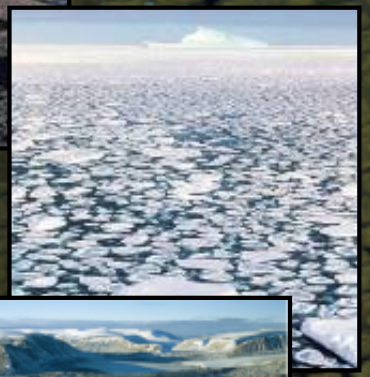
Modeling Arctic terrestrial processes and feedbacks



David Lawrence

Charlie Koven, Dave McGuire, Sean Swenson, Andrew Slater, Chad Thackeray, Chris Fletcher, Merritt Turetsky, Christina Schaedel

National Center for Atmospheric Research, Boulder, CO

NESL

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Office of Science

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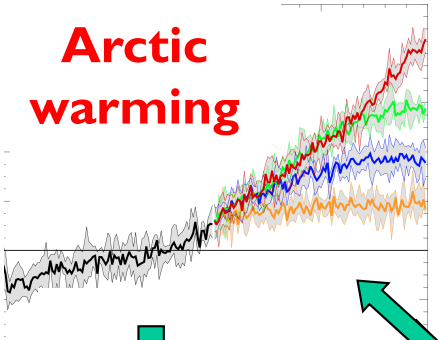
NCAR is sponsored by the National Science Foundation

Arctic terrestrial climate-change feedbacks

Global warming

Arctic warming



CO_2 uptake

Vegetation growth or dist. shift

CO_2 fert

Enhanced [nitrogen]

Microbial activity increases

Permafrost warms and thaws

Snow albedo feedback

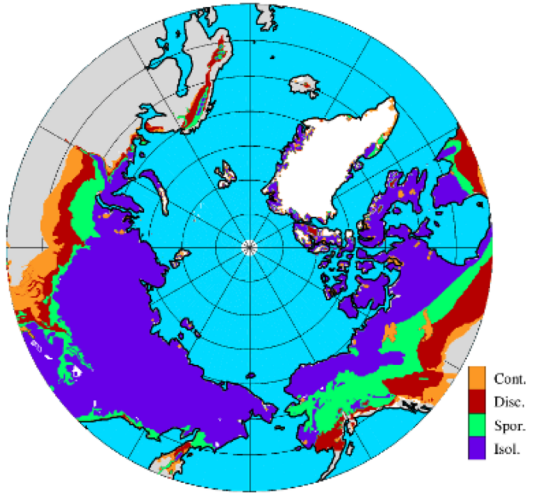
Expanded wetlands, thermokarst lakes

Soil drying, lakes drain

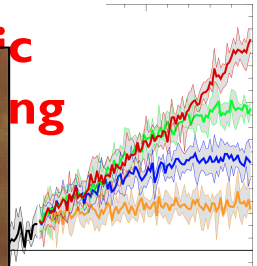
CO_2 efflux

CH_4 efflux

Runoff increases, changes in runoff timing



Arctic terrestrial climate-change feedbacks



Arctic
ng

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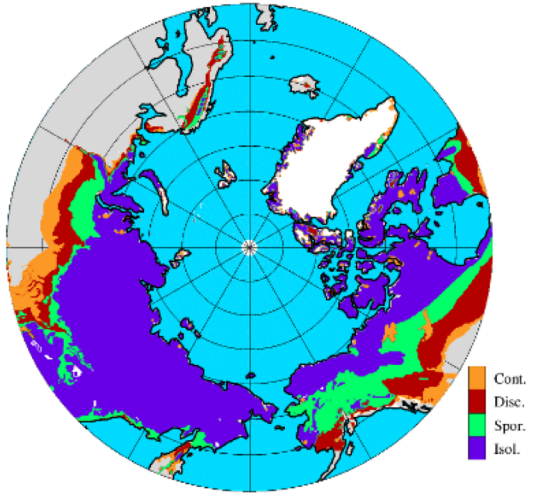
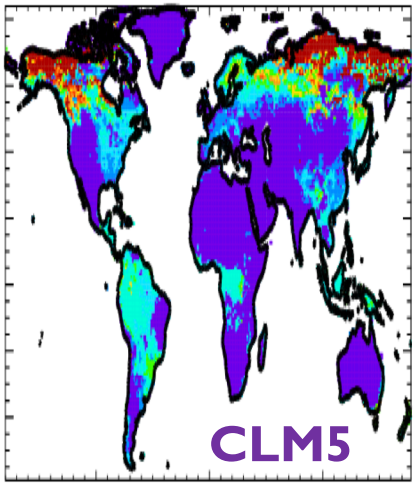


Arctic runoff increases, changes timing

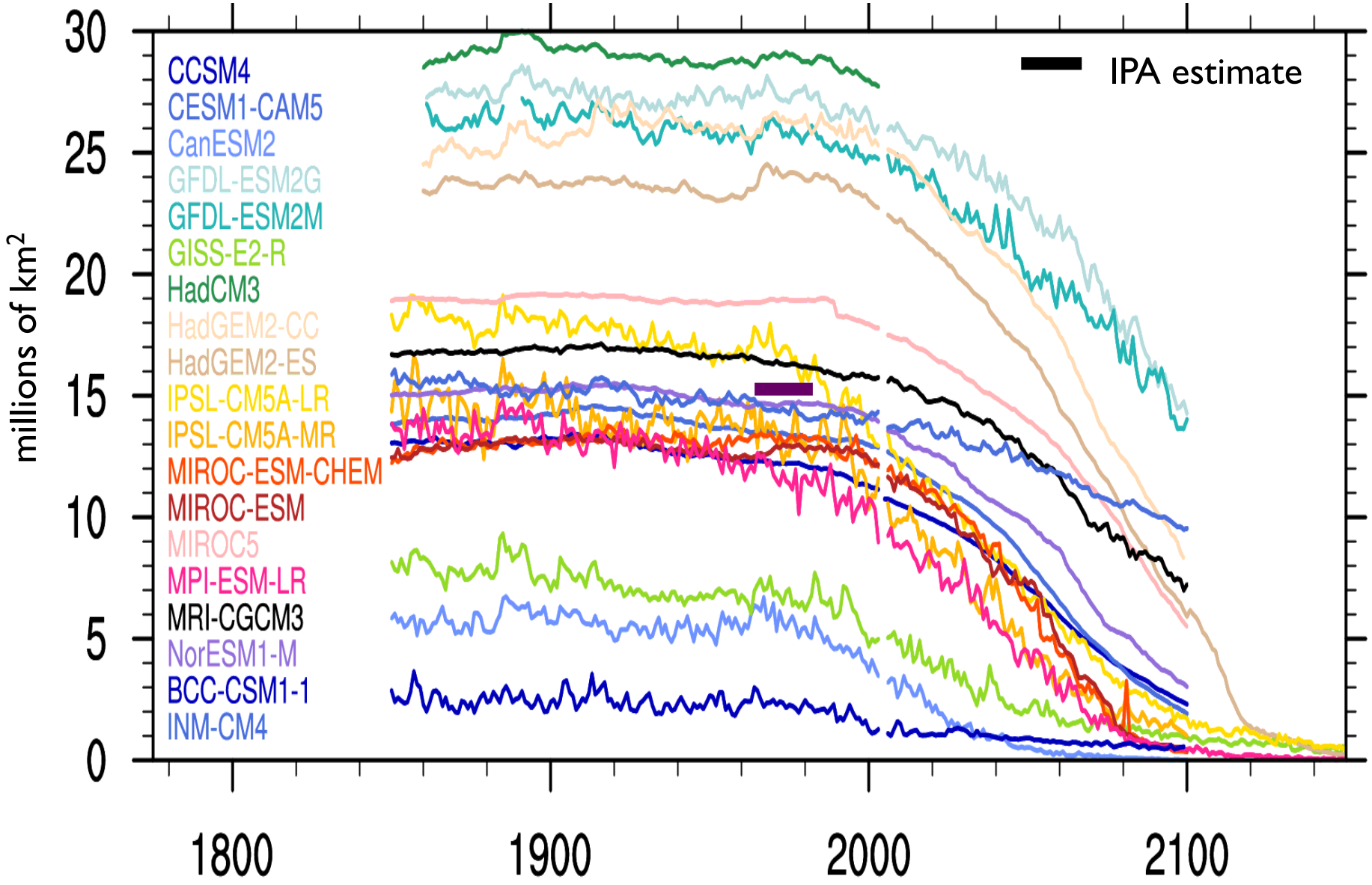
Permafrost climate-carbon feedback

Ecosystem Carbon



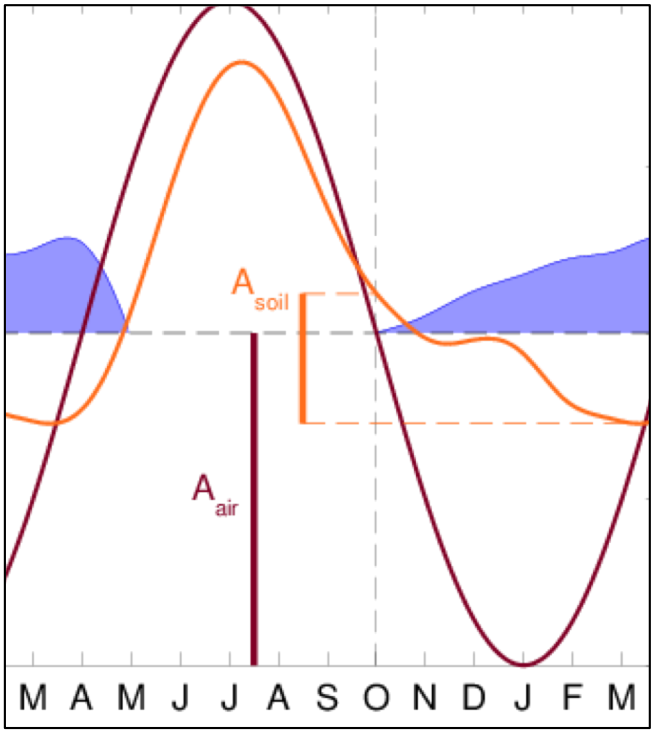
- >1700 PgC stored in permafrost soils
- Substantial permafrost thaw projected, especially at high emission scenarios
- Permafrost climate-carbon feedback not represented in CMIP5 models

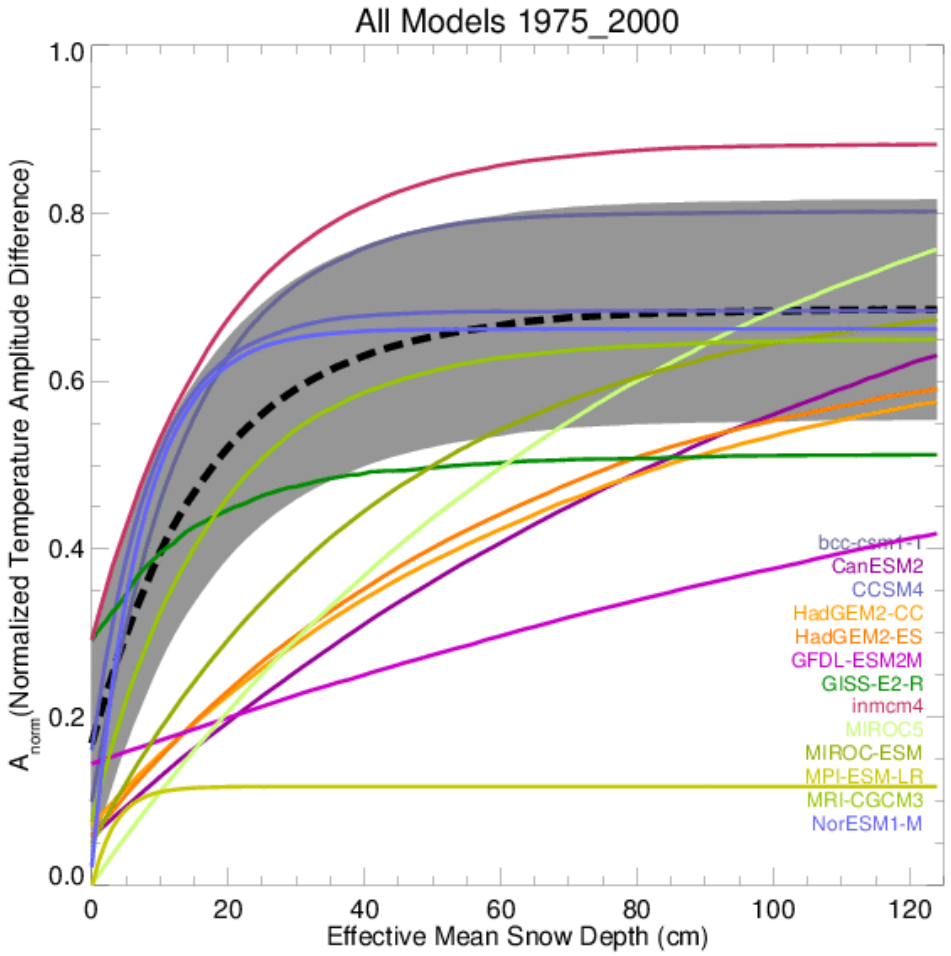
CMIP5 Models: Near-surface permafrost extent (RCP 8.5)



