Development and verification of an aerosol forecasting system with data assimilation using GCOM-C aerosol product

Taichu Y. Tanaka[1]

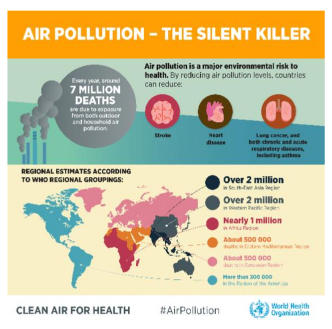
1. *Meteorological Research Institute, Japan Meteorological Agency*

PI Number: ER2GCN213

Introduction

Aerosols are an essential component of the atmosphere for climate because of their effects on atmospheric radiation and cloud properties. Since these effects affect seasonal and short-term forecasts in numerical weather prediction, accurate representation of atmospheric aerosols and their effects may improve the accuracy of weather prediction. Aerosols also cause air pollution, which affects people's living environment and health. The World Health Organization (WHO) estimates that 7 million people a year die before their life expectancy due to air pollution, both indoors and outdoors. Aerosol-induced phenomena, such as dust storms and smoke pollution from vegetation fires, which threaten people's health, lives, and property, are of concern because of how their aspects may change with the ongoing global warming.

➔ Monitoring and prediction of air pollutants is important for mitigating their health effects and improving the accuracy of future predictions of climate.



An infographic by WHO (2017)

The Global Change Observation Mission – Climate (GCOM-C; Shikisai)

The Global Change Observation Mission - Climate (GCOM-C) satellite was launched on 23 December 2017, for long-term environmental monitoring of the Earth. The GCOM-C satellite carries the second-generation global imager (SGLI), which is a multi-wavelength optical radiometer that has 19 observation wavelength bands from near-ultraviolet to thermal infrared and has characteristic functions such as polarization, multi-directional, and near-ultraviolet observation.

GCOM-C SGLI Aerosol Product

We use aerosol properties in the GCOM-C standard product.

Non-polarization aerosol product (ARNP)

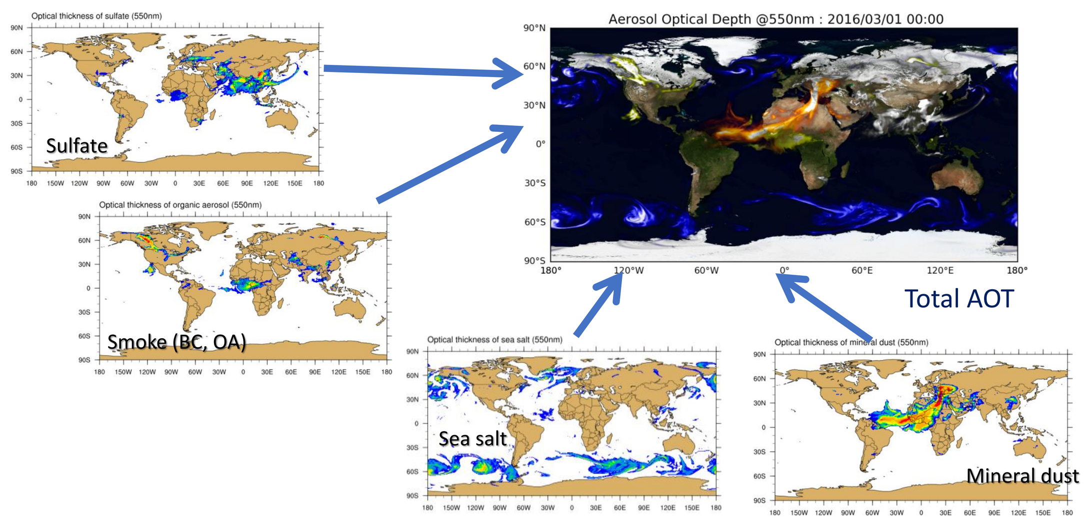
- 500 nm Aerosol optical thickness (AOT)
- Angstrom exponent: (ARAE)

We use the SGLI standard product version 2 product in this study. SGLI standard product version 3 was released on 29 November 2021. We are now preparing to apply the SGLI version 3 product, and the results shown here presents the results of the SGLI version 2 product.

