A simulation study of the ensemble-based data assimilation of satellite-borne lidar aerosol observations

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1. Introduction

We developed a four-dimensional Ensemble Kalman filter (4D-EnKF) data assimilation system for the aerosol observations of the satellite-borne lidar instrument CALIPSO/CALIOP, which was launched by NASA. Using this data assimilation system, Sekiyama et al. (2010) directly assimilated the Level 1B data of CALIPSO/CALIOP, i.e., pre-retrieved satellite observations (attenuated backscatter and its depolarization ratio), and successfully isolated a dust aerosol from other aerosols. Furthermore, Sekiyama et al. (2011) estimated the Asian Dust emission intensity using the data assimilation system. They validated their aerosol analysis through a comparison with independent ground-based lidar observations and operational weather reports. However, most of the aerosol plumes cannot be measured and isolated with high accuracy and high frequency at a global or synoptic scale for model verification. In this situation, observing system simulation experiments (OSSEs) are very useful tools for evaluating the performance of data assimilation systems.

The OSSE technique uses a model-generated proxy for the real atmosphere, commonly called "truth". Therefore, a data assimilation system can be validated quantitatively by OSSEs because of the existence of a known "truth". Assessment using OSSEs is a well-established technique in numerical weather predictions (NWP). The aim of this study is to assess whether the aerosol data assimilation system has the ability to produce a better analysis of dust and sulfate aerosols with the use of the OSSE technique. This study is the first OSSE assessment in which satellite-borne lidar observations are simulated, assimilated, and validated, to the best of the authors' knowledge. As demonstrated in the following sections, the OSSE results successfully indicate the beneficial impact of the satellite-borne lidar data assimilation (in detail, see Sekiyama et al. 2012).

References

Sekiyama et al.: Data assimilation of CALIPSO aerosol observations, *Atmos. Chem. Phys.*, **10**, 39–49, doi:10.5194/acp-10-39-2010, 2010.

Sekiyama et al.: The effects of snow cover and soil moisture on Asian dust: II. Emission Estimation by Lidar Data Assimilation, *SOLA*, **7A**, 40–43, doi:10.2151/sola.7A-011, 2011.

Sekiyama et al.: A simulation study of the ensemble-based data assimilation of satellite-borne lidar aerosol observations, *Geosci. Model Dev. Discuss.*, **5**, 1877-1947, 2012.

2. Model Evaluation Tools

The importance of verification methods has been emphasized within the aerosol modeling community. The data assimilation system in this study was evaluated by the application of an object-based verification tool, the Method for Object-based Diagnostic Evaluation (MODE). We used aerosol optical thickness (AOT) as the analysis object of this MODE tool.

Traditional Methods

Model simulation or data assimilation results generally have been verified by the root-mean-squared error (RMSE), correlation scores. Indeed, the RMSE and correlation scores have performed very well when the verified quantity is continuous and does not exhibit sharp fluctuations; e.g. temperature, pressure, and geopotential height. However, aerosol plumes are highly localized phenomena and present extremely sharp fluctuations. The traditional verification methods are no use in aerosol forecast/analysis verification (Fig. 1).

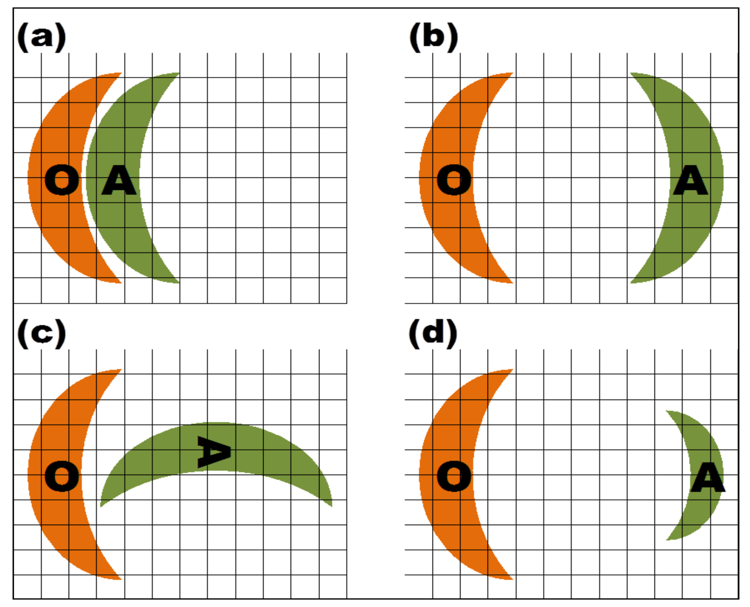


Fig 1. A schematic example of various observation and analysis combinations. (a)–(c) These all yield the same RMSE, whereas (d) has the best RMSE. However, (a) would probably be evaluated as the best subjectively.