Koven et al., J.Clim, 2013

A snow heat transfer metric



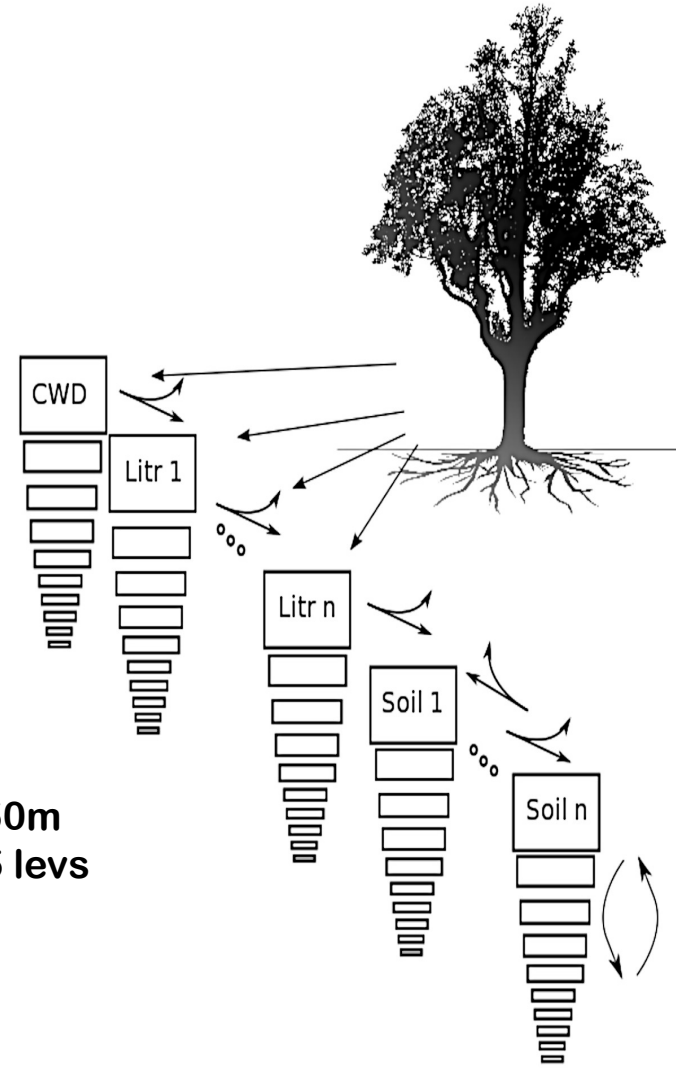


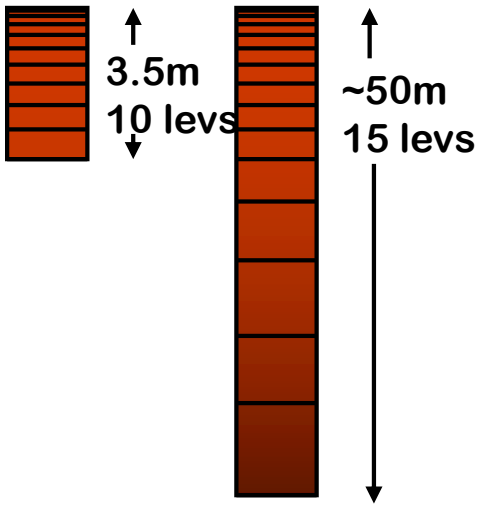
Many models do not correctly represent snow insulation

Slater et al. 2017

Key land model features for permafrost simulations

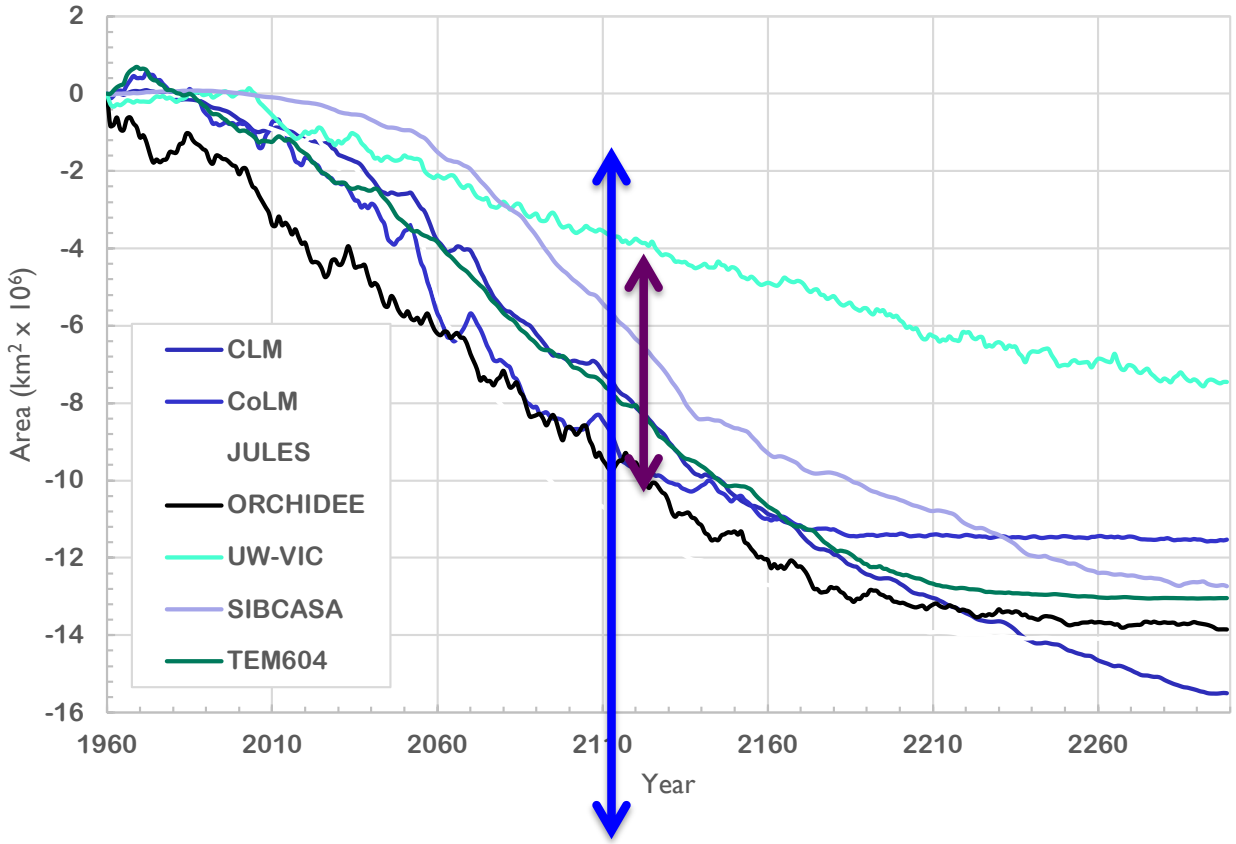
- Snow model that treats snow insulation reasonably (Koven et al. 2013)
- Explicit treatment of thermal and hydraulic properties of soil organic matter (Nicolsky et al. 2007, Lawrence and Slater, 2008)
- Deep ground column ~50m depth (Alexeev et al. 2007, Lawrence et al., 2008)
- Cold region hydrology, 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)

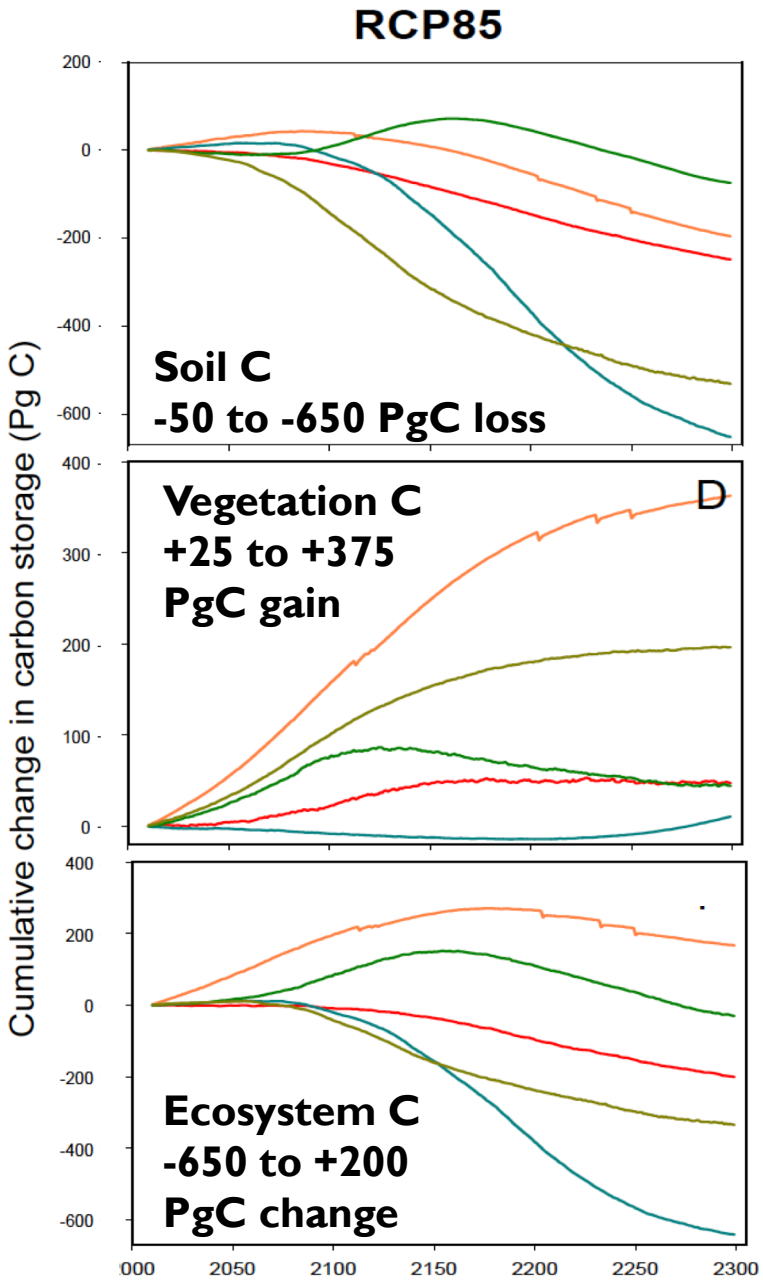


PCN 4 -10 million km²

CMIP5 1-18 million km²

McGuire et al., 2018

PCN: "Permafrost Model intercomparison"
Diverse permafrost C predictions



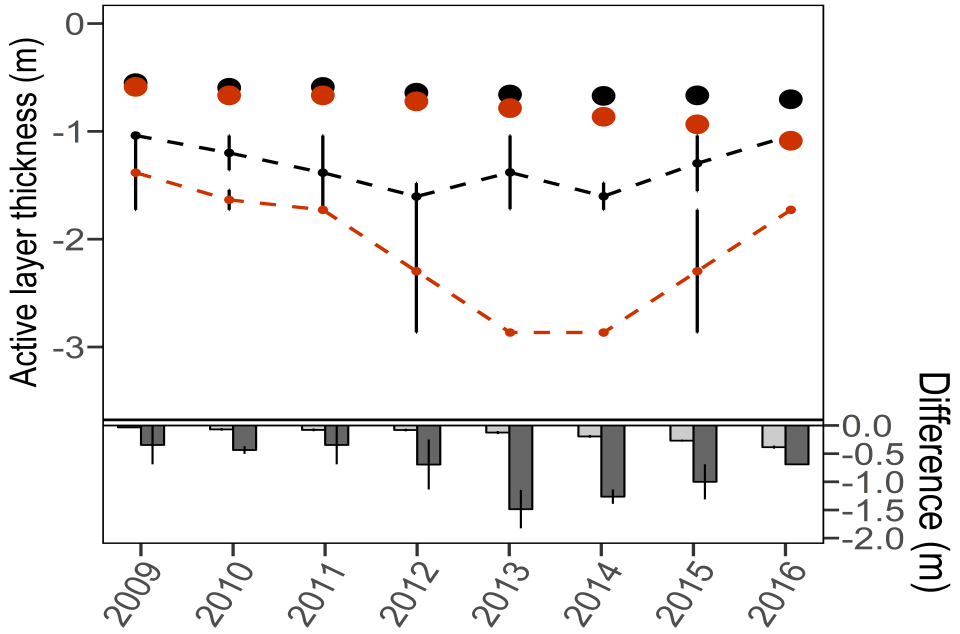
Needs for permafrost-carbon feedback modeling

- 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

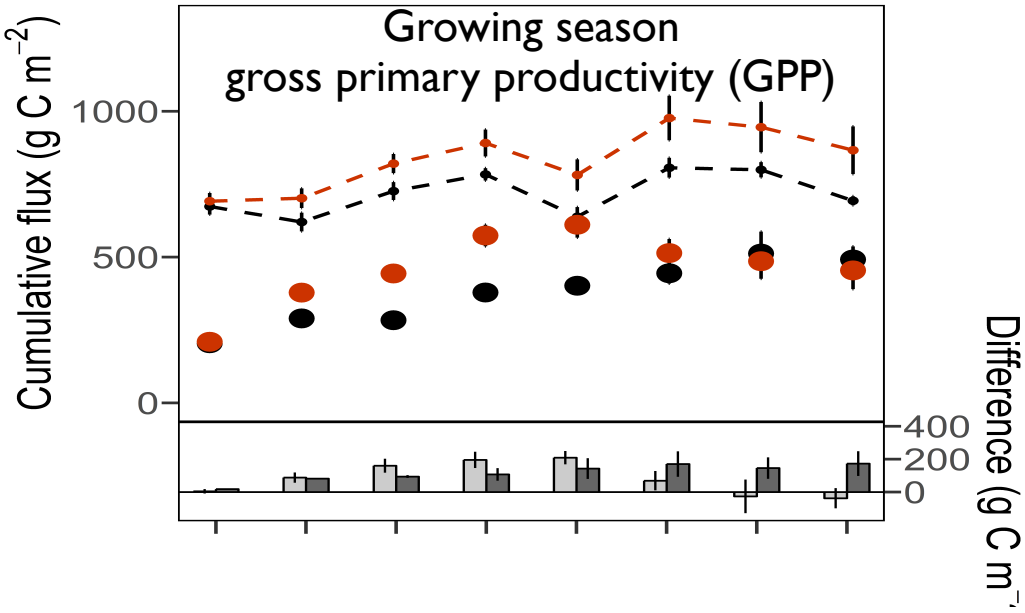
Benchmarking models against field experiments

