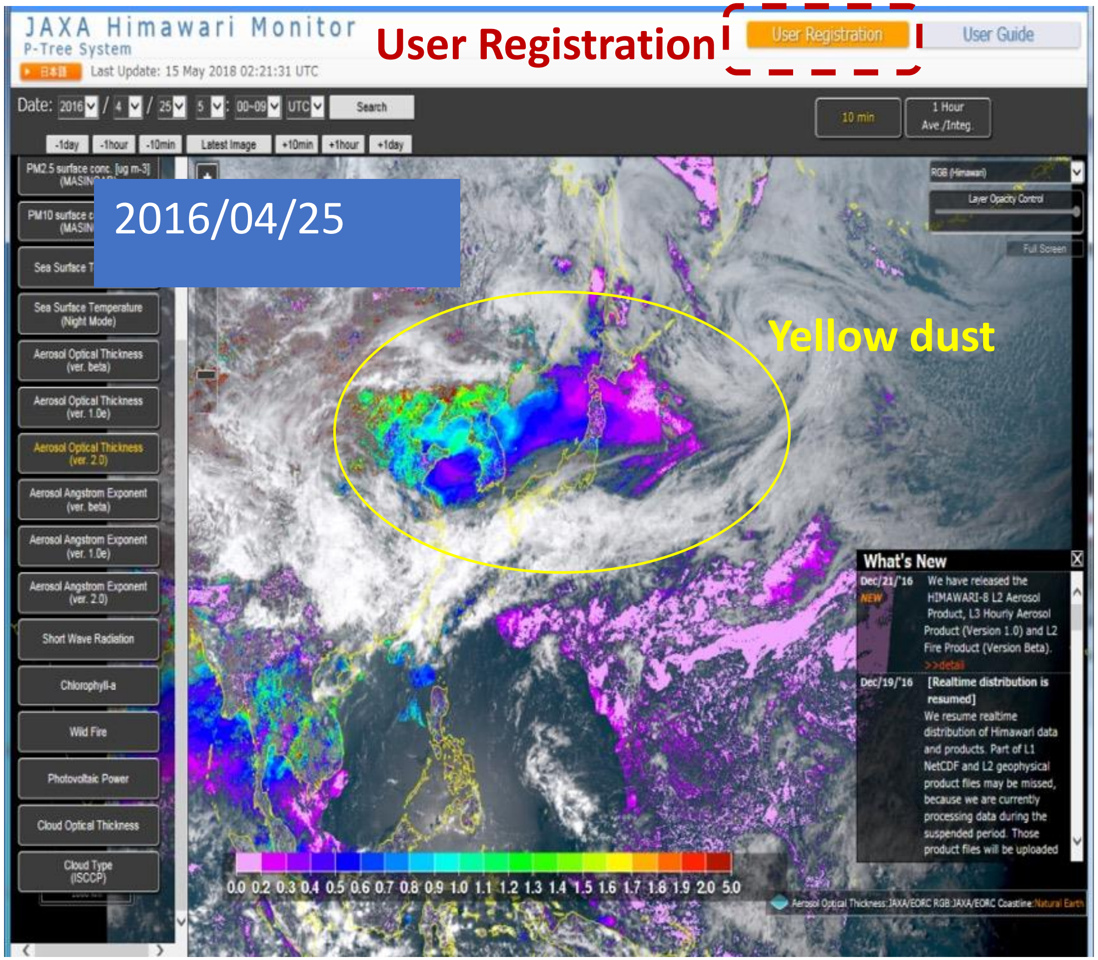
By assimilating Himawari-8 AOT, overestimated and underestimated AOT over inland China (A) and south part of Japan (B) are improved, respectively.

→ Improve a prediction accuracy of aerosols, such as yellow sand and PM2.5.

Yumimoto@Kysyu Univ.

JAXA Himawari Monitor

http://www.eorc.jaxa.jp/ptree/index.html



Himawari-8/AHI

- Aerosol optical thickness
- Aerosol Ångström exponent
- Day time SST
- Night time SST

etc.

https://gportal.jaxa.jp/

Other Japanese satellite data

Aerosol :

- GCOM-C

EORC

- Data can be achieved with simple user registration

Summery and Future work

- GOSAT-2 was launched on October 29, 2018

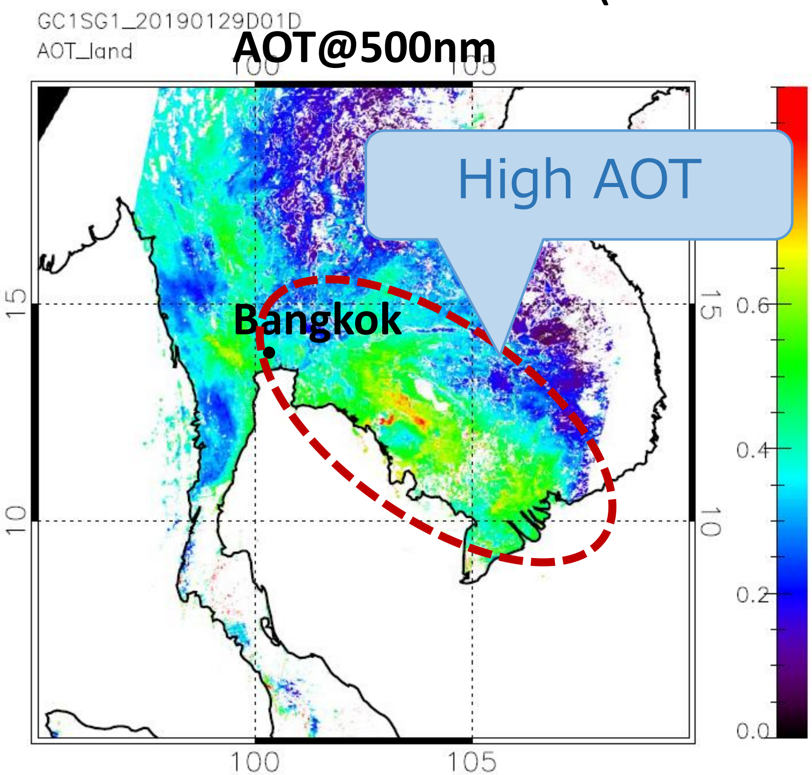
- GOSAT-2/CAI-2 is a sensor for Cloud and Aerosol
  →One of CAI-2 goal is Monitoring air pollution, that is, retrieve aerosol properties and estimate PM2.5 concentration and BC volume ratio.
  → Now Preparing to provide aerosol optical properties