Method for Object-based Diagnostic Evaluation (MODE)

The aerosol analysis can be verified by object-based approaches, in which aerosol plumes are compared and verified as objects through characterizations according to attributes such as location, size, and intensity. Of the object-based approaches, we utilized the MODE tool; this was developed for the evaluation of precipitation forecasts by the National Center for Atmospheric Research (NCAR). MODE includes the following multistep process to perceive two-dimensional graphical patterns:

Step 1) Identify objects,

Step 2) Measure the object attributes,

Step 3) Merge the objects in the same field,

Step 4) Match the objects from the analysis and observation fields,

Step 5) Compare the attributes of the analysis and the observation objects.

The process that takes place between Steps 1 and 3 is illustrated with an example of precipitation distribution in Fig. 2. After the merging is complete, the attributes are recalculated for the composite object in the same way before matching. In this step, the attributes include mutual quantities, such as centroid distance, object intersection, and union areas. The OSSE evaluation results of the CALIPSO/CALIOP data assimilation are shown in Figs 3 and 4, and Tables 1 and 2.

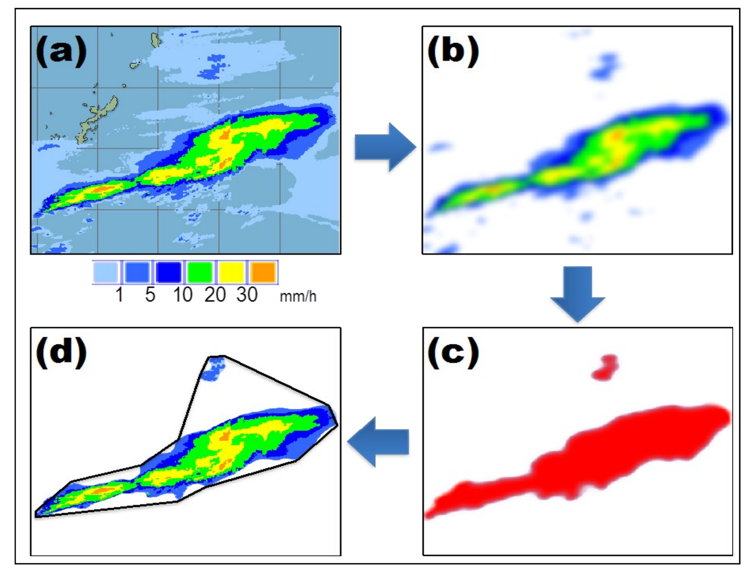
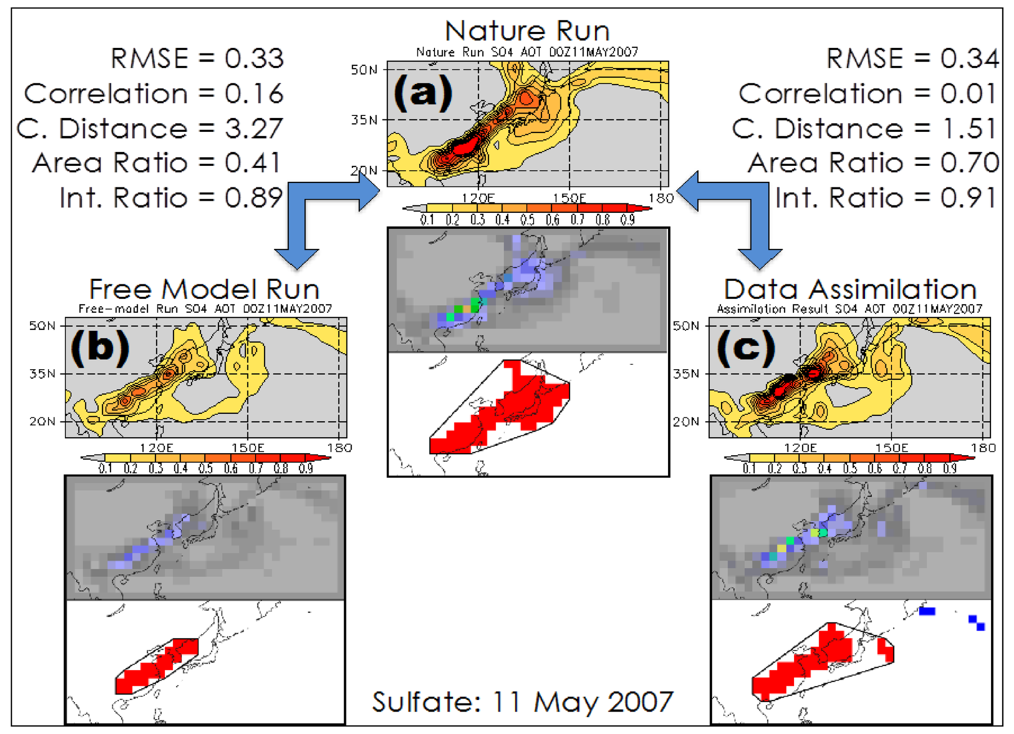


