Global CO2 simulations and the impacts of cloud convection on atmospheric CO2 distributions

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Acknowledge:
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Phil Rasch (NCAR)
Shiliang Wu (Harvard)
Objectives

• Explore on what extent the convection schemes impact on atmospheric CO2 distribution
  (three referred cloud convection schemes are used to test their impacts on the atmospheric CO2 distributions.)

• Examine the sensitivity of atmospheric CO2 to its regional emission/sink
  (three emission scenarios are constructed constrained by IPCC 2001 framework to examine their impacts on the atmospheric CO2 under a ‘fixed’ convection.)
‘Standard’ simulation

- Simulate global CO2 at year 2000 with Unified Chemistry Transport Model (UCTM) by repeating Kawa’s work (2004);

- Obtain concurrent CO2 observations from CMDL surface and CMDL aircraft database to evaluate the simulations;

UCTM setting for ‘standard’ simulation:
- Spatial resolution: 2° (latitude) x 2.5° (longitude) x 25 eta layers
- Temporal resolution: 15 minutes for dynamical processes
- Driven by GEOS-4 version 3 3-hour assimilated meteorological fields
- Same transport algorithms as in PCTM [Kawa et al., 2004], convection code denoted as CONV1
- A ‘background’ emission scenario (Emi.1) from TransCom3
## Features of model and observations

<table>
<thead>
<tr>
<th></th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2° x 2.5°</td>
<td>daily average</td>
</tr>
<tr>
<td>CMDL surface</td>
<td>on site</td>
<td>instantaneously, weekly sample</td>
</tr>
<tr>
<td>CMDL aircraft</td>
<td>on site</td>
<td>instantaneously, usually afternoon, 0-2 samples /month</td>
</tr>
</tbody>
</table>

- **Representation error**
- **Rectification error**
Aircraft CO$_2$ (ppm)

Model CO$_2$ (ppm)

0-2 KM
2-4 KM
> 4 KM
<table>
<thead>
<tr>
<th></th>
<th>Conv1</th>
<th>Conv2</th>
<th>Conv3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implemented in</td>
<td>PCTM</td>
<td>GOCART; GOES-CHEM</td>
<td>MATCH; GOES-CHEM</td>
</tr>
<tr>
<td>Differentiate tracer</td>
<td>a semi-implicit</td>
<td>an upstream differencing</td>
<td>an upstream differencing</td>
</tr>
<tr>
<td>in &amp; out cloud</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Numerical scheme</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differentiate shallow &amp; deep cloud</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Constrained by</td>
<td>cloud mass flux</td>
<td>cloud mass flux;</td>
<td>shallow: shallow cloud mass;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>detrainment;</td>
<td>overshoot parameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>entrainment</td>
<td>deep: updraft; downdraft;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>updraft entrainment;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>downdraft entrainment</td>
</tr>
</tbody>
</table>
CMDL

UCTM

Conv.1                      Conv.2                      Conv.3

ALT (82.45N, 62.52W)
ICE (63.34N, 20.29W)
UUM (44.45N, 111.10E)
MLO (19.53N, 155.58W)
SEY (4.67S, 55.17W)
ASC (7.92S, 14.42W)

CMDL

UCTM

Surface CO2 [ppm], January 2000

Conv.1

Max.  Min.
373.3  344.0

Conv.2

373.4  344.8

Conv.3

375.3  346.3
Surface CO2 [ppm], July 2000

Max.  Min.

363.8  335.4

363.4  339.1

363.1  343.1
Three emission scenarios

IPCC 2001

(Fg C/yr)

6.3 ± 0.4

Fossil fuel

Biosphere

Ocean - Atmospheric

Residual terrestrial sink

Land use change

Land - Atmospheric

Atmospheric

6.3 ± 0.4

-1.7 ± 0.5

1.7 (0.6 to 2.5)

-1.9 (0.3 to -3.9)

3.2 ± 0.1

-54.82

-2.19

1.0

-1.8

3.98

3.16

3.18

54.82

3.2 ± 0.1

3.16

3.18

Emi.1

Emi.2

Emi.3
Surface CO2 [ppm], January 2000

Max.      Min.
375.3    346.3
375.0    345.4
374.9    345.0
Surface CO2 [ppm], July 2000

Max. Min.

363.1 343.1

363.4 338.7

364.5 337.2
Summary

• Atmospheric CO discrepancies are apparent by using different convection transport algorithms within a single CTM framework.

• The maximum displacements occur in boreal forest summer season, and it reasonably occurs between CONV1 and CONV3 with a CO2 difference of 7.7 ppm, which is about a quarter of the CO2 seasonality for that area.

• This summer largest discrepancy is primarily attributed to the season’s severe deep cloud activities which are represented in different ways in three convection approaches.

• The discrepancies shown here serve the low bound of potential convection error in the forward models.
• Differences between the “complete” and “approximate” cloud transport forms have similar magnitude to uncertainties in the emissions, in the context of agreement between simulations and observations.