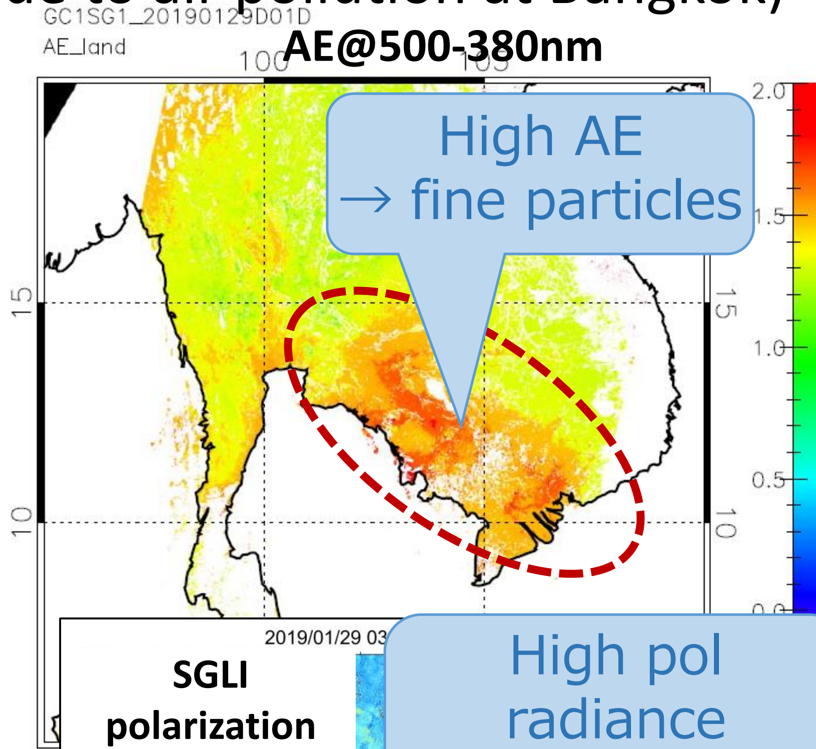
- Provide Himawari-8 Aerosol data to assimulate and predict air pollution.
  → Provide aerosol data from GCOM-C, GOSAT-2, and EarthCare as a futurwork.

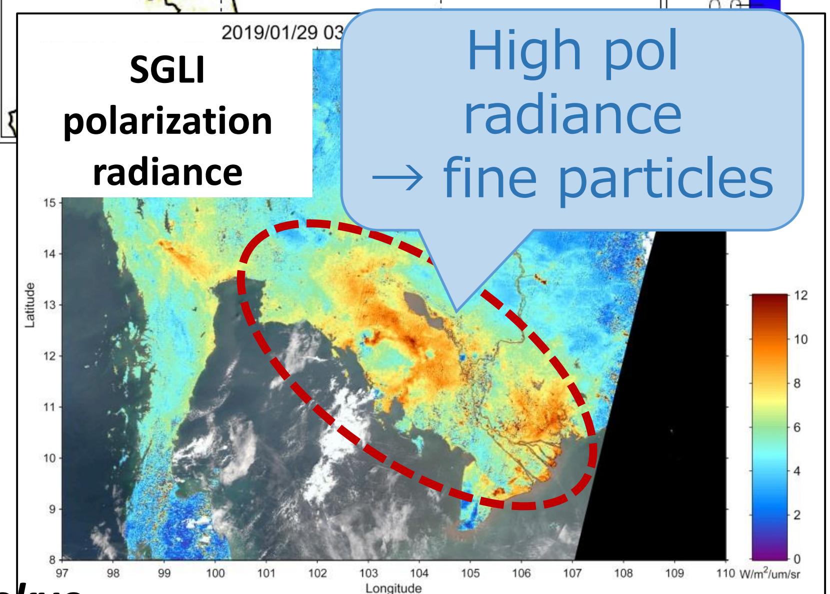
Thank you for your attention!

Retrieval Results (GCOM-C/SGLI)

29 Jan. 2019 Thailand (school closed due to air pollution at Bangkok)







- **The high AOT and AE (i.e. fine particles) are estimated corresponding to local air pollution report**
- **Estimated AOT and AE are consistent with SGLI polarization observation**

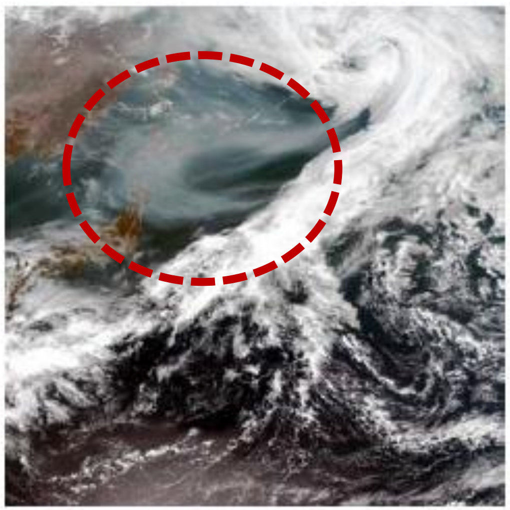
M. Yoshida@JAXA and T. M. Nagao@University of Tokyo

Retrieval Results (H8/AHI)

