Simulating the Warm Arctic Environment for the Latest Cretaceous Using the Community Climate System Model (CCSM3)

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Motivation: How to Achieve a Warm Arctic in Climate Models...

...without degrading the tropics?

The Problem:

Some Proposed Mechanisms:

- Increase greenhouse gases
- Polar Stratospheric Clouds
- Deep polar convection/LW Cloud Forcing
- Ocean heat transport
- Vegetation
- Liquid cloud properties (cloud number density and cloud drop size)

Motivation: Warm Arctic in Climate Models?

Are liquid cloud properties the solution?

Effect of Low Aerosol Concentrations on Warm Clouds

- Cloud properties are determined by pre-anthropogenic aerosols (e.g. sea salt, dust, biogenic sources)
- Use present day observations in very pristine regions to determine cloud drop number (50 per cc) and cloud drop size (17 microns)
- Lower cloud drop number for low warm clouds means: 1) lower cloud amount thru increased precipitation 2) more solar absorption by larger cloud drops. Both of these effects lead to warmer high latitude surface.
Model Details

CCSM3 (NCAR): Fully Coupled: Atm, Land, Ocean, Ice Models
T31 Atm/Land (3.75°) x3 Ocean/Ice (~3°)
Vertical resolutions: 26 Atm/25 Ocn

Experiment List: 66Ma Surface and Boundary Forcing

Controls:
6X PI CO₂ (1680 ppm), 2000ppb CH₄, other trace gases = PI
2X PI CO₂ (560 ppm), 2000ppb CH₄, other trace gases = PI

CH4 Sensitivity: (6X PI CO₂ + PI CH₄, other trace gases = PI)

Cloud properties Sensitivity: 6X PI CO₂, 2000ppb CH₄, cloud physics changes
2X PI CO₂, 2000ppb CH₄, cloud physics changes

Topography Sensitivity: 6X PI CO₂, 2000ppb CH₄, cloud physics changes, removal of Siberian Mountain Range

Vegetation Sensitivity: 2X PI CO₂, cloud physics changes, no vegetation (bareground)
2X PI CO₂, 2000ppb CH₄, no changes to cloud physics, no vegetation (bareground)
Results: Model Sensitivities

Mean Annual (Surface Air) Temperature MAT
Results: 2X Model Sensitivities

Mean Annual (Surface Air) Temperature MAT
Temperature Proxy Data (Gary Upchurch):
Paleobotany (CLAMP and Leaf Margin Analysis, other)
Terrestrial vertebrate delta O18
Marine carbonate delta O18 (exceptional preservation only)
Fish tooth delta O18
TEX86
Results: Model vs. Obs
Zonal Averaged MAT (°C)

Observational Spread of Data

Model Spread of Simulations

Latitude (degrees N)
Results: Model Vs. Obs: MAT (°C)

Western Hemisphere

2X Warmpole
81N 132W,
North Slope of Alaska
Model = 7.6°C

Proxy Data
81N 132W,
North Slope of Alaska
LFA = 5°C
Results: Model Vs. Obs: MAT (°C)
Eastern Hemisphere

Model = 7.3°C

Proxy Data
57°N 103°E, Vilyui Basin
Adjusted CLAMP = 10.5°C
Results: Model Vs. Obs: MAT (°C)
Eastern Hemisphere

6x Warmpole, No Siberian Mtns
57N 103E, Vilyui Basin
Model = 17.7°C

Proxy Data
57N 103E, Vilyui Basin
Adjusted CLAMP = 10.5°C
Results: Model vs. Obs: Mean Annual Temp (MAT °C)

Model grid output extracted at each paleo-latitude/paleo-longitude compared to point proxy data.
Results:
Model Precipitation (mm)

2X Warm pole

Tropical Rainforest (Upchurch):

Tropical rainforests occur in equatorial Africa, equatorial South America, and north-central Mexico, based on the combination of coal distribution and paleobotanical data (leaf physiognomy, large seeds, tree ferns).
Table 1. Mean annual surface temperature, model simulations