Artificial warming
Snow fence experiment



Field
- Control
- Warming

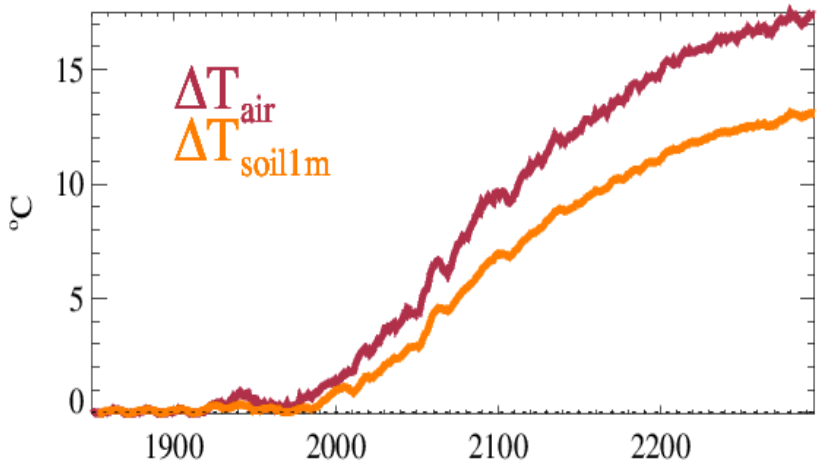
Model
- Control
- Warming

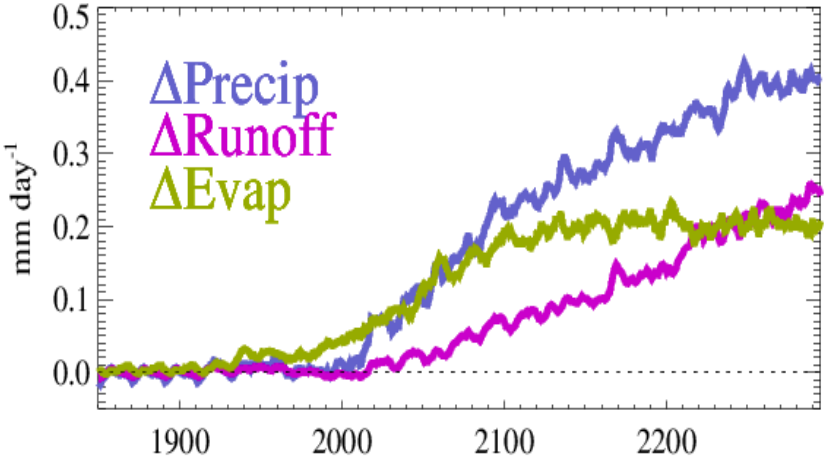


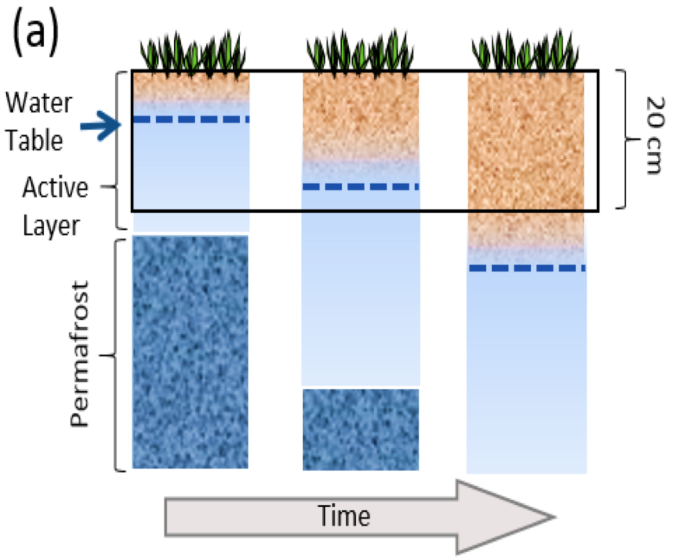
Schaedel et al, in prep

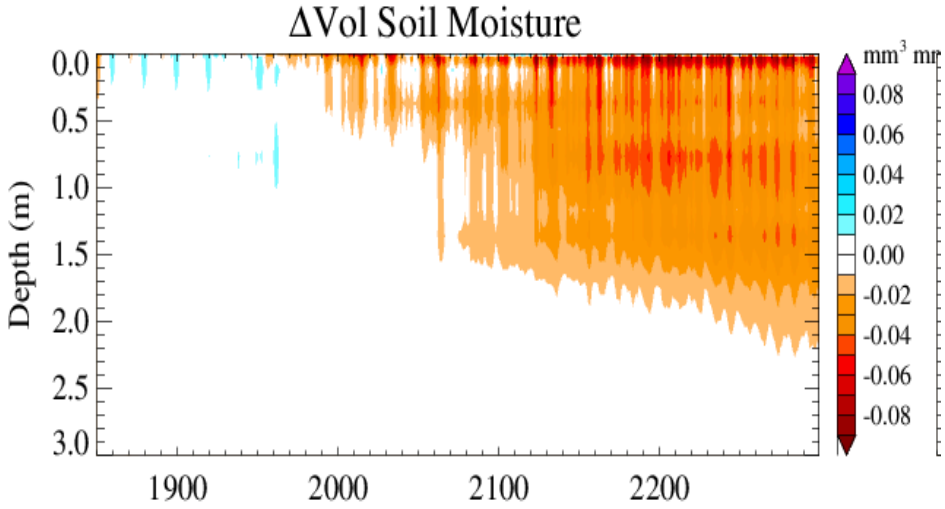
Using models to assess sources of uncertainty
Example: Uncertainty related to soil moisture projections

CESM Projections of temperature and water balance for permafrost domain (RCP8.5)



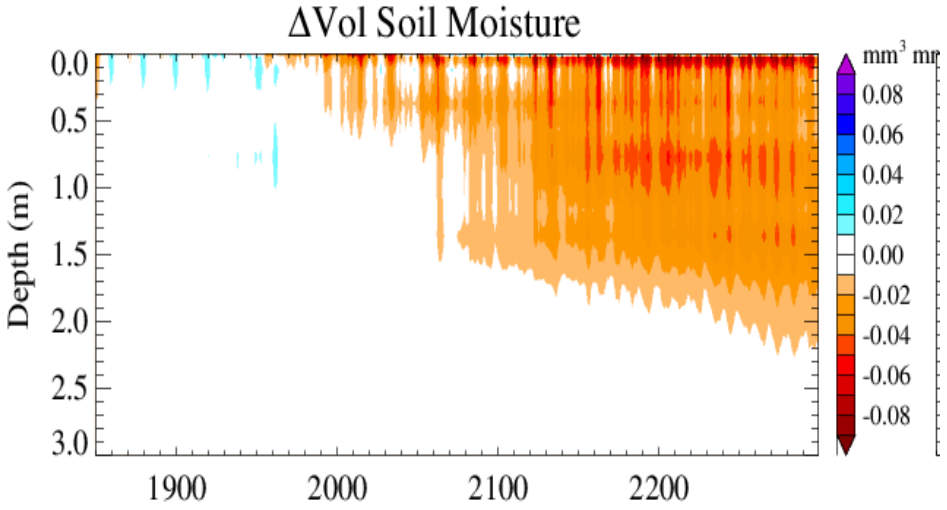


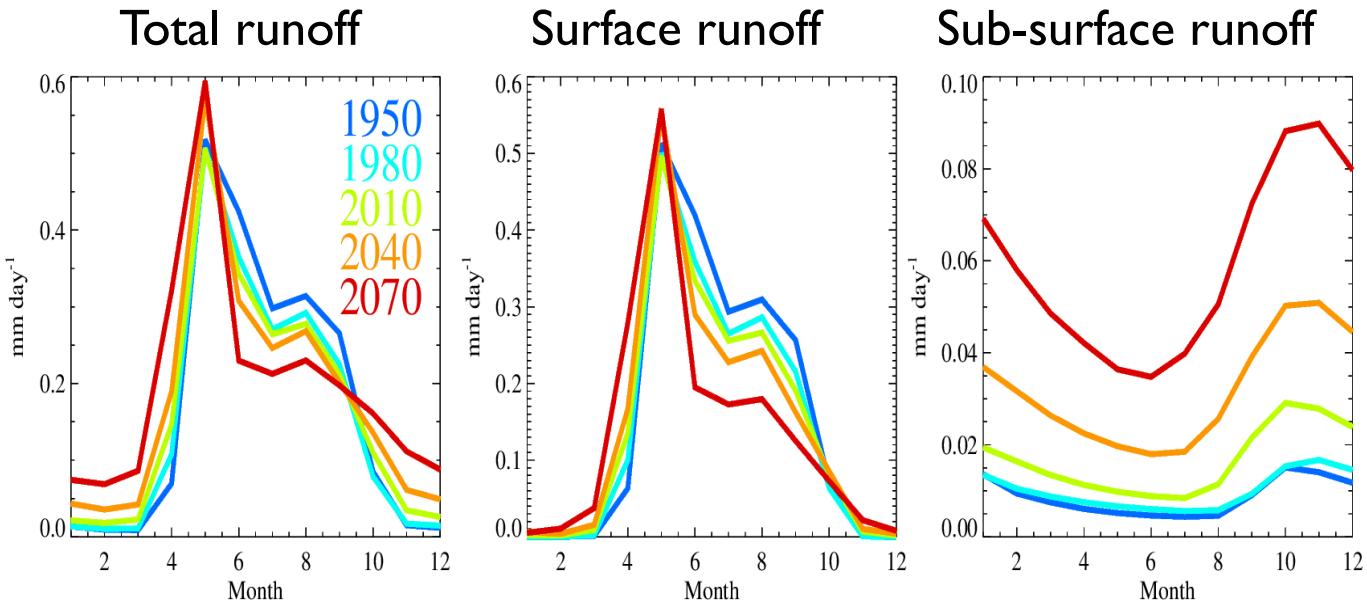




Permafrost-thaw driven transitions in runoff characteristics

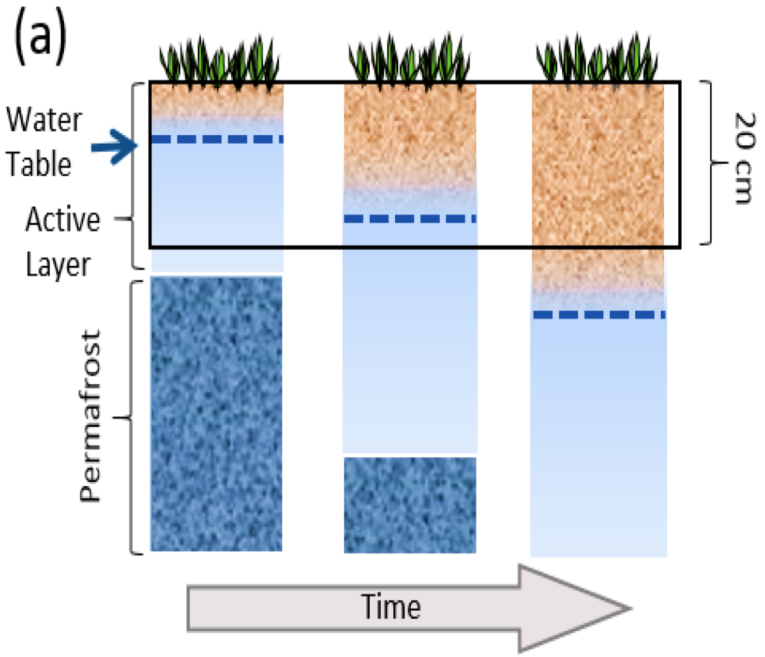
- After permafrost thaw, transition to higher proportion baseflow
- Consistent with 'observations' and other hydrologic models
  (Walvoord and Striegl, 2007, Bense et al. 2009, Walvoord et al. 2012)
- High divergence in SM and runoff projections in PCN models
  (Andresen et al., in prep)



