Status of carbon cycle to be incorporated in AOGCMs

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AGCI
Earth Systems Models: The Next Generation
The global carbon cycle

- **Ocean (39,000)**
  - DOC, DIC export: 0.8
  - Ocean sink: 1.7
  - Accumulation: +3.2

- **Living Carbon (600)**
  - Photosynthesis: 120
  - Plant respiration: 60
  - Soil respiration: 55

- **Dead Carbon (1600)**
  - Charcoal formation: <0.1

- **Combustion CO₂ (3.5)**
  - Aerosols: <0.1

- **Combustion CO (0.5)**

- **Déforestation**
  - 2

- **Air-sea gross fluxes**
  - 90

- **CO → CO₂ oxidation**

- **Land Sink**
  - 3

- **Emissions**
  - 6
Budget from Observations

CO$_2$  
O$_2$

ATMOSPHERE

fossil

land

ocean

SEDIMENTS
$CO_2 = FF - Land - Ocean$

$O_2 = \alpha FF - \beta Land$

Diagram showing the budget from observations with arrows indicating the flow of $CO_2$ and $O_2$ through the atmosphere, land, fossil, ocean, and sediments.
Processes

• Ocean
  – *Air-sea exchange driven by \_pCO2*
  – *Export through circulation*

• Land
  – *Fertilization effect*
  – *Nitrogen deposition*
  – *Land cover change legacy*
  – *Climate change/variability*
  – ???
Examples of carbon cycle models (ORCHIDEE and PISCES)

Krinner et al., 2005

Aumont et al., 2003
Climate-carbon coupling

• Rational
  – CO₂ is a greenhouse gas
  – Land and ocean carbon cycle play a role in the CO₂ growth rate
  – Land and ocean carbon cycle respond to climate
Land and ocean carbon cycle response to climate

- Sinks saturate with increasing CO$_2$
- Sinks reduce with future climate

*IPCC TAR, 2001*
Development of IPSL-CM2-C

- IPSL-CM2 ocean atmosphere climate model
- SLAVE land carbon cycle
- HAMOCC3 ocean carbon cycle

- Offline simulations
- Online simulations
Offline simulations

Atm CO₂ → ATM → OCN → Climatic fields → OCN → BIO → CO₂ Flux

IN

CMIP (1%/yr)

[CO₂]

time

CO₂ emission

time

OUT

CO₂ emission?
Offline simulations

- Similar to the IPCC TAR figure:
  - Land and ocean uptake saturate with \( \text{CO}_2 \)
  - Climate change reduces these uptakes
  - Compatible emissions are reduced

Friedlingstein et al., 2001
First estimate of the feedback

\[ \Delta T^{COU} = \frac{\partial T}{\partial C} \frac{\partial C}{\partial T} \Delta T^{UNC} \]

\[ = \frac{1}{1 - g} \Delta T^{UNC} \]

\[ = f\Delta T^{UNC} \]

\( \partial T/\partial C \) known from CMIP

\( \partial C/\partial T \) estimated here

Feedback factor = \( \sim 1.2 \)

Friedlingstein et al., 2001
Online simulations

from 1860 to 2100*

*2049-2100 done at DKRZ
Simulation design

- Coupled (changing climate)
- Uncoupled run (constant climate)

Allows to estimate the feedback on atmospheric CO$_2$
Global response

- CO2 growth rate is faster in the coupled run than in the uncoupled.
- 80 ppmv by 2100.
- Feedback = 20% (as estimated in the offline runs)

Dufresne et al., 2002
The carbon cycle response

- Land uptake is reduced (40%)
- Ocean uptake unaffected

Dufresne et al., 2002
The land response

Increase in soil aridity

Extension of the growing season

Berthelot et al., 2002
The ocean no-response

- In a coupled system, the ocean is affected by the land through the atmosphere.
- The reduced land uptake induces an increased ocean uptake.

Dufresne et al., 2002
Sensitivity to the simulated climate (CMIP database)

- Although all CMIP models have different control climate, they all simulate a reduction of SLAVE carbon uptake

*Berthelot et al., 2005*
Hadley Centre results

CO₂ concentrations (ppmv)

Cox et al., 2000

Positive feedback

200 ppm by 2100
Hadley Centre

Scenario

Fixed climate

Cox et al., 2000
Hadley Centre

Amazon die-back

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Map</th>
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<tbody>
<tr>
<td>2020–2029</td>
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<td>2030–2039</td>
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<td>2090–2099</td>
<td><img src="image8" alt="Map" /></td>
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Cox et al., 2000
C4MIP activity

- IGBP/GAIM (AIMES) - WCRP/WGCM coordinated activity to explore the coupled climate carbon cycle feedback

- Started with 2 models,

- Then: LLNL, UVIC, UMD, CCSM1, CLIMBER, Frontiers, MPI, BERN, and (last but not least) IPSL LOOP
Back to C4MIP global results

Friedlingstein et al., 2006
C4MIP implications

- Uncertainty due to the carbon cycle uncertainty
- Higher $[\text{CO}_2]$, larger climate change

- C4MIP $\text{CO}_2$ : 750-1000 ppm
  AR4 $\text{CO}_2$: 830 ppm

- Estimate of $\Delta T$ accounting for non-$\text{CO}_2$ GHG and aerosols RF
- Accounting for their feedback on $[\text{CO}_2]$ and therefore on $\Delta T$
1st conclusion