• A potentially much greater investment for this type of work would be to work on-line in the GCM and develop a convective transport configuration that works well for both meteorology and for trace gases (SF6, radon, CO2, etc)
Approach

_ Simulate global CO2 at year 2000 with Unified Chemistry Transport Model (UCTM) by repeating a “Standard simulation”;_

_ Obtain concurrent CO2 observations from CMDL surface and CMDL aircraft database to evaluate the simulations;_

_ Apply three referred cloud convection schemes to investigate their impacts on the atmospheric CO2 distributions._

_Construct three emission scenarios constrained by IPCC 2001 framework and examine their impacts on the atmospheric CO2 under a ‘fixed’ convection._
UCTM

- Spatial resolution: 2° (latitude) x 2.5° (longitude) x 25 eta layers
- Temporal resolution: 15 minutes for dynamical processes
- Driven by GEOS-4 version 3 3-hour assimilated meteorological fields
- Processes for CO2 including emissions and transport
- A ‘background’ emission scenario from TransCom3
Impacts of emission uncertainties in CO2 ecosystem on atmospheric CO2 distributions
CO2 emissions (Pg C/yr):

<table>
<thead>
<tr>
<th>Fossil Fuel</th>
<th>Biosphere</th>
<th>Land</th>
<th>RTS</th>
<th>Ocean net</th>
<th>Atmos.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEP1</td>
<td>NEP2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Andres et al., 1996)</td>
<td>(Randerson et al., 1997)</td>
<td></td>
<td></td>
<td>(Takahashi et al., 1999)</td>
<td></td>
</tr>
<tr>
<td>Emi. 1</td>
<td>6.17</td>
<td>-13.61</td>
<td>+13.61</td>
<td>-2.19</td>
<td>3.98</td>
</tr>
<tr>
<td>Emi. 2</td>
<td>6.17</td>
<td>-13.61</td>
<td>+13.61</td>
<td>-0.82</td>
<td>-2.19</td>
</tr>
<tr>
<td>Emi. 3</td>
<td>6.17</td>
<td>-13.61</td>
<td>+13.61</td>
<td>1.00</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

* NPE1 covers the regions dominated by NPP and NEP2 dominated by RESP.

** Land change contains fire and deforestation and distributes as the same as biomass burning.

*** RTS stands for residual terrestrial sink and contains extra plant growth and ecosystem uptake. It is assumed to be distributed as the same as NEP1 and the magnitudes to be 0.06 and 0.1324 of NEP1, respectively.
**CO2 Budgets:** (unit: Pg C/mon or Pg C /yr):

<table>
<thead>
<tr>
<th></th>
<th>Fossil Fuel</th>
<th>Biosphere</th>
<th>Ocean</th>
<th>Atmos.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NPP</td>
<td>RESP.</td>
<td>NEP1</td>
<td>NEP2</td>
</tr>
<tr>
<td>(Andres et al., 1996)</td>
<td></td>
<td>(Randerson et al., 1997)</td>
<td></td>
<td>(Takahashi et al., 1999)</td>
</tr>
<tr>
<td>Jan.</td>
<td>-3.19</td>
<td>3.83</td>
<td>-0.59</td>
<td>1.23</td>
</tr>
<tr>
<td>Feb.</td>
<td>-3.05</td>
<td>3.88</td>
<td>-0.61</td>
<td>1.44</td>
</tr>
<tr>
<td>Mar.</td>
<td>-3.53</td>
<td>4.09</td>
<td>-0.72</td>
<td>1.28</td>
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<tr>
<td>Apr.</td>
<td>-3.76</td>
<td>4.42</td>
<td>-0.65</td>
<td>1.31</td>
</tr>
<tr>
<td>May</td>
<td>-5.20</td>
<td>4.80</td>
<td>-1.19</td>
<td>0.80</td>
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<tr>
<td>Jun.</td>
<td>-6.73</td>
<td>5.13</td>
<td>-2.19</td>
<td>0.59</td>
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<tr>
<td>Jul.</td>
<td>-7.38</td>
<td>5.39</td>
<td>-2.72</td>
<td>0.73</td>
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<tr>
<td>Aug.</td>
<td>-6.42</td>
<td>5.41</td>
<td>-1.98</td>
<td>0.97</td>
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<tr>
<td>Sept.</td>
<td>-4.67</td>
<td>5.15</td>
<td>-0.94</td>
<td>1.42</td>
</tr>
<tr>
<td>Oct.</td>
<td>-3.99</td>
<td>4.67</td>
<td>-0.78</td>
<td>1.47</td>
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<tr>
<td>Nov.</td>
<td>-3.55</td>
<td>4.17</td>
<td>-0.62</td>
<td>1.24</td>
</tr>
<tr>
<td>Dec.</td>
<td>-3.36</td>
<td>3.89</td>
<td>-0.61</td>
<td>1.14</td>
</tr>
<tr>
<td>Ann.</td>
<td>6.17</td>
<td>-54.82</td>
<td>+54.82</td>
<td>-13.61</td>
</tr>
</tbody>
</table>