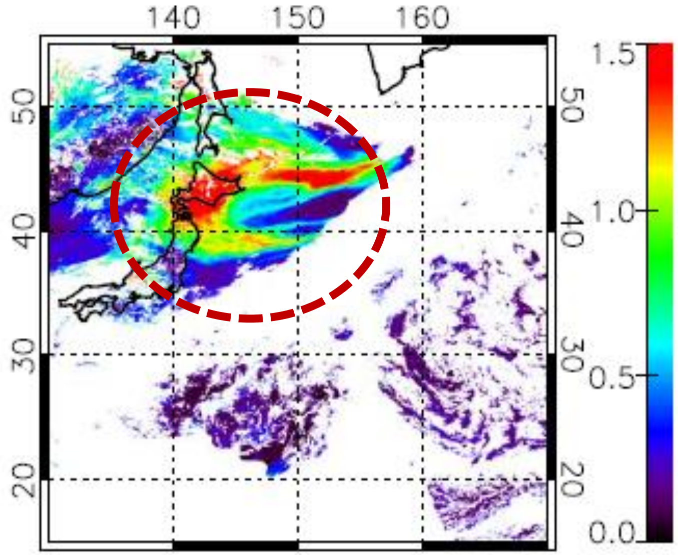
02UTC, 19 May 2016

Aerosol originated from wildfires at a proximity to Lake Baikal in Russia

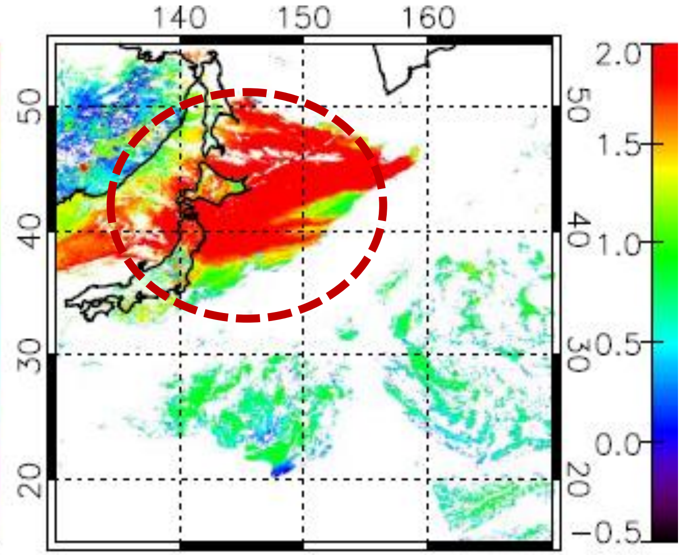
RGB



AOT@500nm



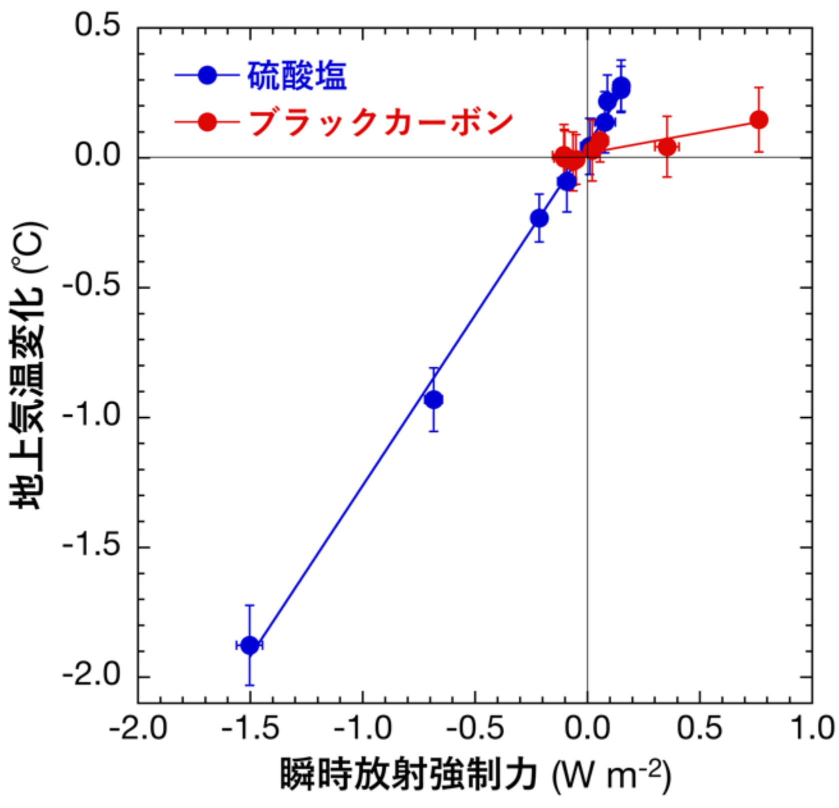
AE@400-600nm

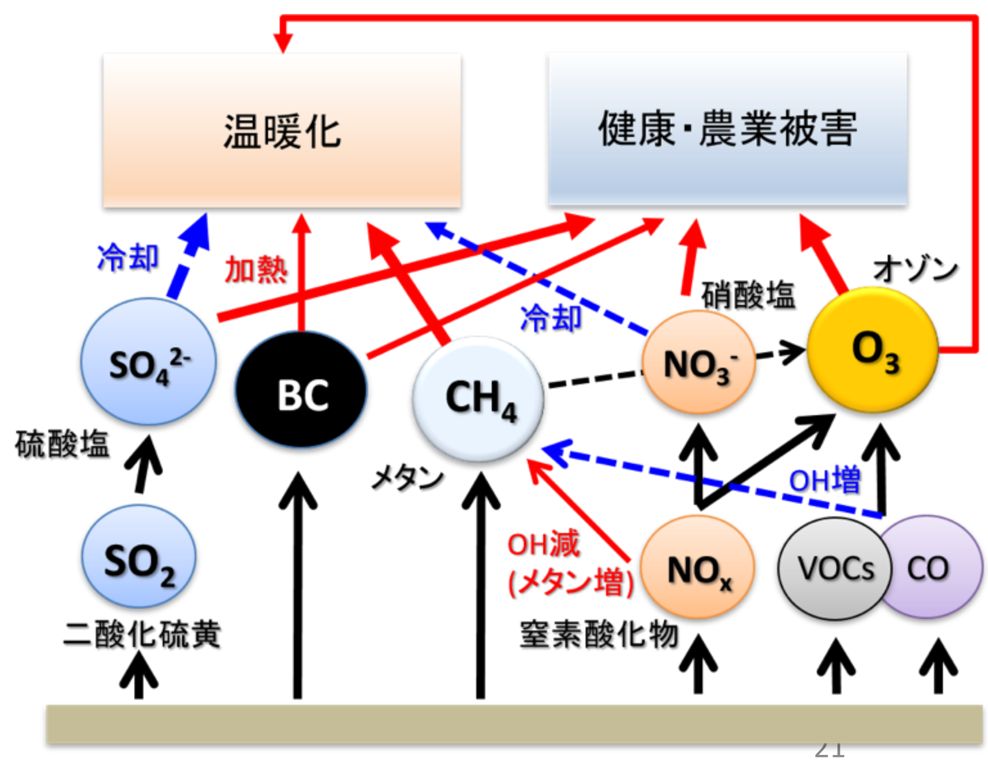


- **The high AOT and AE (fine particles) are estimated over land and ocean, corresponding to aerosol transport from the continent**
- **nearly continuous AOT over land and ocean**

S12研究の結果、二つの不都合な事実が明白になってきた

- **BCと窒素酸化物の排出削減による地球温暖化緩和は限定的**
- **ただしモデル依存性がある**
- **相対的にメタン削減の重要になってきた**
- **これらの相互作用を考慮して、メタン、炭素系物質（COやVOC）, BC, NOxの削減を組み合わせた削減シナリオが必要**