Fig 2. Example of application of the object-identification approach used in MODE, illustrated by precipitation distribution. (a) Original precipitation distribution, (b) convolved distribution after the smoothing operation has been applied, (c) masked distribution following application of the intensity threshold, and (d) filtered distribution showing the precipitation intensities inside the identified objects.

3. Results



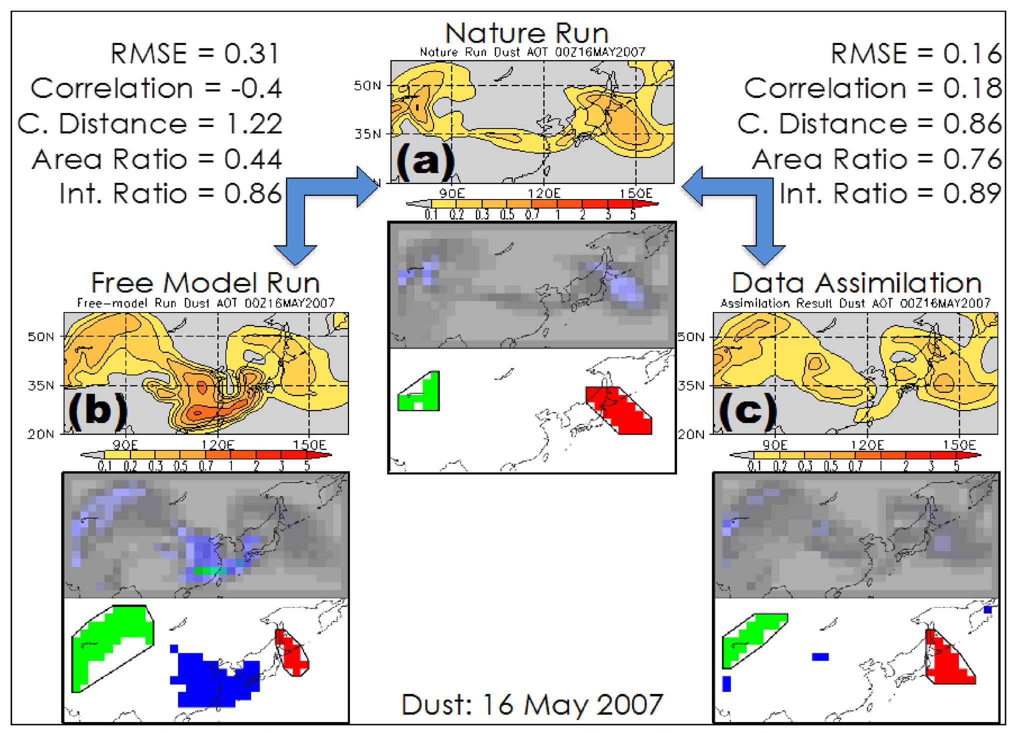