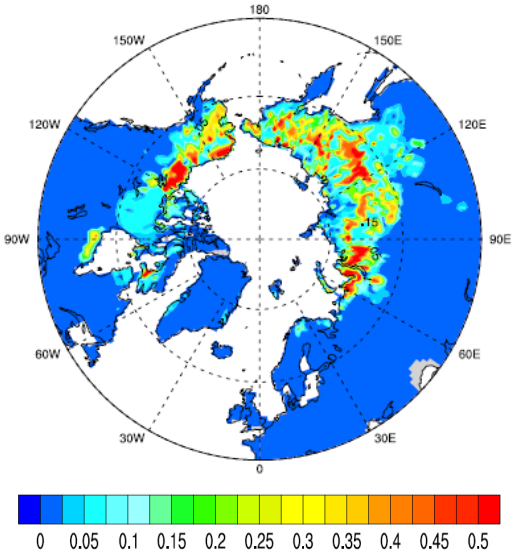


Lawrence et al., ERL, 2015

Active layer deepening and soil subsidence



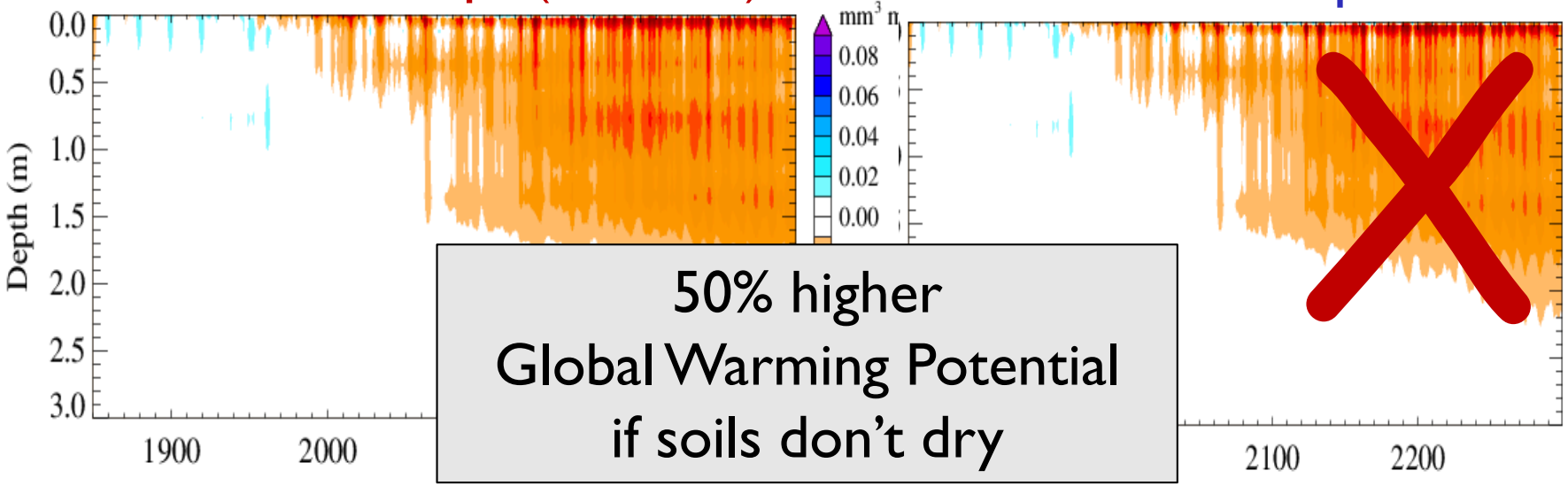
CLM projection of subsidence by 2100



Permafrost carbon-climate feedback with and without soil drying

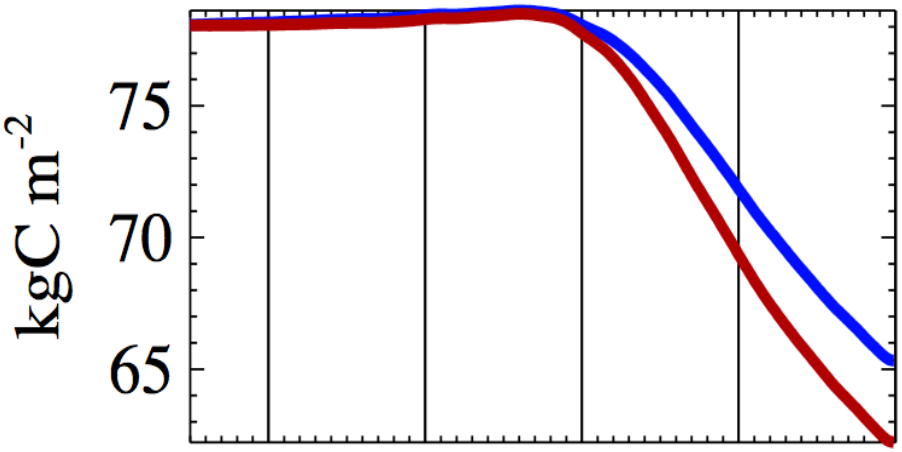
DRY Soil Expt (Control)

WET Soil Expt

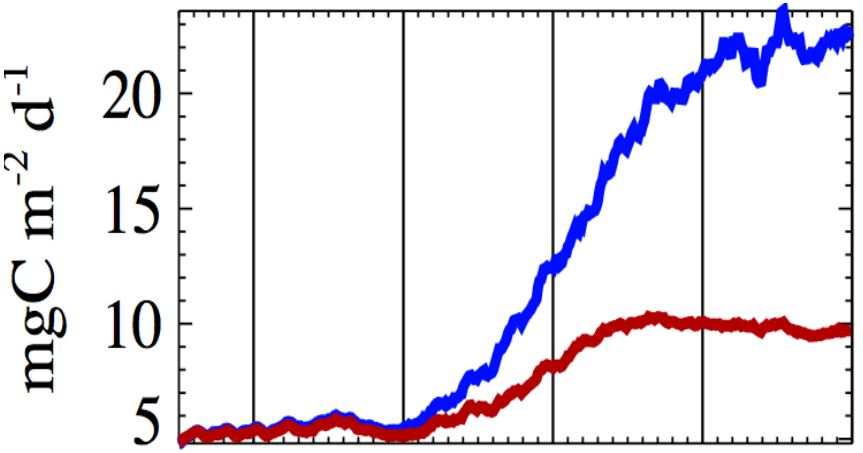


50% higher
Global Warming Potential
if soils don't dry

Ecosystem Carbon



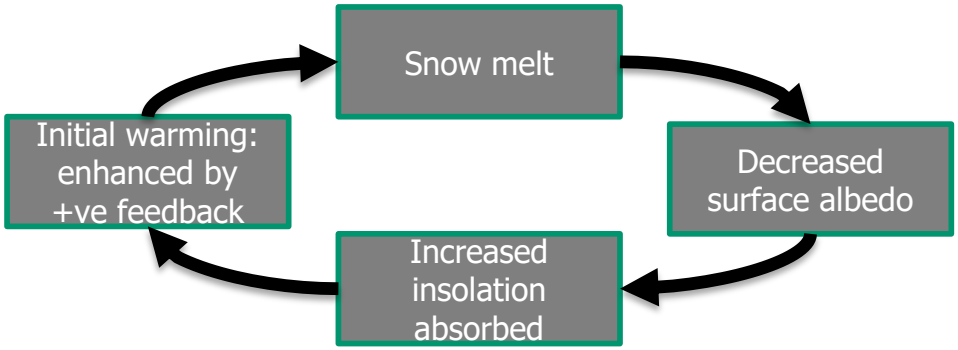
CH_4 emissions

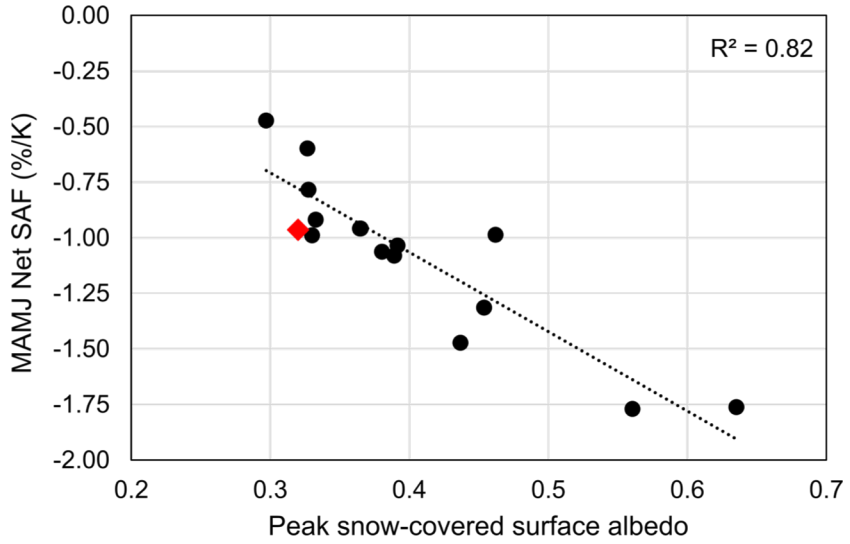


Lawrence et al., ERL, 2015

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

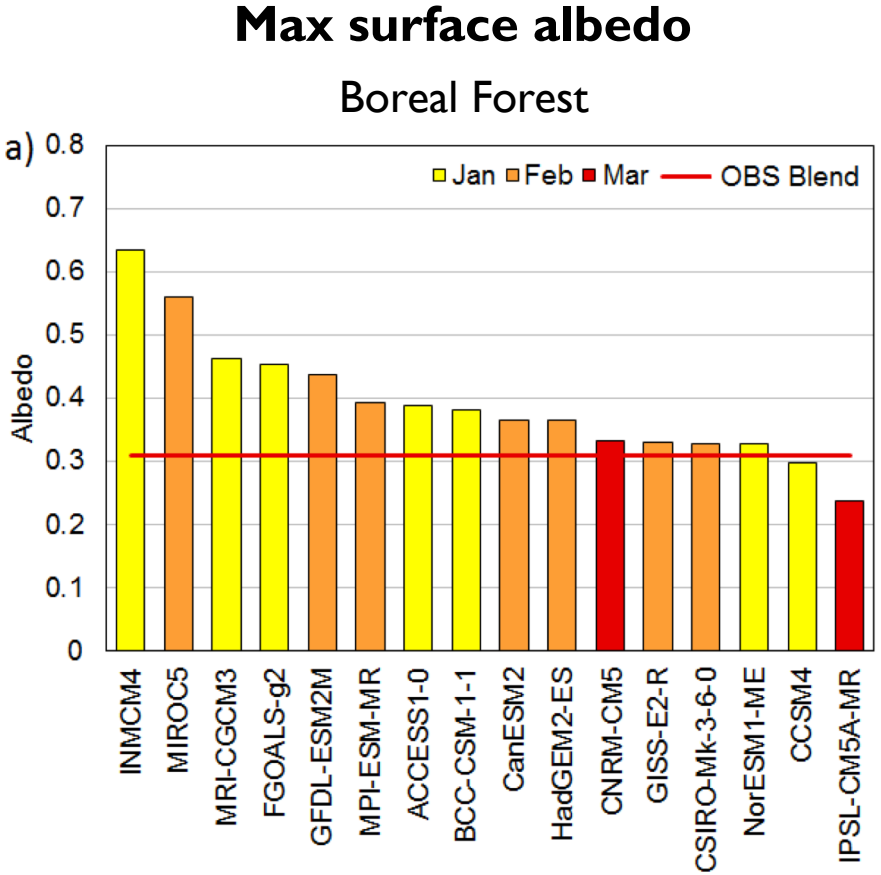




Relationship between peak snow-covered surface albedo and spring SAF from models (black) and OBS (red) across the boreal forest.

Fletcher et al., 2012

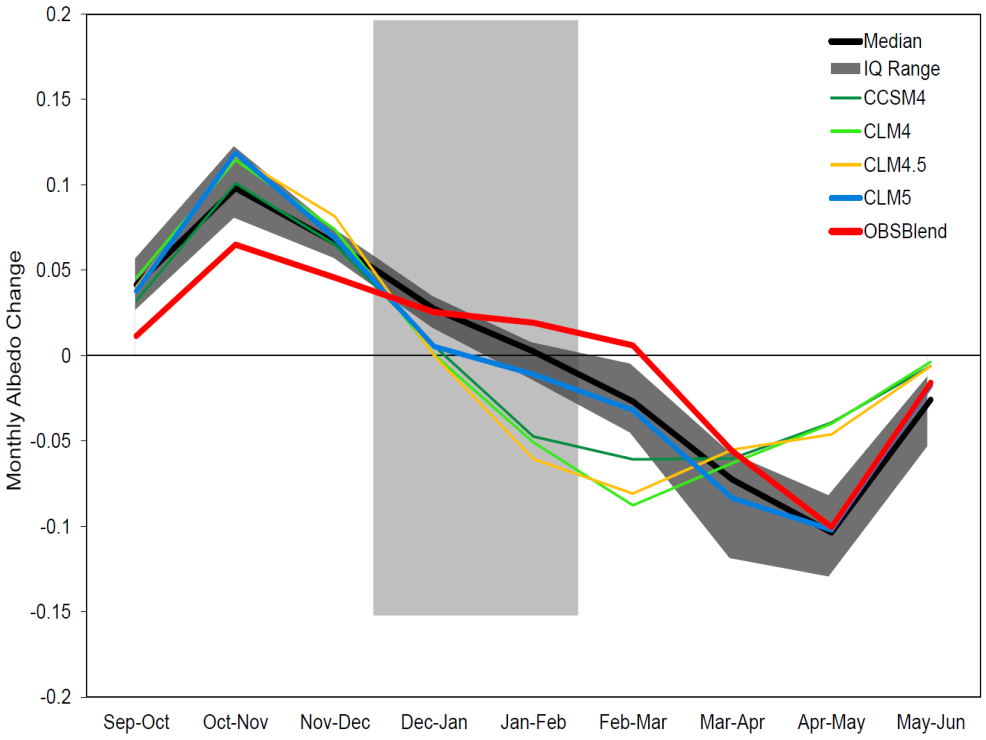
Large biases in snow-covered surface albedo



- 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 → weak SAF.

Thackeray et al., 2015

Reduction of SAF bias in CMIP6?