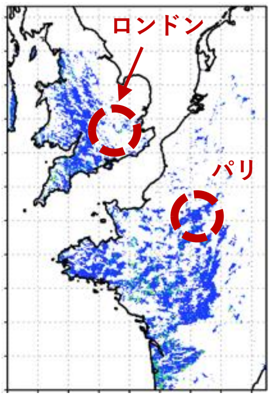
GOSAT-2/CAI-2

■ **GOSAT-2/CAI-2 Aerosol**

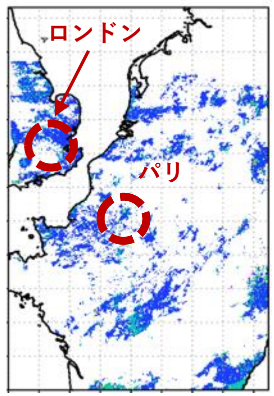
陸上

by Google

2019/02/10
パス45 フレーム14

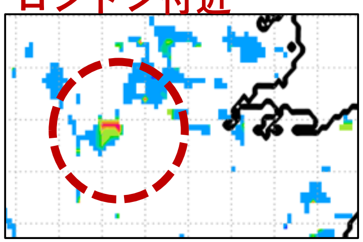


2019/02/09
パス44 フレーム14

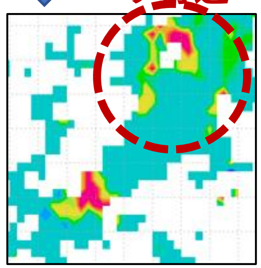


都市域付近で高いAOT →

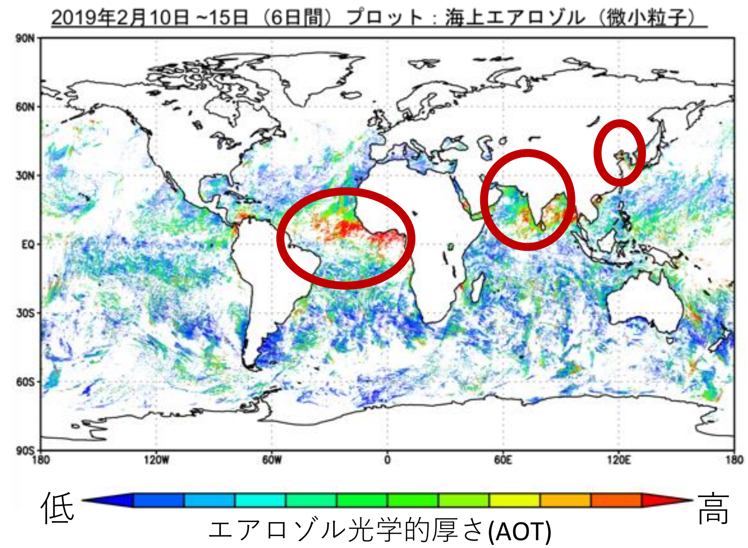
ロンドン付近



パリ付近

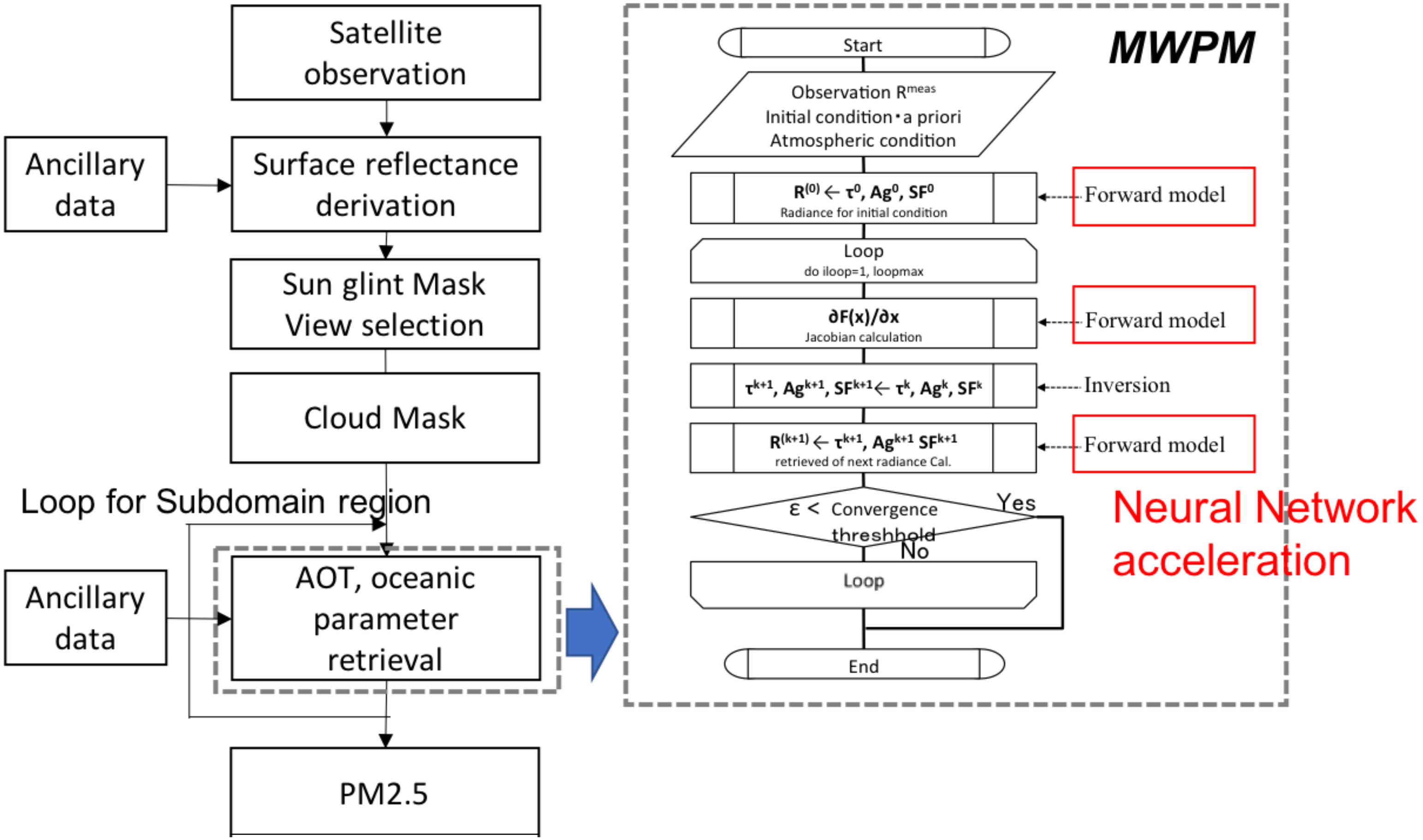


海上



陸上領域、全球海上のエアロゾルの濃淡。
アフリカ大陸ギニア湾、インド周辺、黄海辺り→大陸由来
(陸上：By 橋本 真喜子)
(海上：By 石 崇, 橋本 真喜子,中島 映至, RESTEC)

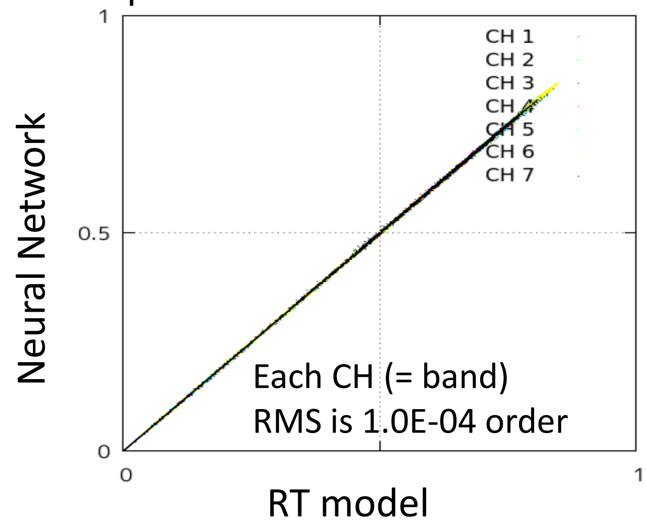
Flow chart of aerosol retrieval using CAI / CAI-2



