
Tsuyoshi Thomas Sekiyama\(^1,2\), Keiya Yumimoto\(^1\), Taichu Y. Tanaka\(^1,3\), Takashi Nagao\(^4\), Maki Kikuchi\(^2\), and Hiroshi Murakami\(^4\)

\(^1\)Meteorological Research Institute, Tsukuba, Japan
\(^2\)Arid Land Research Center, Tottori University, Tottori, Japan
\(^3\)Japan Meteorological Agency, Tokyo, Japan
\(^4\)Japan Aerospace Exploration Agency, Tsukuba, Japan

Abstract

Himawari-8 is a Japanese geostationary weather satellite that was launched in October 2014 and has been in operation since July 2015. Himawari-8 is equipped with an outstanding high-performance imager that has 16 spectral channels (3 for visible, 3 for near-infrared and 10 for infrared wavelengths) with a 10-minute observation interval. We retrieved aerosol optical thickness (AOT) from visible and near-infrared multispectral observations of Himawari-8 and assimilated the AOT data into a global aerosol forecast model with an ensemble Kalman filter system. The data assimilation result was validated by comparison with conventional products derived from polar-orbiting satellite aerosol observations (i.e., Moderate Resolution Imaging Spectroradiometer (MODIS)) AOT of an Asian dust storm in June 2015. The Himawari-8 AOT data assimilation successfully produced an analysis and forecast of the Asian dust that was comparable or superior to those of the MODIS AOT data assimilation. The Himawari-8 aerosol product has a much higher temporal coverage than that of polar-orbiting satellites, which is promising for aerosol data assimilation. This study is a first step in the application of geostationary satellites for aerosol research.


1. Introduction

Himawari-8, a Japanese geostationary weather satellite, was launched on 7 October 2014 from the Tanegashima Space Center, Japan and entered operational service on 7 July 2015 at 140 degrees East. It is notable that Himawari-8, in contrast to other legacy geostationary weather satellites, is equipped with an outstanding high-performance imager. The imager has 16 spectral channels (3 for visible, 3 for near-infrared and 10 for infrared wavelengths) as opposed to the 5 channels (1 for visible and 4 for infrared) of its predecessors, Himawari-6/7 and GOES-N/O/P. The visible and near-infrared (VNIR) multispectral observations have been drawing the attention of aerosol researchers since before its launch because those wavelengths are optically sensitive to aerosol and are likely to be used for aerosol optical thickness (AOT) retrieval with a quality much higher than that provided by the single VNIR channel of past geostationary weather satellites. Geostationary satellites have an advantage over polar-orbiting satellites for aerosol measurements because their high temporal resolution provides multiple observations for a single location which are likely to be cloud-free. Furthermore, the temporal resolution of Himawari-8 is 10 min (in the case of a full-disk shot) as opposed to more than 30 min for its predecessors, so the amount of missing data due to cloud masking is significantly reduced compared to that of past geostationary and polar-orbiting satellite observations.

Aerosols are ubiquitous in the atmosphere, but their concentrations fluctuate significantly and their distributions are not spatially homogeneous. Inhomogeneous aerosol distributions affect many environmental applications, including climate change, daily weather and air quality, all with a large impact on life. This drives the motivation for aerosol monitoring and forecasting, in which data assimilation plays a major role for coupling aerosol observations and models. Many aerosol data assimilation studies have been performed using Himawari-8 aerosol observations (e.g., Zhang et al. 2008, 2014; Benedetti et al. 2009; Sekiyama et al. 2010, 2011, 2012; Yumimoto and Takemura 2011, 2015; Rubin et al. 2015), but most of the observations have been provided by polar-orbiting satellites such as CALIPSO, which carries a lidar instrument, and Terra/Aqua, which each carries a Moderate Resolution Imaging Spectroradiometer (MODIS). One of the few geostationary satellite observations used for aerosol data assimilation is Geostationary Ocean Color Imager (GOCI) data studied by Park et al. (2014) and Saide et al. (2014). Herein we also report on the data assimilation of geostationary satellite aerosol observations and validate its performance relative to that of polar-orbiting satellite observations. The aerosol retrieval dataset based on Himawari-8 measurements used in this study is still a preliminary version. As shown below, this early version of the Himawari-8 aerosol retrievals permits a first assessment of the advantages of high frequency geostationary data.

