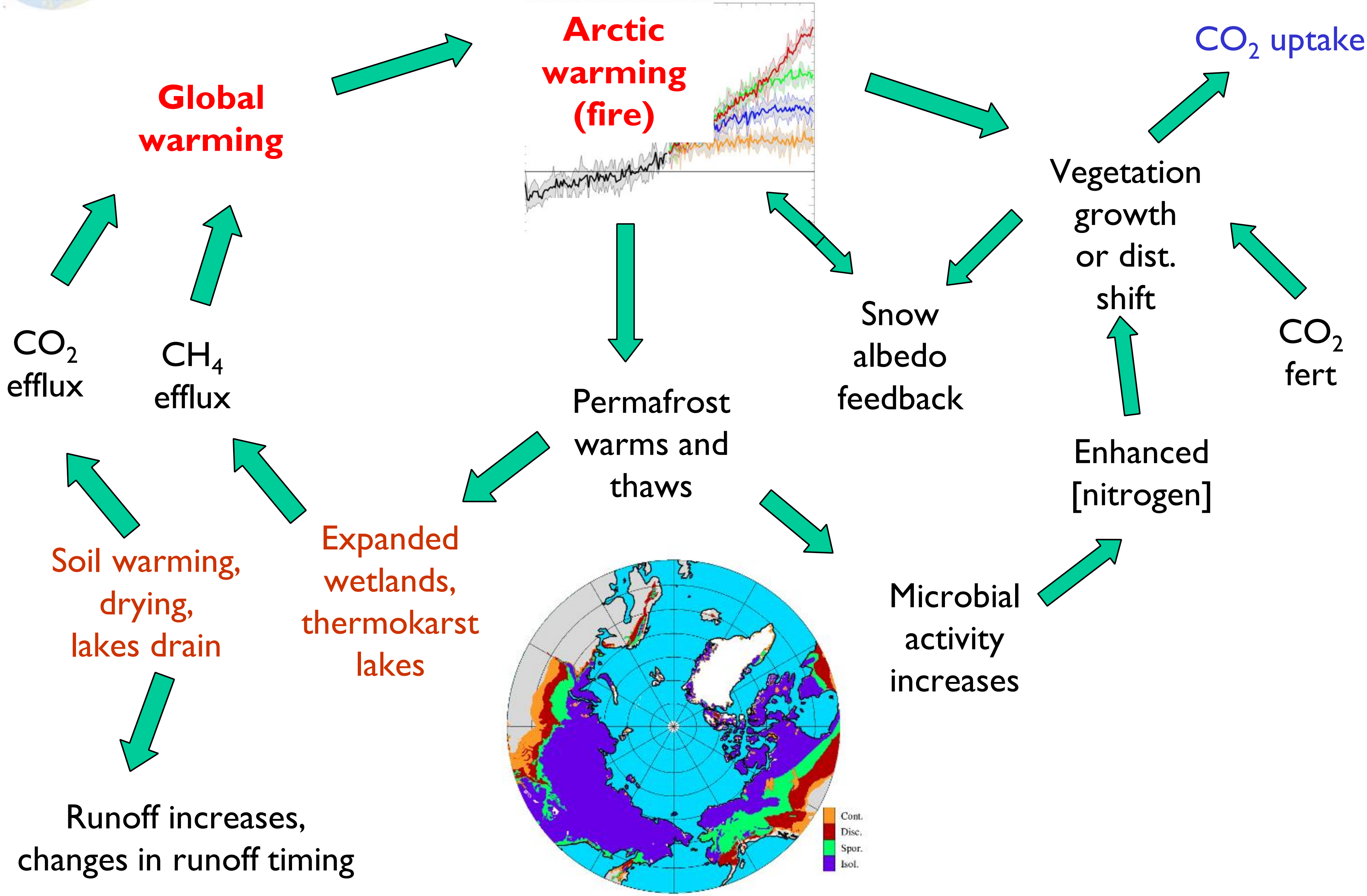
Permafrost in Land Surface Models: Where we are now and where do we need to go?

