The ECPP Hybrid Approach for Aerosols and Trace Gases in MMF Models

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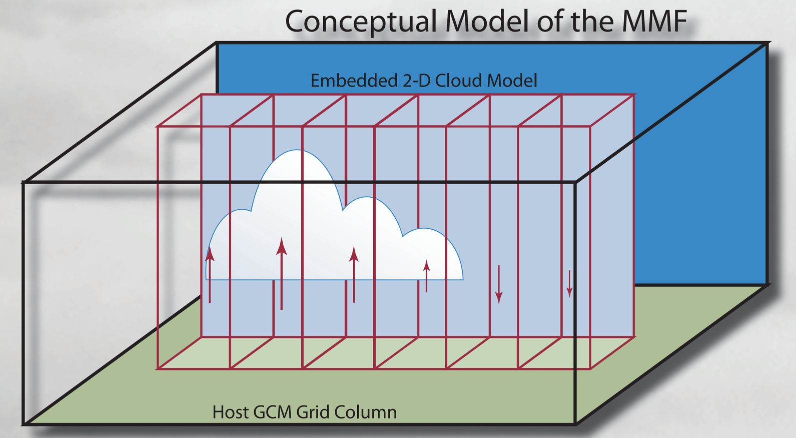
Introduction

Accurately simulating aerosols and their effects on radiation and clouds is important for improving climate forecasts since the uncertainties in estimates of these effects are of comparable magnitude with climate forcing by anthropogenic greenhouse gases. However, cloud processing of aerosols and trace gases (transformation, removal, and sub-grid vertical transport) within global climate models (GCMs) is currently inadequate due to their inability to parameterize cloud-scale processes accurately. Of particular importance is processing by convective clouds.

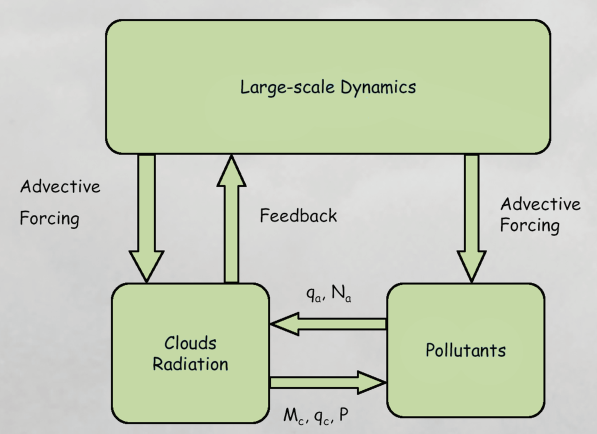
In the Multiscale Modeling Framewok (MMF) traditional cloud parameterizations are replaced by 2- or 3-dimensional cloud models embedded within each column of a host GCM. Within MMF, two options exist for the handling of tracers. The first is to simulate tracers within the embedded cloud models. The second is to treat tracers in a traditional manner on the coarse GCM grid. The first option is presumably more accurate, but would be computationally too expensive, even if the tracer chemistry and physics is streamlined. The second option is cheaper, but it does not take advantage of the sub-grid cloud information provided by the embedded cloud models.

An alternative approach harnesses the information from the high-resolution embedded cloud models in the MMF to parameterize vertical transport and processing of tracers by clouds. A technique using this hybrid approach is the Embedded-Cloud Parameterized-Pollutant (ECPP) parameterization.



The ECPP Parameterization

In ECPP, tracers are carried on the coarse GCM grid, and some processes (e.g. horizontal transport and gas-phase chemistry) are treated traditionally on this grid. Vertical velocity and microphysical parameter statistics from the embedded cloud models are used within ECPP for an enhanced treatment of vertical transport and wet scavenging.



- Mean cloud mass flux used to treat vertical transport of pollutants
- Mean updraft velocity used to determine aerosol activation and droplet nucleation
- Cloud fraction and in-cloud water content used for aqueous chemistry
- Mean precipitation fraction and rate used to treat precipitation scavenging
- RH from the cloud model to calculate water uptake and direct effects
- Droplet number and cloud water from cloud model for indirect effects
- Aerosol direct and indirect effects on climate are driven by GCM grid-cell mean statistics from the embedded cloud model

ECPP Theory

1. Classify each cloud model grid cell as updraft ($w > w_{up\text{-}thresh}$), downdraft ($w < w_{dn\text{-}thresh}$), or quiescent environment. Calculate profiles of mass flux (M_j, j=up, dn, env), fractional area (A_j), and microphysical parameters by averaging over the appropriate grid cells.