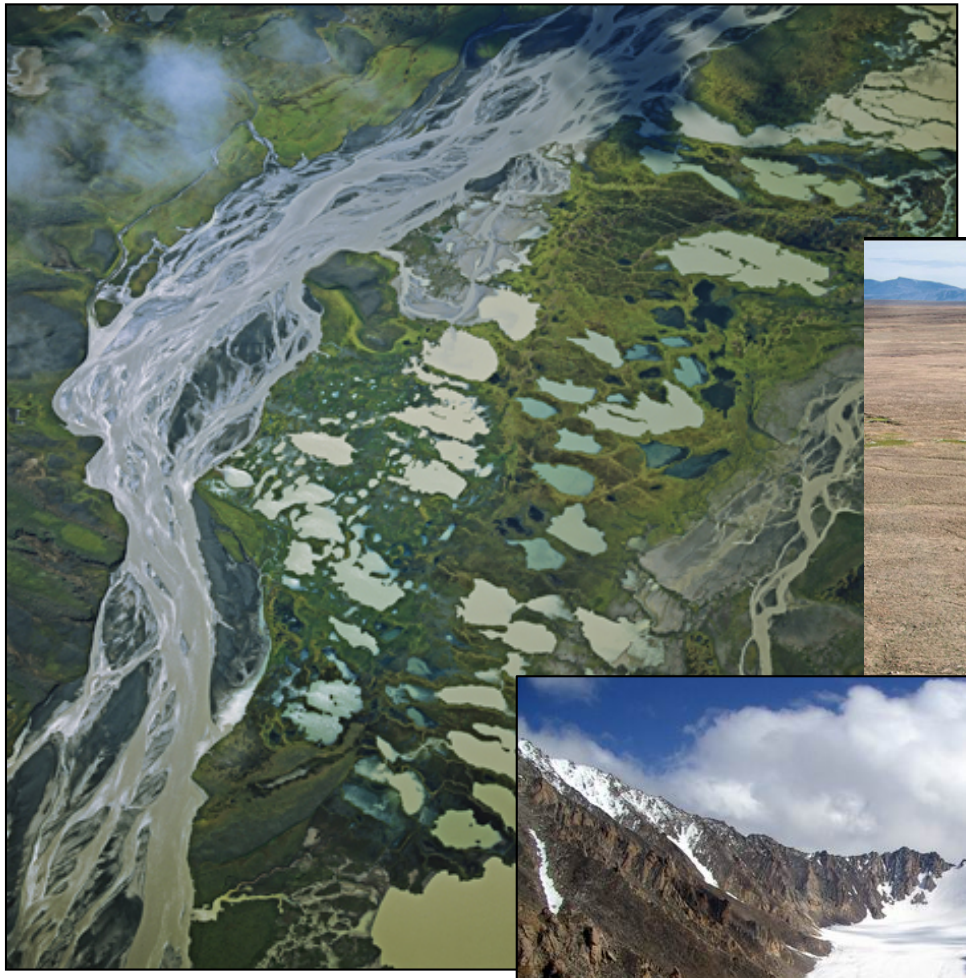
Monthly climatological albedo change across the boreal forest. The light gray box shows when observational uncertainty is largest.

Model	Boreal Spring SAF (%/K)
CCSM4	-0.60
CLM4	-0.64
CLM4.5	-0.68
CLM5	-0.83
MODIS	-0.87

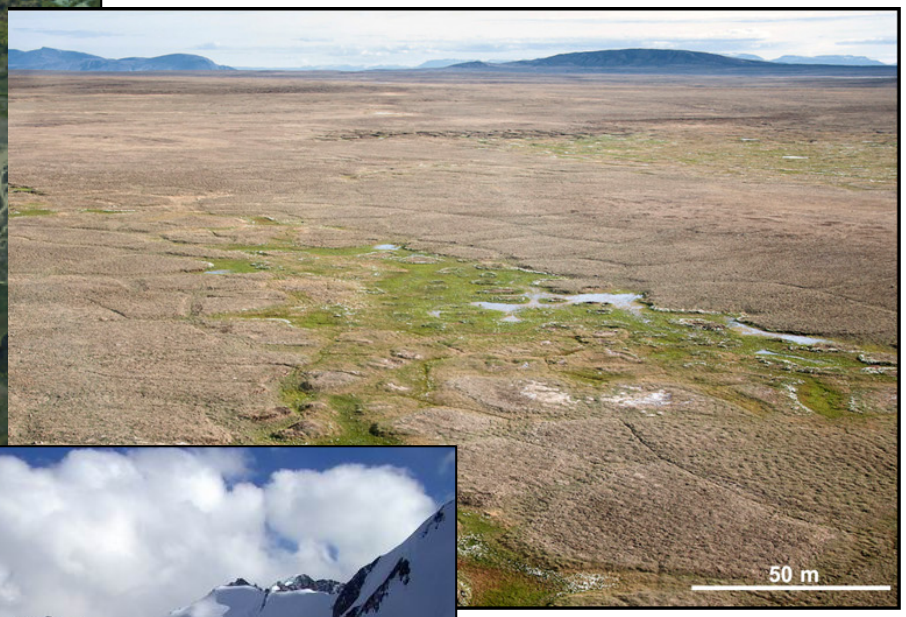
- New canopy snow storage and unloading scheme reduced bias in seasonality of snow-covered surface albedo and thus, SAF
- Cautious expectation for reduced bias in SAF in CMIP6 models
- Snow-MIP to address snow-climate interactions

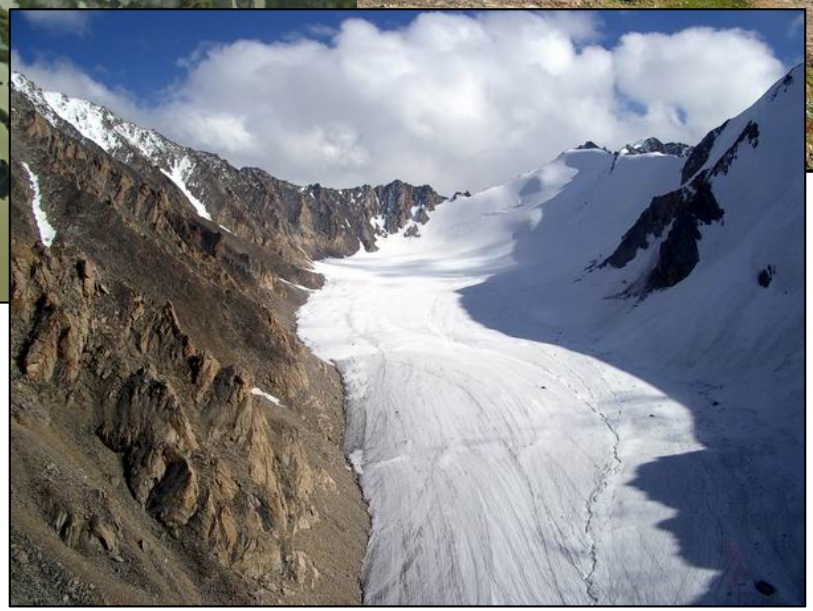
Slide courtesy Chad Thackeray

Challenge of heterogeneity



How much do unrepresented heterogeneous land responses to environmental change affect the strength of the overall feedbacks?

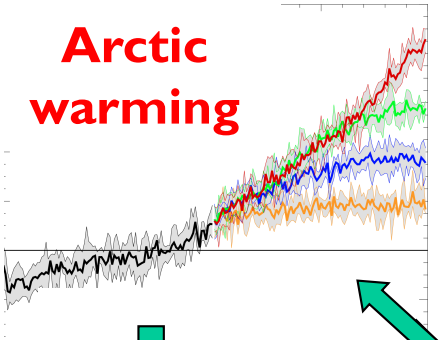




Potential Arctic terrestrial climate-change feedbacks

Global warming

Arctic warming



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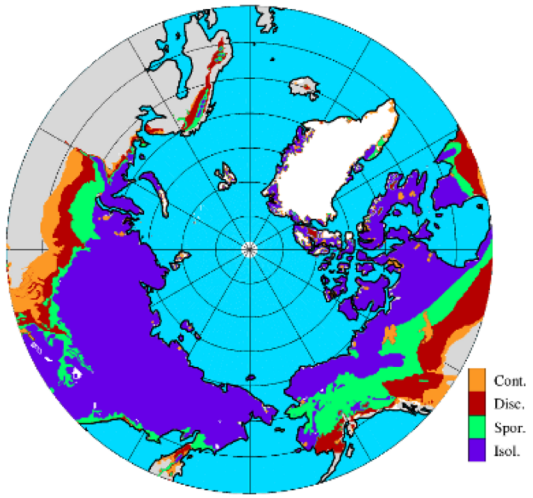


Permafrost in CMIP6 models?

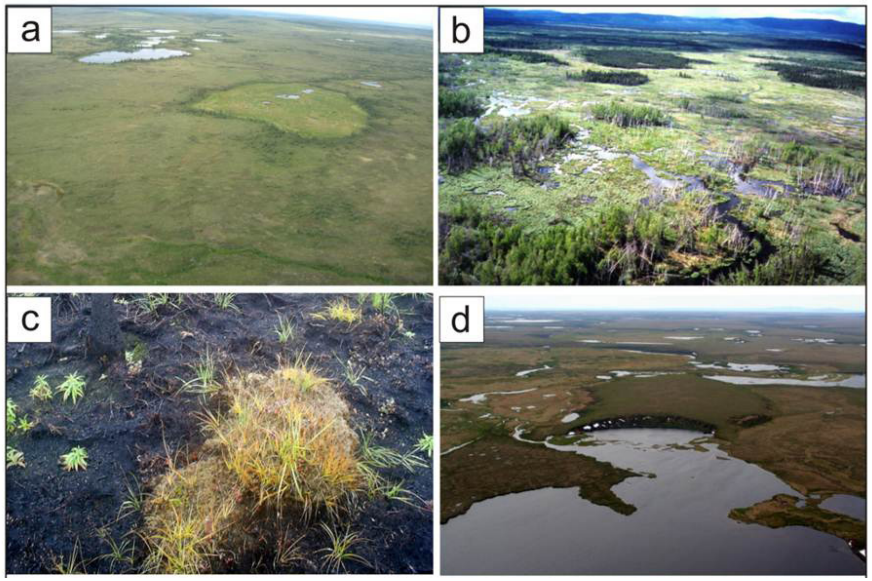
Process/Model	CESM	GFDL	UKESM	MPI-ESM	IPSL	NorESM	EC-Earth
Permafrost physics	on	on	on	offline	on	on	on
Permafrost C	on	?	no	offline	offline	on	offline
CH_4 emissions	on	?	on	offline	offline	on	offline
CN interaction	on	on	on	on	on	on	on

The challenge of heterogeneity
Example: Impact of thermokarst processes on permafrost C dynamics

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%



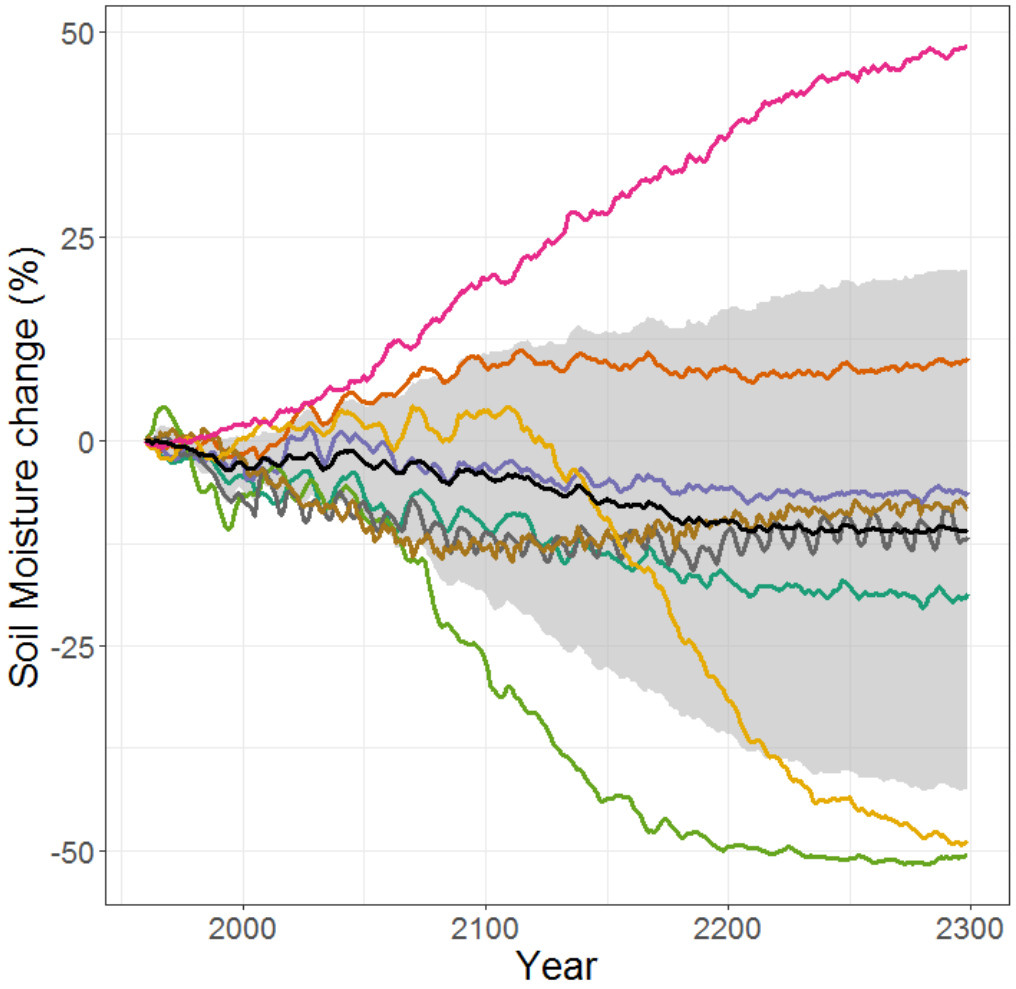
Thermokarst is subsidence of the surface that is caused by the melting of ground ice leading to fens/bogs, thermokarst lakes, thaw slumps, etc

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).

