Analysis of tropical convective transport of trace gases and lightning NOx production during the TC4 mission using the GMI model

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Introduction

Deep convection, especially in the tropics, is a vital transport mechanism of trace gases to the upper troposphere (Dickerson et al., 1987; Pickering et al., 1992) Longer chemical lifetimes and stronger winds in the upper troposphere provide global distribution for local sources of trace gases. The lightning attendant with convection is also an important producer of NOx in the upper troposphere, where it is an important contributor to ozone production (Pickering et al., 1996).

Thus, both the dynamical and chemistry components of a model are vital to accurate portrayal of trace gas profiles. Here, we evaluate the convective parameterization in a global model in terms of convective cloud distributions and in terms of the trace gas distribution for different implementations of the same chemical transport model. This is achieved using both aircraft measurements and satellite products during NASA's Tropical Composition, Cloud, and Climate Coupling (TC4) field experiment in July-August 2007, based in Costa Rica (Toon et al., 2010).

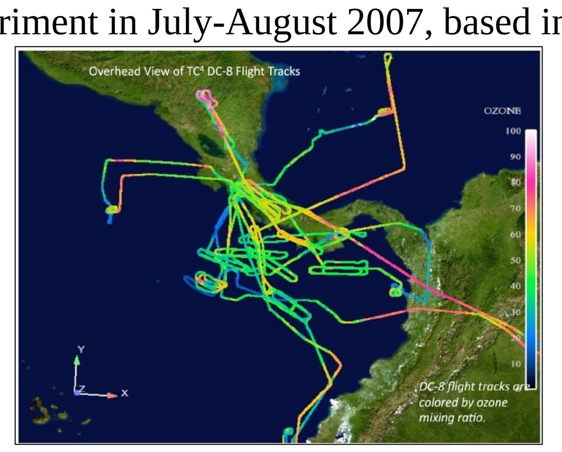

Figure 1. DC-8 flights during TC4 mission, with paths colored by measured ozone concentrations. From Avery, et al (2010).

Models and methods

The focal point of this investigation is the NASA Global Modeling Initiative (GMI) chemical transport model (CTM), a three dimensional offline model with full stratospheric and tropospheric chemistry. In this investigation, it is driven by data from the GEOS-4 and GEOS-5 global assimilation systems run by the NASA Global Modeling and Assimilation Office.

The GEOS-4 uses the Zhang-McFarlane convection scheme (Zhang and McFarlane, 1995), where each updraft and downdraft is initially the same magnitude before being modified by environmental entrainment, and CAPE is consumed using a fixed exponential function of time. Entrainment occurs throughout the plume, with a maximum entrainment set by the top of shallowest plume. Detrainment occurs at or above this level. GEOS-4 has 42 vertical levels and a 1.25x1.00 degree horizontal resolution.

The GEOS-5 uses a modified Relaxed Arakawa Schubert scheme (Bacmeister, 2005). A fixed cloud base and selected detrainment level determine the entrainment profile for each plume, and the fate of the plume is determined once quasi-equilibrium is achieved with CAPE. The plumes themselves do not interact with each other, but rather with the environment. GEOS-5 has 72 vertical levels and 0.67 x 0.5 degree horizontal resolution.

The aircraft data were generated by flights of the NASA DC-8 and the WB-57. O_3, CO, NO, and NO_2 were measured at high frequency (~1s). The DC-8 was confined to the troposphere, whereas most of the WB-57 flight time was in the lower stratosphere.

Satellite data were used to evaluate both the convective clouds and the trace gas distributions resulting from convective transport. Convective clouds were compared against IR cloud distributions and cloud top heights from the GOES-12 weather satellite, while the trace gas distribution evaluation utilized data from the OMI, MLS, and TES instruments onboard NASA's Aura satellite. TES data from both the Global Survey and the Step-and-Stare modes during the TC4 experiment were utilized.