LSMS 2022

David Lawrence, Sarah Chadburn, Charlie Koven, Kjetil Aas, Victor Brovkin, Eleanor Burke

Arctic terrestrial climate-change feedbacks



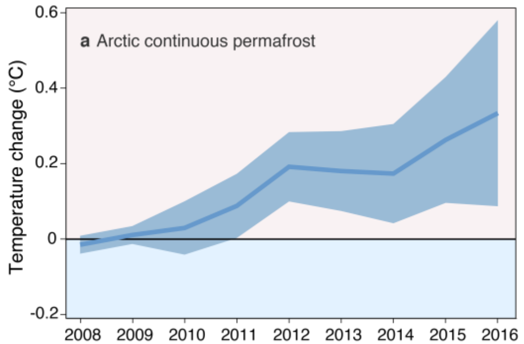
Permafrost projections – where are we now?

High Confidence
- Permafrost temperature increases
- Fire accelerating thaw rates
- Importance of abrupt thaw in C release
- Projections of permafrost area change

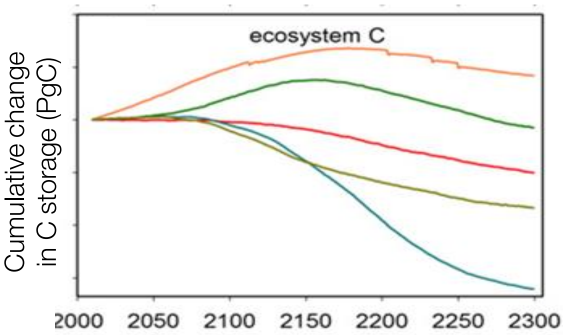
Medium Confidence
- Permafrost C stocks
- Rates of active layer thickening
- Ground ice distribution & volume
- Role of abrupt thaw in permafrost change
- Projections of vegetation change

Low Confidence
- Projections of future abrupt thaw area
- Projections of wetting vs. drying

IPCC SROCC



Biskaborn et al. (2019)