*NEP=NPP-RESP.*

*NEP1 covers the regions dominated by NPP and NEP2 dominated by RESP.*
Cloud convection algorithm (Conv.1)

A semi-implicit convective module, constrained by the subgrid-scale cloud mass flux from the assimilation system (Kawa et al, 2004)

Vertical cloud transport is calculated by:

\[ q_{k}^{t+\Delta t} - q_{k}^{t} = \frac{g\Delta t}{\Delta p_{k}} \left[ C_{k+1} \left( q_{k+1}^{t} - q_{k}^{t} \right) - C_{k} \left( q_{k}^{t} - q_{k-1}^{t} \right) \right]^{t+\Delta t/2} \]

- \( q \) : is the tracer concentration,
- \( C_{k}, C_{k+1} \) : are the net convective mass flux at the upper and lower edges of layer \( k \),
- \( t \) : is the model time step,
- \( \Delta p_{k} / g \) : is the air mass of the layer.
Cloud convection algorithm (Conv.2)

An upwind differencing scheme derived from the steady state mass continuity of the background air and the cloud air in a vertically discretized flux-form transport equation, constrained by the subgrid-scale cloud mass flux (C) and detrainment (D) from the assimilation system (Lin, 1996)

Vertical cloud transport is calculated by:

\[ M_k q_{k+1}^t = M_k q_k^t + \Delta t \left\{ C_{k+1} \left[ Q_{k+1}^* - q_k^t \right] - C_k \left[ Q_k^* - q_{k-1}^t \right] \right\} \]

\[ M_{km} Q_{km} = M_{km} q_{km}^t - \Delta t C_{km} \left[ Q_{km}^* - q_{km-1}^t \right] \]

\[ (C_k + D_k) Q_k^* = E_k q_k^t + C_{k+1} Q_{k+1}^* \]

\[ E_k = (C_k + D_k) - C_{k+1} \]

\[ q_k, q_{k+1}, q_{km} \] : are the tracer mixing ratios at layer k, k+1, and cloud base,

\[ Q_k^* \] : is the tracer mixing ratio inside the cloud,

\[ M_k = 100 \frac{\Delta p_k}{g} \] : is the background air mass per unit area [kg/m²],

\[ t \] : is the model time step,

\[ E \] : the rate of entrainment.
Cloud convection algorithm (Conv.3)

The scheme considers shallow (Hack) convection and deep (Z-M) convection (used in NCAR MATCH transport model and Harvard GEOS-CHEM model).

Shallow convection uses cloud mass fluxes and overshoot parameters in a characteristic convective adjustment time scale from the Hack scheme to mix the passive constituents.

Deep convection distinguishes the mass fluxes from updraft, downdraft, updraft entrainment, updraft detrainment, and downdraft entrainment.
Cloud convection algorithm (Cont.)

Deep convection uses simple first order upstream biases finite differences to solve the steady state mass continuity equations for the ‘bulk’ updraft and downdraft mixing ratios and the mass continuity equation for the gridbox mean [Collins et al., 2004]

\[
\frac{\partial (M_x q_x)}{\partial p} = E_x q_e - D_x q_x
\]

\[
\frac{\partial \tilde{q}}{\partial t} = \frac{\partial}{\partial p} \left( M_u \left( q_u - \tilde{q} \right) + M_d \left( q_d - \tilde{q} \right) \right)
\]

Here subscript \( x \) is used to denote the updraft (u) or downdraft (d) quantity. \( M \) is the mass flux in units of Pa/s defined at the layer interfaces, \( q_x \) is the mixing ratio of the updraft or downdraft. \( Q_e \) is the mixing ratio of the quantity in the environment (that part of the grid volume not occupied by the up and downdrafts), and is assumed to be the same as the gridbox averaged mixing ratio. \( E_x \) and \( D_x \) are the entrainment and detrainment rates (units of \( s^{-1} \)) for the up- and downdrafts. Updrafts are allowed to entrain or detrain in any layer. Downdrafts are assumed to entrain only, and all of the mass is assumed to be deposited into the surface layer.
What are the differences of transport fields between GEOS-4 and GEOS-3?
Zonal mean cloud mass flux (g/m²/s) at 2000
Zonal mean vertical diffusion diffusivities (m²/s) at 2000

GEOS-4

JAN

GEOS-3

JAN

Pressures (mb)

-60  -30   0    30    60

-60  -30   0    30    60

JUL

JUL

Latitude

Pressure (mb)

0  4   8  12  16  20  24  28  32  36  40

Layers

Color Scale
Zonal mean cloud mass flux (g/m²/s) at 2000
Surface CO (ppb) in 200007

GEOS-3, Conv. 2

GEOS-4, Conv. 1

GEOS-4, Conv. 2

GEOS-4, Conv. 3