Results- Convective Clouds

Areal Coverage/Location

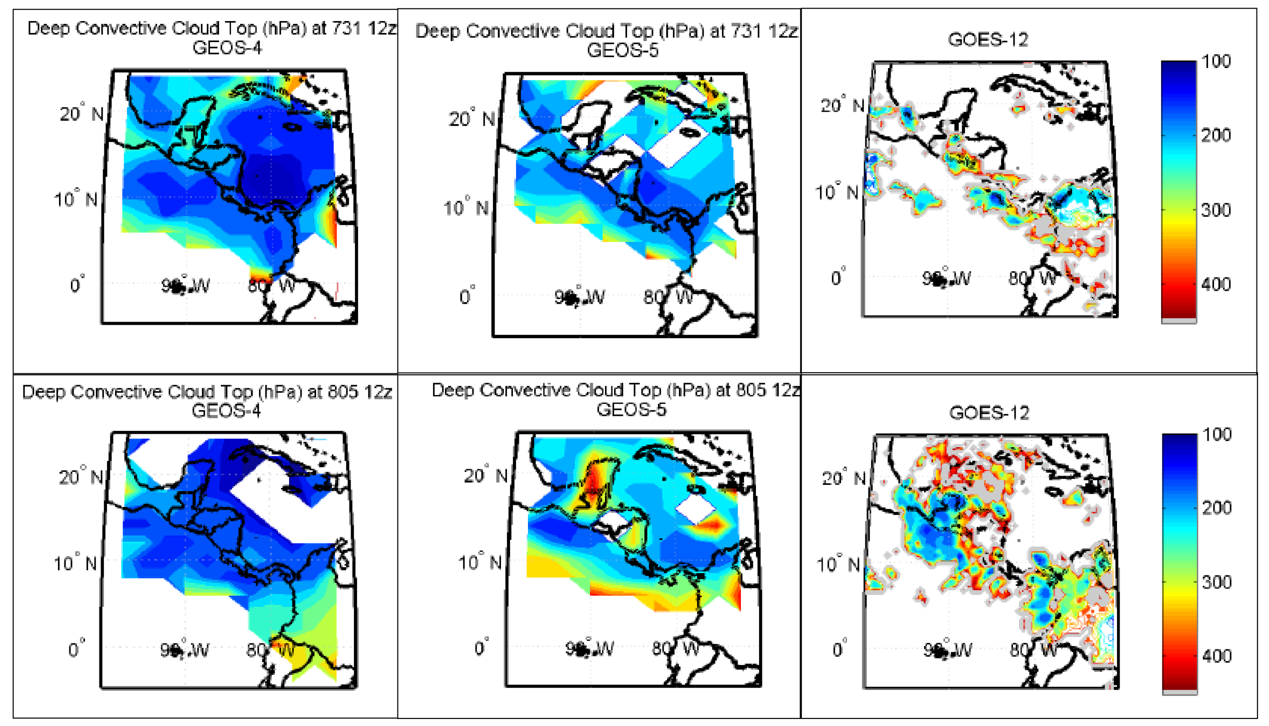

Figure 2. Convection comparison between GEOS-4 (left) GEOS-5 (center) and GOES-12 (right) for July 31st (top) and August 5th (bottom).

- Model cloud top heights were determined using the ISCCP definition of convective clouds (cloud mass flux above 440 hPa & optical depth greater than 26)
- GEOS-4 routinely had >25% larger regions of convective activity than GEOS-5, with very deep convection (above 250 hPa) >33% larger
- GEOS-5 had superior areal coverage of actual convection (approximately 75% hit rate), but the convection was often too shallow

