Aerosol data assimilation using data from Himawari-8, a next-generation geostationary meteorological satellite


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Abstract Himawari-8, a next-generation geostationary meteorological satellite, was launched on 7 October 2014 and became operational on 7 July 2015. The advanced imager on board Himawari-8 is equipped with 16 observational bands (including three visible and three near-infrared bands) that enable retrieval of full-disk aerosol optical properties at 10 min intervals from geostationary (GEO) orbit. Here we show the first application of aerosol optical properties (AOPs) derived from Himawari-8 data to aerosol data assimilation. Validation of the assimilation experiment by comparison with independent observations demonstrated successful modeling of continental pollution that was not predicted by simulation without assimilation and reduced overestimates of dust front concentrations. These promising results suggest that AOPs derived from Himawari-8/9 and other planned GEO satellites will considerably improve forecasts of air quality, inverse modeling of emissions, and aerosol reanalysis through assimilation techniques.

1. Introduction

On 7 October 2014, the Japan Meteorological Agency launched Himawari-8, the eighth Japanese geostationary meteorological satellite (GMS); the satellite became operational on 7 July 2015. Himawari-8 and the yet to be launched Himawari-9 are equipped with more advanced multispectral imagers (Advanced Himawari Imager; AHI) ahead of other planned GMSs [Reshho et al., 2016]. The AHI has 16 observation bands from visible to infrared with high spatial (0.5–1.0 km visible and 1–2 km for infrared) and temporal (six full-disk images per hour) resolution and provides about 50 times more data than previous GMSs. It is an attractive characteristic for aerosol research that the AHI includes observational bands in visible and near-infrared wavelengths sensitive to aerosol scattering and absorption. This characteristic allows the AHI data to provide full-disk images of aerosol optical properties (AOPs), including aerosol optical thickness (AOT) and Ångström exponent (AE), at 10 min intervals over wide areas of the globe (East and Southeast Asia, the western Pacific Ocean, Oceania, and the Australian continent).

The start of the operational phase of Himawari-8 was an important first step in the advance of global monitoring of aerosols. In October 2016, the U.S. National Oceanic and Atmospheric Administration and National Aeronautics and Space Administration plan to launch the first of the Geostationary Operational Environmental Satellite-R (GOES-R) series, which will be equipped with an Advanced Baseline Imager with comparable capabilities to those of the AHI. There are other plans to launch geostationary satellites to observe atmospheric composition (e.g., geostationary Korea Multi-Purpose Satellite [Lee et al., 2010]; Tropospheric Emissions, Monitoring of Pollution [Chance et al., 2013]; and sentinel-4 [Imgnmann et al., 2012]), which will allow continuous monitoring of the spatial distribution of aerosols around the globe.

In recent years, AOPs from low Earth orbit (LEO) satellites have had an important role in improving aerosol data assimilation and forecasting [Benedetti et al., 2009; Saide et al., 2013; Dai et al., 2014; Rubin et al., 2015; Yumimoto et al., 2015], in inverse modeling of emissions [Schutgens et al., 2012; Wang et al., 2012; Yumimoto and Takemura, 2015], and in the production of reanalysis data sets [Benedetti et al., 2009; Rienecker et al., 2011; Lynch et al., 2016]. However, owing to the orbital periods and swath widths of LEOS, AOPs derived from them have limited spatial coverage and observation frequencies. AOPs derived from geostationary satellites can overcome these limitations. Lahoz et al. [2011], Yumimoto [2013], and Zoogman et al. [2014] used an observing system simulation experiment framework to investigate the impact of the
use of geostationary observations on data assimilation of atmospheric compositions. Wang et al. [2004] used AOT from Goddard Earth Observing System-8 to constrain boundary conditions of an aerosol transport model. Saide et al. [2014] and Lee et al. [2016] performed data assimilation experiments with AOPs retrieved from the Geostationary Ocean Color Imager data and evaluated its impacts. Their results showed positive impact of geostationary data on air quality prediction and implied that future geostationary missions also have potential to greatly contribute to that.

We performed an aerosol data assimilation experiment with AOPs derived from Himawari-8 AHI data and an aerosol data assimilation system [Yumimoto et al., 2015] targeting transboundary pollutants and dust outflows over East Asia during 14–17 April 2015 (the operational testing period for Himawari-8). In this paper we describe results of the experiment showing the impact of those data on data assimilation and modeling of air quality in East Asia.