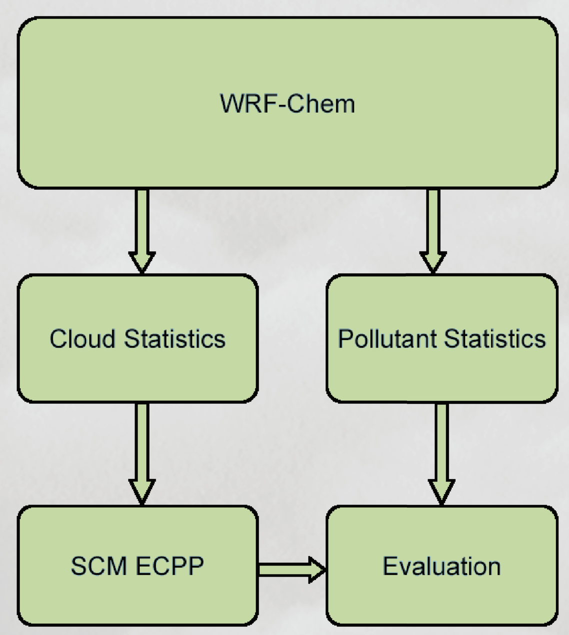
2. Diagnose up- and downdraft entrainment (E_j) and detrainment (D_j) mass tendencies from
$$\frac{\partial(\rho A_j)}{\partial t} + \frac{\partial M_j}{\partial z} = E_j - D_j$$
by assuming that at each level, one equals 0 and the other is >0.

3. Solve continuity equations for trace-species mixing ratios in the updraft, downdraft, and environment subareas ($q_{j,L}$). For updraft and downdraft subareas,
$$\frac{\partial(\rho A_j q_{j,L})}{\partial t} = -\frac{\partial(M_j q_{j,L})}{\partial z} + (E_j q_{env,L} - D_j q_{j,L}) + S_j$$
where S_j is the subarea source/sink term (cloud chemistry and wet removal). For the environment subarea,
$$\frac{\partial(\rho A_{env} q_{env,L})}{\partial t} = -\frac{\partial(M_{env} q_{env,L})}{\partial z} + (D_{up} q_{up,L} - E_{up} q_{env,L}) + (D_{dn} q_{dn,L} - E_{dn} q_{env,L}) + S_{env}$$

4. The updrafts and downdrafts can be assumed steady-state, as is often done in convective cloud parameterizations. In this case, the updraft and downdraft entrainment and detrainment are diagnosed using
$$\frac{\partial M_j}{\partial z} = E_j - D_j$$
and the updraft and downdraft trace-species mixing ratios using
$$\frac{\partial(M_j q_{j,L})}{\partial z} = (E_j q_{env,L} - D_j q_{j,L}) + S_j$$