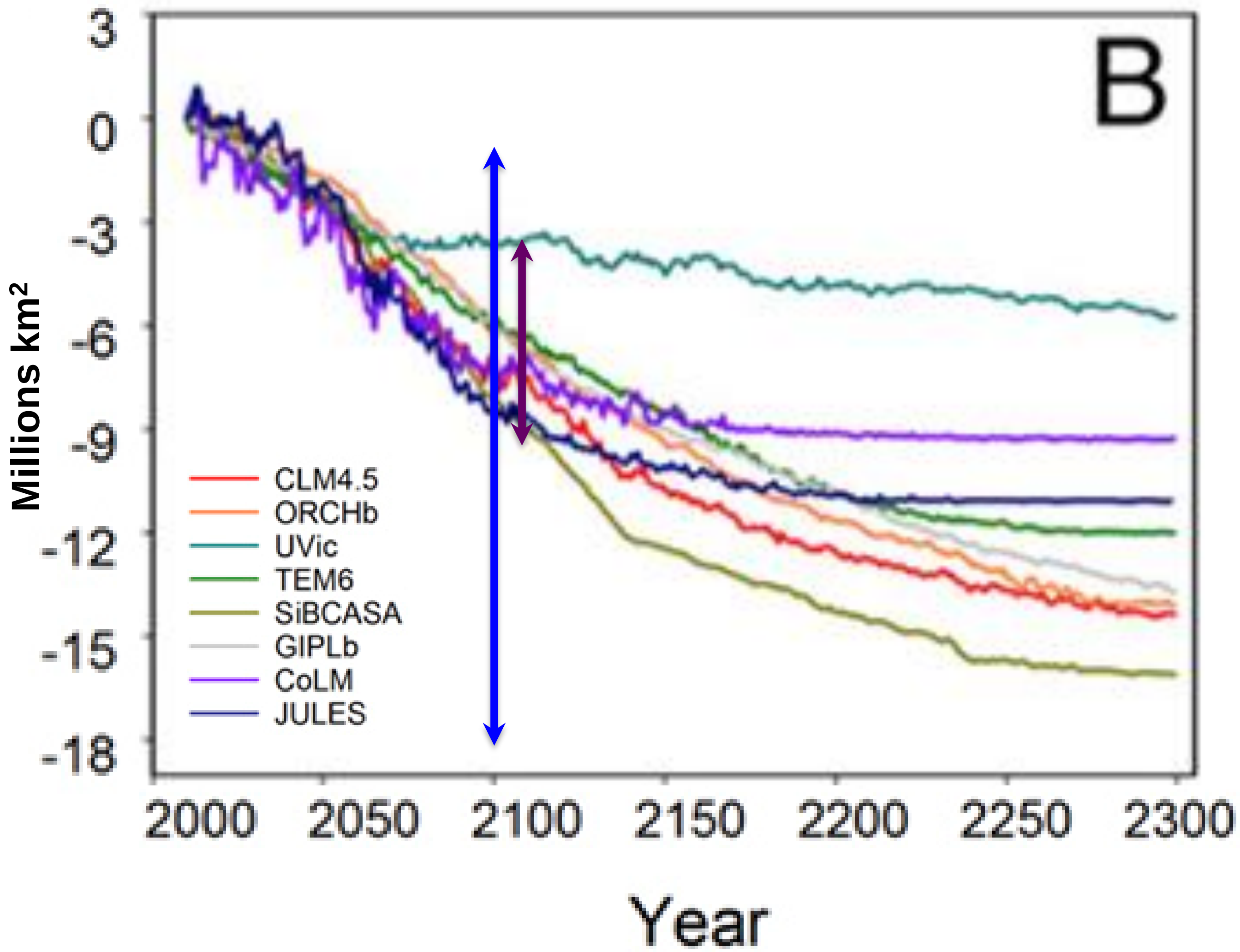


McGuire et al. (2018)

PCN: “Permafrost-enabled Model intercomparison”

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

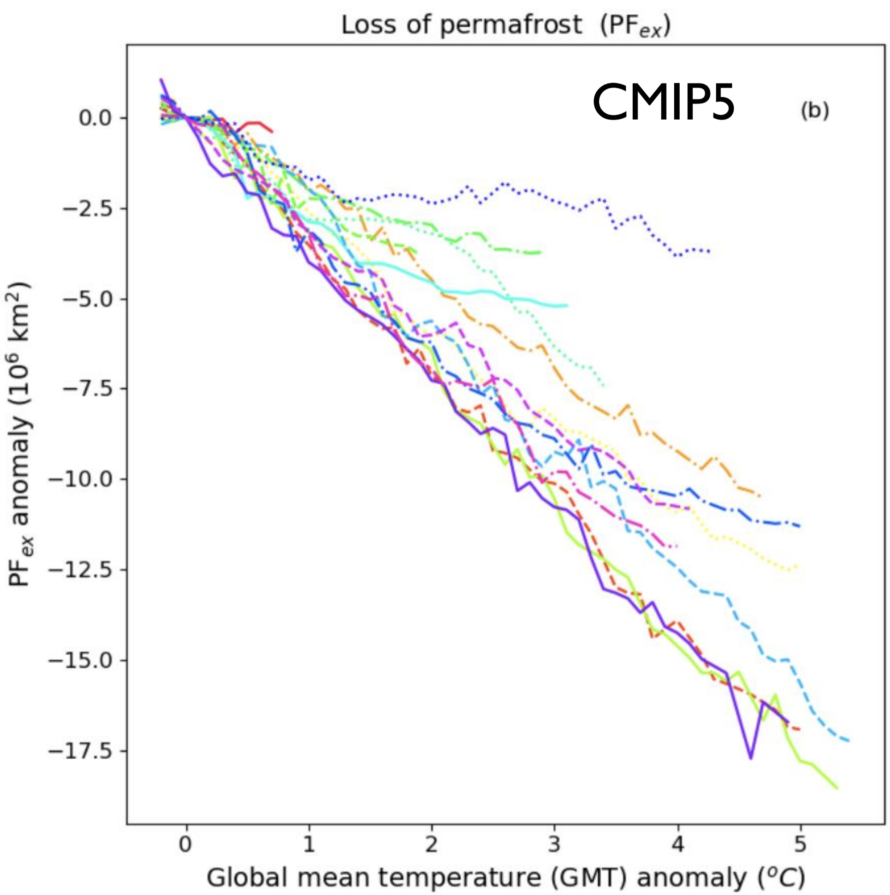
Permafrost Area Loss 1960-2299 (RCP 8.5)