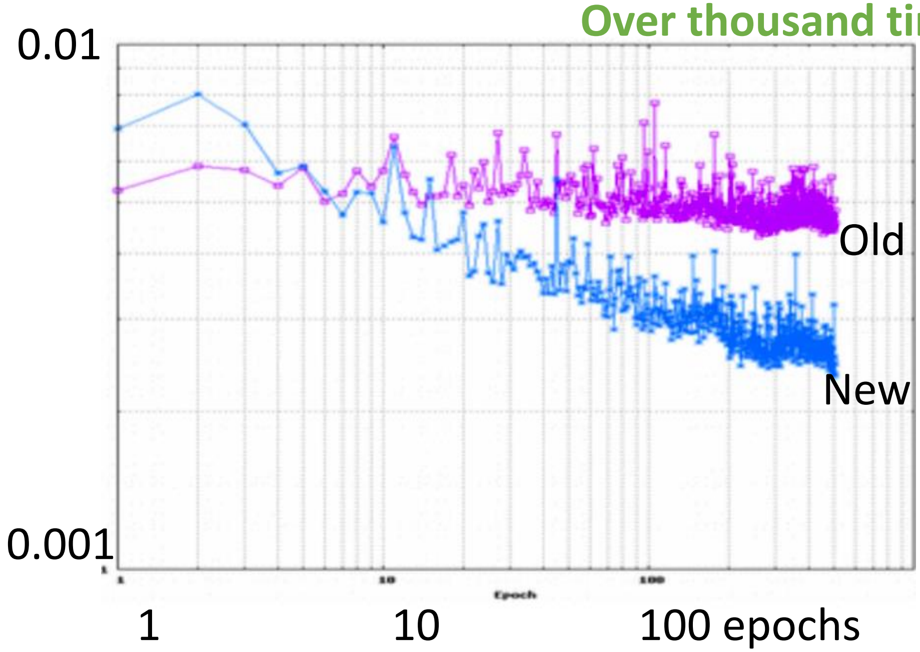
Algorithm acceleration: Neural Network

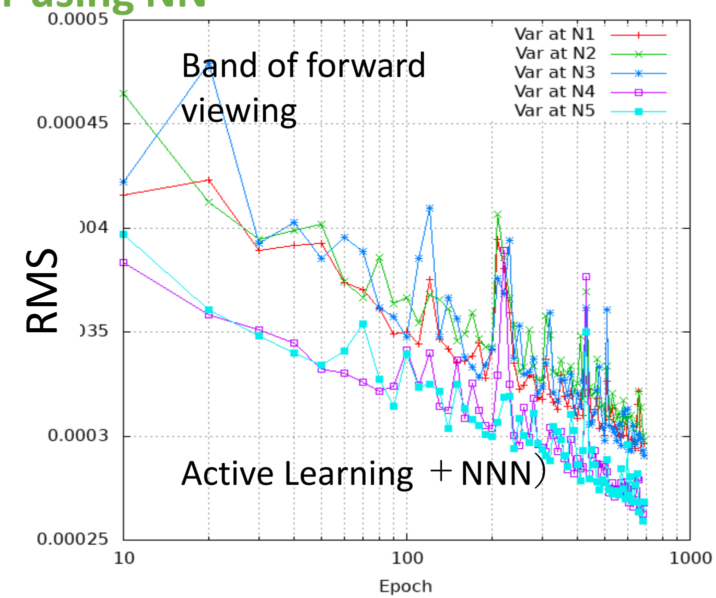
- Old version：Distortion BP method （Takenaka+, JGR'11)
- New version （NNN; Takenaka+, 2019. EXAM, Active Learning ）
- JAXA JSS2 （ SORA-MA ） Training data generation from model→ calculation time @JSS2 ：1~3 sec/time (land)、16~18sec/time(ocean) （ 7 bands of CAI2 simultaneous）
- Training data number RT model (Rstar 7)：577M
- Acceleration from NN：6.0E-04 sec/time （ 7 bands of CAI2 simultaneous）

Comparison between Rstar7 and NN



Over thousand times faster using NN

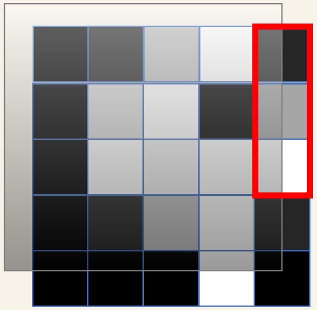




H.Takenaka@JAXA

GOSAT-2 L2 エアロゾルアルゴリズム(MWPM)

❖ MWP法（Multi-wavelength and -pixel method）



$$\rightarrow \; R = f(u) + e$$

$$R = R_a + R_g \approx A_g + \tau \cdot [c_1 \cdot \omega P(\Theta) - c_2 \cdot A_g]$$

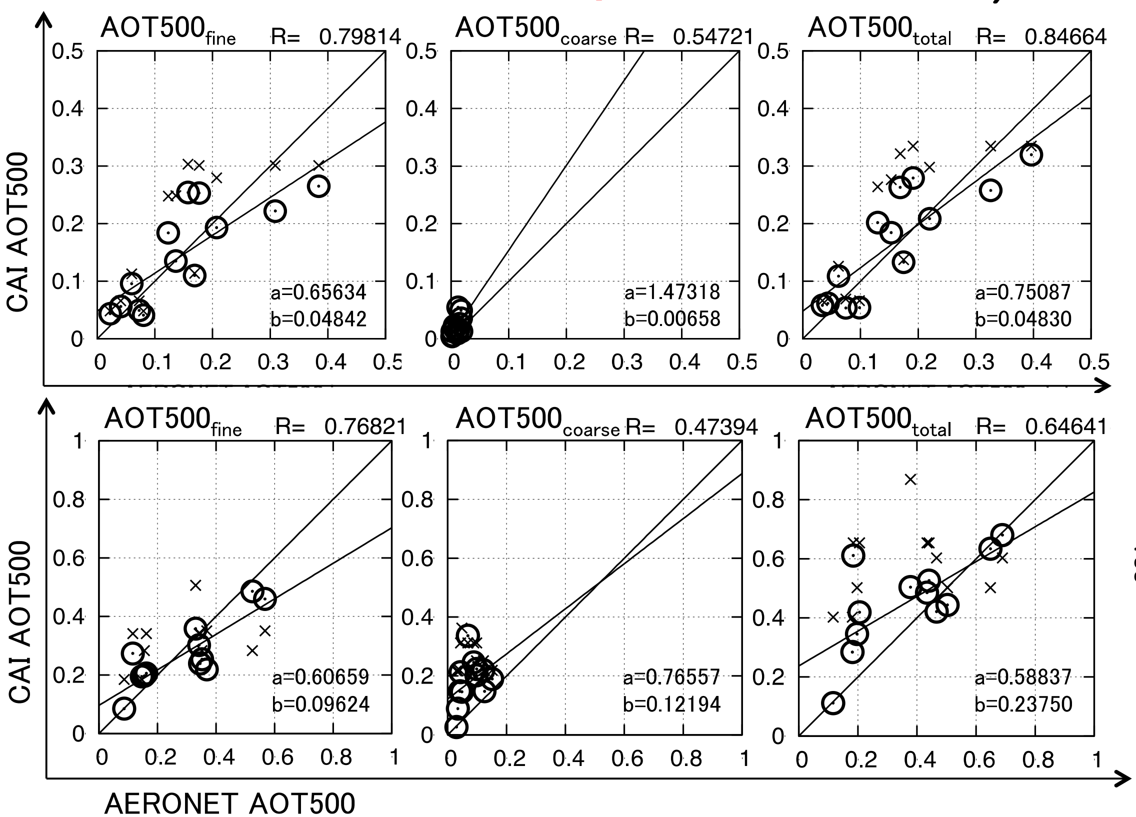
=0 (Independent of AOT*)

（**R**: Reflectance, τ: AOT, ω: SSA, $P(\Theta)$: Phase function）

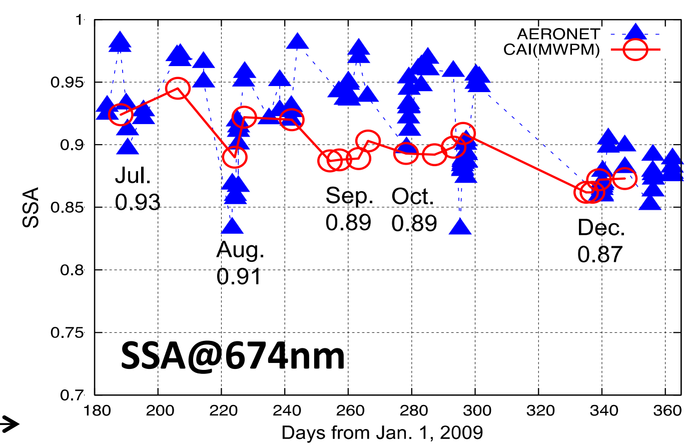
$$R = [R_{\mathrm{band1}}, R_{\mathrm{band2}}, \cdots, R_{\mathrm{band}N}]_x^{\mathrm{T}}, \quad u = [\tau_{550,fine}, \tau_{550,coarse}, w, \{A_g\}_\lambda]_x^{\mathrm{T}}, \quad \lambda = \{\lambda_i, i = 1, N_{band}\}$$