Thackeray et al., in prep for GRL

High uncertainty in permafrost-domain soil moisture projections in PCN models

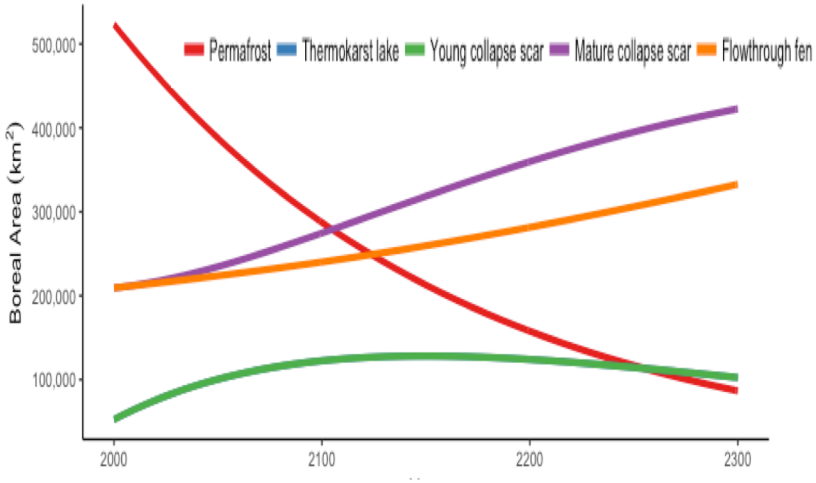


Andresen et al., in prep

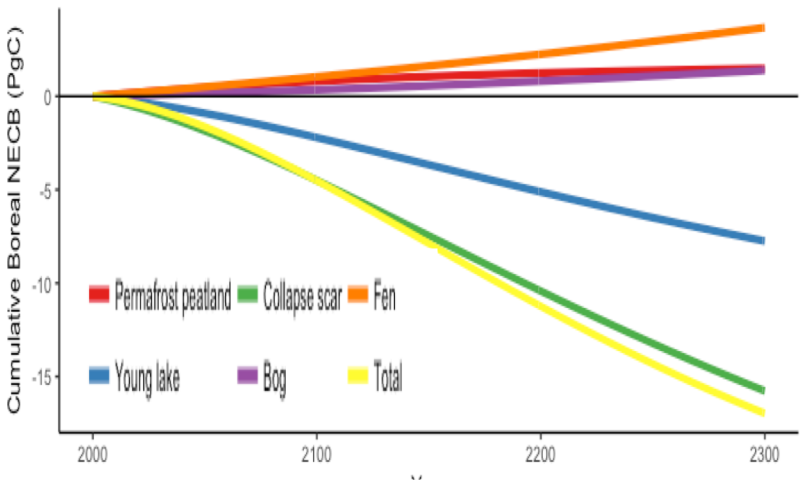
Thermokarst "state-and-transition" conceptual modeling

Ex. for Lowland Organic Terrain (Wetlands)

Change in area of successional state



Change in C balance



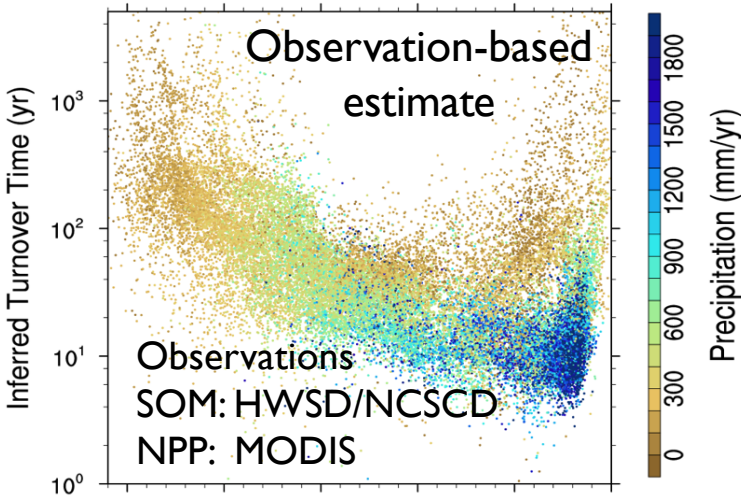
- Summed for all thermokarst processes, Global Warming Potential due to thermokarst ~50% of that due to ALT deepening
- Feedbacks under warming climate not captured by state-and-transition approach
- Challenge: integrate thermokarst parameterizations into ecosystem models

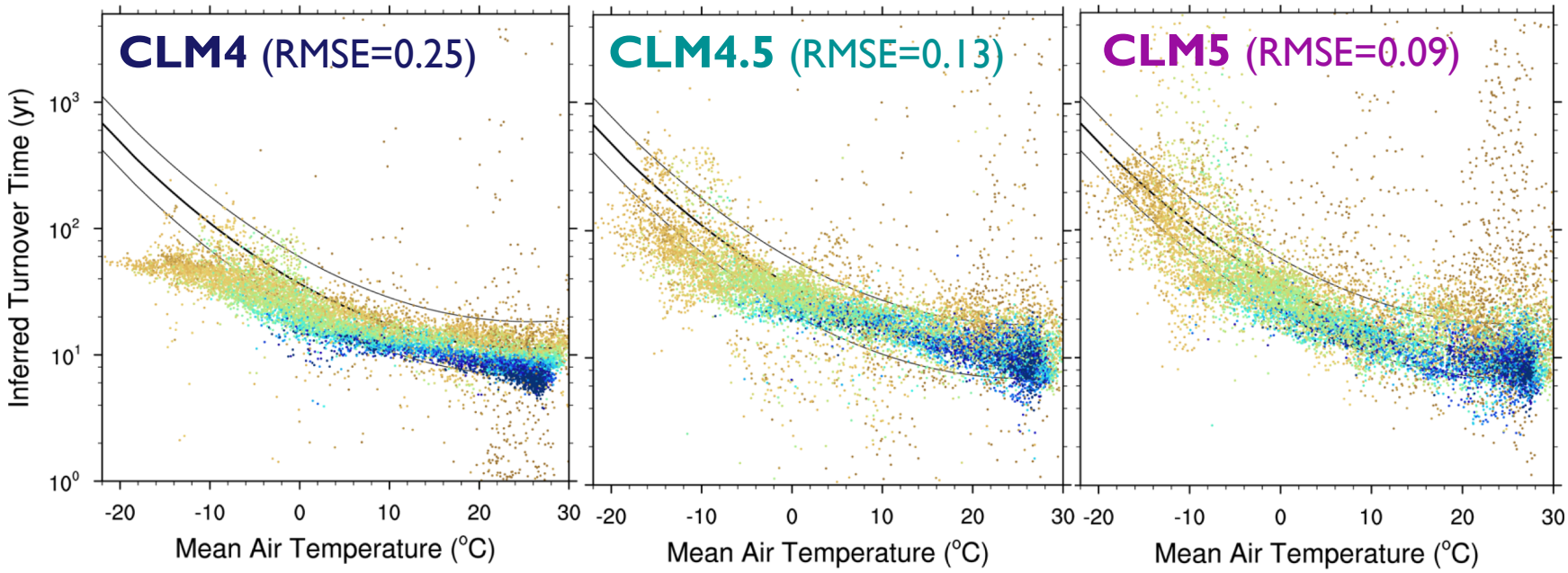
Turetsky et al., in preparation

Metric for soil carbon turnover timescale

Inferred soil carbon turnover timescale

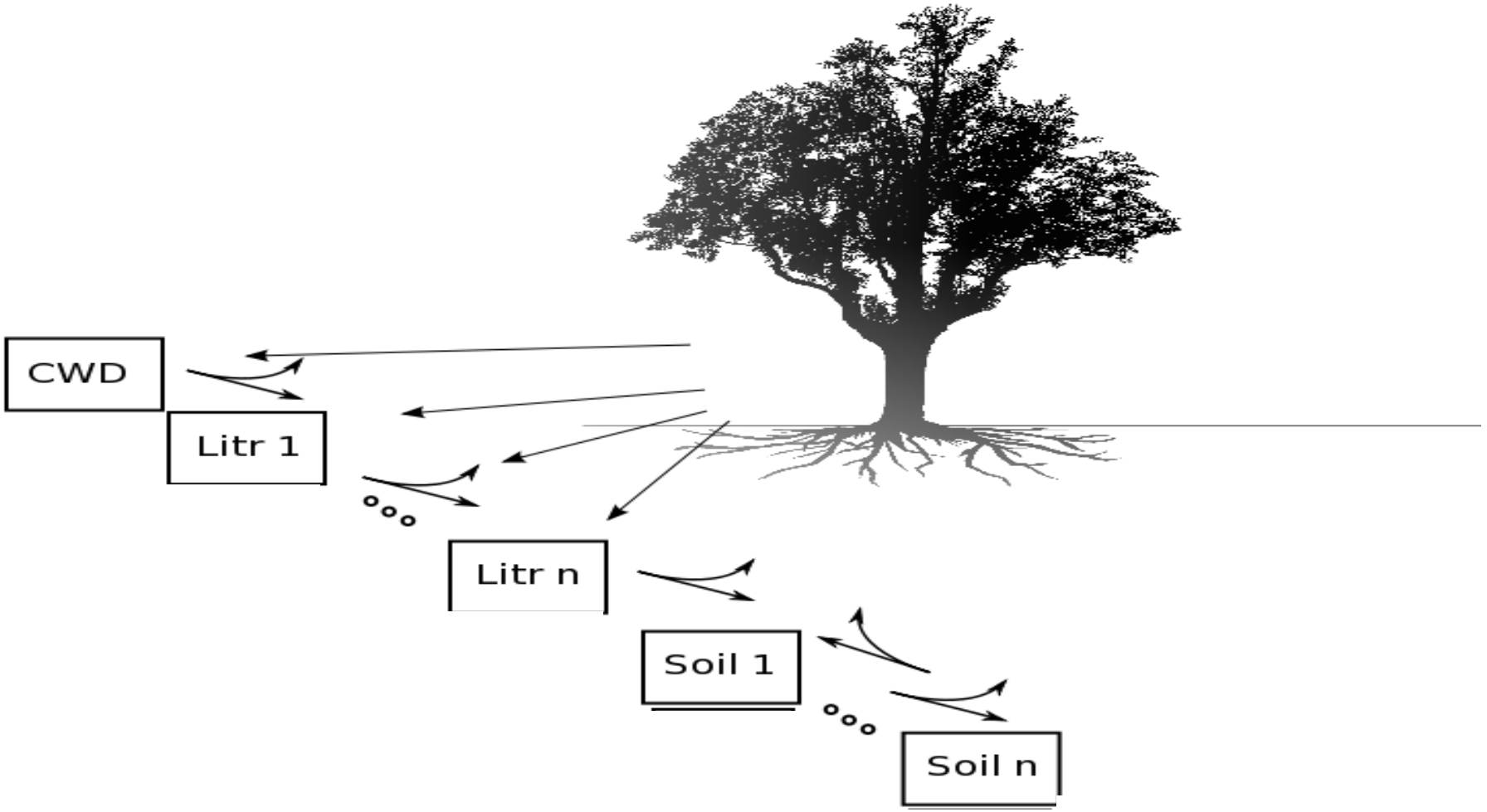
$$\tau = \frac{carbon\ stocks\ (SOM)(gC)}{carbon\ inputs\ (NPP)(\frac{gC}{s})}$$





