Modeling Arctic terrestrial processes and feedbacks

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Arctic terrestrial climate-change feedbacks

Global warming

- CO₂ efflux
- CH₄ efflux
- Soil drying, lakes drain
- Runoff increases, changes in runoff timing
- Expanded wetlands, thermokarst lakes
- Permafrost warms and thaws
- Snow albedo feedback
- Enhanced [nitrogen]
- Microbial activity increases

CO₂ uptake
- Vegetation growth or dist. shift
- CO₂ fert

Arctic warming
Arctic terrestrial climate-change feedbacks

- Arctic warming
- Enhanced nitrogen uptake
- Global warming
- CH4 efflux
- Microbial activity increases
- Vegetation growth or dist. shift
- Expanded Wetlands
- Permafrost warms and thaws
- Snow albedo feedback
- Enhanced [nitrogen]
- Microbial activity increases
- Soil drying, Lake drain
- Arctic runoff increases, changes timing
- CO2 uptake

Map of Arctic region with various climate and ecological indicators.
• >1700 PgC stored in permafrost soils
• Substantial permafrost thaw projected, especially at high emission scenarios
• Permafrost climate-carbon feedback not represented in CMIP5 models
CMIP5 Models: Near-surface permafrost extent (RCP 8.5)

Koven et al., J.Clim, 2013
Many models do not correctly represent snow insulation

Slater et al. 2017
Key land model features for permafrost simulations

- Snow model that treats snow insulation reasonably (Koven et al. 2013)
- Explicit treatment of thermal and hydraulic properties of soil organic matter (Nicolsky et al. 2007, Lawrence and Slater, 2008)
- Deep ground column ~50m depth (Alexeev et al. 2007, Lawrence et al., 2008)
- Cold region hydrology, ice impedance, perched water table (Swenson et al. 2012)
- Vertically-resolved soil biogeochemistry including nitrogen (Koven et al. 2014)
- CH\(_4\) emissions (Riley et al., 2013)
- Soil excess ice (Lee et al. 2015)
PCN: “Permafrost-enabled Model intercomparison”

Permafrost Area Loss 1960-2299 (RCP 8.5)

PCN 4 -10 million km²
CMIP5 1-18 million km²

McGuire et al., 2018
Needs for permafrost-carbon feedback modeling

- Standardize structural representation of permafrost and carbon
- Develop data sets and methodologies to benchmark models
- Utilize models to assess sensitivities to processes
- Assess and represent C impact of permafrost thermokarst responses to warming (simple model estimates suggest +50% amplification of permafrost climate-carbon feedback)

McGuire et al., 2018
Benchmarking models against field experiments

Artificial warming
Snow fence experiment

Field  Model
● Control  ● Control
■ Warming  ■ Warming

Schaedel et al, in prep
Using models to assess sources of uncertainty

Example: Uncertainty related to soil moisture projections

CESM Projections of temperature and water balance for permafrost domain (RCP8.5)
Permafrost-thaw driven transitions in runoff characteristics

- After permafrost thaw, transition to higher proportion baseflow
- Consistent with ‘observations’ and other hydrologic models (Walvoord and Striegl, 2007, Bense et al. 2009, Walvoord et al. 2012)
- High divergence in SM and runoff projections in PCN models (Andresen et al., in prep)

Lawrence et al., ERL, 2015
Active layer deepening and soil subsidence

CLM projection of subsidence by 2100
Permafrost carbon-climate feedback with and without soil drying

18% less permafrost soil carbon lost in WETSOIL case

Permafrost carbon - climate feedback with and without soil drying

Ecosystem Carbon

CH₄ emissions

Lawrence et al., ERL, 2015
Snow Albedo Feedback (SAF)

- SAF is a positive feedback climate mechanism and important driver of regional climate change
- Models exhibit large variability SAF
- Intermodel spread in SAF explains 40-50% of the CMIP5 variability in projected spring NH land warming.
- Much of the spread in SAF can be explained by differences in simulated maximum snow-covered surface albedo and the timing of the spring albedo transition

**Relationship between peak snow-covered surface albedo and spring SAF from models (black) and OBS (red) across the boreal forest.**

Fletcher et al., 2012
Many climate models struggle to capture **timing** and/or **magnitude** of seasonal changes in albedo over boreal forest and Arctic tundra regions.

- CCSM4: albedo decreases too early $\rightarrow$ weak SAF.

Thackeray et al., 2015
Reduction of SAF bias in CMIP6?

- New canopy snow storage and unloading scheme reduced bias in seasonality of snow-covered surface albedo and thus, SAF
- Cautious expectation for reduced bias in SAF in CMIP6 models
- Snow-MIP to address snow-climate interactions

Monthly climatological albedo change across the boreal forest. The light gray box shows when observational uncertainty is largest.

<table>
<thead>
<tr>
<th>Model</th>
<th>Boreal Spring SAF (%/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCSM4</td>
<td>-0.60</td>
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<tr>
<td>CLM4</td>
<td>-0.64</td>
</tr>
<tr>
<td>CLM4.5</td>
<td>-0.68</td>
</tr>
<tr>
<td>CLM5</td>
<td>-0.83</td>
</tr>
<tr>
<td>MODIS</td>
<td>-0.87</td>
</tr>
</tbody>
</table>

Slide courtesy Chad Thackeray
Challenge of heterogeneity

How much do unrepresented heterogeneous land responses to environmental change affect the strength of the overall feedbacks?
Potential Arctic terrestrial climate-change feedbacks

- Global warming
  - CO$_2$ efflux
  - CH$_4$ efflux
  - Vegetation growth or dist. shift
  - Microbial activity increases

- Permafrost warms and thaws
  - Expanded wetlands, lakes
  - Snow albedo feedback
  - Enhanced [nitrogen]

- Arctic runoff increases, changes timing
- Soil drying, Lake drain

- CO$_2$ uptake

- Arctic warming
## Permafrost in CMIP6 models?