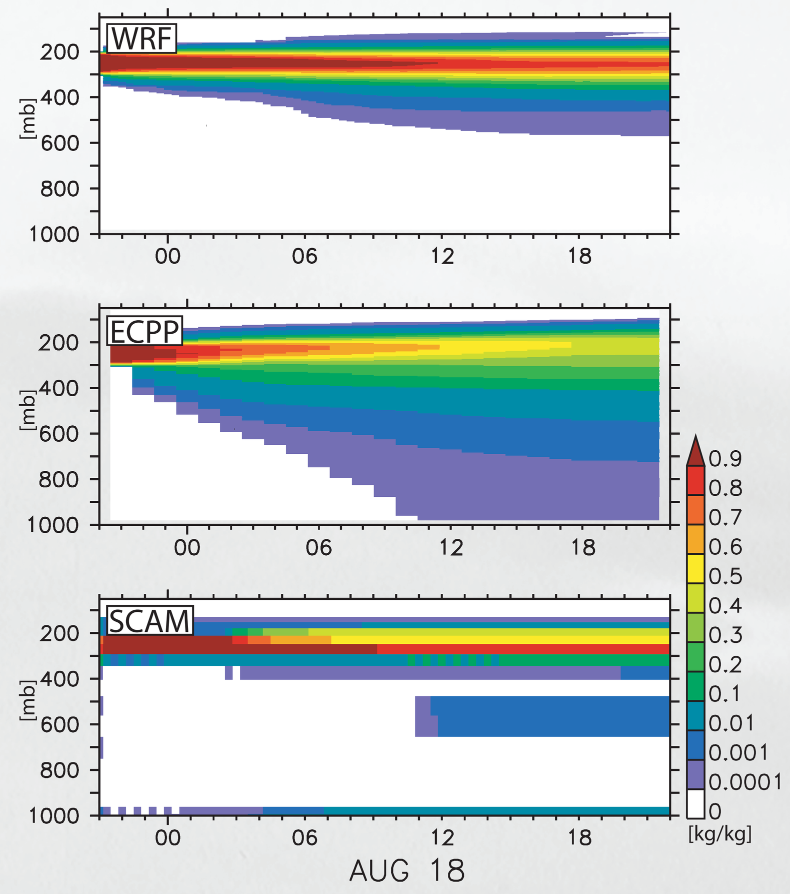
ECPP Proof of Concept

Before embedding ECPP into a full GCM, tests have been done using WRF-Chem with cloud-resolving resolutions similar to what would be used for the cloud model in MMF.

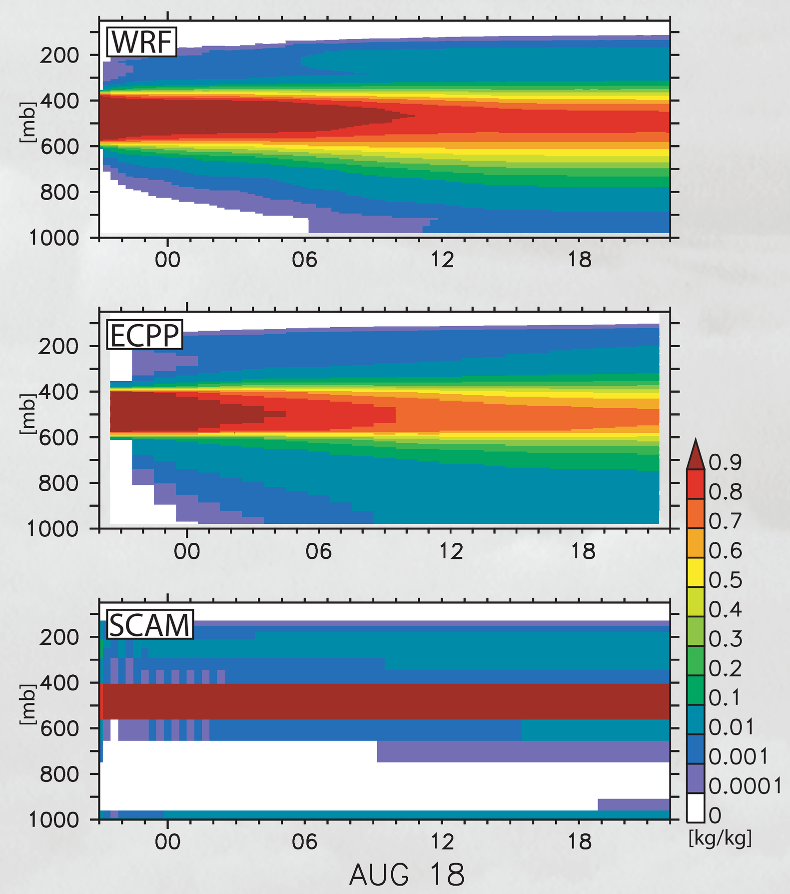


- 3-D WRF-Chem simulations were done with 2-km grid spacing to act as an idealized control. Inert tracers were initialized at selected model levels.
- Domain averaged statistics were calculated for the 3-D WRF-Chem cloud fields.
- The 3-D WRF-Chem results were used to drive an ECPP enabled single column version of WRF, which represents a host GCM grid column.
- The 3-D control run also is used to compare how well the ECPP methodology mixes the pollutants at the coarse resolution.

