Vertical transport by convective clouds: Comparisons of three modeling approaches

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Abstract. We have performed a preliminary comparison of the GEOS-1 (Goddard Earth Observing System) data assimilation system convective cloud mass fluxes with fluxes from a cloud-resolving model (the Goddard Cumulus Ensemble Model, GCE). A short line case study (10-11 June 1985 Oklahoma PRESTORM episode) is the basis of the comparison. Regional (central U. S.) monthly total convective mass flux for June 1985 from GEOS-1 compares favorably with estimates from a statistical/dynamical approach using GCE simulations and satellite-derived cloud observations. The GEOS-1 convective mass fluxes produce reasonable estimates of monthly-averaged regional convective venting of CO from the boundary layer at least in an urban-influenced continental region, suggesting that they can be used in tracer transport simulations.

Introduction
A critical component of all 3-D global tropospheric chemical transport models is the representation of vertical transport through convective clouds. Global chemical transport models must be capable of accurately simulating convective transport if they are to be used in assessments of chemical and radiative effects of anthropogenic activities.

Because convection takes place on spatial scales smaller than the size of a grid cell of a global model, the transport associated with this process must be parameterized. Chemical transport in 3-D global models is driven by meteorological fields produced by data assimilation systems or by free running general circulation models. In this paper we compare estimates of convective cloud mass flux from one global data assimilation system containing parameterized convection with vertical fluxes from a cloud-resolving model. First, a case study of a particular squall line event (the well-studied 10-11 June 1985 PRESTORM episode) is chosen as representative of summertime mid-latitude continental convection. In both the GEOS-1 and GCE models, estimates of vertical flux are made to approximate the amount of venting of the boundary layer. Vertical profiles of cloud mass flux from the two models are also compared. Comparison of the subgrid parameterized convective mass flux from GEOS-1 with the flux from the GCE model is valid because no large-scale vertical velocity is included in the GCE simulation. Second, from monthly-averaged satellite cloud observations and GCE model simulations of the 10-11 June 1985 event and other episodes, we have estimated a convective mass flux for all of June 1985 in the central US. This is compared to the GEOS-1 convective mass flux over the same period and region. Finally, because we are interested in the role of convection in venting the boundary layer over urban-influenced regions like the central U. S., estimates of the vertical transport of an O3 precursor, carbon monoxide, are made using the two regional sets of convective mass fluxes.

Models and Methods
The Goddard Earth Observing System (GEOS-1) data assimilation system [Schubert et al., 1993] uses available meteorological observations to generate model-assimilated global analyses. The GEOS-1 assimilation algorithm pays special attention to temporal continuity, and provides fields which should be especially useful for chemical transport applications. Extensive diagnostics are also archived. Penetrative convection originating in the boundary layer is parameterized using the relaxed Arakawa-Schubert (RAS) scheme [Moorthi and Suarez, 1992]. The assimilated data sets contain six-hour average values of cloud mass flux and cloud detrainment at 20 levels in the vertical on a horizontal grid with 2° latitude by 2.5° longitude resolution. The assimilation produces reasonable patterns of convective precipitation in the tropics, as well as in midlatitude regions such as the central United States [Schubert et al., 1993].

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We compare the cloud mass flux from GEOS-1 with that estimated from a cloud-resolving model, the two-dimensional version of the Goddard Cumulus Ensemble Model (GCE) [Tao et al., 1991; 1993]. The GCE model is nonhydrostatic and variables include horizontal and vertical velocities, potential temperature, and mixing ratios of water vapor, cloud water, rain, cloud ice, snow, and hail/graupelem. Winds from the GCE model are used to drive a cloud-scale offline tracer transport model.

Case Study - June 10-11, 1985

A major squall line type mesoscale convective system occurred over Kansas and Oklahoma on June 10-11, 1985, during the Preliminary Regional Experiment for Stormscale Operational and Research Meteorology Program - Central Phase (PRE-STORM). Scattered convective cells forming a line were first seen on radar at about 2100 UT June 10 in southwestern Kansas. The system quickly developed and intensified, reaching peak intensity between 0200 and 0300 UT June 11. At this time the squall line extended from east-central Kansas across northwestern Oklahoma.