2. Aerosol Data Assimilation System and Methodology

We used the data assimilation system of Yumimoto et al. [2015], which combines the Model of Aerosol Species IN the Global AtmosphereRe Mark 2 (MASINGAR mk-2), the global aerosol transport model of Yukimoto et al. [2011, 2012], and the Local Ensemble Transport Kalman Filter (LETKF) scheme of Hunt et al. [2007]. The aerosol model is coupled online with the Meteorological Research Institute-atmospheric general circulation model MRI-AGCM3 [Mizuta et al., 2012; Yukimoto et al., 2012] and accounts for major tropospheric aerosol components and their precursors, including black and organic carbon, soil dust, sea salt, and sulfate. Soil dust and sea salt are represented by 10 bins of particle size, covering particle diameters from 0.2 to 20 μm.

LETKF is based on the Ensemble Kalman Filter [Evensen, 1994] and its assimilation process is expressed as

\[
\delta x = x_f + K(y - Hx_f)
\]  

where \(x_f\) and \(x^a\) represent aerosol mass mixing ratios. Superscript suffixes \(f\) and \(a\) indicate forecast and analysis, respectively. \(K, y, \) and \(H\) denote the Kalman gain, observations, and a linear observation operator that converts mass mixing ratios into AOT and then interpolates from model space into observation space. An important characteristic of LETKF is the localization technique, in which the analysis is calculated independently in local regional divisions, which reduces spurious error covariance in dust sampling errors attributable to limited ensemble members and enables parallel processing to reduce computational cost. We adapted the multiple inflation method [Whitaker et al., 2008] to avoid filter divergence. More details of the assimilation system are described by Yumimoto et al. [2015]. Previous applications of LETKF in simulations of atmospheric composition have been reported by Schutgens et al. [2010], Yumimoto [2013], and Miyazaki et al. [2012].

MASINGAR mk-2 was configured with TL319 horizontal resolution (about 60 km) and 40 vertical layers. Dust emissions were calculated online using the scheme developed by Shao et al. [1996]. Anthropogenic and biomass burning emissions were from the MACCity emission inventory [Granier et al., 2011] and Quick Fire Emissions Data set [Darmenov and da Silva, 2014], respectively. To perform an ensemble simulation, emission inventories were randomly perturbed for each model grid and integral step [Yumimoto et al., 2015; Schutgens et al., 2010]. The perturbation factors were generated by a lognormal distribution, with mean = 1.00 and variation = assuming uncertainties. Emission uncertainties assigned were from Kurokawa et al. [2013] and Carmichael et al. [2008]. Wind velocity at 10 m, snow cover, and soil moisture content that affect dust and sea salt emissions were also perturbed. An ensemble number of 32 was used.

Our experiments were performed for the period 14–18 April 2015, during which transboundary anthropogenic pollution and dust outflow were recorded at ground observation sites in Japan, with 3 month of spin-up. We performed three experiments to investigate the impact of Himawari-8 retrievals on the modeling. The first one is a simulation without assimilation (a free running) (RF simulation hereafter). In the second one, we assimilated hourly snap shots of AOT derived from Himawari-8 retrievals (DA simulation hereafter). Figure S1 in supporting information shows time series of the number of Himawari-8 AOTs used in the assimilation. Himawari-8 AOT was available 14–15 h d over the globe (11–12 h d in East Asia), and about 120,000 (24,000) data points per day were assimilated over the globe (in East Asia). Thus, hourly outputs from the cycling DA simulation are analyzed during daylight hours and short forecasts at night. Additionally, we...
performed a sensitivity experiment in which Himawari-8 AOT at only 0200 and 0500 UTC (about 1100 and 1400 local time; blue bars in Figure S1) was assimilated mimicking LEO (i.e., Terra and Aqua satellites) samples (DA_LEO simulation hereafter). The number of Himawari-8 AOT assimilated in the DA_LEO simulation is about one fifth of that assimilated in the DA simulation. Comparison of DA simulation with DA_LEO simulation would show the effect of Himawari-8 data on aerosol assimilation relative to LEO data.