- All C4MIP models simulate a positive feedback
  - *larger warming*
  - *or larger reduction in emissions*

- Uncertainty in the 21st century CO$_2$ (range: 750 – 1000 ppm)

- Large uncertainty on the feedback (20 to 220 ppm)

- Feedback analysis to attribute uncertainty
Feedback analysis

\[ \Delta CO_2 = EMI - \Delta F_{ao} - \Delta F_{ab} \quad (1) \]
\[ \Delta T = \alpha \Delta CO_2 + \Delta T_{ind} \quad (2) \]

with:

\[ \Delta F_{ao} = \beta_{ao} \Delta CO_2 + \gamma_{ao} \Delta T \quad (3) \]
\[ \Delta F_{ab} = \beta_{ab} \Delta CO_2 + \gamma_{ab} \Delta T \quad (4) \]

(3) and (4) in (1), then (1) in (2) gives:

\[ \Delta T_{cou} = \frac{1}{1-g} \Delta T_{unc} \]

with:

\[ g = \alpha (\gamma_{ao} + \gamma_{ab})/(1+ \beta_{ao} + \beta_{ab}) \]

\( g \) is the gain of the feedback

Friedlingstein et al., 2003, 2006
Feedback analysis

g, the gain, is large if:

\[ \alpha, \text{ the GCM temperature sensitivity to CO}_2 \text{ is large} \]

\[ \gamma_{ao} \text{ and } \gamma_{ab}, \text{ the ocean and land carbon cycle sensitivities to climate change are large} \]

\[ \beta_{ao} \text{ and } \beta_{ab}, \text{ the ocean and land carbon cycle sensitivities to CO}_2 \text{ are low} \]
\( \alpha \) climate response to CO\(_2\)
$\beta$  C-cycle response to CO$_2$

IPSL-CM2_C  IPSL_CM4_LOOP  Friedlingstein et al., 2006
γ C-cycle response to climate

Friedlingstein et al., 2006
Why such a large uncertainty on $\gamma_L$
2nd conclusion

• It’s in the land
• In the tropics
• Large uncertainty due to differences in regional
  – climate change
  – land carbon response to climate change
How to reduce the uncertainty

- Need for
  - *real validation*
  - *more realistic climate*
  - *more realistic carbon cycle*
LOOP
The new IPSL C-C model

\[ \frac{d[CO_2]}{dt} = (EMI - Flux_{land} - Flux_{ocean}) \]

\[ \Delta t = \text{physical time step} \]

\[ \Delta t = \text{1 day} \]

\[ \text{CO}_2 \text{ concentration re-calculated each month} \]

EMI = external forcing
[Marland et al, 2005
Houghton, 2002]

Cadule et al., in prep

Atmospheric
[CO_2]

Flux
land
+ Flux
ocean

Net total carbon flux

Terrestrial biosphere
ORCHIDEE
(STOMATE activated)

Marine
Biochemistry
PISCES

Climate

Atmosphere
LMDZ4

Ocean
ORCA-LIM
OPA 8.2

Coupler
OASIS 2.4

Carbon

Land flux GtC/mth

Ocean flux GtC/mth

[Marland et al, 2005
Houghton, 2002]
Zero Order Validation

Carbon dioxide Concentration [ppm]

Global mean surface temperature anomalies

Base period: 1961-1990

Cadule et al., in prep
First Order Validation

• “IPCC” carbon budget (GtC/yr)

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<thead>
<tr>
<th></th>
<th>Atmosphere</th>
<th>Ocean</th>
<th>Land</th>
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<tbody>
<tr>
<td>1980’s</td>
<td>LOOP</td>
<td>IPCC</td>
<td>LOOP</td>
</tr>
<tr>
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<td>2.7</td>
<td>3.3</td>
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<tr>
<td>1990’s</td>
<td>2.0</td>
<td>1.8±0.8</td>
<td>2.0</td>
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<tr>
<td></td>
<td>2.8</td>
<td>1.6 (-0.3 to 4)</td>
<td>3.3</td>
</tr>
</tbody>
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Atmospheric carbon variation

Land use, fossil fuel, land, ocean

Cadule et al., in prep
Second Order Validation

- Atmospheric CO2
  - Offline transport over 1979-2003

Cadule et al., in prep
- Seasonal cycle
- Long term trend

Cadule et al., in prep
Improving the carbon cycle

- Coupled C-C run with fires and land-use
- Include nitrogen cycle
SPITFIRE

- Currently implemented in ORCHIDEE
  - will allow to estimate role of fire on CO₂
  - will allow to estimate impact of climate change on fire and feedback on climate
  - Emissions of CH₄, NOx,…

Thonicke, et al., 2005
Land use
Nitrogen

Motivation:

• Controls the carbon cycle
  – Impact on carbon uptake
  – Impact on the C-C feedback estimate
Nitrogen gap

Hungate et al., 2003
Conclusions

• The land biosphere is a key, but poorly known, player in the carbon and climate system
• The climate carbon cycle feedback is positive but we still have to quantify it
• Fire and nitrogen may affect the C-C feedback
• The land use effect on the system is still poorly known