Present-day and Future Permafrost Conditions in CCSM4 and Potential Feedbacks on Climate

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Permafrost extent and active layer thickness in CCSM/CLM Model

### Permafrost extent (million km²) 1970-1989

<table>
<thead>
<tr>
<th>Model</th>
<th>Permafrost extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPA obs</td>
<td>~16±?</td>
</tr>
<tr>
<td>CLM4</td>
<td>13.7</td>
</tr>
<tr>
<td>CCSM4</td>
<td>12.5</td>
</tr>
<tr>
<td>CLM3</td>
<td>11.1</td>
</tr>
<tr>
<td>CCSM3</td>
<td>11.7</td>
</tr>
</tbody>
</table>
Coupled versus offline comparison of deep (> 15m deep) ground temperatures

CCSM4

Bias = 2.96

CLM4

Bias = -1.31

Observed Temperature (°C)

CCSM4 Temperature (°C)

CLM4 Temperature (°C)
Surface air temperature biases (obs: CRU)

CCSM4
DJF Bias = 1.27°C
MAM Bias = -0.36°C
JJA Bias = 0.79°C
SON Bias = -0.86°C

CCSM3
DJF Bias = 2.95°C
MAM Bias = 1.05°C
JJA Bias = -2.93°C
SON Bias = -0.66°C

°C
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
Snowfall and snow depth bias in CCSM4

CCSM4

NDJFMA Bias = 0.49 mm d⁻¹

Anomaly of Winter Normalized Snow Depth: Permafrost Region (1986-2005)

Anomaly (m)

mm d⁻¹
1.0
0.5
0.3
0.0
-0.3
-0.5
-1.0
Projections of near-surface permafrost degradation

Bernhard Edmaier
National Geographic
Arctic land area surface air temperature (ANN)

CCSM4

The graph illustrates the projected changes in Arctic land area surface air temperature from 1900 to 2100 under different Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The blue line represents the 20th-century trend, while the other lines show the projected trends for the different RCPs. The data shows an increase in temperature over time, with RCP8.5 projecting the highest increase by 2100.
Near-surface permafrost degradation rates ~25% slower in CCSM4
Near-surface permafrost degradation in climate bias-corrected simulations

- CLM simulations forced by historical and RCP CCSM4 meteorological forcing data but with climate bias removed (dashed lines)

- Colder initial state → near-surface permafrost degradation ~20% slower
Permafrost in CESM1(CAM5)?

**CCSM4**
NDJFMA Bias = 0.49 mm d⁻¹

**CESM1(CAM5) – CCSM4**
DJF

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<td>~16±?</td>
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<tr>
<td>CESM1</td>
<td>13.4</td>
</tr>
<tr>
<td>CCSM4</td>
<td>12.5</td>
</tr>
</tbody>
</table>
Mean Soil Temperature @ 3.3m in CMIP5 models (RCP 8.5)

Mean Soil Temperature at ~3.3m Over Present Day Permafrost Area (RCP85)

Slater and Lawrence, J.Clim, submitted
So we (think) we have a model that can reasonably simulate permafrost. Can we use it to study Arctic terrestrial feedbacks?
Potential Arctic terrestrial climate-change feedbacks

- **Global warming**
- **CO₂ efflux**
- **CH₄ efflux**
- **Lakes drain, soil dries**
- **Arctic runoff increases**
- **Expanded wetlands**
- **Permafrost warms and thaws**
- **Microbial activity increases**
- **Carbon sequester**
- **Shrub growth**
- **Enhanced [nitrogen]**

Adapted from McGuire et al., 2006
Impact of projected shrub area expansion on climate and permafrost (see poster)

In CAM4/CLM4 shrub-albedo warming feedback dominates over shrub shading effect suggesting that shrub area expansion may increase rather than decrease permafrost vulnerability.

Lawrence and Swenson, ERL, 2011

Bonfils et al, ERL, 2012
Potential Arctic terrestrial climate-change feedbacks

Global warming → Arctic warming

$\text{CO}_2$ efflux → $\text{CH}_4$ efflux

Permafrost warms and thaws

Expanded wetlands

Lakes drain, soil dries

Arctic runoff increases

Carbon cycle

Carbon stocks in permafrost-affected soil

$\sim 1700 \text{ PgC}$ (Tarnocai et al., 2009)

Atmos carbon content

$\sim 750 \text{ PgC} + \sim 9 \text{ PgC} \text{ yr}^{-1}$

Adapted from McGuire et al., 2006
Permafrost-carbon feedback: Results from reduced-complexity carbon cycle model

But, many processes missing incl. representation of fast carbon response due to landscape-scale processes, deep carbon pools, vegetation feedbacks, nitrogen feedbacks, etc.