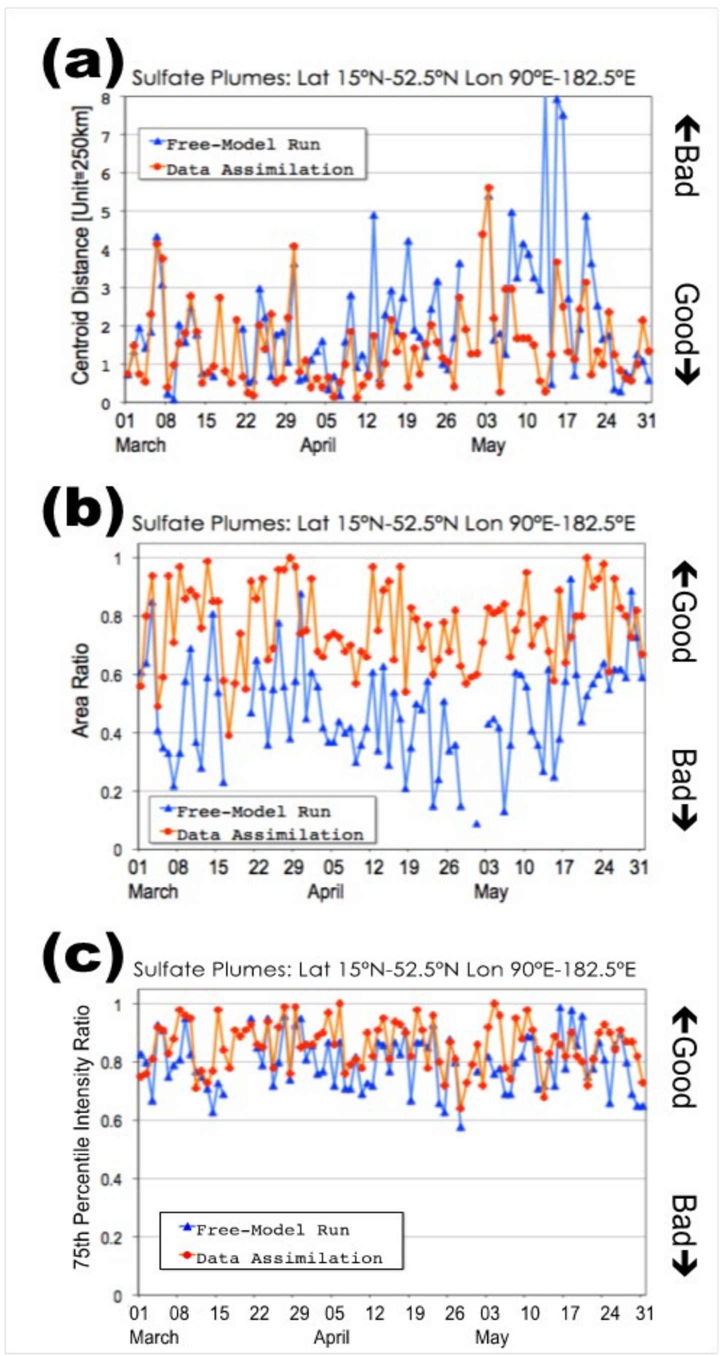


Fig 3-1. (Upper) The comparison of sulfate AOT distributions and performance scores at 00 UTC on 11 May 2007: (a) the Nature Run, (b) the free model run without data assimilation, and (c) the data assimilation result with the standard condition. The distance between two object centroids is presented in grid units.

Fig 3-2. (Lower) The same as Fig. 3-1, but the comparison of dust AOT at 00 UTC on 16 May 2007.