<table>
<thead>
<tr>
<th>Process/Model</th>
<th>CESM</th>
<th>GFDL</th>
<th>UKESM</th>
<th>MPI-ESM</th>
<th>IPSL</th>
<th>NorESM</th>
<th>EC-Earth</th>
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</thead>
<tbody>
<tr>
<td>Permafrost physics</td>
<td>on</td>
<td>on</td>
<td>on</td>
<td>offline</td>
<td>on</td>
<td>on</td>
<td>on</td>
</tr>
<tr>
<td>Permafrost C</td>
<td>on</td>
<td>?</td>
<td>no</td>
<td>offline</td>
<td>offline</td>
<td>on</td>
<td>offline</td>
</tr>
<tr>
<td>CH₄ emissions</td>
<td>on</td>
<td>?</td>
<td>on</td>
<td>offline</td>
<td>offline</td>
<td>on</td>
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<td>on</td>
<td>on</td>
<td>on</td>
<td>on</td>
</tr>
</tbody>
</table>
Contrary to ‘top-down’ thaw, thermokarst processes can tap into deep permafrost C, resulting in rapid C release.

Estimating magnitude of C loss due to ‘thermokarst’ response to warming

1. Define areas vulnerable to thermokarst processes
2. Document current extent of “thermokarst” features
3. Analyze recent trends in thermokarst processes
4. Assess impacts of thermokarst processes on landscape transitions and C dynamics

5. **Initial assessment suggests that thermokarst could amplify permafrost climate-carbon feedback by 50%**

Thermokarst is subsidence of the surface that is caused by the melting of ground ice leading to fens/bogs, thermokarst lakes, thaw slumps, etc.

*Slide from Merritt Turetsky and Dave McGuire*
• SAF spread was not reduced from CMIP3 to CMIP5 despite considerable land model development - largely due to shortcomings from two models.
  – The largest SAF biases arise because of structural errors relating to the distribution/type of vegetation or the parameterization of surface albedo (i.e. vegetation masking of surface) rather than parametric errors.

• Preliminary signs from ongoing model development are positive and suggest a likely improvement in SAF among most existing models.

• However, failure to update structural errors in a couple of models will likely limit the amount of reduction in SAF spread across the CMIP6 models. This drawback may further be exacerbated by the participation of a considerable amount of new modeling centers in CMIP6.

• Therefore, the extensive land model development undergone in many modeling centers may not achieve a great reduction in SAF spread across the CMIP6 models. To this cause, concerted efforts by the whole community are needed (e.g., ESM-SnowMIP).
High uncertainty in permafrost-domain soil moisture projections in PCN models

Andresen et al., in prep
Thermokarst “state-and-transition” conceptual modeling

Ex. for Lowland Organic Terrain (Wetlands)

- Summed for all thermokarst processes, Global Warming Potential due to thermokarst ~50% of that due to ALT deepening
- Feedbacks under warming climate not captured by state-and-transition approach
- Challenge: integrate thermokarst parameterizations into ecosystem models

Turetsky et al., in preparation
Inferred soil carbon turnover timescale

\[ \tau = \frac{\text{carbon stocks (SOM)(gC)}}{\text{carbon inputs (NPP)(gC/s)}} \]

- **Observations**
  - SOM: HWSD/NCSCD
  - NPP: MODIS

**Metric for soil carbon turnover timescale**

- **CLM4** (RMSE=0.25)
- **CLM4.5** (RMSE=0.13)
- **CLM5** (RMSE=0.09)

- Observations

Koven, Hugelius, Lawrence, and Wieder, NCC, 2017
Vertically-resolved soil biogeochemistry

Koven et al., 2013
Diverse soil column configuration among land models

Soil Depth (m)

- CLM
- CoLM
- JULES
- LPJ_GUESS
- ORCHIDEE
- SiBCASA
- TEM604
- UWVIC

Layers

- CLM: 19
- CoLM: 10
- JULES: 30
- LPJ_GUESS: 8
- ORCHIDEE: 12
- SiBCASA: 18
- TEM604: 8
- UWVIC: 3
Increased focus on terrestrial processes in CMIP6

Coordinated activities to assess land role in climate and climate change

- **Land-only simulations** forced with obs historical climate and common future, land-systematic biases

- **Land Use = LUMIP**
  land use forcing on climate, biogeophysics and biogeochemistry with policy relevance

- **Land = LS3MIP**
  biogeophys feedbacks including soil moisture and snow feedbacks

- **Carbon Cycle = C4MIP**
  land biogeochemical feedbacks on climate, *emissions-driven* SSP5-8.5 21st and Extension to 2300

*Updated from Meehl et al., EOS, 2014*
High uncertainty in permafrost-domain soil moisture projections

Andresen et al., in prep
PCN: “Permafrost Model intercomparison”
Diverse permafrost loss predictions

Needs for permafrost-carbon feedback modeling

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Soil C
-50 to -650 PgC loss

Vegetation C
+25 to +375 PgC gain

Ecosystem C
-650 to +200 PgC change
Projected soil moisture change (RCP8.5) CLM4.5

Column soil moisture change by 2100

Column soil moisture change by 2300
CLM representation of permafrost hydrology

(a) Diagram showing the layers of soil and permafrost with time.

Soil water content over time:

- Total runoff
- Surface runoff
- Sub-surface runoff

Graphs showing the changes in runoff over time for different years: 1950, 1980, 2010, 2040, 2070.