Atmos. Chem. Phys. Discuss., 9, S2300–S2305, 2009
www.atmos-chem-phys-discuss.net/9/S2300/2009/

Atmospheric Chemistry and Physics Discussions

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9, S2300–S2305, 2009

Interactive Comment

Interactive comment on "Data assimilation of CALIPSO aerosol observations" *by* T. T. Sekiyama et al.

T. T. Sekiyama et al.

Received and published: 27 May 2009

Dear anonymous referee#2:

Thank you very much for your fruitful comments on our manuscript. The responses to these comments are as follows. We hope these are satisfactory ones for you.

> 1) Abstract and Summary: The authors described that the application corrected 'global' dust emission distribution. However, the paper described validations over the Asian region only. The authors should show validations for other dust sources.

We think the data assimilation results should be validated globally, not only within Asia, in a near-future study. When this manuscript is revised, the sentence "The intensity of dust emission at each grid point was also globally corrected" is replaced to "The intensity of dust emission at each grid point was also rationally corrected."

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Interactive Discussion

Discussion Paper

$>$ 2) Section 2: Please describe the methodology and setting of the application in greater detail because this paper specifically explained development and validation of a new data assimilation system. $>$ 2a) Page 5793, Line 6: Please briefly describe the LETKF methodology.

We change the sentences Page 5792 Line 2-5 into "As these EnKF techniques improved and became a viable choice in the field of operational NWP, the Japan Meteorological Agency (JMA) developed a four-dimensionally expanded LETKF (4D-LETKF) and applied it experimentally to NWP models (Miyoshi and Aranami, 2006; Miyoshi and Sato, 2007; Miyoshi and Yamane, 2007; Miyoshi et al., 2007a; Miyoshi et al., 2007b). As well as LEKF and LETKF, the 4D-LETKF of JMA has an advantage over most other EnKF implementations in its computational efficiency with simultaneous assimilation of increasing observations. Furthermore, one of major differences between LETKF (or the 4D-LETKF) and LEKF is that LETKF does not require local patches, and thus it allows a flexible choice of observations to be assimilated at each grid point (Hunt et al., 2007). The original implementation of LEKF separates the global model grid into local patches uniformly in the model grid space. The physical length between two successive grid points in the longitudinal direction is proportional to cosine of latitude. Therefore, the physical size of the local patch in the Polar Regions is much smaller than that in lower latitudes. This causes discontinuity in the analysis, which is not preferable. Moreover, Miyoshi and Yamane (2007) indicate that computational time is increased quadratic with the local patch size. LETKF removes local patches and implements natural localization weighting determined only by the physical distance (Miyoshi et al., 2007b). Miyoshi et al. (2007b) indicate that the computation without local patches is accelerated and more robust with choices of localization scales. These advantages of LETKF are suitable for not only higher resolution NWP models but also chemistry-transport models which includes much more prognostic variables than NWP models. Additionally, four-dimensional expansion of LETKF enables continuous observations, such as those of polar-orbit satellites (e.g., CALIPSO), to be assimilated effectively."

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> 2b) Page 5792, Line 10: Please describe the observation operator in greater detail.

We change the sentences Page 5792 Line 10-18 into "In order to assimilate attenuated backscattering and its depolarization measured by CALIPSO/CALIOP, we used an observational operator that emulates atmospheric optics induced by molecules (Rayleigh scattering), particles such as sulfate and sea-salt aerosols (Mie scattering), and dust particles. Specifically, suppositional Bl,m(z), Bl,p(z), Tl,m(z), and Tl,p(z) in Eq. (1) are calculated from model variables (i.e., pressure, temperature, and aerosol concentrations) using the formulae of Rayleigh scattering and Mie scattering at each wavelength l. Bl,m(z) is the backscattering coefficient of atmospheric molecules of which concentrations can be estimated from model pressure and temperature using the equation of the gas law. The transmittance Tl,m(z) can be estimated by accumulation of the extinction coefficients of atmospheric molecules between the lidar instrument and altitude z. The backscattering coefficient of aerosol particles Bl,p(z) is the sum of the backscattering coefficients of sulfate, sea-salt, and dust aerosols of which concentrations are model prognostic variables. These backscattering coefficients are calculated dependently on the aerosol type and size using the equations of the Mie scattering theory. The transmittance of aerosol particles Tl,p(z) can be estimated by accumulation of all the extinction coefficients of aerosol particles as in the estimation of Tl,m(z). It is noted that the dust extinction coefficient is empirically approximated from the Mie scattering theory, and the dust backscattering coefficient is estimated with the extinction coefficient divided by an empirical value of 50 sr. In this observational operator, it is assumed that depolarization of the 532nm backscattering is induced only by dust aerosol, and that the depolarization ratio is equal to 0.35 (Shimizu et al., 2004). Equation (1) with these Bl,m(z), Bl,p(z), Tl,m(z), and Tl,p(z) derives the attenuated backscattering B'l(z) which should be observed by CALIPSO/CALIOP under the clear sky condition if the model simulation was the real world. This observational operator needs only forward calculation, although it is nonlinear. When the observational operator is nonlinear, EnKF has a distinct advantage over 3D-Var or 4D-Var in that EnKF does not require a linearized observational operator or its adjoint."