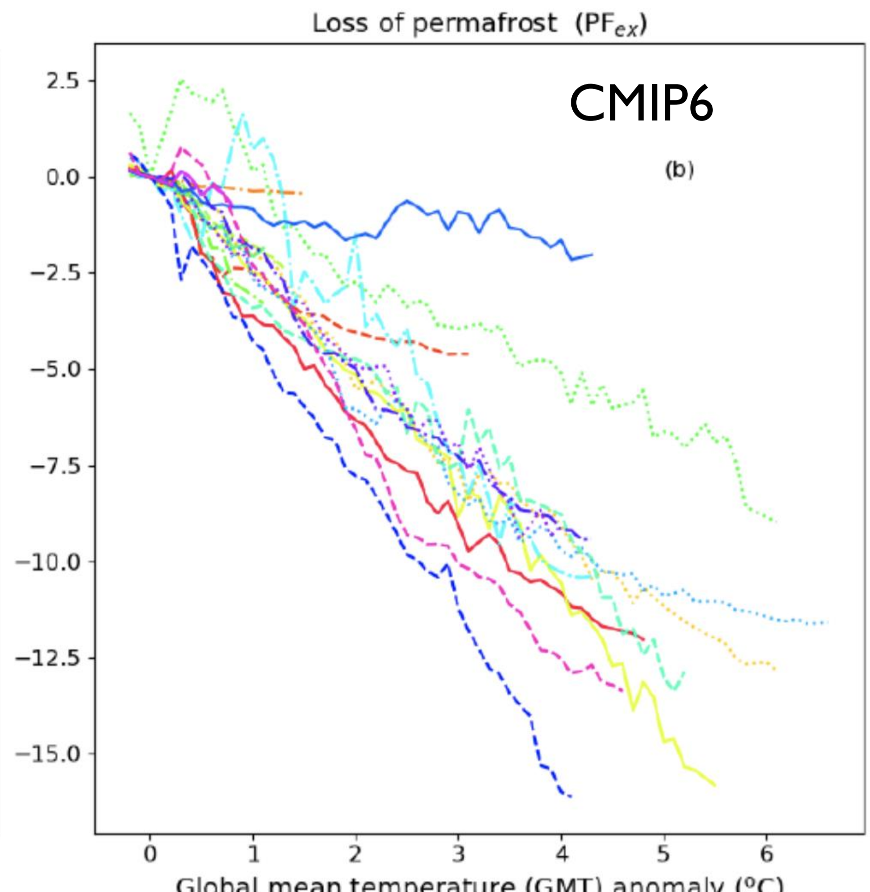


McGuire et al., 2018

Permafrost thaw in Earth System Models

CMIP6: improvement in present-day permafrost on some metrics, but similar wide range of projected loss to CMIP5