Cloud mass flux estimates produced by the GEOS-1 assimilation for the peak intensity period of the squall line are shown in Figure 1. The values in this figure are for the model level, sigma = 0.874, where sigma = (P - P_T)/(P_S - P_T), P_S is the surface pressure and P_T is the pressure at the top of the model (10 mb). This level is at about 1.55 km over the Oklahoma/Kansas region, approximately the top of the boundary layer. Therefore, the mass fluxes represent the amount of air being vented from the boundary layer. The GEOS-1 cloud parameterization places the greatest cloud mass flux associated with this weather system over Nebraska. This location is about 2 model grid cells north of where the strongest convective activity was noted on radar and satellite imagery. This position error likely results either from errors or inadequacies in the data entering the assimilation system or from the cumulus parameterization itself. A region of greater than or equal to 0.06 kg m⁻² s⁻¹ covers a region with dimensions of approximately 450 km in the north-south direction and 200 - 300 km in the east-west direction. These dimensions are similar to those of the observed squall line.

A simulation of the entire life cycle of the most intense region of the June 10-11 squall line using the 2-D GCE model has been described in detail by Tao et al. [1993] and Pickering et al. [1992a]. The model produced a cloud that extended to about 14 km, in good agreement with radar data [Rutledge et al., 1988]. The time series of computed vertical velocities compares favorably with that deduced from Doppler radar data by Rutledge and MacGorman [1988]. The 2-D wind fields from the cloud model were used to transport tracers from each of eight layers. The amount of tracer from the lowermost two layers (total initial depth of 1.735 km) that is lifted above the top of the second layer during the 6.5 hour simulation in a 274 km wide sector centered on the main convective region of the squall line is 10.9% h⁻¹. We can estimate the cloud mass flux over the same time period as in the assimilation (6 hours) assuming an air density of 1.025 kg m⁻³ at 1.735 km:

\[
\text{Cloud mass flux} = 1.025 \text{ kg m}^{-3} \times 0.109 \text{ h}^{-1} \times 1735 \text{ m} = 0.054 \text{ kg m}^{-2} \text{s}^{-1}
\]

This value compares favorably with the cloud mass flux of 0.06 kg m⁻² s⁻¹ computed in the GEOS-1 assimilation.

Figure 2 shows a comparison of the profiles of cloud mass flux produced by GEOS-1 and by the GCE model. The GEOS-1 profile is an average over four grid cells that comprise the cloud mass flux maximum seen in Figure 1. The GCE-based profile was computed from 8-layer net upward tracer transport results. While the magnitudes of the two profiles are quite similar, there are some differences in the profile shape. The GCE profile shows values increasing with altitude in the lower troposphere, indicating that the cloud system was entraining air throughout the lower levels. In contrast, the GEOS-1 profile is nearly constant with altitude in the lower and middle troposphere, and cloud entrainment (also produced by the RAS parameterization) is quite small (typically, 0.001 - 0.006 kg m⁻³ s⁻¹) in this altitude range. These results suggest that the RAS parameterization is causing most of the cloud air to be entrained at the bottom of the cloud. The GCE flux is larger than the GEOS-1 flux at the upper levels, suggesting that the cloud produced in the assimilation did not penetrate as high as that generated in the cloud-resolving model.

Regional Comparison

We have also compared the performance of the data assimilation system in estimating cloud mass flux over the period of a month (June 1985) over the central United States. In this analysis we compare the assimilation estimate of regional cloud mass flux from the boundary layer to the free troposphere with one based on cloud-resolving model transport statistics and satellite-derived convective cloud cover statistics.

We extracted upward cloud mass flux from assimilation output every 6 hours during the entire month of June 1985 and computed a total for the month for each grid cell at the 0.874 sigma level (Figure 3a). A pronounced east to west gradient is evident, and maximum values are found over Missouri and Arkansas and over northern Minnesota and Wisconsin.
We use the statistical/dynamical technique developed by Pickering et al. [1992b] to estimate upward cloud mass flux for the region. Monthly mean gridded statistics for deep convective cloud cover taken from the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1991) for June 1985 are used with statistics from GCE model simulations of prototype convective events (including the June 10-11, 1985 PRE-STORM squall line). Figure 3b presents the results (upper and lower limit estimates) from the statistical/dynamical technique. Lowest values of the cloud mass flux are in the northwestern portion of the region. A rather sharp peak in flux (up to 54 x 10^3 kg m^-2 month^-1 for two upper limit grid cell values) over eastern Kansas and northern Missouri results from a pronounced maximum in deep convective cloud cover in that area. Several mesoscale convective complexes passed through that area during June 1985. For these grid cells the flux estimate based on GEOS-1 is close to the lower limit estimate. However, the maximum cloud mass flux in the region as produced by the GEOS-1 model covers a considerably larger area than do the observationally-based estimates.