Column Mass Flux/Detrainment

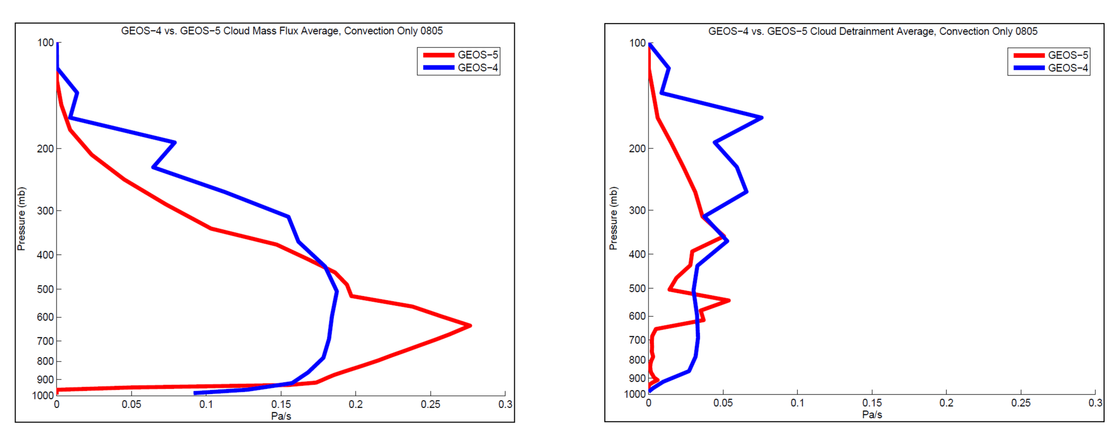

Figure 3. Convective mass flux (left) and detrainment (right) comparison between GEOS-4 (blue) GEOS-5 (red)

- These profiles are taken from those columns which have a threshold value (0.1 Pa/s) near the level of non-divergence (500 hPa)
- Peak detrainment occurs much lower in GEOS-5, near 550 hPa, far below where detrainment would be expected (upper troposphere)
- GEOS-5 mass flux profile is consistent with the tuned GEOS-5 run in single column models used in Ott, et al (2009); which showed that the GEOS-5 mass flux profile does not compare favorably with other SCMs

Results- Trace Gas Distribution

Ozone

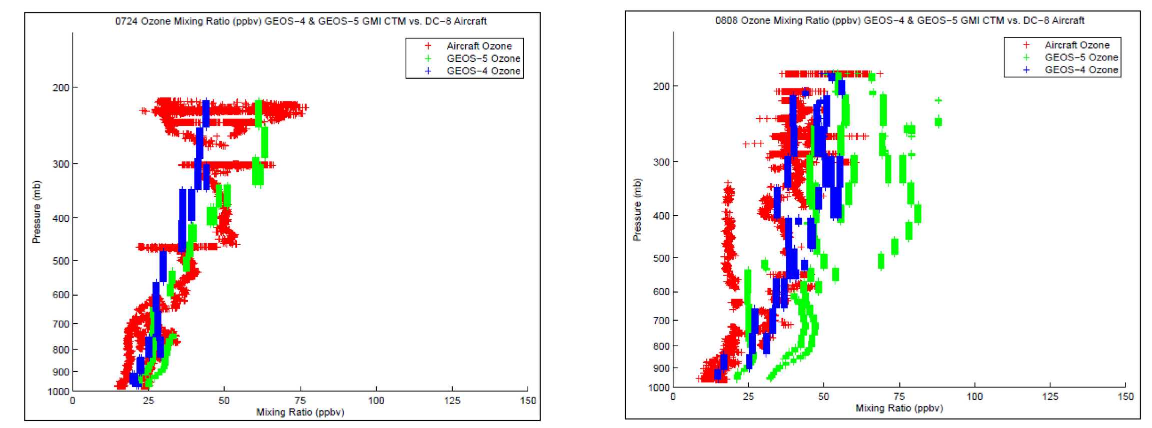

Figure 4. Ozone comparison in convection between GEOS-4 (blue) GEOS-5 (green) and DC-8 (red of each panel) for July 24th (left) and August 8th (right)

- The July 24th flight , flown directly in convection, exemplifies the lack of boundary layer air detrainment in the upper troposphere for the GEOS-5, as the modeled ozone values are much higher than the majority measured
- The August 8th flight, which was in the outflow only, shows an amplified effect