Global aerosol model

In this study, we use MASINGAR (Model of Aerosol Species in the Global Atmosphere), a global aerosol model developed by the Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI). This model treats the 5 major aerosol species in the atmosphere: mineral dust, sea salt, sulfate, black carbon, and organic aerosols. Emission fluxes of mineral dust, sea salt and dimethyl sulfide are calculated from near-surface variables computed by the model. Emission fluxes of anthropogenic sulfur dioxide, black carbon, and organic carbon are given based on their respective emission inventories. Mineral dust and sea salt aerosols are treated independently for 10 particle size fractions in the range of 0.2 - 20 μm.

MASINGAR is used in the operational JMA dust prediction. In the JMA dust forecast, the model has a grid resolution of TL479L40 (grid spacing of about 0.375° × 0.375°, with 40 vertical layers up to 0.4 hPa), which is the same resolutions in this study. The model is coupled online with the atmospheric general circulation model MRI-AGCM3. The meteorological field was nudged to the JMA global analysis data. The anthropogenic source fluxes of sulfur dioxide, black carbon, and organic carbon are taken from MACCity (Granier et al. 2011), and the vegetation fire source fluxes are taken from GFAS (Kaiser et al. 2012).



Data assimilation method

A two-dimensional variational method (2D-VAR, Yumimoto et al. 2017) was used for data assimilation in this experiment. The 2D-VAR system uses a localization method that divides the space of the model into parts at specified localization scales and analyzes each part independently. This reduces the pseudo-dispersion associated with the distance and reduces the computational cost through parallel processing.

The 2D-VAR data assimilation system has been applied to JAXA/EORC Himawari-8 AOT and MODIS AOT and to aerosol reanalysis JRAero v1.0 (Yumimoto et al., 2017, GMD). It is also applied to the JMA's aeolian dust forecasting since January 2020.

Experiment

Experimental conditions

To investigate the effect of data assimilation, we will compare the results of near-real-time data assimilation experiments under the following three conditions:

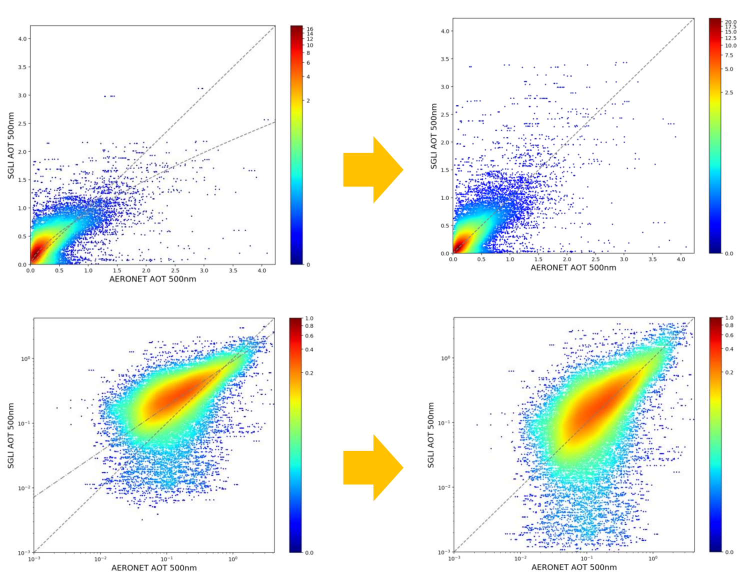
1. data assimilation of SGLI aerosol products
2. MODIS Level 3 data for data assimilation (MCDAODHD) and Himawari 8 AHI aerosol product Level 3
3. No data assimilation

Aerosol near-real-time data assimilation by MODIS L3+AHI in the experimental condition 2 has been provided to JAXA Himawari Monitor as a research product (as level 4 data), ICAP (International Collaboration for Aerosol Prediction) and WMO VFSP-WAS (Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System) southeast Asia and North America nodes.