3. Observation Data
The visible (0.47, 0.51, and 0.64 nm) and near-infrared (0.86 nm) channels of the AHI were used to retrieve AOPs. AOPs over land were calculated by using the three visible channels and an algorithm developed by Fukuda et al. (2013). Over the ocean, we used the longest visible and near-infrared channels and an algorithm developed by Higurashi and Nakajima (1999). Movie S1 in the supporting information is an animation of AOT at 550 nm from Himawari-8 data at 10 min intervals. More details of AOP retrieval processes are provided in M. Kikuchi et al. (Development of Hourly Combined Aerosol Optical Thickness Algorithm from Himawari-8, submitted to IEEE Transactions on Geoscience and Remote Sensing); the Himawari-8 AOPs are available at the Japan Aerospace Exploration Agency (JAXA) Himawari Monitor website (http://www.eorc.jaxa.jp/ptree/index.html). In this study, the original Himawari-8 AOTs at 500 nm were extrapolated to AOTs at 550 nm using AE, regridded to the model grid, and then used in data assimilation. We estimated observation errors to be the retrieval uncertainty attached to the Himawari-8 AOP data plus a standard deviation calculated as the representative error in the regridding [Zhang et al., 2008]. The retrieval uncertainty ranged from 0.0001 to 1.04 with average of 0.013 and has larger values in the land relative to over the ocean.

Observations from LEO satellites and from ground observation sites were used for independent validation of our simulations. Moderate Resolution Imaging Spectroradiometer (MODIS) AOT data correspond to the "optical depth land and ocean mean" provided by Collection 5.1, L2 aerosol data from the Terra, and Aqua LEO satellites [Remer et al., 2005; Levy et al., 2007]. The overpass times of Terra (1030 local time (LT)) and Aqua (1330 LT) correspond to about 0130 UTC and 0430 UTC at 135°E, respectively. To allow comparison of simulation results from LEO and Himawari-8 data, the MODIS AOTs were regridded to the resolution of our model. The Asian Dust Network (AD-Net) [Sugimoto et al., 2008; http://www-lidar.nies.go.jp] distributes Mie lidar data over East Asia and provides vertical profiles of extinction coefficients and depolarization ratios. We used AD-Net vertical profiles of extinction coefficient at 532 nm at five Japanese sites. The Aerosol Robotic Network (AERONET; http://aeronet.gsfc.nasa.gov/) provides AOPs measured by sun photometers [Holben et al., 1998]. We used an AOT at 550 nm derived from linear interpolation of AERONET AOT measured at 500 and 675 nm of Level 1.5 for our validation. We used the AERONET AOTs at two South Korean sites (Baengnyeong and Gowan, Seoul National University) and two Japanese sites (Fukuoka and Shirahama). Sky radiometers deployed by SKYNET (http://atmos2.cr.chiba-u.jp/skynet/) provide AOP measurements. We used AOT measured by SKYNET at two Japanese sites (Chiba and Saga) for validation of our experiments. Statistical metrics used in the validation are described in Text S1 in the supporting information.

4. Results
A snapshot of AOT derived from Himawari-8 observations at 0700 UTC on 15 April (Figure 1a) shows anthropogenic air pollution from continental areas extending over the Korean Peninsula and western Japan. AOTs derived from MODIS data were consistent with the spatial distribution and magnitude of the Himawari-8 AOTs (Figures 1b and 1c). The RF simulation (Figure 1d) failed to reproduce the pollution, whereas the DA simulation successfully reproduced the pollution observed over western Japan (Figure 1e) but showed a little modification in the pollution around the Korean Peninsula. This indicates that no ensemble of the ensemble could capture the pollution around the Korean Peninsula, indicating a need to improve model transport processes, anthropogenic emissions, and ensemble generation. The RF simulation modeled a large dust storm over Inner Mongolia and central-east China (Figure 1d) that was considerably overestimated according to the satellite observations. The DA simulation reduced the degree of overestimation.

On 16 April, AOT derived from Himawari-8 data showed that the anthropogenic pollutant of the previous day had moved eastward and was over central Japan and the western north Pacific and that there was evidence
of a dust front in the Yellow Sea (Figure 1f). These phenomena were also apparent in the MODIS AOTs (Figures 1g and 1h). In contrast, the RF simulation (Figure 1i) predicted much cleaner air over central Japan and the western Pacific. Furthermore, the southwestern part of the dust front (27°–38°N and 110°–130°E) was overestimated compared to the AOT derived from Himawari-8 data. Data assimilation corrected these errors and provided simulation results that were closer to observations (Figure 1j).