R: Measurement
f (*u*) : Radiation model
u : Aerosol parameters
e : Errors

❖ *Retrieval from GOSAT/CAI 4 bands* *July to December, 2009. VS AERONET*

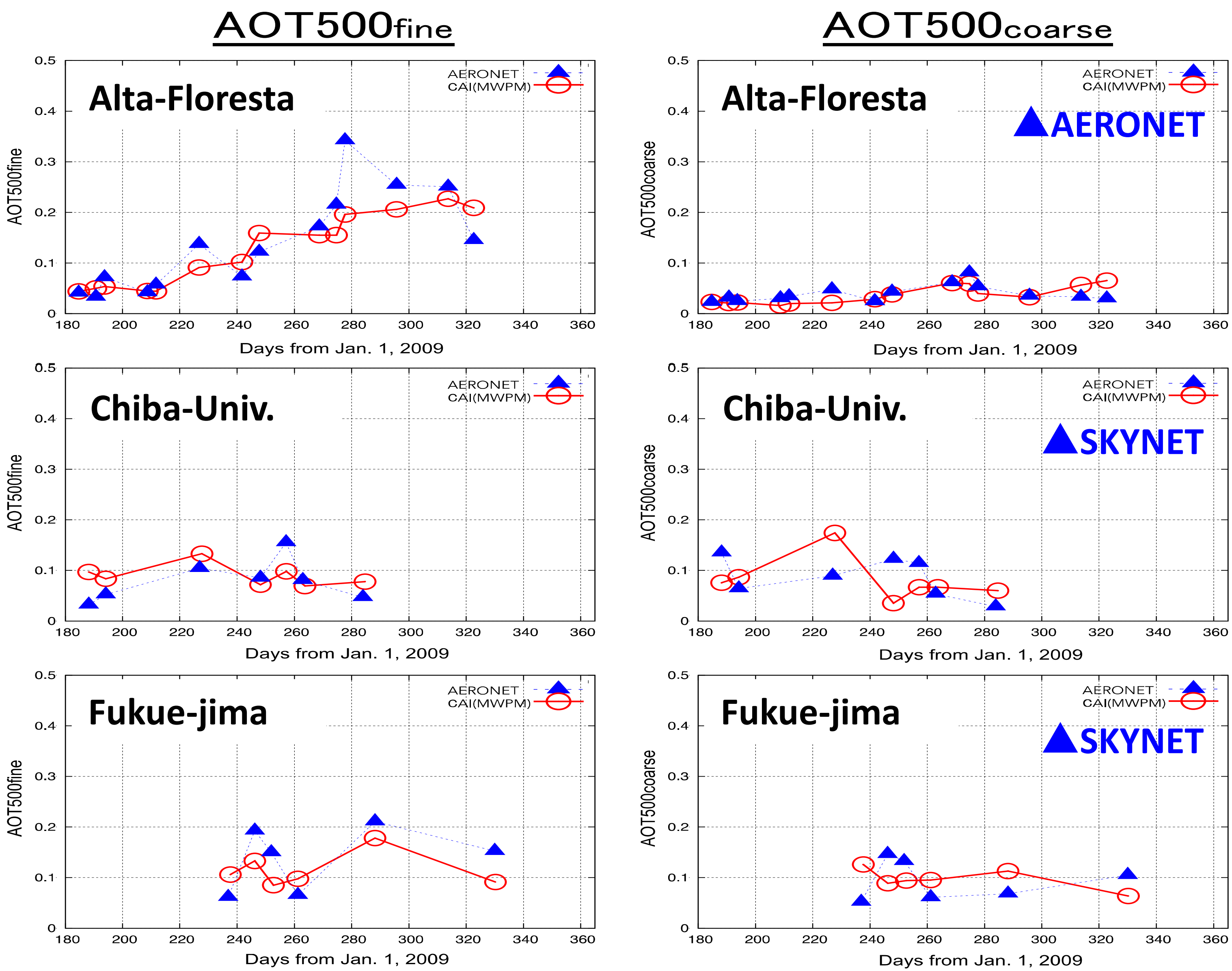


←チェサピーク湾周辺
↓北京周辺
Retrieval result of AOT(fine), AOT(coarse) and AOT(total)@550nm, SSA@674nm



GOSAT-2 L2 エアロゾルアルゴリズム(MWPM)時系列

2009年7月~12月: GOSAT/CAIエアロゾルAOT VS AERONET/SKYNET AOT



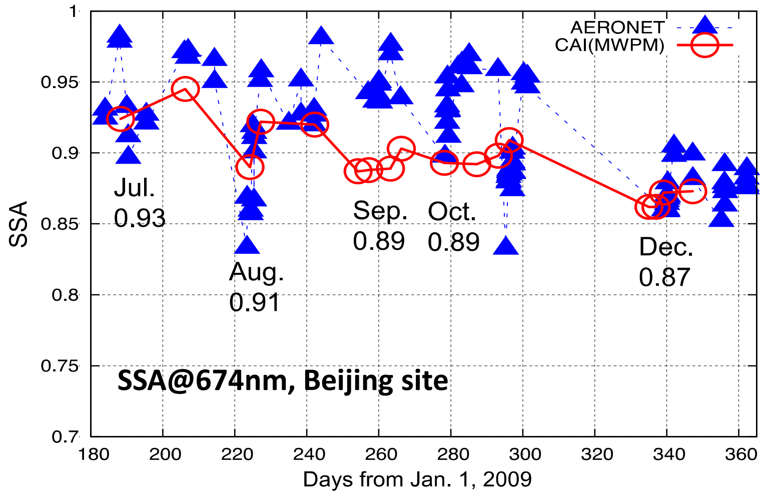
Aerosol retrieval using CAI measurements over land

SSA/BCの比較：北京上空での解析結果（2009年7月～12月）

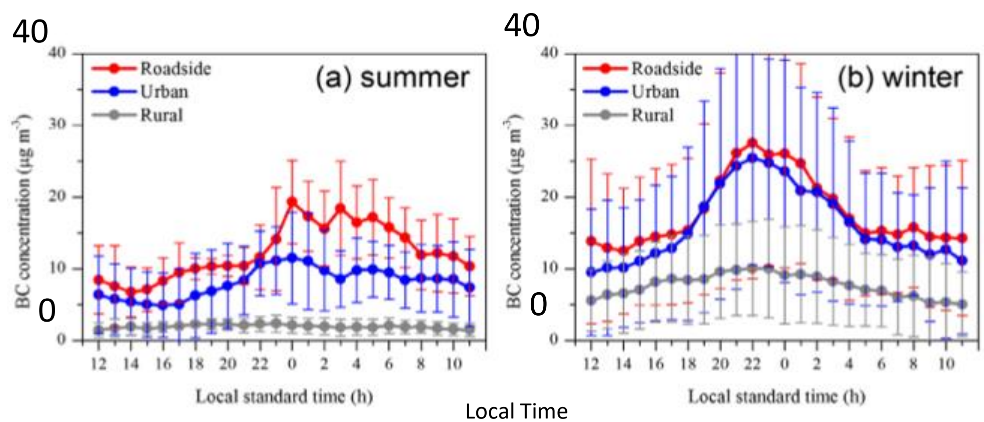
※SFでは比較できないので，SSAで比較

求めたAOT(fine)とSFを用いてBCを算出。BCの密度は仮定。

SSA : 本手法　SSA : AERONET



北京一日のBC濃度の変化 [μgm^{-3}](Song etal., 2013)