2. Data and experimental design

To derive AOT values from the Himawari-8 raw data, a retrieval process is needed to convert imager-measured radiance to aerosol extinction. The Earth Observation Research Center (EORC) of the Japan Aerospace Exploration Agency (JAXA) is developing a Himawari-8 aerosol retrieval algorithm to provide AOT and angstrom exponent (AE) values (cf. Kikuchi et al. 2015), and the algorithm is based on the work of Fukuda et al. (2013) for retrievals over land, Higurashi and Nakajima (1999, 2002) for retrievals over ocean and Ishida and Nakajima (2009) and Ishida et al. (2011) for cloud-aerosol discrimination. The land retrieval is performed using the 470, 510 and 640 nm channels (the ocean retrieval is performed using the 640 and 860 nm channels) with a 0.05° horizontal resolution every 10 min. The raw data resolution of Himawari-8 is 0.5 km for the 640 nm channel or 1 km for the 470, 510 and 860 nm channels, so the retrieval grid contains tens of raw data pixels. The retrieval details are described in Kikuchi et al. (submitted to IEEE Transactions on Geoscience and Remote Sensing).

In this study, we interpolated 550 nm AOT for land areas and extrapolated it for ocean areas from the retrieved Himawari-8 AOT and AE values. The 550 nm AOT values were then horizontally averaged every 100 km square, consistently with the aerosol model resolution of TL159. The 100 km square pixel data were temporally averaged for 6 h on 00:00, 06:00, 12:00 and 18:00 UTC, which covered ±3 h. Observation errors were determined according to the standard deviations of the AOT retrievals contained within each 100 × 100 km region. These configurations, i.e.,
wavelength, spatial resolution and time interval, were consistent with those of the quality-controlled MODIS 550 nm AOT data used in this study for comparison with the Himawari-8 AOT data (Figs. 1a, e). The quality-controlled MODIS AOT data are denoised and bias-corrected by the Naval Research Laboratory (NRL) with 1° × 1° horizontally and 6-h temporally averaged resolutions for US Navy operational aerosol forecasts (Zhang et al. 2005; Zhang and Reid 2006, 2009; Hyer et al. 2011; Shi et al. 2011). The NRL MODIS AOT data are a composite of land and ocean retrievals derived from two satellites, Terra and Aqua, which pass over the equator at 10:30 and 13:30 local time, respectively.

In this study, we performed three numerical experiments. One was a MODIS assimilation run, in which only the quality-controlled MODIS AOT data were assimilated. A Himawari-8 assimilation run was also performed, in which only the 6-hourly 100-km-gridded Himawari-8 AOT data were assimilated. A control run was also performed, in which aerosol observations were not assimilated. The two data assimilation experiments were performed using a data assimilation system that contains the Model of Aerosol Species in the Global Atmosphere (MASINGAR) coupled with an atmospheric general circulation model (Yukimoto et al. 2012) and the Local Ensemble Transform Kalman Filter (LETKF) (Hunt et al. 2007; Miyoshi and Yamane 2007). This system has successfully worked for aerosol analysis with polar-orbiting satellite observations, notably Asian dust analyses (Sekiyama et al. 2010, 2011, 2012; Yumimoto et al. 2015). The Japan Meteorological Agency (JMA) has been operationally using MASINGAR for dust-aerosol forecasting since 2004.

The three experiments were implemented with the same model configuration: TL159 (1.1° × 1.1°) horizontal resolution, 40 vertical layers from the surface to 0.4 hPa and wind fields nudged with the 6-hourly JMA operational global analysis during the analysis run. The two data assimilation runs were implemented with the same LETKF configuration: 30 ensemble members, 6-hourly assimilation cycle, localization factor of 500 km and dust/sulfate/organic/black-carbon/sea-salt emissions perturbed by randomly generated log-normal distribution factors (cf. Yumimoto et al. 2015). The perturbations are comparable to the size of Himawari-8 AOT observation errors.