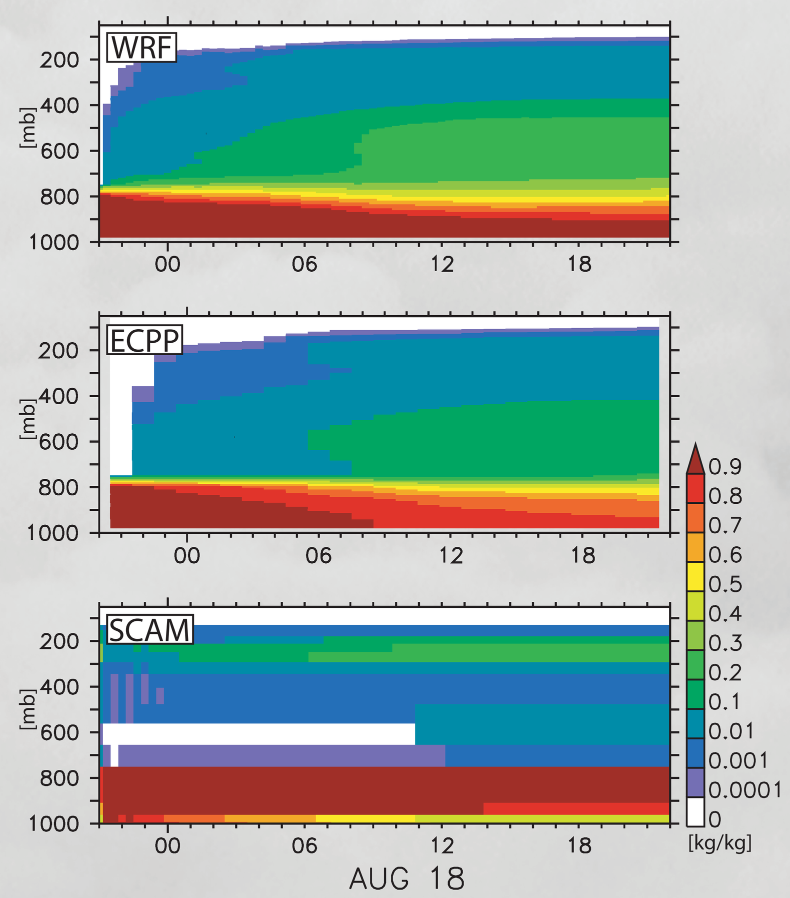
Upper Troposphere Tracer Mixing Ratio



Middle Troposphere Tracer Mixing Ratio



Lower Troposphere Tracer Mixing Ratio



Results and Conclusions

Shown to the left are time-height comparisons between simulations based on soundings and large-scale forcing profiles from the KWAJEX field campaign beginning 17 August 1999 0Z. A 21-hour spin-up period was used followed by an initialization of tracers at selected model levels. The shaded plots show how each simulation mixes the inert tracers during a 24-hour period.

The simulations are:

1. A 3-D cloud-resolving WRF-Chem simulation with 2-km grid spacing and 100x100x40 points. The boundary conditions are doubly periodic.
2. ECPP results driven by domain profiles and statistics from the 3-D WRF-Chem simulation. The profiles and model were set up to mimic a GCM grid column with ECPP embedded in it.
3. A Single Column Community Atmospheric Model (SCAM) simulation using identical forcing information as the WRF simulation.

Important points to note:

- ECPP transports low- and mid-level tracers similarly to the 3-D WRF simulation. This indicates that ECPP is able to reproduce the mixing due to a spectrum of cloud heights available from an embedded cloud model in the MMF.
- ECPP transports high-level tracers downward too much. This is sensitive to the selection criteria for downdrafts, indicating more work is needed for this parameterization detail.
- The updrafts used by ECPP disburse low-level tracers throughout the troposphere more evenly so they more closely resemble the 3-D simulation. SCAM, whose updrafts come from the Zhang-McFarlane parameterization, places most of the mixed tracer at the tropopause.
- The ECPP approach show promise for introducing detailed, interactive aerosol processes in MMF models, with minimal extra cost, by placing aerosols on the coarse grid instead of the cloud-resolving grid.

Future Plans

- Further studies will be conducted this coming year using the WRF-Chem testing framework. These studies will involve aerosols and trace gases and will evaluate the transformation and wet removal simulated by ECPP.
- ECPP will be incorporated into MMF using the interface between the System for Atmospheric Modeling (SAM) cloud model and the Community Atmospheric Model (CAM) global model.
- The ultimate goal is to produce a multiscale aerosol and climate model that treats cloud-aerosol interactions for boundary layer, shallow cumulus, and deep convective clouds. Specific components include:
  - Host GCM
    - Community Atmospheric Model (CAM)
    - MIRAGE aerosol physics
    - Explicit-Clouds Parameterized-Pollutants (ECPP)
  - Embedded cloud model
    - System for Atmospheric Modeling (SAM)
    - Vaughan Phillips 2-moment microphysics
    - Golaz and Larson higher-order turbulence closture
    - Latin hypercube sampling of microphysics

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