Modeling terrestrial Arctic processes in an Earth System Model

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Community Land Model (CLM4)

• Process-based land biogeophysics and biogeochemistry model
• Can be run “offline” forced with observed meteorology or “coupled” to the Community Earth System Model (CESM, formerly CCSM)
• Global, regional, or single point
• Developed by CESM Land Model and Biogeochemistry Working Groups
Soil temperature (permafrost)

OBS

CLM3.5

CLM3.5 + SOILCARB + DEEP SOIL

CLM4CN
Near-surface permafrost extent and active layer thickness

CCSM3

Observations

m

2.30
1.38
0.83
0.49
0.29
0.17
0.09

Disc.
Cont.
Projections of near-surface permafrost degradation

Area Containing Near-Surface Permafrost

CCSM3
CCSM4
CLM3.5 (ORGDEEP)
Shrub expansion may reduce summer permafrost thaw in Siberian tundra

D. Blok*, M. M. P. D. Heijmans*, G. Schaeppman-Strub*,†, A. V. Kononov†, T. C. Maximov† and F. Berendse*

“These results suggest that the expected expansion of deciduous shrubs in the Arctic region, triggered by climate warming, may reduce summer permafrost thaw.”
Arctic tundra vegetation experiments with CLM/CESM

Leaf Area / Stem Area Index

- Grass (LAI)
- Shrub (LAI)
- Grass (SAI)
- Shrub (SAI)
Offline CLM4: SHRUB expt – GRASS expt

Graphs showing temperature, ground heat flux, surface albedo, snow depth, and absorbed solar for both SHRUB and GRASS experiments.
The impact of expanded shrub cover is significantly different in coupled vs offline expts (i.e., increasing vs decreasing ALT)

Offline expts roughly mimic the field manipulation study - i.e., surface properties change from grass to shrub but forcing (T, P, Solar, etc) is the same
Parameterizing Thermokarst

Microtopography PDF

Low relief: e.g. Arctic coastal plains

\[ \frac{\partial \sigma}{\partial t} = \alpha \frac{\partial \text{SOILICE}_{my}}{\partial t} \]

High relief: e.g. after extensive thermokarst

Height above mean surface (m)
Soil heat accumulation
Warm permafrost case, LINEAR warming expt

Talik – layer(s) of perpetually unfrozen soil above permafrost table and below seasonally frozen ground

Lawrence et al., GRL, 2008
Goal: Represent Arctic terrestrial climate-change feedbacks in the Community Climate System Model (CCSM)

**CLM-CN**: soil carbon model undergoing major revision; accounting for effects of cold saturated conditions, vertical C distribution

**CH₄ emission model**: - moisture, T, vegetation controls on CH₄ emissions - ebullition from thermokarst lakes

**Prognostic wetland model**: - works in low relief terrain (TOPMODEL not appropriate?) - accounts for soil subsidence, thermokarst activity on wetland distribution - not all wetlands equal, different biogeochem. implications of bogs vs fens

Adapted from McGuire et al., 2006
• Despite ongoing efforts, with available modeling tools we cannot model the full scope of Arctic terrestrial change nor can we quantify the integrated impact of this change on Arctic and global climate

• Model development is hard; two steps forward, one step back

• Parameterizations need to work across Arctic and globally

• To the extent possible, data from the full annual cycle (and multiple years) is preferable
Relative influence of $\Delta$snow vs $\Delta T_{\text{air}}$ on $\Delta T_{\text{soil}}$

% of $\Delta T_{\text{soil, max}}$ (1m depth) attributable to snow state trends for the period ...

50% means that $T_{\text{soil}}$ trend equally due to snow state and $T_{\text{air}}$ trends
Projected snow changes in CCSM3 (2080-99 – 1950-69)

**NDJFM Snowfall**

**Max Snow Depth**

**Snow Thermal Conductivity**

**AMSO Snow Cover Fraction**

**Day of First Autumn Snow Accum**

**Day of Spring Snow Melt**
Prescribed snow experiments

<table>
<thead>
<tr>
<th>Snow Season Length</th>
<th>Snow Depth</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOLD_MW_DP – HOLD_DP</td>
<td>TRND_DP – HOLD_MW_DP</td>
<td>TRND_DP – HOLD_DP</td>
</tr>
</tbody>
</table>

$\Delta T_{\text{soil, max}}$
Representing the insulative properties of organic-rich Arctic soils

Soil properties are now a weighted combination of mineral and organic content

<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>
Deeper soil column

Motivation:
account for thermal inertia of deep ground layers

Solution:
add additional layers,
hydrologically inactive bedrock

Ignore geothermal heat flux (up to \( \sim 0.1 \text{ W m}^{-2} \))
Observed and modeled soil carbon content

IGBP Soil carbon content (0-1m)

CLM4CN
Wetland formation / thermokarst
Tower flux statistics (15 sites incl. tropical, boreal, mediterranean, alpine, temperate; hourly)

<table>
<thead>
<tr>
<th>Latent Heat Flux</th>
<th>Sensible Heat Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
</tr>
<tr>
<td>CLM3</td>
<td>0.54</td>
</tr>
<tr>
<td>CLM4SP</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Annual cycle-depth soil temperature plots
Siberia

Lawrence et al., 2008a
Controls on Active Layer Thickness and Soil Temperature

- Mean annual air temperature
- Snow cover, depth, and timing of snowmelt
- Thickness of insulating soil organic layer
- Vegetation cover
- Topography / aspect
- Ice content

Sturm et al. 2005
### Prescribed snow experiments (1950 to 2100)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HOLD_DP</strong></td>
<td>Hold SNWDP at 1950-69 levels</td>
</tr>
<tr>
<td><strong>HOLD_MW_DP</strong></td>
<td>Hold mid-winter SNWDP at 1950-69 levels; shoulder season SNWDP transitions linearly from 1950-69 to 2080-2099 levels</td>
</tr>
<tr>
<td><strong>TRND_DP</strong></td>
<td>SNWDP transitions linearly from 1950-69 to 2080-2099 levels</td>
</tr>
</tbody>
</table>

The diagram shows the evolution of snow depth over the year for each experiment, indicating how the snow depth changes from day to day. The experiments are compared as follows:

- **HOLD_MW_DP** – **HOLD_DP**  → impact of snow season length
- **TRND_DP** – **HOLD_MW_DP**  → impact of mid-winter SNWDP
- **TRND_DP** – **HOLD_DP**  → combined SNWDP and season length
Prescribed snow experiments

**Snow Season Length**

\[ \text{HOLD}_\text{MW}_\text{DP} - \text{HOLD}_\text{DP} \]

**Snow Cover Fraction (AMSO)**

**Snow Depth (NDJFMA)**