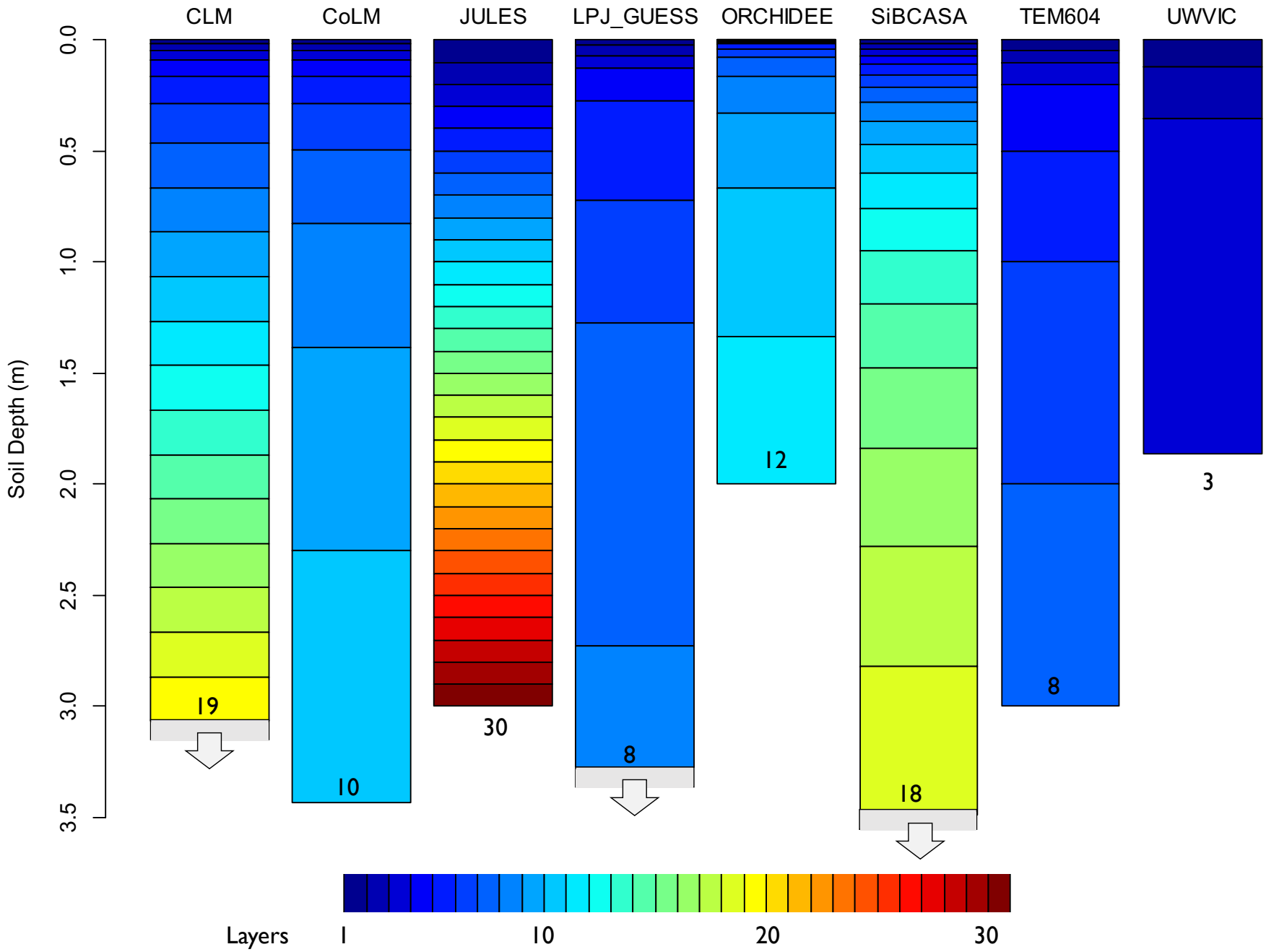
Koven, Hugelius, Lawrence, and Wieder, NCC, 2017

Vertically-resolved soil biogeochemistry



Koven et al., 2013

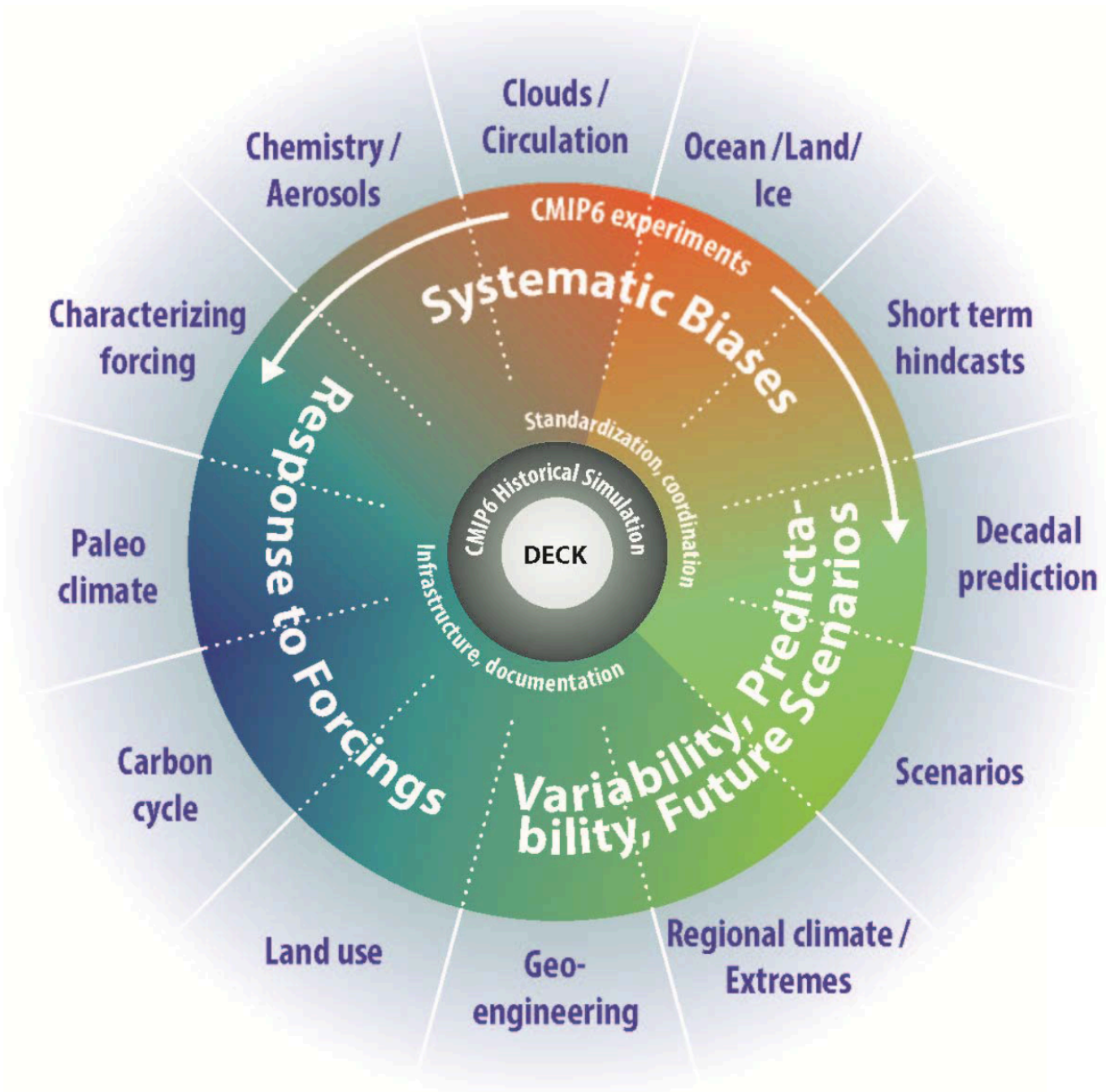
Diverse soil column configuration among land models



Increased focus on terrestrial processes in CMIP6

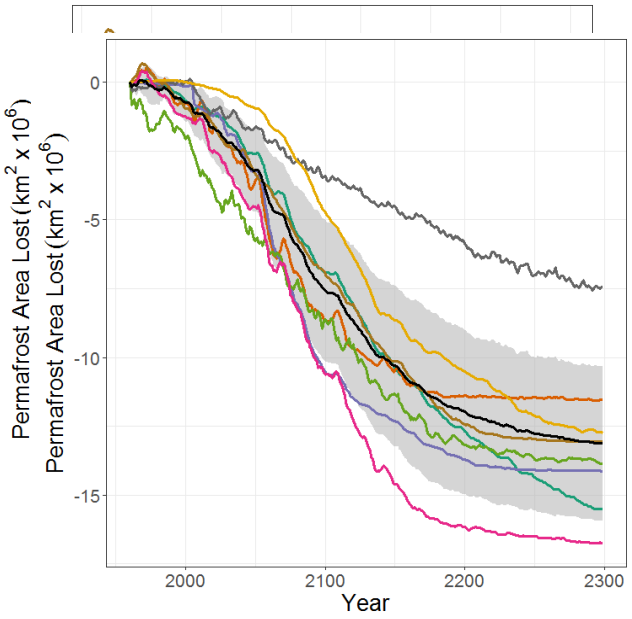
Coordinated activities to assess land role in climate and climate change

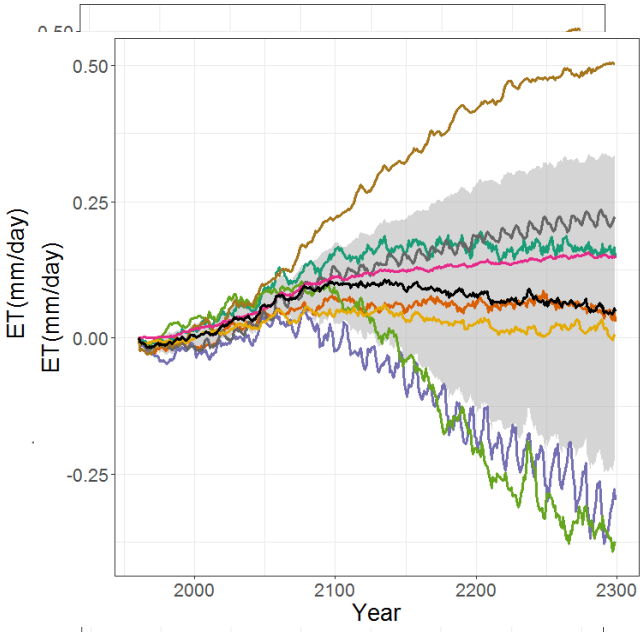
- **Land-only simulations forced with obs historical climate and common future,** land-systematic biases
- **Land Use = LUMIP**
  land use forcing on climate, biogeophysics and biogeochemistry with policy relevance
- **Land = LS3MIP**
  biogeophys feedbacks including soil moisture and snow feedbacks
- **Carbon Cycle = C4MIP**
  land biogeochemical feedbacks on climate, **emissions-driven SSP5-8.5 21st and Extension to 2300**

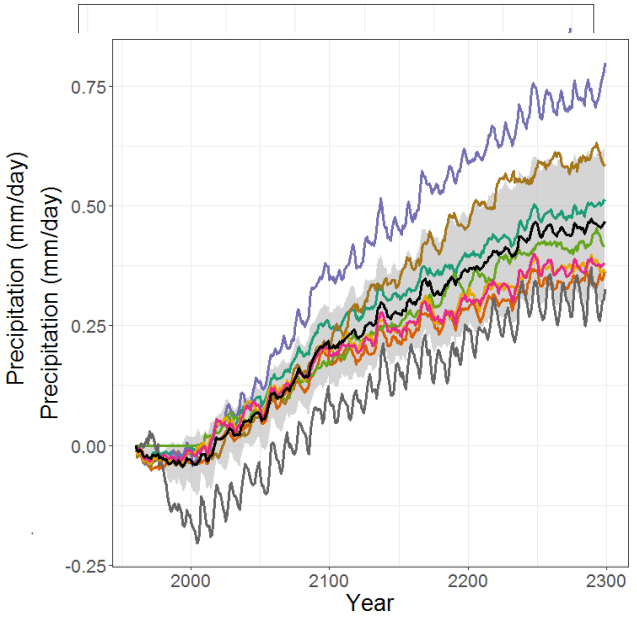


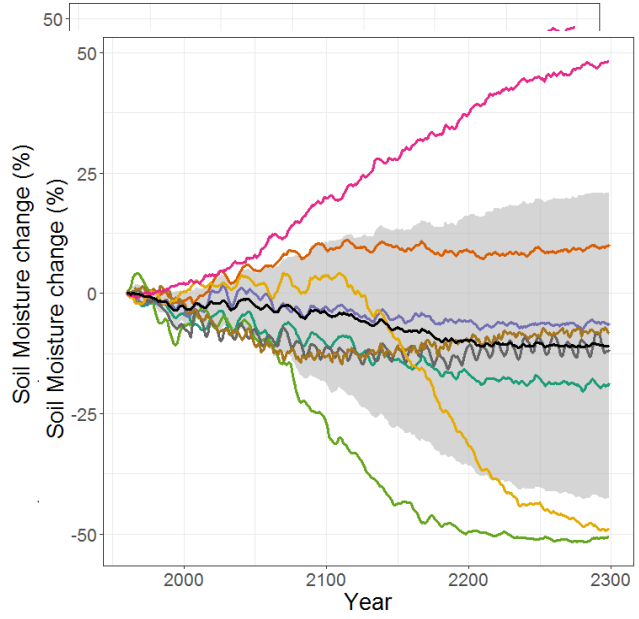
Updated from Meehl et al., EOS, 2014

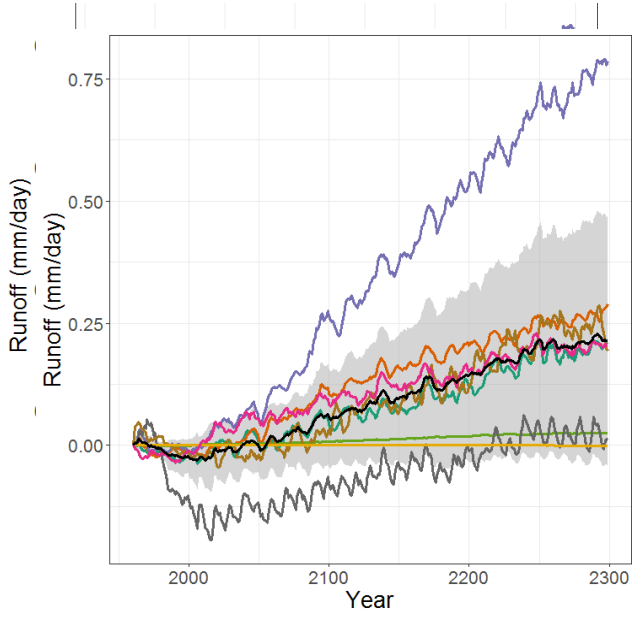
High uncertainty in permafrost-domain soil moisture projections