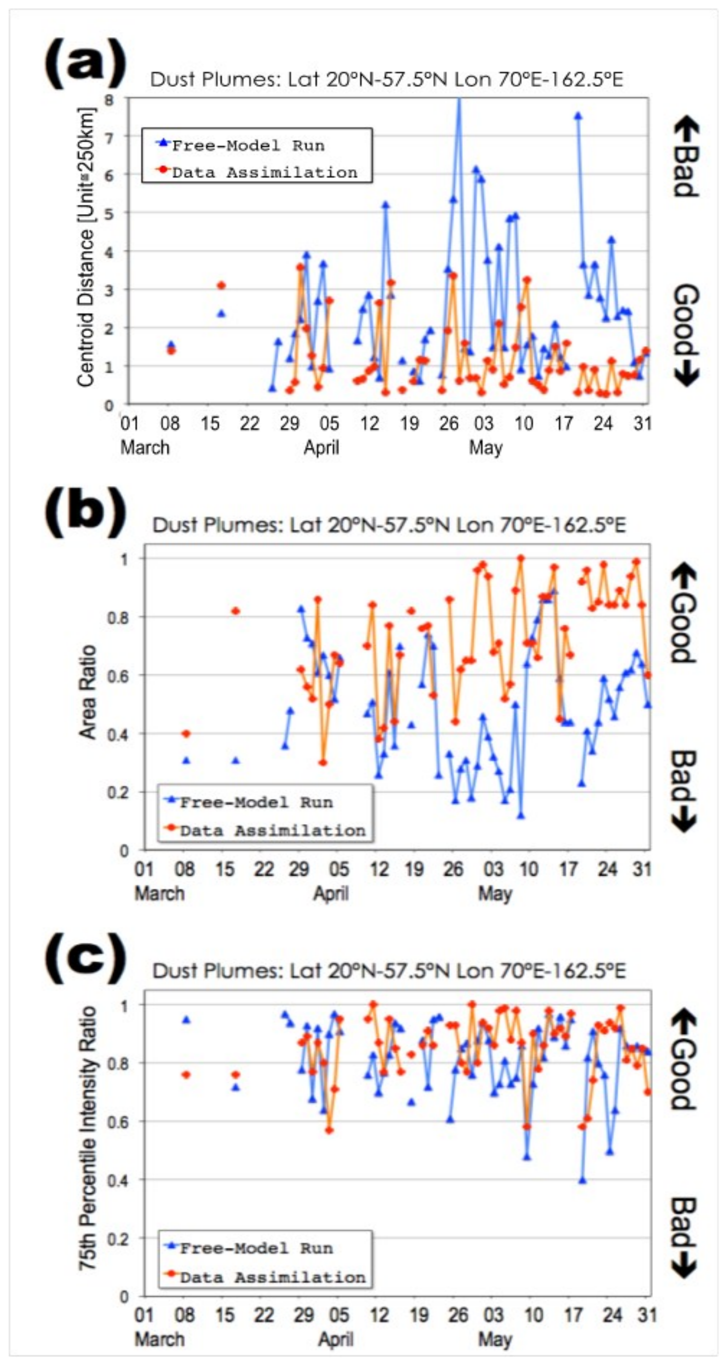


Fig 4-1. (Left) Time series of (a) the two object centroid distance (grid unit ≈ 280 km), (b) the two-object area ratio, and (c) the two-object 75th-percentile intensity ratio of sulfate aerosol plumes. Blue triangles indicate the performance of the free model run without data assimilation. Red circles indicate the performance of the data assimilation with the standard condition. The analyzed region was limited in East Asia and the Northwest Pacific from 15ºN to 52.5ºN in latitude and from 90ºE to 182.5ºE in longitude. If two or more plumes existed in the region in a day, their distances or ratios were averaged.

Fig 4-2. (Lower) The same as Fig. 4-1, but for the dust aerosol plumes in East Asia from 20ºN to 57.5ºN in latitude and from 70ºE to 162.5ºE in longitude.

3. Results (Continued)

Table 1. Traditional and object-based verification scores of sulfate aerosol shown in Fig. 4-1.

		Sulfate aerosol on May 11	
	Scores	Free model run	Data assimilation
Traditional	RMSE (0 is best; ∞ is worst)	**0.33***	0.34
	Correlation (1 is best; 0 is worst)	**0.16***	0.01
Object-based (MODE)	Centroid Distance (0 is best; ∞ is worst)	3.27	**1.51***
	Area Ratio (1 is best; 0 is worst)	0.41	**0.70***
	75th Intensity Ratio (1 is best; 0 is worst)	0.89	**0.91***