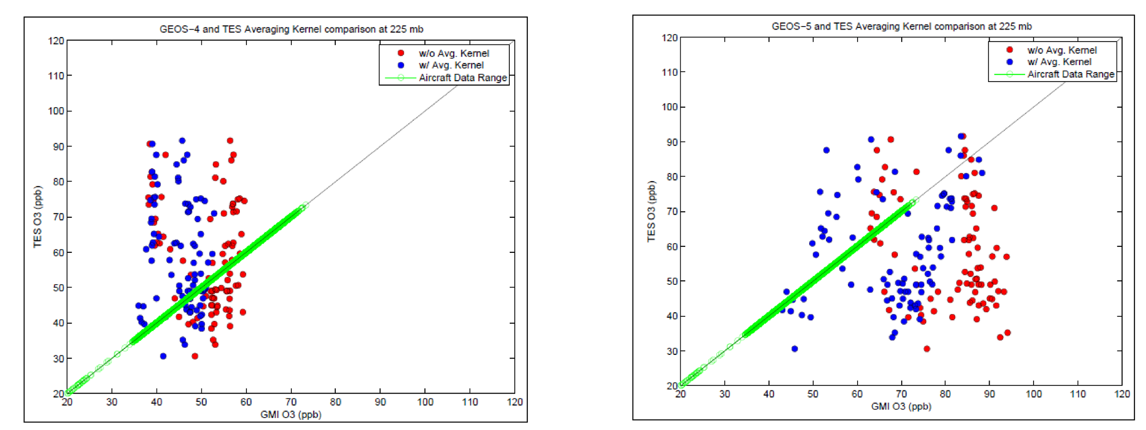

Figure 5. Ozone comparison at 225 hPa between GEOS-4 (left) GEOS-5 (right) and TES (vertical axes of each panel) for August 8th with averaging kernel (blue) and without averaging kernel (red). Green band on diagonal shows range of DC-8 observations.

- GEOS-5 has much higher values in the upper troposphere than the TES satellite instrument, sometimes by nearly a factor of two, whereas the overly broad convection (and detrainment) in GEOS-4 causes much lower values than the satellite

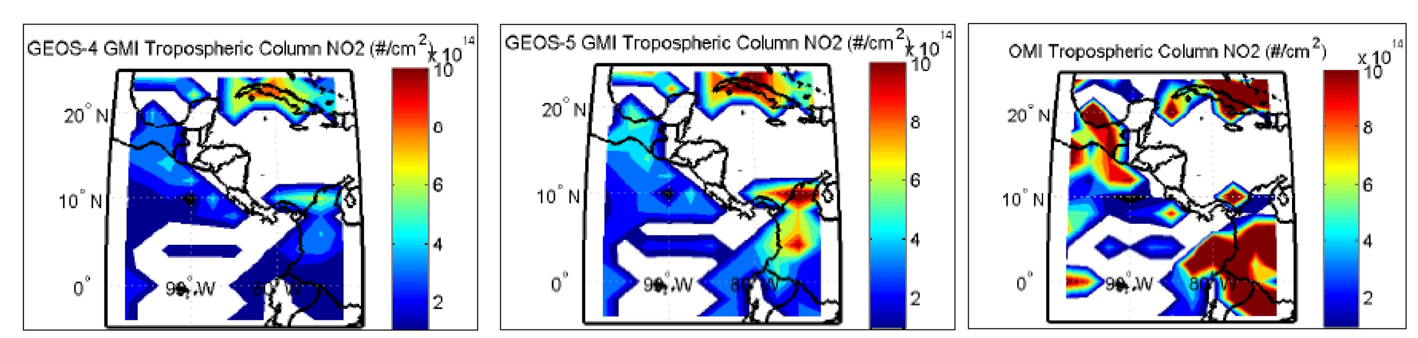

Figure 6. NO_2 comparison at 225 hPa between GEOS-4 (left) GEOS-5 (center) and OMI Level 3 cloud screened (right) August 8th

- Both GEOS-4 and GEOS-5 use similar lightning NOx production parameterization, in which flash rates are a function of cloud mass flux, constrained to satellite climatological monthly means (Allen et al., 2010).
- Tropospheric NO_2 column amounts are much higher in GEOS-5 than GEOS-4, despite significantly less convection (and therefore lightning)
- Mean values of GEOS-4 Tropospheric NO_2 the TC4 region are ~60% less than OMI, while mean values of GEOS-5 are ~40% lower than OMI

