Development of a chemical data assimilation system using a local ensemble transformed Kalman filter

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INTRODUCTION

Atmospheric chemical constituents such as ozone play important roles in determining the radiative balance of the atmosphere. Although numerical models such as chemical transport model (CTM) are powerful tools for analyzing chemical and transport processes of atmospheric chemical constituents, current models typically do not fully succeed in simulating the distribution of chemical constituents. For the reason, importance of developing a system to combine observational information with models using advanced data assimilation methods such as 4D-VAR and ensemble Kalman filter (EnKF) has been increasing.

The goal of this study is to develop an effective system for assimilating ozone and related species into a global CTM that includes detailed chemical and transport processes in the troposphere and stratosphere. In this study, we discuss the ability of using EnKF for both the meteorological and chemical assimilations in the constituent analysis system from perfect model experiments.

CHEMICAL DATA ASSIMILATION SYSTEM

Chemical data assimilation system has been developed using a local ensemble transformed Kalman filter (Hunt et al., 2006) and global CTM (CHASER, Sudo et al., 2002) coupled to the CCSR/NIES/FRCGC AGCM. Localization is applied to avoid sampling errors caused by the limited ensemble size, and the covariance inflation of 10 percent is applied for the forecast error covariance.

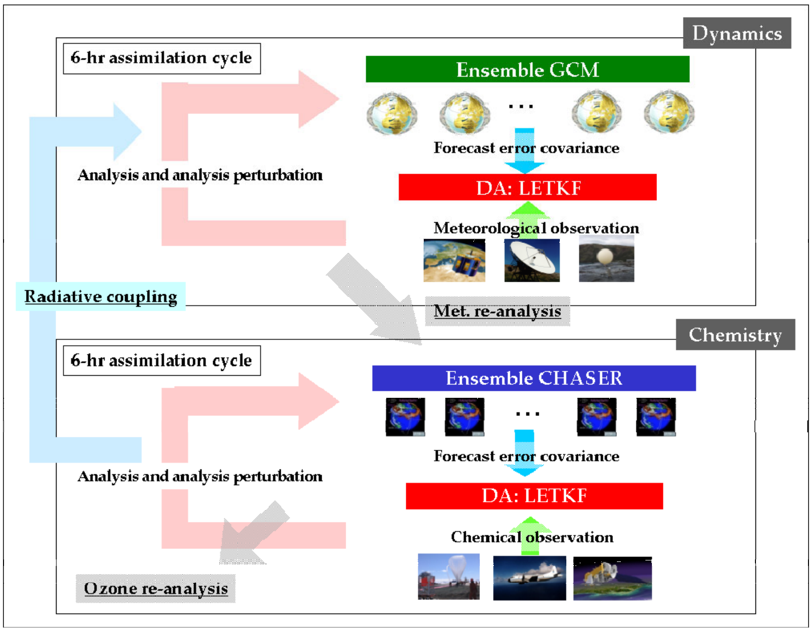

Figure 1 Schematic diagram of the chemical data assimilation system

The performance of the chemical data assimilation system is assessed by assuming that the CTM provides a perfect representation of chemical constituents. Artificial observational data are obtained from the true state obtained from free-running CTM with adding zero-mean Gaussian random noise (observational errors). Data assimilation is applied for both meteorological and chemical constituent; the data assimilation processes are illustrated in Figure 1.

METEOROLOGICAL ASSIMILATION ON TRACER TRANSPORT CALCULATION

First, sensitivity of transport calculation to meteorological assimilation method is investigated from a passive tracer (CO2) transport simulation. Figure 2 compares the root mean square error (RMSE) of CO2 mixing ratio between transport simulations with EnKF and conventional nudging technique. In previous works, the nudging technique has been widely used in the transport simulation with on-line transport model, in which a simple Newton relaxation is used to assimilate meteorological data into the GCM to reproduce past meteorological condition.

EnKF provides better representation of tracer field than the nudging system (left panel in Figure 2). Global mean RMSEs of both CO2 mixing ratio and zonal wind with EnKF are about half of those with nudging in the middle troposphere. An obvious improvement in the EnKF system is found around the strong wind shear region. The improvement is associated with flow-dependent error corrections.