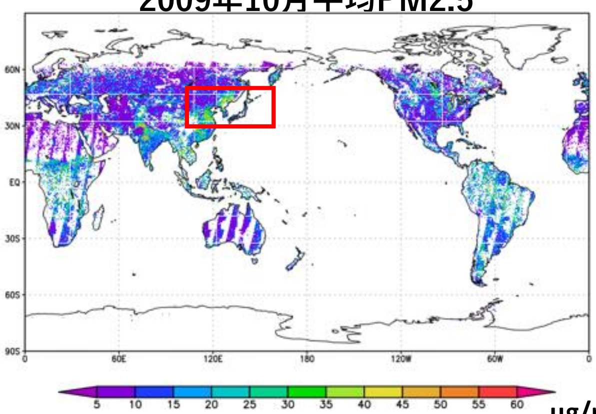


- 2009年の現場観測：BCが冬期に増加（都市部：夏期8.1μgm^{-3}，冬期16.1μgm^{-3}）(Song et al., 2013)
- 冬期においてSSAが小さくなる現象はBC排出の増加と相対湿度の減少によると考えられる
- 地上観測と同様の傾向←SSA(SF)が導出可能

アルゴリズム確認の例(AOT, PM2.5)

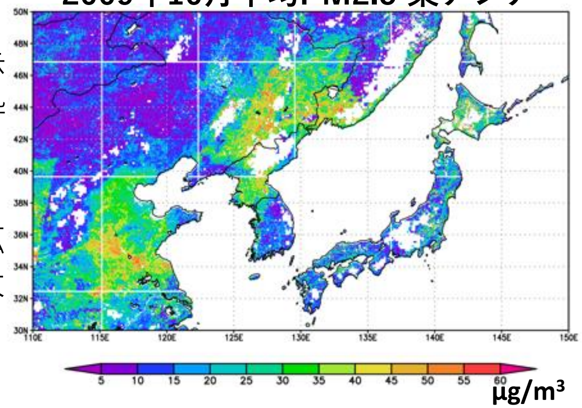
- GOSAT-2/TANSO-CAI-2用のアルゴリズムを使用
- GOSAT/TNASO-CAI の4バンド（380, 674, 870, 1600nm）に適用
- 都市域のAOTをAERONET・SKYNETと比較(右図)。***ΔAOT~0.077***
  → **GOSAT-2/CAI-2エアロゾル、フルサクセスクライテリアを満たす**
- 10月のAOT(fine)よりPM2.5を算出（鉛直分布の仮定の影響大）
  ※ 中国米大使館2009年10月平均～100μg/m³

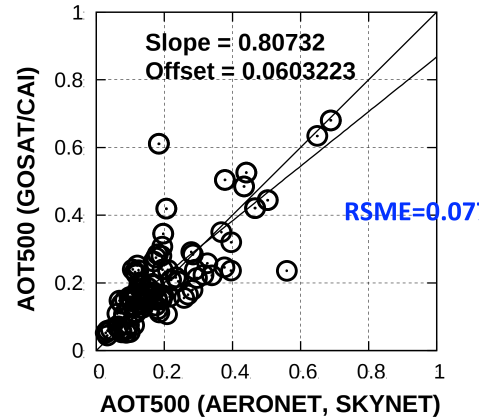
2009年10月平均PM2.5



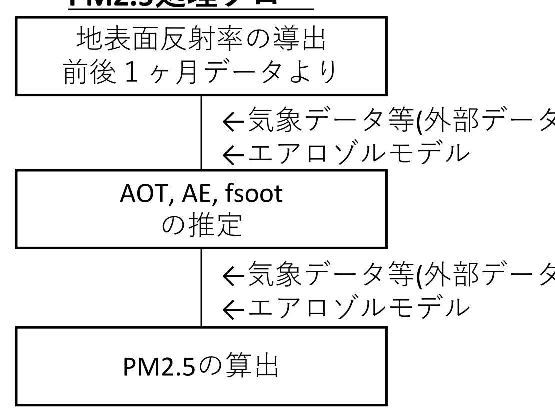
赤枠拡大

2009年10月平均PM2.5 東アジア





PM2.5処理フロー



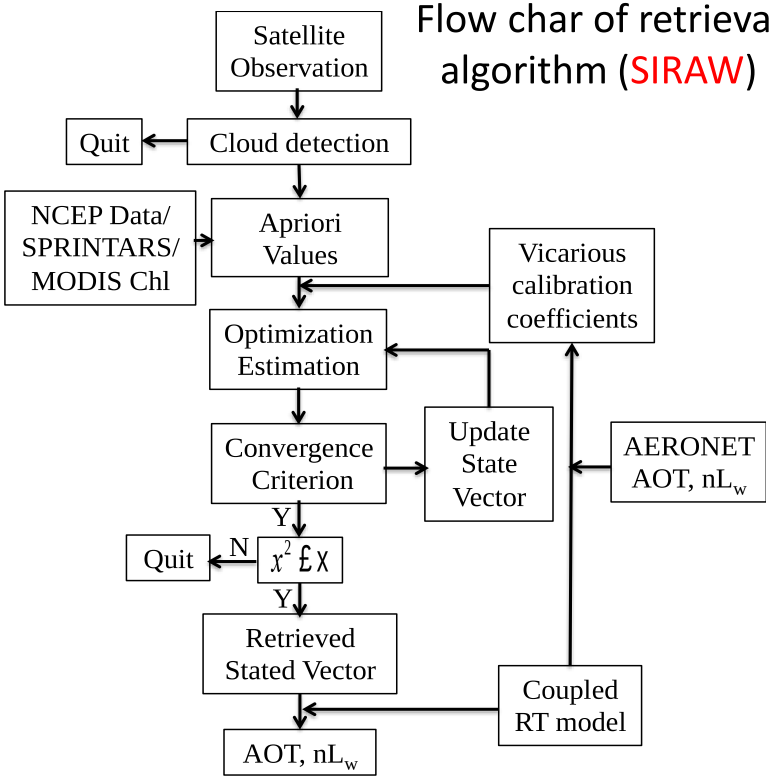
$$v(r) = \frac{dV}{d\ln r} = g(AOT)\cdot\sum_{i=1}^{N} c_i exp\left\{-\frac{1}{2}\left(\frac{\ln r - \ln r_{m,i}}{\ln S_i}\right)^2\right\},\quad \rho_{sulfate} = 1.5\mathrm{g/m^3}\text{(仮定)}$$

$$\mathrm{PM2.5[\mu g/m^3]}^{(※1)} = m_{f.boundary}\cdot\rho_{Sulfate}\cdot\int_{r_{fine.min}}^{r_{fine.max}}\frac{1}{r}\frac{\mathrm{d}V}{\mathrm{d}lnr}\mathrm{d}lnr$$

(※1) Sulfateのみで計算

Simultaneous Retrieval of Aerosol and Oceanic parameters

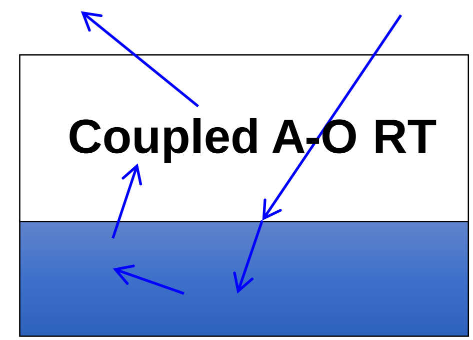
- **Shi & Nakajima (ACP'18)**
- **Shi et al. (ACP'19): w MWPM**