Schneider et al. 2011, Koven et al. 2011, Schaefer et al. 2011
Our ["expert"] estimate for the amount of carbon released by 2100 is 1.7–5.2 times larger than those reported in several recent modeling studies. This reflects, in part, our perceived importance of the abrupt thaw processes, as well as our heightened awareness of deep carbon pools. Active research is aimed at incorporating these main issues, along with others, into models.”

Abrupt thaw, as seen here in Alaska’s Noatak National Preserve, causes the land to collapse, accelerating permafrost degradation and carbon release.

High risk of permafrost thaw

Northern soils will release huge amounts of carbon in a warmer world, say Edward A. G. Schuur, Benjamin Abbott and the Permafrost Carbon Network.

Arctic temperatures are rising fast, and permafrost is thawing. Carbon released into the atmosphere from thawing permafrost has the potential to accelerate climate change. This is largely because of the realization that organic carbon is stored much deeper in frozen soils than was thought. Inventories typically measure the carbon content of the top 1 meter of soil, which is much less than the total carbon that is stored in frozen layers.

Greenhouse gas with about 25 times more warming potential than CO₂ over a 100-year period. However, waterlogged environments like tundra can release both CO₂ and CH₄ when permafrost begins to thaw.
Progress in CLM4.5

**CLM-CN**: revised soil biogeochemistry model with vertically resolved carbon pools, longer-lived carbon pools, anoxia effects on decomposition

**CH$_4$ emission model**: - moisture, T, vegetation controls on CH$_4$ emissions

**Prognostic wetland model**: - account for soil subsidence, thermokarst activity on wetland distribution

Adapted from McGuire et al., 2006
Soil carbon stock improvements in CLM4.5

CLM and most other land models within Earth System Models cannot build up massive permafrost carbon stocks seen in real world

CLM4.5 (beta) figure courtesy Charlie Koven
The representation of permafrost is improved in CLM4 and CCSM4, though climate biases, particularly snowfall biases, degrade the simulation.

Substantial near-surface permafrost degradation is projected for the 21st century and this is expected to initiate several feedbacks in the terrestrial Arctic system.

With available modeling tools, we cannot yet quantify the integrated impact of permafrost degradation climate (but progress towards this goal is being made).

Large-scale permafrost degradation and associated feedbacks appear likely to amplify climate change.

NCAR is sponsored by the National Science Foundation.
Offline Historical and RCP simulations

- MPI/JSBACH
- CESM-CLM
- IPSL/ORCHIDEE
- TEM6
- HIRAM
- GIPL
- SibCASA Hadley/JULES
Projections of degradation of near-surface permafrost

1970-1990

RCP2.6 (8.4)
2080-2100

RCP8.5 (3.5)
2080-2100

Lawrence et al., 2012, J. Clim.
Impact of biases in the simulated CCSM4 climate
Soil carbon in permafrost zone

Tarnocai et al. 2009
CLM soil carbon density dataset
Source data from Global Soil Data Task

Calculate thermal and hydraulic soil parameters as a weighted combination of organic and mineral soil values

Lawrence and Slater, 2007a
### Thermal and hydraulic parameters for organic soil

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$\lambda_{\text{sat}}$</th>
<th>$\lambda_{\text{dry}}$</th>
<th>$\Theta_{\text{sat}}$</th>
<th>$k_{\text{sat}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>3.12</td>
<td>0.27</td>
<td>0.37</td>
<td>0.023</td>
</tr>
<tr>
<td>Clay</td>
<td>1.78</td>
<td>0.20</td>
<td>0.46</td>
<td>0.002</td>
</tr>
<tr>
<td>Peat</td>
<td>0.55</td>
<td>0.05$^a$</td>
<td>0.9$^{a,b}$</td>
<td>0.100$^b$</td>
</tr>
</tbody>
</table>

\[
f_{\text{sc},i} = \frac{\rho_{\text{sc},i}}{\rho_{\text{peat}}} \quad \text{fraction of layer } i \text{ that is organic matter}
\]

\[
\Theta_{\text{sat},i} = (1 - f_{\text{sc},i}) \left( 0.489 - 0.00126 \% \text{ sand}_i \right) + f_{\text{sc},i} \Theta_{\text{sat},\text{sc}}
\]

- $\lambda_{\text{sat}}$: sat. thermal conductivity
- $\lambda_{\text{dry}}$: dry thermal conductivity
- $\Theta_{\text{sat}}$: volumetric water at saturation
- $k_{\text{sat}}$: sat. hydraulic conductivity

\(a\) Farouki (1981), \(b\) Letts et al. (2000)
Impact on soil temperature (SOILCARB – CONTROL)
Motivation:
account for thermal inertia of deep soil layers

Solution:
add additional layers, hydrologically inactive

Ignore geothermal heat flux (up to ~0.1 W m⁻²)
Annual cycle-depth soil temperature plots

Siberia