The meteorological fields used in the experiment are horizontal wind speeds (u, v) nudged toward JMA global data, and sea surface temperatures (SSTs) from MGDSST.

SGLI AOT bias correction by comparison of SGLI AOT and AERONET AOT

The right figure presents a comparison of the SGLI ARNP 500 nm AOT data to be assimilated with the AERONET 500 nm AOT data. The comparison data were matched from the SGLI ARNP AOT data, which were grid-valued every three hours, and the AERONET level 1.5 data, which were averaged every hour. The figure on the right is a scatter plot of the stations from July 2019 to April 2020. As shown in the figure, the AOT by SGLI is slightly larger than the AOT by AERONET in the regions with small values (AOT <~ 1). This trend is also shown in the comparison with SKYNET and AERONET by the SGLI verification group. We made quality controlled SGLI AOT dataset by applying a function based on the relationship between SGLI and AERONET 500 nm AOT.



SGLI 500 nm AOT vs AERONET 500 nm AOT

Quality controlled SGLI 500 nm AOT vs AERONET 500 nm AOT

Evaluation by AERONET

We use root mean square error (RMSE), mean bias (MB), modified normalized mean bias (MNMB), and Pearson's correlation coefficient (R) to evaluate the aerosol assimilation results. RMSE, MB, and MNMB are defined as

$$\mathrm{RMSE} = \left\{ \frac{1}{N} \sum_{i=1}^{N} (\mathrm{Model}_i - \mathrm{OBS}_i)^2 \right\}^{\frac{1}{2}}$$

$$\mathrm{MB} = \frac{1}{N} \sum_{i=1}^{N} (\mathrm{Model}_i - \mathrm{OBS}_i)$$

$$\mathrm{MNMB} = \frac{1}{2} \sum_{i=1}^{N} \frac{\mathrm{Model}_i - \mathrm{OBS}_i}{\mathrm{Model}_i + \mathrm{OBS}_i}$$

where OBS_i is the observed value, Model_i is the value analyzed by the numerical model, and N is the number of observations. The 500 nm AOT data from NASA AERONET Level 1.5 data was used for the evaluation in this study.

Results

Score evaluations with AERONET level 1.5 500 nm AOT

To investigate the effect of data assimilation, we will compare the results of near-real-time data The time series of daily scores for the AERONET level 1.5 500 nm AOT from May 15 to Nov. 29, 2021, is shown in **Table 1**. RMSE is 0.205 without data assimilation, while SGLI assimilation is 0.192 and MODIS+AHI is 0.195. On average, both SGLI and MODIS+AHI experiment show improvements in RMSE score. Especially, SGLI data assimilation experiment shows the best RMSE score in this comparison.

The mean bias (MB) was -0.007 without data assimilation and -0.066 with MODIS+AHI, while the bias was different with SGLI assimilation at -0.035. In terms of absolute values, the results of SGLI data assimilation have the lowest mean bias. The modified normalized mean bias (MNMB) is -0.045 without data assimilation, -0.322 negative for MODIS+AHI, and -0.045 for SGLI assimilation. The best results of the absolute values of the MB and MNMB are scores of experiments without data assimilation, which indicates that the aerosol model itself has little AOT biases on average. Also, MODIS+AHI DA experiment has systematic negative bias against AERONET AOT.

The correlation coefficient score is best for MODIS+AHI (0.682), while the SGLI result (0.656) is slightly worse than the value for no data assimilation (0.654).

Overall, the SGLI DA simulation shows improved RMSE against no DA, the score is similar to the MODIS+AHI DA experiment. The SGLI DA also shows better MB and MNMB scores than the MODIS+AHI DA experiment.

The time series of the daily AOT evaluation scores show that the RMSE, MB, and MNMB are worsened from July to September, when the intense smoke from vegetation fires increased the AOT in the Northern Hemisphere. The DA system tends to suppress the large AOT values caused by smoke too much.