Similar to situation in conventional analysis with 3DVAR products (e.g., Schoeberl et al., 2003), the nudging system reveals excessive vertical dispersion, causing large analysis errors in the tracer filed in the tropical upper troposphere and lower stratosphere. In contrast, EnKF suppresses the excessive dispersion and improves the representation of tracer variations.

Performance of meteorological assimilation strongly depends on the model bias. With considering a realistic temperature bias of GCM (cold bias of approximately 4-5 K in the lower stratosphere), EnKF yields more realistic circulation and tracer fields than nudging even without any bias corrections.

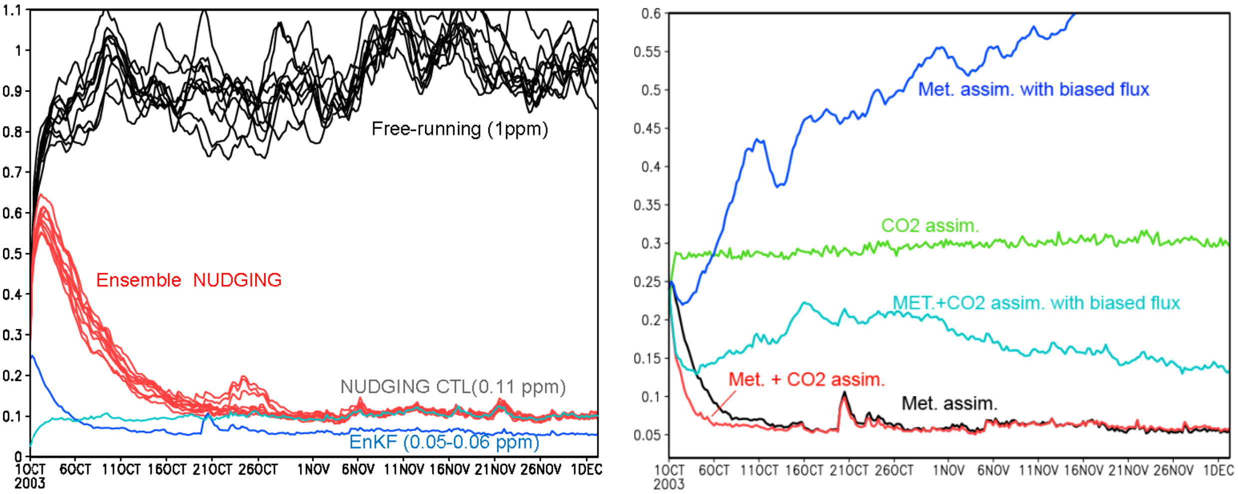

Figure 2 Global RMSE of CO2 mixing ratio (ppm) at 790 hPa.

ASSIMILATION OF TRACER CONCENTRATION

Second, we demonstrate relative importance of assimilating meteorological field and tracer concentration on the tracer simulation (right panel in Figure 2). In the perfect model scenario, meteorological assimilation greatly reduces the tracer analysis errors; while assimilating concentration results in smaller changes. However, in the realistic case with the consideration of the possibly errors in surface tracer flux (or chemical processes for chemically active species), significant improvement arises from assimilation of constituent concentration.

CHEMISTRY-CLIMATE COUPLING DATA ASSIMILATION EXPERIMENT

Perfect model experiments using a chemistry-climate coupling data assimilation system with full-chemistry model has investigates the importance of considering chemistry-climate interactions on both meteorological and constituent analyses.

Figures 3 and 4 compare RMSEs of ozone and geopotential height between different assimilation experiment with (1) meteorological assimilation with non-coupled system (monthly and zonal mean ozone data is used in radiative heating rate calculation), (2) meteorological assimilation with considering radiative coupling (simulated 3-D ozone field is used in radiation calculation), (3) ozone assimilation with radiative coupling, and (4) meteorological and ozone assimilations with radiative coupling. By assimilating ozone into the CTM and considering the radiative interaction between the CTM and GCM, analysis errors in both chemical and meteorological fields are greatly reduced (left panel in Figures 3 and 4). Assimilated ozone field improves temperature and wind through radiative processes particularly in the upper troposphere and stratosphere, while improved meteorological fields reduce errors in chemical and transport processes of chemical constituents. In the non-coupled system, obvious analysis error results from ozone analysis error though radiative imbalance. Chemistry-climate coupling data assimilation obtains a best analysis for both meteorological and constituent fields throughout the troposphere and stratosphere (right panel in Figures 3 and 4). Analysis error of ozone can also be reduced by assimilating related chemical species (i.e., NOx) into the CTM through chemical interaction via complex chemical processes (not shown in figure).