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> 2c) Page 5793, Line 15: Please briefly explain how the authors initialized ensemble members. In addition, add some brief discussion related to the ensemble size.

When the manuscript is revised, we add a phrase "the initial ensemble spreads were generated by adding random Gaussian noise to this initial field" after Page 5793 Line 11, and phrases "Miyoshi and Yamane (2007) suggested that LETKF is significantly stabilized with more than 20 ensemble members in their realistic weather forecasting system. However, it is not obvious that the properties are applicable to our aerosol LETKF assimilation system" after Page 5800 Line 5.

> 2d) Page 5793, Line 13: I could find no explanation about local regions used for this study: the localization parameters are sensitive not only to the assimilation performance but also to the ensemble size.

We have to apologize for the lack of explanation about localization. When the manuscript is revised, we add a phrase "The localization scale was set to horizontally 1000 km and vertically 15 grids with Gaussian localizations" after Page 5793 Line 14. Our LETKF system includes only a localization scale, and a local patch is excluded as mentioned above.

> 2e) Page 5793, Line 20: Hunt, Kostelich and Szunyogh (2006) suggested that an inappropriately long time interval (or assimilation window) leads to unreasonable assimilation results. Please add brief comments related to the setting of the time interval.

Yes, we agree with your opinion. We set the assimilation window size (48 hours in our study) as short as possible to make CALIPSO orbits cover globally. That means most of the aerosol clouds can be probably detected by CALIPSO and assimilated within 48 hours somewhere and sometime (if the sky is perfectly clear) with a 1000 km horizontal localization scale and an average wind speed in the troposphere. When the manuscript is revised, we add a phrase "With the 48-hour time window and the 1000 km horizontal localization, aerosol clouds are probably detected and assimilated without omission globally, as long as the sky is clear" after Page 5793 Line 14.

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> 2f) Page 5793, Line 5: Did the dust emission factor have a negative value after assimilation?

When the emission factor was directly optimized by the 4D-LETKF, this factor sometimes had a negative value as Lin et al. (2008a) reported. Lin et al. (2008a) set the negative values to be zero, but this settlement is not good. If the negative values are arbitrarily set to be zero, the ensemble mean analyzed by EnKF will shift and the ensemble spread set by EnKF will be broken. In order to avoid the arbitrary operation, we defined the emission factor = gˆk (g is a constant more than 1), and made the 4D-LETKF optimize the parameter k. Consequently, the dust emission factor never had a negative value in our study. Research on the dust flux estimation will be presented in another paper in the near future.

> 3) Figure 1: Please add longitude to the X-axis in Fig. 1 or draw the CALIPSO orbit in Fig. 2 or Fig. 5.

When the manuscript is revised, we are going to draw the CALIPSO orbit in Fig. 2.

> 4) Figure 1 and Page 5795, Line 5: Although the 4D-LETKF considerably improved the dust vertical distribution near 30-40N, my concern lies with the reference model result. According to Fig. 1 and Hara et al. referred in this paper, the main dust cloud existed between 36-42N at 2-5 km centering at ?40N. The reference model result could not capture the dust cloud critically. One would consider that the model presented some problems and that the authors should improve the dust emission scheme or the physics and dynamics procedures of the model before assimilation.

The emission accuracy depends on many factors, e.g., the calculation formula, surface friction velocity estimation, surface humidity, vegetation, short-term surface conditions (covered with snow or not, etc), long-term surface conditions (getting changed anthropogenically or not, etc), and intensity of mixture in the lowermost boundary layer. Most of them are "poorly known parameters" or variables related to the poorly known parameters. Nevertheless, our aerosol model,

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MASINGAR, has been used for dust forecasts in the Japan Meteorological Agency (http://www.jma.go.jp/en/kosafcst/index.html), and its "relatively high" performance has been proved through their routine work (e.g., http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline-nwp/pdf/pdf4/outline4_8.pdf). However, the dust emission still has large uncertainties because of the poorly known parameters. Therefore, we have to adopt an advanced data assimilation system and optimize the parameters in order to improve the estimation of the dust emission and distribution.

> 5) Figure 5: I recommend adding the aerosol distribution from passive satellite measurements to make your results more rigorous.

When the manuscript is revised, we add the optical depth distribution measured by Terra MODIS. The image is consistent with our assimilation result. Unfortunately, Aqua MODIS observation and OMI aerosol index on the day do not cover the areas surrounding Japan appropriately.

> 6) Some mention of which parameter (concentrations or the emission factor) is more sensitive to (or important for) the dust assimilation results would be useful.

If you want to know dust emission intensity, the emission factor has to be analyzed by data assimilation or inversion techniques. On the other hand, the aerosol concentration can be analyzed by EnKF even if the emission factor is not involved in the assimilation system. Combination of the concentration analysis and the emission factor analysis generally lets EnKF yield more reliable assimilation results, but sometimes does not. It is difficult to determine whether the assimilation should involve the emission factor analysis or not. We are going to evaluate the sensitivity and importance of the emission factor analysis for the concentration analysis in the next study.

Interactive comment on Atmos. Chem. Phys. Discuss., 9, 5785, 2009.

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