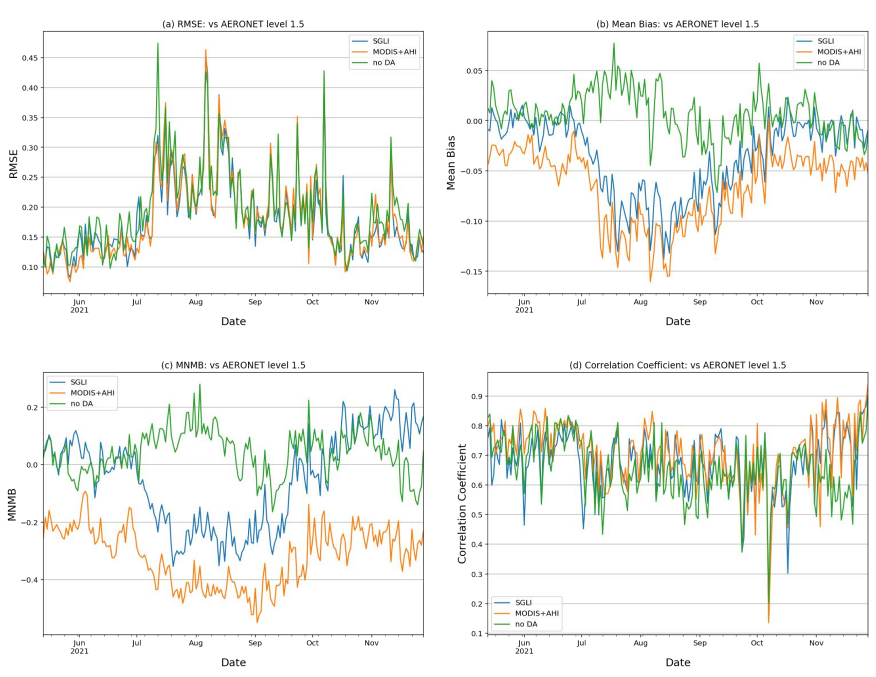
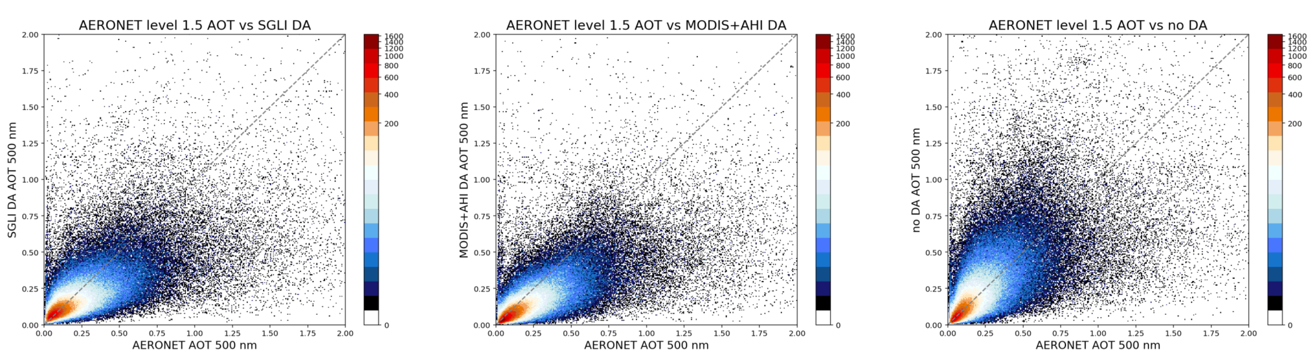


Figure: Time-series of the daily AOT evaluation scores against AERONET version 3 level 1.5. (a) RMSE, (b) mean bias, (c) modified normalized mean bias, and (d) correlation coefficient.