Scatter diagrams of AOT derived from Himawari-8 data versus modeled AOT are shown in Figure S2 in the supporting information. Statistical metrics are listed in Table S1 in the supporting information. In general,
the RF simulation provided underestimates in regions where AOT derived from Himawari-8 data was greater than 0.2. These underestimates were also reflected in negative normalized mean bias values (Table S1). A plausible explanation for the underestimates is the poor reproducibility of the anthropogenic pollution shown in Figure 1. The DA simulation reduced the underestimation and showed much better agreement with AOT derived from Himawari-8 data. However, on 15 April there were some underestimates in the DA simulation (Figure 2b); these might be attributable to a lack of improvement of the modeling of the pollution around the Korean Peninsula (Figure 1c). Assimilation provided improvements in all statistical metrics. Root-mean-square errors (RMSE) and normalized mean errors (NME) were reduced by 21.7–36.6%. The DA_LEO simulation generally brought positive effects (especially on 15 April), but the improvement was limited, particularly for the underestimate of the anthropogenic pollution. The snap shots by satellites

Figure 2. Scatter diagrams of AOT on 15, 16, and 17 April 2015 comparing observed values derived from MODIS with modeled result: (a, d, and g) the RF simulation, (b, e, and h) the DA simulation, and (e, h, and i) the DA_LEO simulation. Red and green dots denote MODIS/Terra and MODIS/Aqua, respectively. Solid black solid line is a 1:1 line. Data between 122–150°E and 20–46°N were used.
sometimes failed to capture the main parts of the pollutions due to cloud covers (see Figure 1). Hourly Himawari-8 AOT could provide more opportunities to obtain the information about the pollutions, because clouds at the upper air might be transported faster than the pollutions in the boundary layer. In the assimilation procedure (equation (1)), analysis value is obtained by a linear combination of modeled and observed values weighted by the background and observation errors. So more observations bring the analysis value closer to the observed value. This indicates that the hourly Himawari-8 AOTs used in the DA simulation yields larger sample number for the pollution and leads to the apparent reduction of the observation error comparing with the Himawari-8 AOTs twice a day used in the DA_LEO simulation. These are plausible reasons that the DA simulation produced superior results to the DA_LEO simulation.

We also produced scatter diagrams and calculated statistical metrics for the AOTs derived from MODIS data (Figure 2 and Table S2 in supporting information). These scatter diagrams showed similar distributions to those for the AOTs derived from Himawari-8 data. Higher modeled AOT in the RF simulation on 15 April corresponds to overestimated dust and carbonaceous aerosols in northeastern China (see Figure 1e). Almost all of the statistical metrics for the DA simulation were better than those of the RF simulation, but a positive bias seems to manifest in assimilations for 16 and 17 April (see normalized mean bias values in Table S2), which suggests that there is bias between AOTs derived from Himawari-8 and MODIS data. The DA simulation reduced both the RMSE and NME by 2.2–29.6% compared to the AOT derived from MODIS data except for MODIS/Aqua data for 16 April. The DA_LEO simulation also showed better agreements, but improvement was less than that by the DA simulation.

Figure 3 shows time-height cross sections of observed and simulated extinction coefficients at Fukuejima, Nagasaki, and Niigata (similar cross sections at Matsue and Chiba are provided in Figure S3 in the supporting information). Lidar measurements captured layers of spherical (nondust) aerosol particles (i.e., anthropogenic pollution) on 15 April in western Japan (Fukuejima and Nagasaki) and on 16 April in central Japan (Niigata). These observations are consistent with the AOT derived from Himawari-8 data (Figures 1a and 1f). The RF simulation successfully reproduced the distribution of this pollution but considerably underestimated its density. Similar underestimates were evident in comparisons of RF simulated data with AOT derived from Himawari-8 data (Figure 1). Data assimilation reduced the underestimation and provided better agreement with lidar data. However, the failure of both the RF and DA simulations to capture a layer of pollution observed at 3000 m altitude is attributed mostly to the vertical resolution of the model at around 3000 m altitude (400–600 m), which is too coarse to reproduce a layer of pollution layer of ~1000 m thickness. Moreover, data assimilation had little effect on modeling at the elevation of that layer. Lack of information about the vertical profile in the data assimilation might also have contributed to the failure to identify this layer.
Depolarization ratios (not shown) indicated that dust particles were dominant in an aerosol layer detected on 17 April. For that layer, the DA simulations provided better agreement with lidar data than the RF simulations, especially for sites in central Japan (i.e., Niigata and Matsue).