Flow char of retrieval algorithm (SIRAW)

- Forward radiation simulation (I,Q,U) conducted by a coupled A-O RT model (**Pstar: Ota et al., JQSRT, 2010**)
- Improved Pstar with CASE2 water module

Turbid A& Murky O



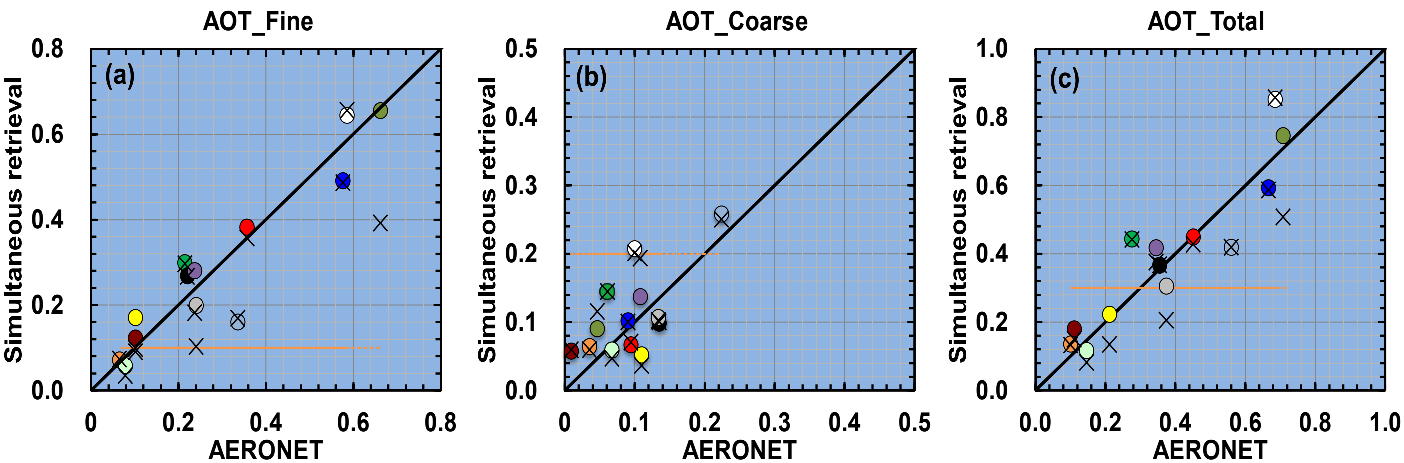
➢ Retrieved parameters are derived by the optimization estimation approach.

$$x_{i+1} = x_i + \left[\left(\mathbf{K}_i^T \mathbf{S}_e^{-1} \mathbf{K}_i + (1+\gamma)\mathbf{S}_a^{-1}\right)\right]^{-1} \cdot \left[\mathbf{K}_i^T \mathbf{S}_e^{-1}\left(y - F(x)\right) - \mathbf{S}_a^{-1}\left(x_i - x_a\right)\right]$$

x: Retrieved parameters (8)
atmosphere: AOT_fine, AOT_seasalt, AOT_dust, soot fraction
ocean: wind speed, Chl, sediment, CDOM

C. Shi@JAXA

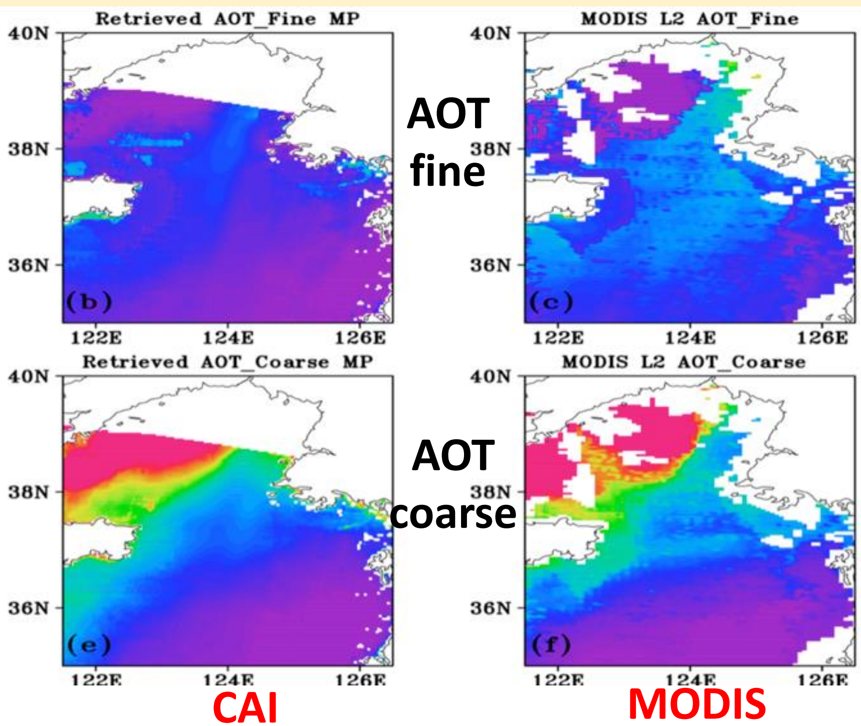
Aerosol retrieval using CAI measurements over ocean



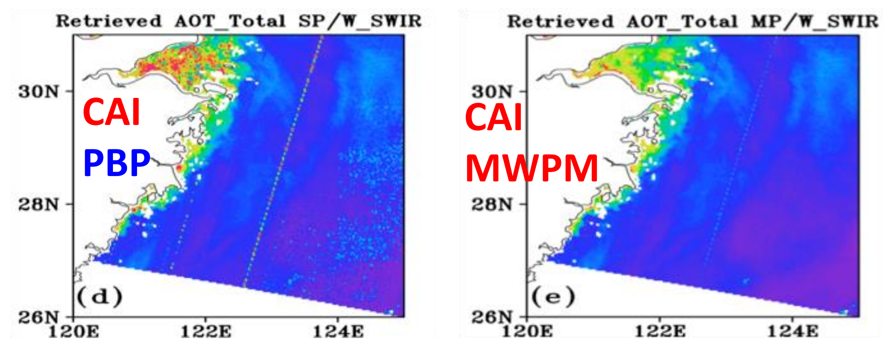
Retrieval based on the GOSAT/TANSO-CAI

- O Multi-pixel method
- × Single-pixel method
- – A priori values

Asian Dust Monitoring (2012/04/27)



Aerosol retrieval over turbid waters



High turbid over the East China Sea

$$x_{i+1} = x_i + \left[\left(\mathbf{K}_i^T \mathbf{S}_e^{-1} \mathbf{K}_i + (1+g)\mathbf{S}_a^{-1}\right)\right]^{-1} \cdot \left[\mathbf{K}_i^T \mathbf{S}_e^{-1}\left(y - F(x)\right) - \mathbf{S}_a^{-1}\left(x_i - x_a\right)\right]$$

x: Retrieved parameters (8)
atmosphere: AOT_fine, AOT_seasalt, AOT_dust, soot fraction
ocean: wind speed, Chl, sediment, CDOM

C. Shi@JAXA