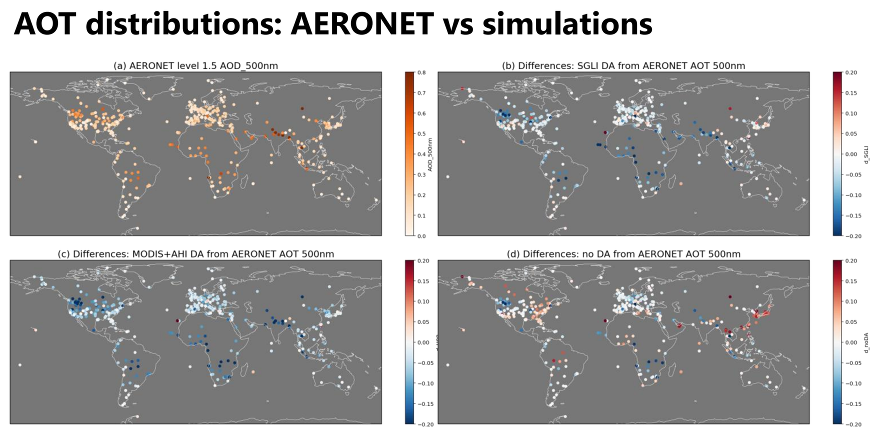
Table 1. Scores of the global AOT simulations against AERONET AOT. The number in red indicate the best scores among the experiments.

	RMSE	MB	MNMB	R
SGLI DA	**0.192**	-0.035	-0.045	0.656
MODIS + AHI DA	0.195	-0.066	-0.322	**0.682**
No DA	0.205	**-0.007**	**+0.037**	0.654



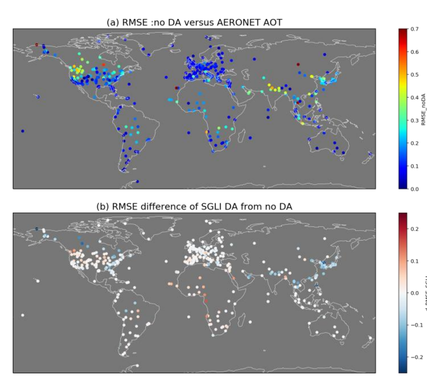
A comparison between the AERONET Level 1.5 observations during this period and the scatter plots of the 500 nm AOTs for each experiment is shown in the figure. Compared to the case without data assimilation (right), the SGLI AOT data assimilation tends to reduce the variability and the slope tends to be underestimated. In the MODIS+AHI data assimilation experiment, the variability is further reduced, but the slope is underestimated.

AOT distributions: AERONET vs simulations

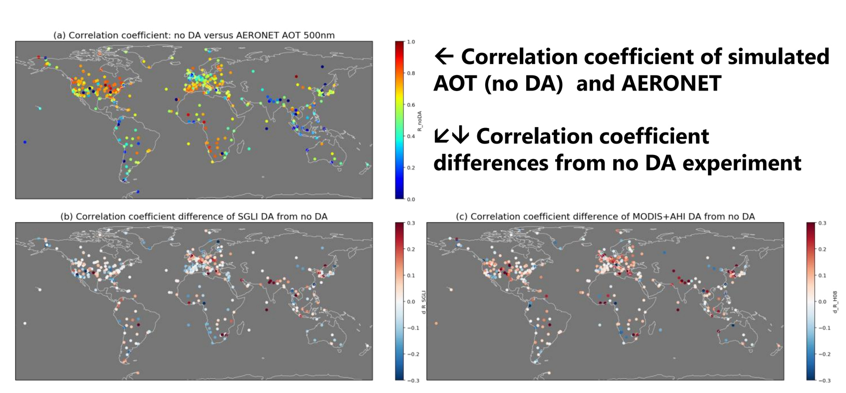


The average 500 nm AOT for each AERONET observation site is shown in Figure a, and the differences between the SGLI DA, MODIS+AHI DA, and noDA experiments and the AERONET average are shown in Figures b, c, and d.

During the experiment, the areas with high AOT are found in North America, Southeast Asia, northern India, and the area around the Gulf of Guinea in Africa, where heavy smoke from vegetation fires and mineral dust affected. The simulation results without data assimilation (Fig. d) show some overestimation around east and southeast Asia and eastern side of North America. The experiments with data assimilation (SGLI and MODIS+AHI) improved the overestimation of east and southeast Asia. However, the DA experiments underestimated the AOT over the Gulf of Guinea and western part of North America.



