The role of North Atlantic Ocean dynamics in simulating glacial inception: a study with CCSM4

Feng He, Steve J. Vavrus, John E. Kutzbach
Center for Climatic Research, University of Wisconsin-Madison

William F. Ruddiman
Department of Environmental Sciences, University of Virginia
400 Thousand Years of Atmospheric Carbon Dioxide Concentration and Temperature Change

CO₂ Concentration (from Antarctic Ice Cores)

Temperature Change (°C) (from Antarctic Ice Cores)

Thousands of years BP (before present)

Current Level
1800 AD Level

CO₂ concentration from Mauna Loa Observations & Antarctic Ice Cores

Data Source CO₂: ftp://cdiac.ornl.gov/pub/trends/co2/vostok.icecore.co2

Graphic: Michael Ernst, The Woods Hole Research Center
CCSM4 simulations of Glacial inception

### CCSM4 Simulations: 3 fully-coupled & 3 slab ocean runs

**Ocean dynamics:**
*difference between fully-coupled and slab-ocean runs*

<table>
<thead>
<tr>
<th>1° resolution</th>
<th>Fully-Coupled (FC)</th>
<th>Slab Ocean Model (SOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>355 ppm</td>
<td>355 ppm</td>
</tr>
<tr>
<td>PI</td>
<td>285 ppm</td>
<td>285 ppm</td>
</tr>
<tr>
<td>NA (NoAnthro)</td>
<td>245 ppm</td>
<td>245 ppm</td>
</tr>
</tbody>
</table>
## CCSM4 Simulations: initialization of fully-coupled runs

<table>
<thead>
<tr>
<th>Fully-coupled run</th>
<th>Initialization</th>
<th>Run length</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>Year 1990 of NCAR 20th Century Ensemble Member (b40.20th.track1.1deg.004)</td>
<td>360 years</td>
</tr>
<tr>
<td>PI (NCAR)</td>
<td>Performed by NCAR</td>
<td>1,300 years</td>
</tr>
<tr>
<td>NA (NoAnthro)</td>
<td>Year 1300 of NCAR Pre-Industrial Control run (b40.1850.track1.1deg.006)*</td>
<td>180 years</td>
</tr>
</tbody>
</table>

NA run:
*With modified T,S initial condition to account for the cooling from lowered GHG*
CCSM4 simulations:

135-year slab ocean runs: equilibrium is OK

Climatology is calculated as the average of the last 50 years

PD  PI  NA

Global SAT

Top of atmosphere net radiation flux
CCSM4 simulations:

Fully-coupled runs: near equilibrium

Climatology is calculated as the average of the last 50 years

PD (360 years)

PI (NCAR) (1300 years)

NA (180 years)

Global SAT

Top of atmosphere net radiation flux

+0.2 Wm⁻²

-0.1 Wm⁻²

-0.1 Wm⁻²
SOM Run (NA vs. PI)
Global Surface temperature:

CO₂ (245ppm vs. 285 ppm)

ΔT = -0.90 K
Radiative forcing
ΔF = -1.01 W/m²
Climate Sensitivity:
ΔT/ΔF*ΔF₂xco₂
= (-0.90)/(-1.01)*3.7
= 3.3 K
Consistent with
Bitz et.al (2012): 3.2 K
SOM Run (NA vs. PI)
Permanent (12-month) snow:

NA: 8.6 million km$^2$
PI: 6.9 million km$^2$
NA-PI: 1.7 million km$^2$ (25% more than PI)

$CO_2$ (245ppm vs. 285 ppm)

$CO_2$ Values:
NA: 8.6 million km$^2$
PI: 6.9 million km$^2$
NA-PI: 1.7 million km$^2$ (25% more than PI)
Climate transition in CCSM4 SOM runs: **NA-PI vs. PI-PD**

<table>
<thead>
<tr>
<th>Radiative Forcing</th>
<th>Global SAT</th>
<th>NH Sea ice area</th>
<th>NH Permanent snow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NA-PI</strong></td>
<td>-1.01</td>
<td>0.76</td>
<td>1.69</td>
</tr>
<tr>
<td><strong>PI-PD</strong></td>
<td>-2.05</td>
<td>-1.89</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Without ocean dynamics, the climate transition is quasi-linear with respect to the radiative forcing.
Fully-coupled run (NA vs. PI)
Global Surface temperature:

CO₂ (245ppm vs. 285 ppm)

ΔT = -1.42 K,
~60% more than SOM(0.90K)

Climate sensitivity:
ΔT/ΔF*ΔF_{2xco2}
= (-1.42)/(-1.01)*3.7
= 5.2 K

Climate sensitivity for NA/PI transition in fully-coupled run is
~60% larger than SOM (3.2 K)
Fully-coupled run (NA vs. PI)
Permanent (12-month) snow:

NA: 10.3 million km²
PI: 6.2 million km²

NA-PI: 4.1 million km², **140% more than SOM** (1.7 million km²)

CO₂ (245ppm vs. 285 ppm)

Months of Snow Cover
SOM Run (NA vs. PI)
Permanent (12-month) snow:
NA: 8.6 million km²
PI: 6.9 million km²
NA-PI: 1.7 million km²

CO₂ (245ppm vs. 285 ppm)
NA: 8.6 million km²
PI: 6.9 million km²
NA-PI: 1.7 million km²

Months of Snow Cover
Fully-coupled Run (PI vs. PD)
Global Surface temperature:

CO₂ (285ppm vs. 355 ppm)

ΔT= -1.37 K

Climate sensitivity:
ΔT/ΔF*ΔF₂xCO₂

= (-1.37)/(-2.05)*3.7

= 2.5 K

Climate sensitivity for PI/PD transition in fully-coupled run is ~20% less than SOM (3.2 K)
Climate transition in fully-coupled runs:

**NA-PI vs. PI-PD**

- Radiative Forcing
- Global SAT
- NH Sea ice area
- NH Permanent snow
- Global 3D Ocean Temp

With ocean dynamics, the climate transition is nonlinear.
- Larger climate sensitivity during colder climate transition.
Larger climate sensitivity during colder climate transition in fully-coupled runs

Manabe & Bryan (1985)

Fig. A2. The area mean surface air temperature from two series of the CO$_2$ experiments. The thick solid line denotes the M1 model. The thin solid line denotes the MII model.

Manabe & Bryan (1985)
Ocean dynamics increases the climate sensitivity during colder climate transition

NA - PI

Fully-coupled minus Slab Ocean

Fully-coupled

Slab Ocean

Ocean dynamics
Ocean dynamics causes larger sea ice increase south of Greenland (PI/NA)
Ocean convection is shut off south of Greenland (PI/NA transition)

PI (280 ppm)  NA (245 ppm)

PI-NA

Mixed-Layer Depth
Suppressed ocean convection accelerates sea ice growth south of Greenland during PI/NA transition

Sea ice in March

Maximum mixed-layer depth
Suppressed ocean convection accelerates sea ice growth

CO$_2$ reduction

CO$_2$ cooling

Threshold crossed

Sea ice blocks air-sea interaction

Gradual Sea ice growth

Active ocean convection

Reduction of ocean convection, less heat flux out of the ocean

Accelerated sea ice growth

New equilibrium

Ocean convection collapses

Sea ice spreads across south of Greenland


Sea ice (%) vs Model Year

Maximum Mixed-Layer Depth (m) vs Model Year
AMOC in all three simulations are about 25 Sv. So AMOC does not contribute to the nonlinearity of the climate sensitivity.

PI has the largest AMOC.

Not clear why the collapse of the deep water formation does not affect the strength of AMOC during PI/NA transition.
Conclusion

Fully-coupled CCSM4 simulations exhibit nonlinear climate sensitivity, with larger climate sensitivity during colder climate transitions (Manabe & Bryan 1985)

Ocean dynamics reduces climate sensitivity during PI/PD transition, but amplifies climate sensitivity during NA/PI transition

During NA/PI transition, the larger climate sensitivity results from the positive feedback between sea ice formation and ocean convection south of Greenland

For PI/NA transition, ocean dynamics amplifies the cooling by 57% (1.42 vs. 0.90 K), and amplify the increase of the permanent snow by 140% (4.1 vs 1.7 million km²)
Larger climate sensitivity during colder time

Without the 40 ppm CO$_2$ increase from early agriculture, incipient glacial inception might have begun in late Holocene.