In this study, we investigated one case of an Asian dust storm that originated in the Gobi desert and whose plume reached Japan on 12 June 2015. The storm occurred just before the official start of Himawari-8 operations; nevertheless we assumed that the Himawari-8 instrumental calibration had already been completed before the storm event. The data assimilation runs were started on 1 June 2015 with a 6-hourly assimilation cycle. Then, 48-h forecast runs were performed with MASINGAR without wind-field nudging; the initial aerosol conditions were derived from the MODIS data assimilation (MODIS DA) run, the Himawari-8 data assimilation (Himawari-8 DA) run on the non-DA control run. Those forecast results were validated with the surface observations of suspended particulate matter (SPM = PM7.0) in Japan derived from the Atmospheric Environmental Regional Observation System (AEROS) (http://soramame.taiki.go.jp/) managed by the Ministry of the Environment (MOE). The SPM observations were denoised and corrected for bias by Dr. Masamitsu Hayasaki of the National Institute for Environmental Studies, Japan (personal communication). The quality-controlled SPM data were then averaged with a TL159 (1.1° × 1.1°) horizontal resolution (shown in Fig. 2) and compared to the forecast results.

3. Results and discussion

According to the JMA observatories’ weather report, the aeolian dust was visually observed in western Japan on 12 and 13 June 2015 (http://www.data.jma.go.jp/gmd/en/ko sap/hkoa_table_2015.html). The AEROS SPM observation confirmed that the dust plume reached Tsushima Island at approximately 08:00 UTC and the Japanese main islands at approximately 12:00 UTC on 12 June 2015 according to the AEROS SPM observations. Conversely, the AOT distribution represented by the model simulations indicated that the dust plume arrived over Japan in the upper air layer on 10 or 11 June (Figs. 1b, c, d). Unfortunately, neither the NRL MODIS AOT nor Himawari-8 AOT (Figs. 1a, e) provided good observational coverage over the dust plume area; therefore, it was difficult to capture a complete picture of the dust plume distribution by using satellite observations. Furthermore, even under such conditions, data assimilation can provide a maximum likelihood estimate of the distribution of dust from the surface to the upper air (Figs. 1b, d). This is one of the reasons why data assimilation is necessary for aerosol research.

The AOT retrieval coverage of MODIS was much smaller than that of Himawari-8, as we expected, even though two polar-orbiting satellites provided the MODIS data. During the time period shown in Fig. 1, no observation of the NRL MODIS AOT was made at 00:00 UTC 11 June, and very few observations were made at 00:00 UTC 12 June in East Asia (Fig. 1a). Notably, both the MODIS and Himawari-8 imagers are passive sensors, which need sunlight to measure aerosols, and consequently, the aerosol retrieval data in East Asia can be obtained only at 00:00 (±3 h) and 06:00 (±3 h) UTC in the local daytime in the 6-hourly assimilation cycle. Therefore, we plotted only the 00:00 and 06:00 UTC AOT in Fig. 1. The MODIS DA could not modify the AOT distribution on 00:00 UTC 11 June and 00:00 UTC 12 June (Fig. 1b), during which the dust plume was just being advected by the wind field because there were no observations at the time of the data assimilation. If forecast runs start at those hours, their initial conditions do not contain the latest observational information; therefore, the MODIS DA will be at a disadvantage compared to Himawari-8 DA.

Figure 1e shows the large coverage of the Himawari-8 AOT compared to that of the MODIS AOT. At the same time, the Himawari-8 AOT is noticeably noisy. The standard deviation of the Himawari-8 AOT was several times larger than that of the NRL MODIS AOT in the study area and period. The version of the Himawari-8 AOT retrieval that was used is still preliminary, and the cloud screening and quality control algorithms therefore are less developed than the MODIS AOT retrieval algorithms. Despite the noisiness, however, Fig. 1 shows that the Himawari-8 DA performs as well as the MODIS DA, adjusting the model overestimation cycle by cycle. We expect that the noise can be reduced with a small decrease in the AOT coverage area in the future work because Himawari-8 collects high-frequency observations at 10-min intervals that are available for a temporal composite algorithm.

In order to verify the DA results with independent observations, we performed forecast runs as shown in Fig. 2. The runs were for 48-h (FT = 48), 24-h (FT = 24) and 12-h (FT = 12) forecasted surface SPM concentrations. The initial conditions were provided by the Non-DA control run, the MODIS DA run and the Himawari-8 DA run. All the snapshot times were 12:00 UTC 12 June 2015, which was just after the arrival of the dust plume on the Japanese main islands at the surface. Root-mean-square-errors (RMSE) were calculated between the AEROS observations (shown in the upper panel of Fig. 2) and the forecast.