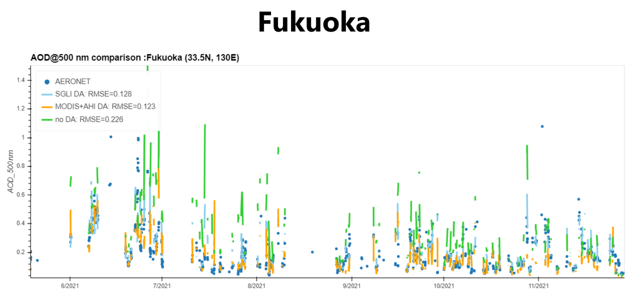
The figure shows the AOT data assimilation results show that RMSE generally improves around East Asia, southeast Asia, eastern part of North America, and India. However, the DA experiments show worsened RMSE around western part of North America and the Gulf of Guinea, where intense vegetation fires occurred.



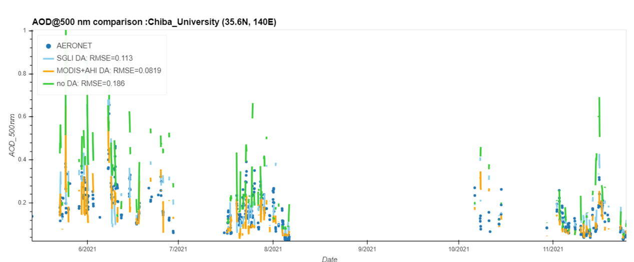
The figure above shows the distributions of the correlation coefficients between AERONET and simulated AOT. The simulated results generally show good correlations in North America and Africa, while poor correlations are found in India, Southeast Asia and South America. Both DA experiments show improvements of the correlation coefficients over India, Europe, Korean peninsula, and North America. The improvements of SGLI DA experiment is smaller than MODIS+AHI experiment, which uses 2 polar-orbiting and 1 geostationary satellites.