Figure 4 shows comparisons of RF, DA, and DA_LEO simulation results with AOTs from AERONET and SKYNET. Time series of Himawari-8 AOT at 10 min intervals are also shown in Figure 4. Himawari-8 AOTs were in good agreement with AOTs measured by AERONET, SKYNET, and MODIS. It is worth noting that Himawari-8 can capture temporal evaluations of AOT like AERONET and SKYNET. The anthropogenic pollution detected in Himawari-8 and MODIS data on 15 April (see Figures 1a–1c) was also detected by AERONET at South Korean stations Baengnyeong (Figure 4a) and Gosan_SNU (Figure 4b). Although the RF simulation at Gosan_SNU failed to reproduce that pollution on 15 April, the DA simulation did, albeit with a much lower AOT than was observed. In the region of the Korean Peninsula, the dust front (Figure 1f) that passed on 16 April was captured by observations at Gosan_SNU. The DA simulation at Gosan provided a lower dust concentration in the front than did the RF simulation, thus demonstrating better reproduction of observed data. The DA_LEO simulation showed similar time series to the RF simulation.

The anthropogenic pollution of 15 April was evident in AERONET and SKYNET data for western Japan (Saga and Fukuoka; Figures 4c and 4d) and was consistent with its distribution according to satellite and lidar observations. The RF simulation considerably underestimated that pollution, but the DA simulation produced an AOT that agreed better with observed data. The DA_LEO simulation increased AOT but still underestimated significantly comparing with the observed value. Although simulations produced dense AOT events at Saga and Fukuoka on 16 April, observed data failed to capture the event because of a lack of nighttime observations. This anthropogenic pollution was transported eastward and detected at Shirahama (central Japan) on 16 April (Figure 4e). The DA simulation almost tripled the peak concentration of the pollution modeled without assimilation and agreed well with observations. The DA_LEO simulation showed similar time series to the observation and failed to improve the reproducibility of the peak. At Chiba (Figure 4f), the DA simulation showed AOT increasing on the morning of 17 April in response to a dust storm (Figure 3g), but clouds and rain prevented SKYNET observations at that time. At all four Japanese sites, data assimilation considerably improved the modeled peaks of anthropogenic pollution. However, the DA simulation still underestimated peak AOT levels, likely because of its inability to reproduce the pollution layer at 3000 m elevation.
5. Conclusions

We applied data assimilation hourly to data acquired by Himawari-8, a next-generation geostationary meteorological satellite, from 14 to 18 April 2015 over East Asia to assess its impact on modeling of transboundary anthropogenic pollution and dust storms in the region.

Data assimilation with hourly snap shots of Himawari-8 AOT data had a positive effect on the simulation. Modeling with data assimilation reproduced observed transboundary pollution that was not captured without data assimilation and reduced overestimations of concentrations at the dust front. Validation of the simulation results by comparison with independent satellite and ground-based measurements (MODIS, AERONET, SKYNET, and AD-Net) confirmed the benefits of data assimilation. However, there are limitations to the modeling that we attributed to errors in the model, the uncertainties in emissions, the coarseness of the model resolution, and the lack of vertical profile data for the assimilation. Further refinement of the model and inclusion of data on the vertical profile of aerosols in the assimilation will bring further benefits. We also performed an additional experiment in which Himawari-8 AOT was assimilated twice a day imitating LEO samples. The results of the additional assimilation showed improvement of limited magnitude compared to those of the assimilation with hourly data. This indicates that the high-frequency observation achieved by Himawari-8 could extend more opportunities to capture pollution during transport and provide more information for data assimilation comparing with conventional LEO observations.

The results presented here are promising for future simulations of both anthropogenic air pollution and natural dust outflow. However, data assimilation with AOPs derived from geostationary satellites is still in the development stage. Future studies should include comparison of data assimilations using AOPs derived from Himawari-8 data versus those derived from LEO satellite data [Sekiyama et al., 2016], testing of data assimilation with spatially and temporally composited AOPs derived from Himawari-8 data [M. Kikuchi et al., 2016], and also performing an additional experiment in which Himawari-8 AOT was assimilated twice a day imitating LEO samples.

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References