<table>
<thead>
<tr>
<th>Simulation</th>
<th>CO₂ ppm</th>
<th>CH₄ ppb</th>
<th>Liquid clouds</th>
<th>Global mean surface temperature</th>
<th>Tropical (20°S–20°N) mean surface temperature</th>
<th>Vilyui Basin mean surface temperature</th>
<th>Latitudinal gradient, 30°N –80°N, gridpoints with geologic data</th>
<th>Latitudinal gradient, 30°N –80°N, zonal average</th>
</tr>
</thead>
<tbody>
<tr>
<td>2xCO₂</td>
<td>560</td>
<td>2000</td>
<td>Standard</td>
<td>19.6°</td>
<td>28.3°</td>
<td>0.1°</td>
<td>0.44°</td>
<td>0.44°</td>
</tr>
<tr>
<td>6xCO₂</td>
<td>1680</td>
<td>2000</td>
<td>Standard</td>
<td>23.8°</td>
<td>31.9°</td>
<td>6.6°</td>
<td>0.39°</td>
<td>0.37°</td>
</tr>
<tr>
<td>6xCO₂, pre-industrial methane</td>
<td>1680</td>
<td>760</td>
<td>Standard</td>
<td>23.2°</td>
<td>31.4°</td>
<td>5.4°</td>
<td>0.40°</td>
<td>0.37°</td>
</tr>
<tr>
<td>2xCO₂ WP</td>
<td>560</td>
<td>2000</td>
<td>Warmpole</td>
<td>23.7°</td>
<td>31.7°</td>
<td>7.3°</td>
<td>10.5°</td>
<td>.0.35-.0.39</td>
</tr>
<tr>
<td>6xCO₂ WP</td>
<td>1680</td>
<td>2000</td>
<td>Warmpole</td>
<td>27.9°</td>
<td>35.5°</td>
<td>13.6°</td>
<td>0.34°</td>
<td>0.32°</td>
</tr>
<tr>
<td>6xCO₂, WP, no Siberian mountains</td>
<td>1680</td>
<td>2000</td>
<td>Warmpole</td>
<td>27.9°</td>
<td>35.5°</td>
<td>17.7°</td>
<td>0.36°</td>
<td>0.33°</td>
</tr>
</tbody>
</table>

Surface temperatures are in °C for 2m height (TREFHT). Zonal average is for all model grid points, and includes interior and high elevation regions that provide no geologic data. Note how warmpole clouds produce an average global warming similar to a tripling of atmospheric CO₂. The adjusted CLAMP temperature for the Vilyui Basin is 10.5°C. The latitudinal temperature gradient from 30°N –80°N based on geologic data is 0.35–0.39°C.

(From Upchurch et. al, submitted 2010)
Conclusions

- Implementing liquid cloud property modifications to the CCSM3 cloud physics improves model simulations at the poles and brings the model closer to the proxy data. (Increases temperatures 3-8°C).

- Among the various CCSM3 simulations, the best fit to the proxy data is the 2xPAL CO₂ simulation that includes the liquid cloud property modifications, realistic vegetation, and 2000 ppb CH₄.

- The 2xPAL CO₂ simulation successfully reproduce warm polar temperatures AND the latitudinal gradient of mean annual temperature without overheating the tropics.

- Removing the Siberian mountain range in CCSM3 removes the strong cold bias in this localized region (compared to proxy data), thus emphasizing the importance of the location and height of mountain ranges in our models.
Thank You

Questions?

NCAR is sponsored by the National Science Foundation
Results: Model Climate Regimes

E-P

Annual

mm/day

Runoff Flux

Annual

x10^{-5} \text{ kg/m}^2/\text{s}
Results: Model SST and SSS and MLD

2X Warmpole

SST °C

Mixed Layer Depth m

Surface Salinity psu

NCAR
• WVEL shows areas of upwelling (nutrient-rich waters).

• Ocean currents and gyres in general agreement with literature except in the Western Interior Seaway of North America.