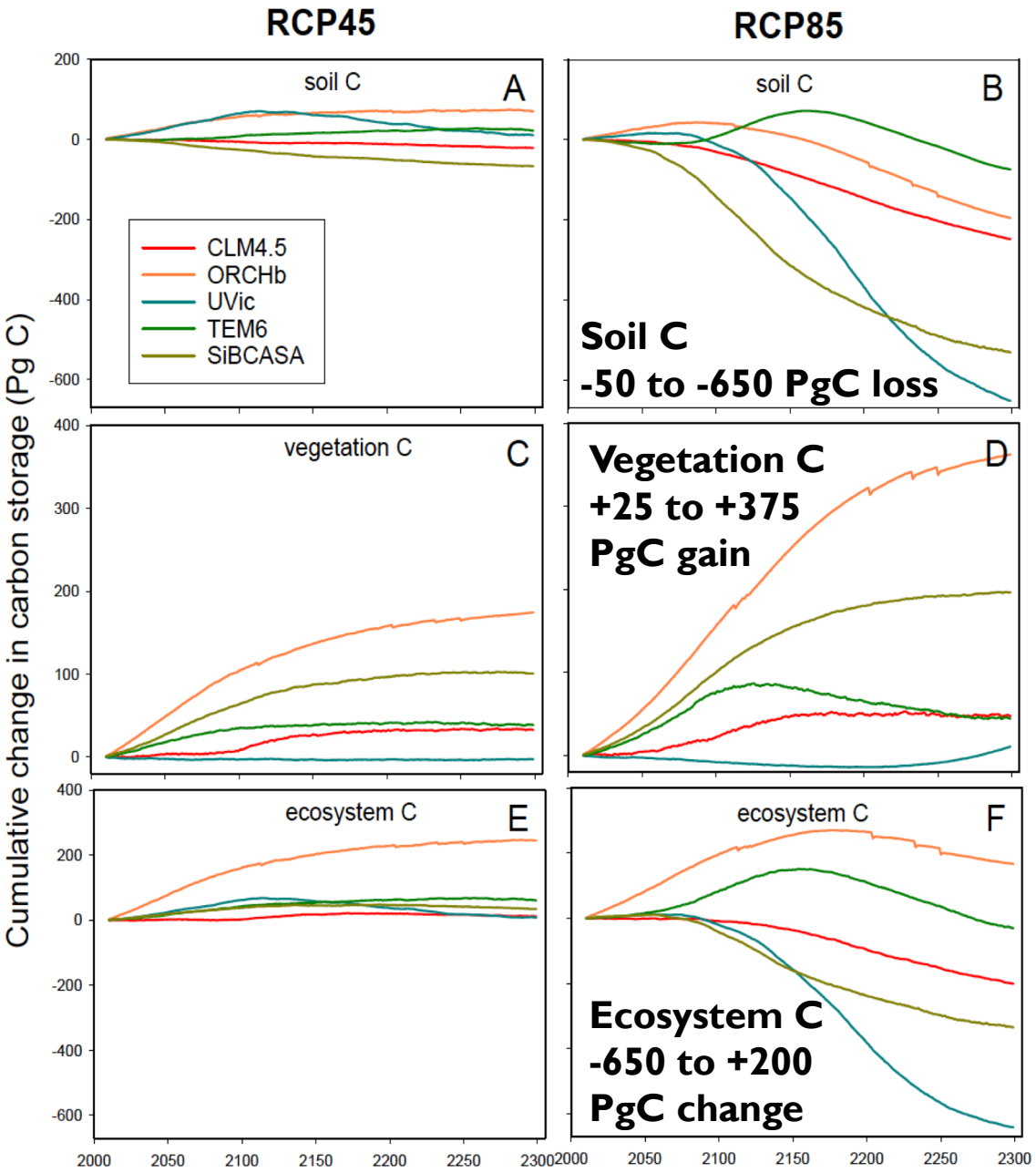






Andresen et al., in prep

PCN: "Permafrost Model intercomparison"
Diverse permafrost loss predictions

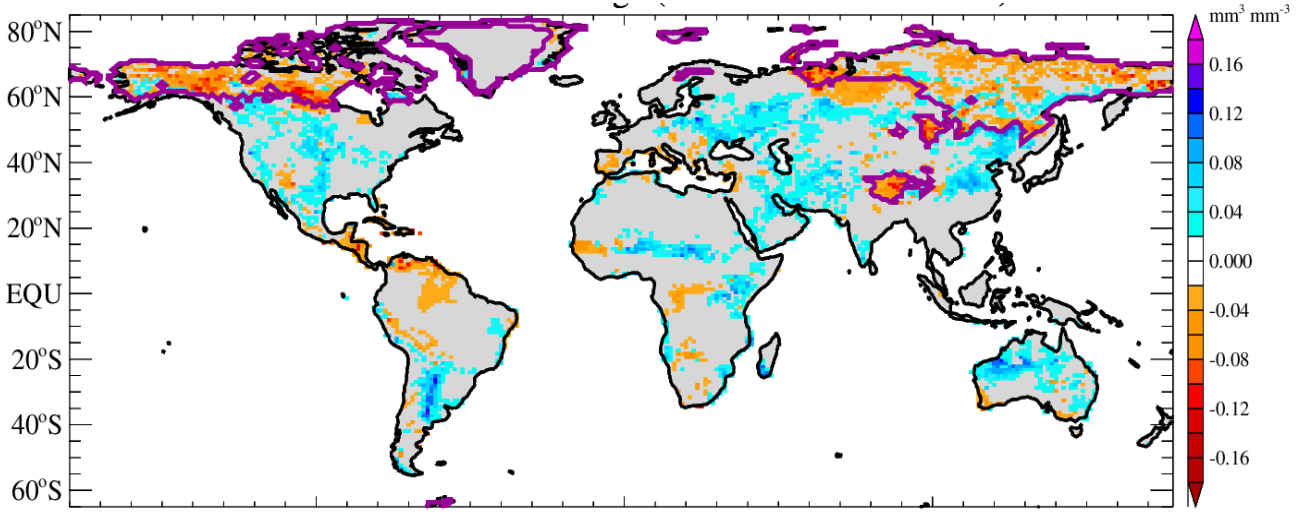


Needs for permafrost-carbon feedback modeling

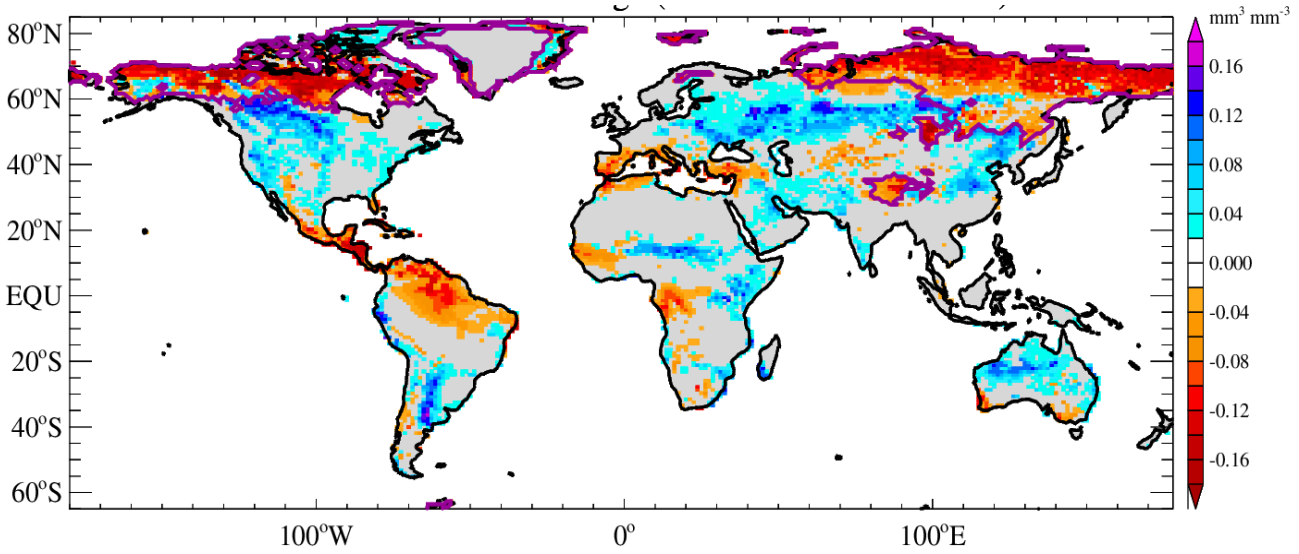
- Standardize structural representation of permafrost and carbon
- Develop data sets and methodologies to benchmark models
- Utilize models to assess sensitivities to processes
- Assess and represent C impact of permafrost thermokarst responses to warming

Projected soil moisture change (RCP8.5)
CLM4.5

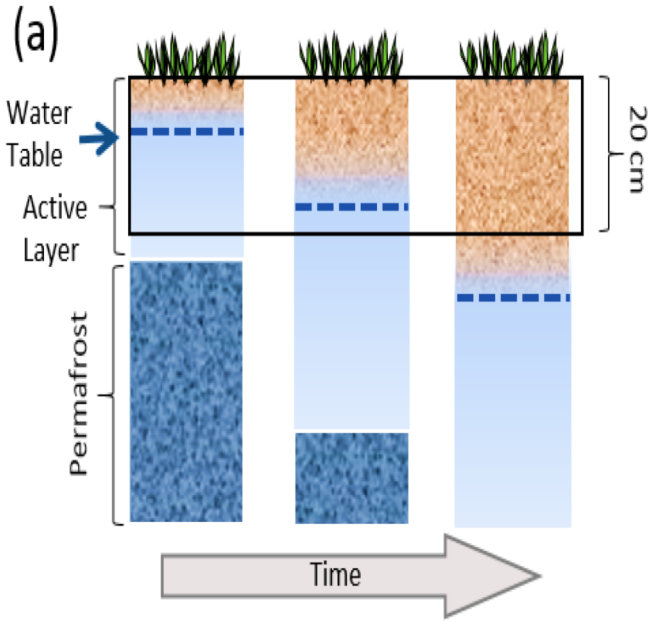
Column soil moisture change by 2100



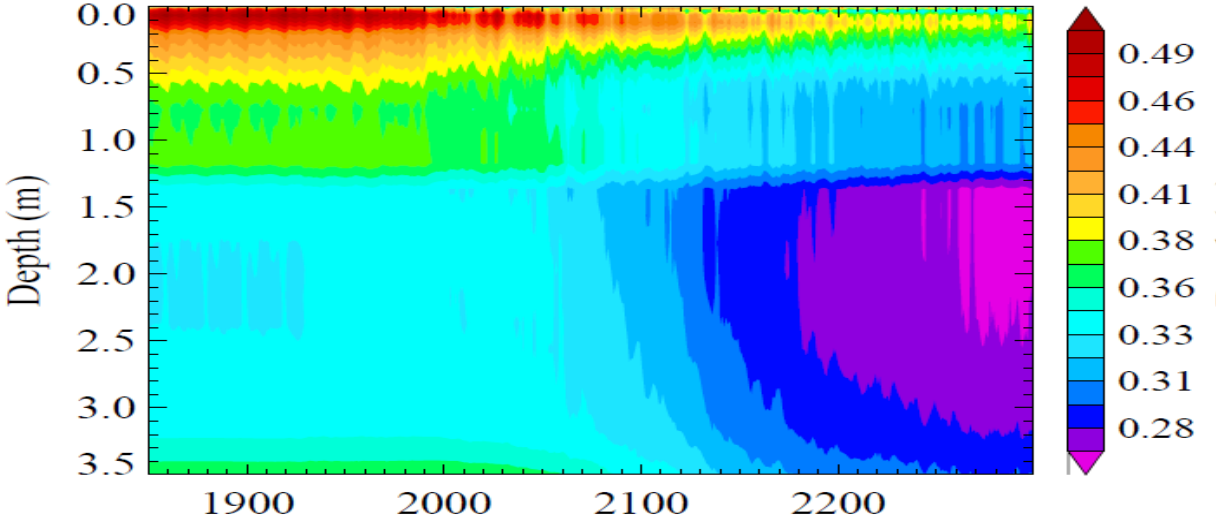
Column soil moisture change by 2300



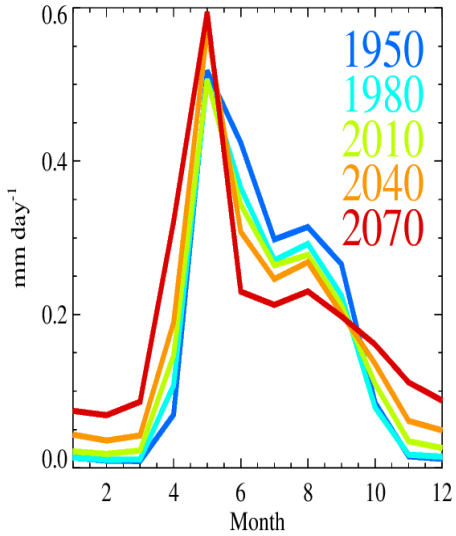
CLM representation of permafrost hydrology



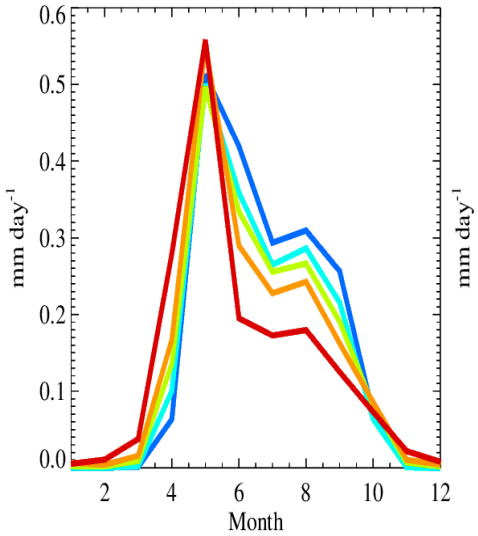
Soil water



Total runoff



Surface runoff



Sub-surface runoff