The 48-h forecasts (FT = 48) were not greatly improved for either the MODIS DA run (RMSE = 150.1) or the Himawari-8 DA run (RMSE = 112.2) compared to those of the Non-DA run (RMSE = 172.7). In this case, the forecasts were started at 12:00 UTC 10 June, when most of the dust plume was still over the land area and was rarely detected by the passive sensors. The improvement, therefore, was not as large as hoped for in the forecasts. Nevertheless, the Himawari-8 DA produced a slightly better forecast than that of the MODIS DA. In contrast, the 24-h (FT = 24) and 12-h (FT = 12) forecasts were significantly improved for both the MODIS DA (RMSE = 37.3 and 39.3, respectively) and Himawari-8 DA (RMSE = 23.1 and 29.4, respectively) runs. The shapes, locations and concentrations of the dust plume were similar to those in the forecasts produced by the MODIS DA and Himawari-8 DA runs for both FT = 24 and FT = 12, whereas the Himawari-8 DA produced better forecast RMSEs. In these cases, the forecasts were started at 12:00 UTC 11 or 00:00 UTC.

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12 June, when the data assimilation was effectively processed for the dust plume.

Furthermore, we examined the comparison of 870 nm AOT between Aerosol Robotic Network (AERONET; Holben et al. 1998; Dubovik and King 2000) observations and the forecasts (Fig. 3). The two AERONET stations were chosen in the area under the dust plume; one is Gosan located in Jeju island of South Korea, and the other is Toyama located in central Japan (shown in the upper panel of Fig. 2). The dust plume arrived at Gosan 1-day earlier than at Toyama. Sunphotometers often do not work when Asian dust plumes hit the place because of high AOT or the clouds associated with the cold front of the extratropical cyclones that cause Asian dust storms. Likewise, in this case study, the AERONET stations could not observe the dust plume when the AOT reaches its peak. However, at least, Fig. 3 illustrates that the Himawari-8/MODIS DA forecasts (orange or green lines) were superior to the Non-DA control run (blue lines) and the shorter forecasts (solid lines) were better than the longer forecasts (dotted or broken lines).

In this study, we investigated a regional dust plume that was extremely overestimated by the Non-DA control run, for which an outstanding improvement was typically obtained by the data assimilation. However, we were able to confirm that the performance of the Himawari-8 DA was comparable or superior to that of the MODIS DA, even though a preliminary version of the Himawari-8 aerosol products was used. The preliminary aerosol products of Himawari-8 have large errors due to cloud contamination and sun glint, but their time/space coverage is much larger than that of MODIS. The large coverage probably improves the performance of Himawari-8 aerosol data assimilation. This is a first step in the application of geostationary satellites for aerosol research.

4. Concluding remarks

This preliminary experiment indicates that the Himawari-8 DA is promising for aerosol research and prediction. However, reducing the noise of the retrieval AOT (i.e., cloud screening) remains a challenge. Bias corrections for the Himawari-8 AOT in the tropics (not shown here) are also a challenge. We used simple averages of 6-h Himawari-8 AOT data (approximately 36 snapshots) for data assimilation in this study, but a more refined composite algorithm is under development. When composite AOT data are used, the assimilation cycle will be shortened or an ensemble Kalman smoother will be applied. The definition of Himawari-8 observation errors should then be more refined. Those efforts will further improve the performance of Himawari-8 aerosol data assimilation. We are undertaking an analysis for other aerosols and areas other than Asian dust and those results will soon be submitted for publication (Yumimoto, personal communication).

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Fig. 2. Surface SPM concentrations [µg/m³] over East Asia at 12:00 UTC 12 June 2015. (Upper panel) the quality-controlled and 1.1° × 1.1° averaged observations derived from the AEROS SORAMAME network. (Lower panels) the 48-h, 24-h, and 12-h forecasts initiated by the MODIS data assimilation run, the Non-DA control run, and the Himawari-8 data assimilation run. The region surrounded by a white line over Japan indicates the AEROS SORAMAME observation area. The root-mean-square-errors (RMSEs) were calculated between the AEROS observations and the forecast.

Fig. 3. Time series of AOT at 870 nm measured/forecasted at Gosan, Korea and Toyama, Japan AERONET stations. The locations of Gosan and Toyama are indicated by a red triangle and a red circle, respectively, in Fig. 2 (upper panel). Black diamonds indicate AERONET observations. Orange, Green, and Blue lines indicate 48-h forecasts of Himawari-8, MODIS, and Non DA experiments, respectively. Dotted, broken, and solid lines indicate the 48-h forecasts initiated at 12:00 UTC 10 June, 12:00 UTC 11 June, and 00:00 UTC 12 June, respectively.

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References


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