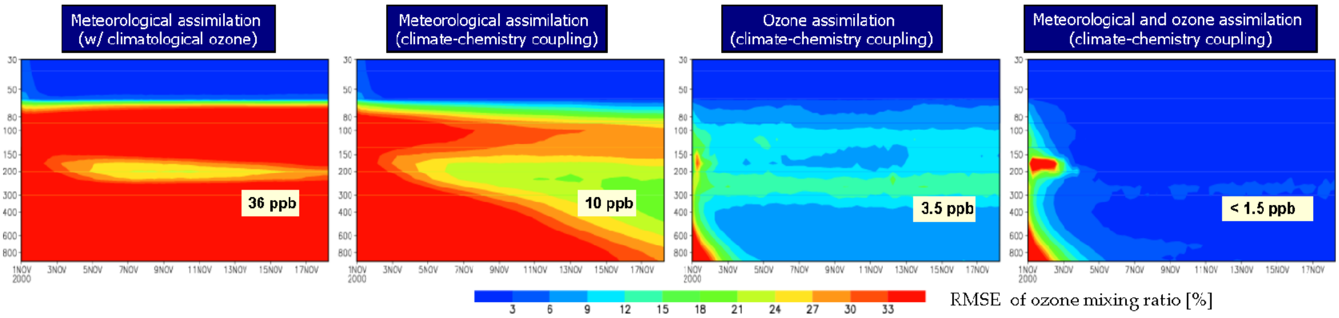

Figure 3 Zonal mean RMSE of ozone mixing ratio (ppb)

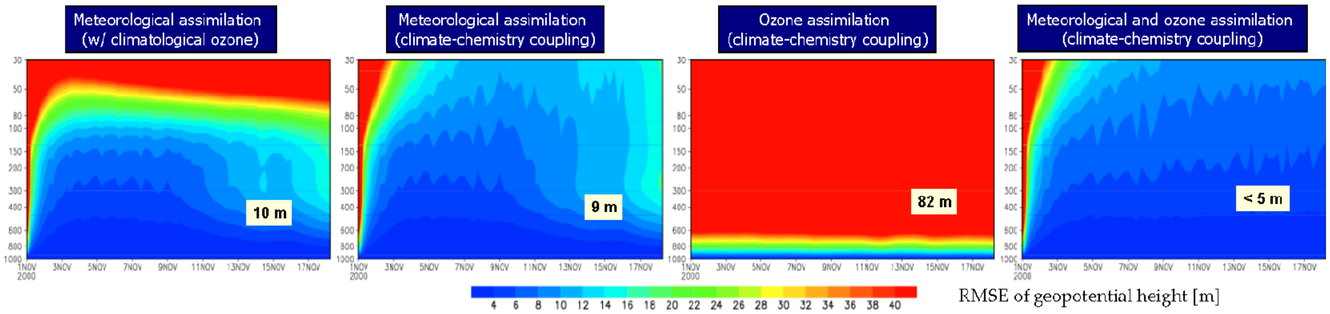

Figure 4 Zonal mean RMSE of geopotential height (m)

CONCLUSION

For making reanalysis of chemical constituent by using a CTM and EnKF in the near future, (1) relative importance of meteorological and concentration assimilations and (2) significance of chemistry-climate coupling on the constituent analysis have been investigated from ideal perfect model experiments.

(1) Tracer analysis is very sensitive to meteorological assimilation method. By improving the representation of atmospheric transport processes, meteorological assimilation with EnKF greatly reduces analysis errors of tracer fields. Importance of assimilating tracer concentration increases with increasing uncertainty in boundary conditions (e.g., surface tracer flux).

(2) Chemistry-climate coupling assimilation framework, by considering radiative effect of simulated ozone, significantly improves the analysis errors for both meteorological and chemical fields. The coupling framework is important to improve both meteorological and constituent analyses.

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