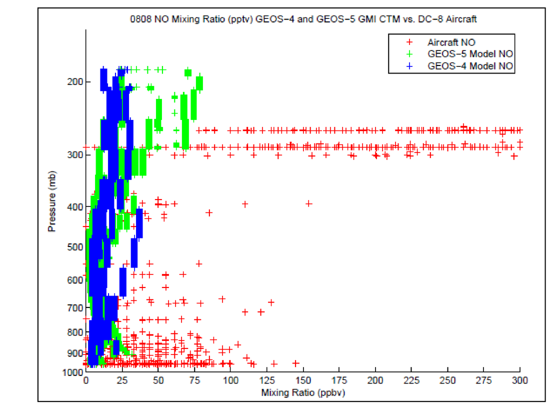

Figure 7. NO comparison between GEOS-4 (blue) GEOS-5 (green) and DC-8 (red) August 8th

- Despite convection that is often weaker, GEOS-5 has higher values of NO_2 and NO than the GEOS-4 likely due to the concentrated area of GEOS-5 convection
- Enhanced NOx values in GEOS-5 mask detrainment problems seen with ozone, as NOx is an ozone precursor

Conclusions

We have shown there are significant differences between the GEOS-4 and GEOS-5 convective parameterizations, which have a significant impact on the distribution of trace gases in the atmosphere. Moreover, our results are inline with previous studies which showed unrealistic detrainment and trace gas profiles in models that use RAS convective scheme (Folkins et al., 2006) . The GEOS-5 has also been found to have peaks in upward cloud mass flux much lower than expected (Ott et al., 2009). Since it is impossible to directly measure upward cloud mass flux and detrainment, future work should focus on evaluating convective transport in a single column model using cloud resolving model output to help assess the parameterizations.

The effects of the convective parameterizations were reflected in trace gas measurements, as the weak upper tropospheric detrainment in GEOS-5 caused higher than measured values of ozone in this region. Errors in the ozone distribution could cause significant errors in radiative balance computed in chemistry/climate models.

Literature cited

Allen, D., K. Pickering, B. Duncan, and M. Damon (2010), Impact of lightning NO emissions on North American photochemistry as determined using the Global Modeling Initiative (GMI) model, *J. Geophys. Res.*, *115*, D22301, doi:10.1029/2010JD014062.

Avery, M., et al. (2010), Convective distribution of tropospheric ozone and tracers in the Central American ITCZ region: Evidence from observations during TC4, *J. Geophys. Res.*, *115*, D00J21, doi:10.1029/2009JD013450.

Bacmeister, J. T., (2005), GEOS-5 SYSTEM: Moist physics parameterizations. [Available online at http://gmao.gsfc.nasa.gov/systems/geos5/STRUCTURE/AGCM/Moist.php.]

Dickerson, R. R., et al. (1987), Thunderstorms: An important mechanism in the transport of air pollutants, *Science, 235*, 460–465.

Folkins, I., et al. (2006), Testing convective parameterizations with tropical measurements of HNO3, CO, H2O, and O3: Implications for the water vapor budget, *J. Geophys. Res.,111*, D23304, doi:10.1029/2006JD007325.

Ott, L.E., et al. (2009), An Analysis of Convective Transport and Parameter Sensitivity in a Single Column Version of the Goddard Earth Observing System, Version 5, General Circulation Model. *J. Atmos. Sci.*, *66*, 627-646. doi:10.1175/2008JAS2694.1.

Pickering, K., A. Thompson, J. Scala, W.-K. Tao, R. Dickerson, and J. Simpson (1992), Free Tropospheric Ozone Production Following Entrainment of Urban Plumes Into Deep Convection, *J. Geophys. Res.*, *97*(D16), 17985-18000.

Pickering, K. E., and Coauthors, (1996), Convective transport of biomass burning emissions over Brazil during TRACE A. *J. Geophys. Res.*, *101*, 23 993–24 012.

Toon, O. B., et al. (2010), Planning, implementation, and first results of the Tropical Composition, Cloud and Climate Coupling Experiment (TC4), *J. Geophys. Res.*, *115*, D00J04, doi:10.1029/2009JD013073.

Zhang, G. J., and N. A. McFarlane, (1995): Sensitivity of climate simulations to the parameterization of cumulus convection in the CCC-GCM, *Atmos.–Ocean, 3*, 407–446.

Acknowledgments

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