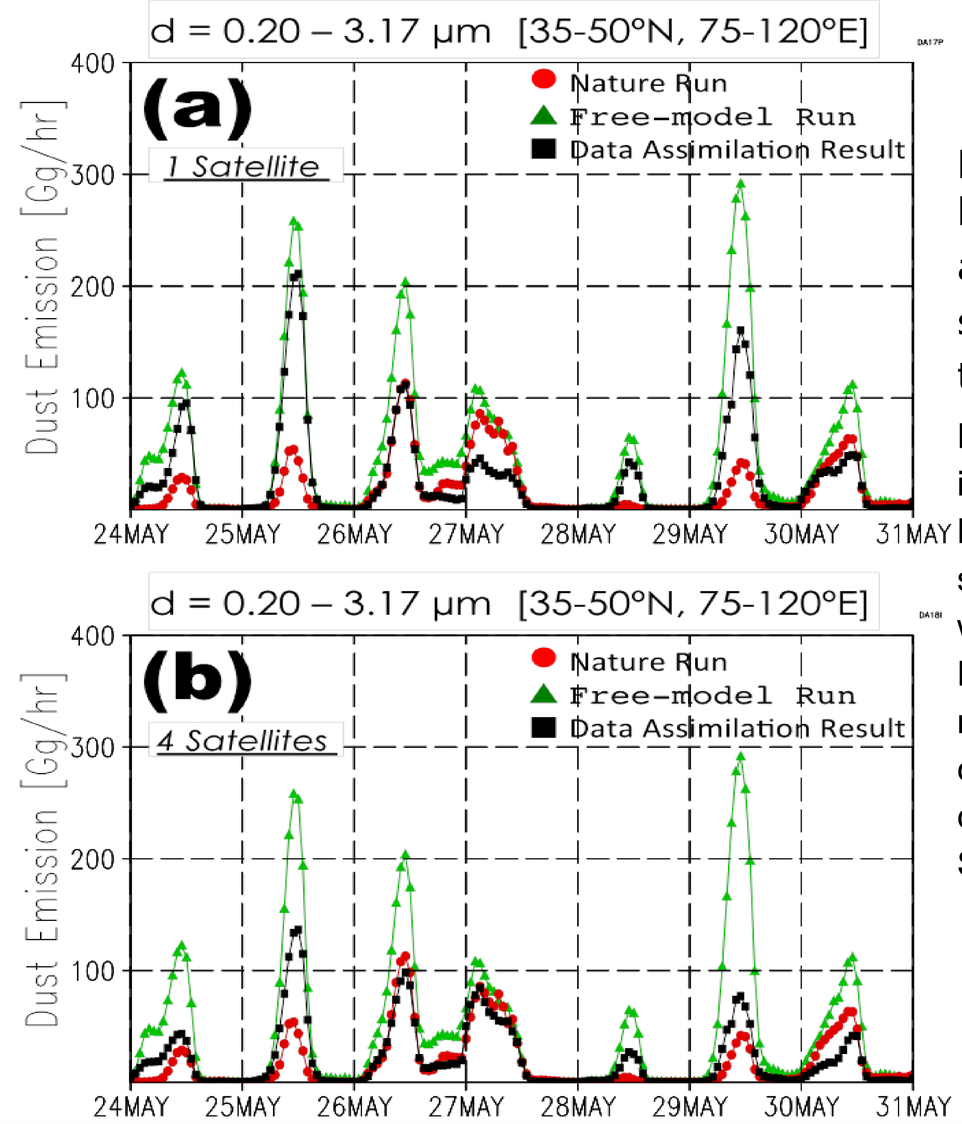
*Bold values indicate better scores between the free model run and the data assimilation.

Table 2. Traditional and object-based verification scores of the dust aerosol shown in Fig. 4-2.

		Dust aerosol on May 16	
	Scores	Free model run	Data assimilation
Traditional	RMSE (0 is best; ∞ is worst)	**0.31***	0.16
	Correlation (1 is best; 0 is worst)†	-0.41	0.18
Object-based (MODE)	Centroid Distance (0 is best; ∞ is worst)	1.22	**0.86***
	Area Ratio (1 is best; 0 is worst)	0.44	**0.76***
	75th Intensity Ratio (1 is best; 0 is worst)	0.86	**0.89***

*Bold values indicate better scores between the free model run and the data assimilation.

†A controversy might exist over which is the worst correlation, 0 or -1.



Flux estimation is one of the most important products of aerosol data assimilation, along with the plume distribution analysis. We evaluated Asian dust emission flux between the Nature Run and the analysis results.

Fig 5. Time series of the dust emission flux totaled in the Asian Dust source region (mainly China and Mongolia) in late May 2007. The dust weights of six size bins from 0.200 μm to 3.17 μm in diameter were accumulated. Red circles indicate the Nature Run. Green triangles indicate the free model run result without data assimilation. Black squares indicate the data assimilation result with the standard condition. Only one satellite was used for the OSSE in (a), and four satellites were used in (b).

Acknowledgments

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