Summing over all the grid cells we obtain upper and lower limit estimates of the total cloud mass flux of 3.20 x 10^{16} and 5.17 x 10^{16} kg month^{-1}, respectively for the region. The GEOS-1 regional estimate (5.77 x 10^{16} kg month^{-1}) is just slightly greater than the upper limit estimate from the statistical/dynamical technique. The assimilation product is expected to be slightly greater than that based on the statistical/dynamical approach because the convective parameterization in the GEOS-1 model considers convective clouds of all sizes but the ISCCP data used in the statistical/dynamical approach is only for deep convective clouds.

Regional Convective Flux of CO

We extend our regional analysis to make estimates for the June 1985 upward CO convective flux from the boundary layer to the free troposphere using the GEOS-1 cloud mass fluxes and the statistical/dynamical technique. For CO data we use gridded boundary layer CO observations that were collected in central U. S. summer experiments by R. R. Dickerson and coworkers (Thompson et al., 1994). CO mixing ratios on the grid range from 100 ppbv in the northwestern portion of the region to 175 ppbv in the southeastern corner.

The corresponding gridded values of GEOS-1 cloud mass flux and CO were combined to obtain values of the upward convective flux of CO out of the boundary layer (see Figure 4a). The CO flux is at a maximum at the western edge of the region with values less than 10 x 10^{-4} kg m^{-2} month^{-1} in several grid cells. With greater boundary layer CO mixing ratios and relatively large amounts of cloud mass flux, the vertical flux of CO reaches a maximum (> 50 x 10^{-4} kg m^{-2} month^{-1}) in the ten grid cells in the southeastern corner of the
Convective Mass Flux of CO (GEOS-1) Out of Boundary Layer (10^10 kg/m^2/month)

Figure 4. Same as Figure 3a, except upward flux of CO from boundary layer.

region (Arkansas, Missouri, eastern Kansas and Oklahoma). Summing the vertical CO fluxes over all the grid cells in the region yields a total CO removal from the boundary layer of 8.03 x 10^10 kg month^-1.

The statistical/dynamical approach produced peak values of CO convective flux in the grid cells covering Missouri and eastern Kansas (> 80 x 10^-4 kg m^-2 month^-1) as part of a larger region for which upper limit values exceeded 30 x 10^-4 kg m^-2 month^-1. The maximum CO flux based on the GEOS-1 model covers a considerably larger area than the observationally-based maximum. Summation over all of the grid cells in the region yields a total CO convective flux of 4.74 x 10^9 and 7.66 x 10^9 kg month^-1. The CO convective transport estimate based on the GEOS-1 cloud mass fluxes (8.03 x 10^9 kg month^-1) is only 5% higher than our upper limit estimate based on satellite cloud observations and GCE model transport statistics. Therefore, the convective transport in the GEOS-1 assimilation appears to yield reasonable results when summed over a region for a 1-month period.

The June 1985 values are about 20% higher than the climatological estimates based on an average of seven Junes (Thompson et al., 1994). Therefore, June 1985 was more convectively active than an average June over the central U.S.

Summary

We have demonstrated that the RAS parameterization of convective clouds in the GEOS-1 data assimilation produces reasonable values of cloud mass flux in a case study of a major summertime midlatitude continental squall line and on a regional monthly-total basis. On the basis of these preliminary comparisons with cloud-resolving model transport statistics and with an observationally-based statistical/dynamical approach, it appears that GEOS-1 cloud mass fluxes can be used in tracer studies with a global 3-D chemical transport model to yield reasonable tracer mixing ratios in the free troposphere. We caution that the results presented here are representative of a major midlatitude continental squall line. We have yet to evaluate the GEOS-1 product for weaker systems or for tropical convection.

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