AOT comparison of individual stations

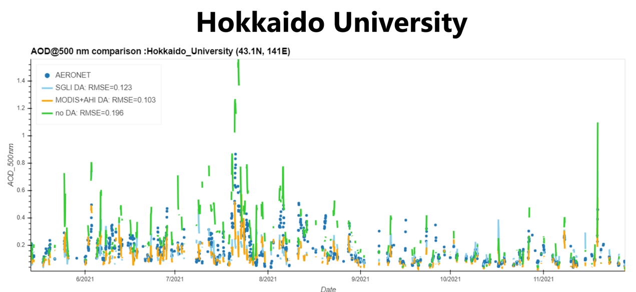
Fukuoka



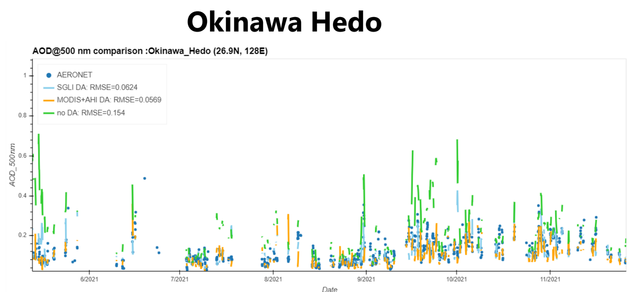
Chiba University



Hokkaido University



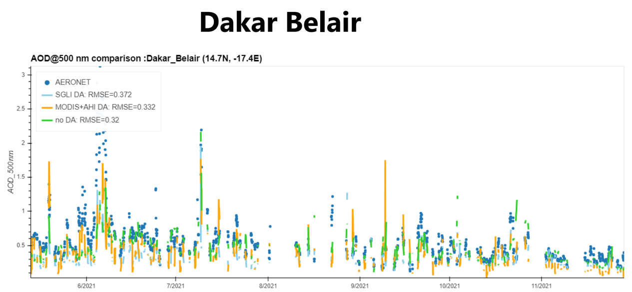
Okinawa Hedo



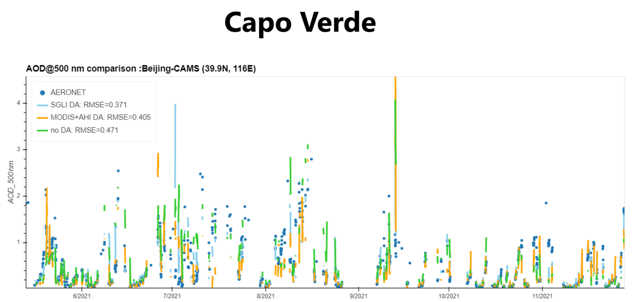
AERONET stations in Japan

In comparison with the AERONET AOT the results of the SGLI and MODIS+AHI data assimilation show an RMSE improvement to no data assimilation, which shows some overestimation. At Fukuoka, the average RMSE of 0.128 with SGLI DA experiment is comparable to that of MODIS+AHI DA experiment (0.123). Overall, the SGLI and MODIS+AHI DA experiments shows lower RMSE than the no DA experiment, and the MODIS+AHI experiment shows the best RMSE scores.

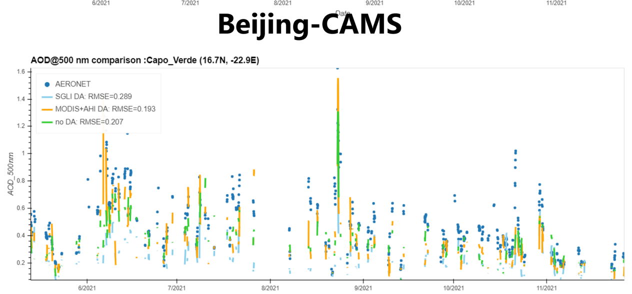
Dakar Belair



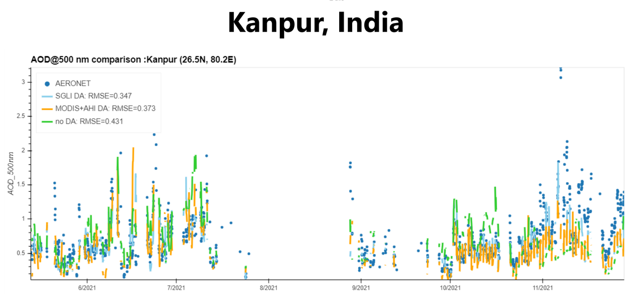
Capo Verde



Beijing-CAMS



Kanpur, India



At Dakar and Capo Verde, where high aerosol concentrations are observed due to mineral dust and smoke, both DA experiments slightly worsen the RMSE scores, due to the underestimation of the high AOT episodes. At Beijing and Kanpur, where high AOT episodes often observed by anthropogenic air pollution and combustions, the simulations tend to underestimate the AOT but both SGLI and MODIS+AHI DA experiment improve the RMSE.

Summary

- We have developed an experimental system for aerosol data assimilation and prediction using aerosol observation products from SGLI on JAXA's GCOM-C satellite.
- We confirmed that aerosol data assimilation using SGLI AOT can improve the score of global aerosol analysis.
- The key to improving aerosol data assimilation using the SGLI AOT is its quality control. Further investigation and improvement is needed to remove bias in the aerosol distribution and to improve the quality of the analysis data.

Acknowledgements

This study was supported by the JAXA Earth Observation Research Announcement (ER2GCN213) and Grant-in-Aid for Scientific Research B (16H02946). The following observation data were also used. We would like to thank

- SGLI standard products: JAXA G-Portal: https://gportal.jaxa.jp/
- JAXA Himawari Monitor: https://www.eorc.jaxa.jp/ptree/
- Aerosol observation data by NASA AERONET: https://aeronet.gsfc.nasa.gov/
- MODIS MCDAODHD (MODIS/Terra+Aqua L3 Value-added Aerosol Optical Depth - NRT): https://cmr.earthdata.nasa.gov/search/concepts/C1426395436-LANCEMODIS.html

Python and its libraries (Numpy, matplotlib, pandas, xarray, HoloViews, etc.) were used for the analysis and figure generation. For the processing of SGLI HDF5 format data, we used SPOT (SGLI Python Open Tool) (https://github.com/K0gata/SGLI_Python_Open_Tool).