Burke et al., 2020

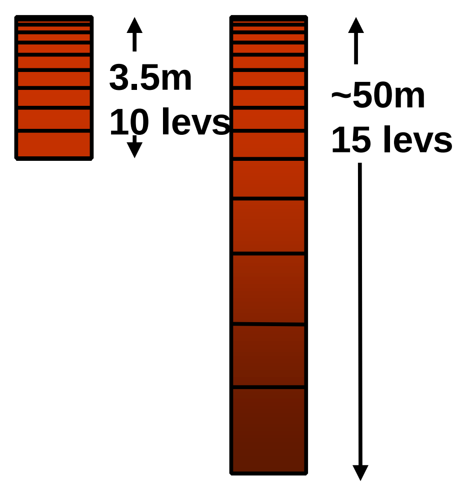
Permafrost Carbon in CMIP6

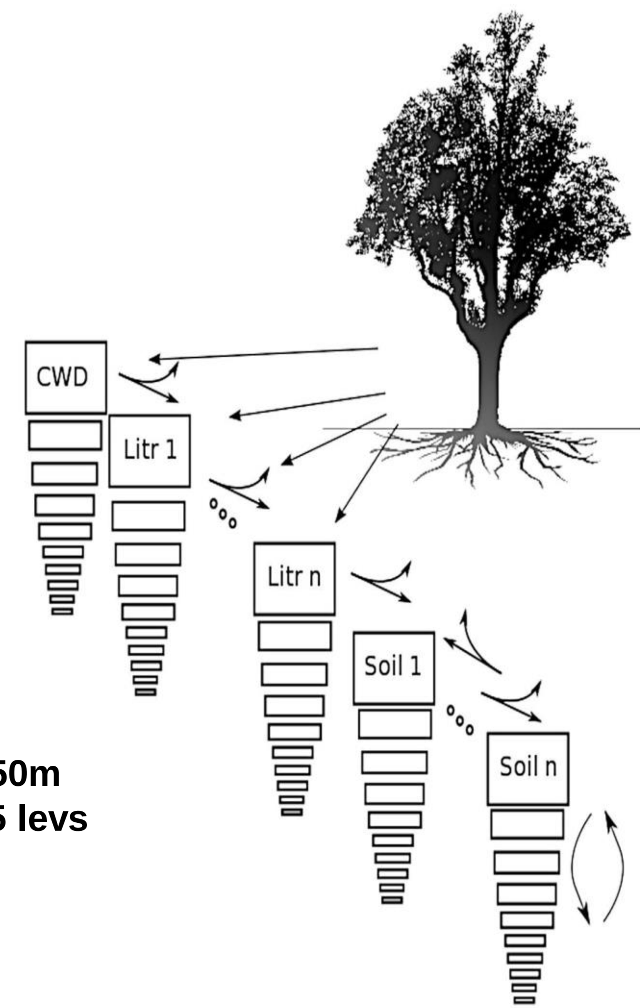
Table 5.4, IPCC AR6 Chapter 5

Modelling Group	CSIRO	BCC	CCCma	CESM	CNRM	GFDL	IPSL	JAMSTEC	MPI	NorESM2-LM	UK
ESM	ACCESS-ESM1.5	BCC-CSM2-MR	CanESM5	CESM2	CNRM-ESM2-1	GFDL-ESM4	IPSL-CM6A-LR	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL
Land carbon/biogeochemistry component											
Model name	CABLE2.4 CASA-CNP	BCC-AVIM2	CLASS-CTEM	CLM5	ISBA-CTRIP	LM4p1	ORCHIDEE (2)	MATSIRO (phys) VISIT-e (BGC)	JSBACH3.2	CLM5	JULES-ES-1.0
Veg C pools	3	3	3	22	6	6	8	3	3	3	3
Dead C pools	6	8	2	7	7	4	3	6	18	7	4
PFTS	13	16	9	22	16	6	15	13	12	21	13
Fire	No	No	No	Yes	Yes	Yes	No	No	Yes	Yes	No
Dynamic Veg	No	No	No	No	No	Yes	No	No	Yes	No	Yes
Permafrost C	No	No	No	Yes	No	No	No	No	No	Yes	No
Nitrogen cycle	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes

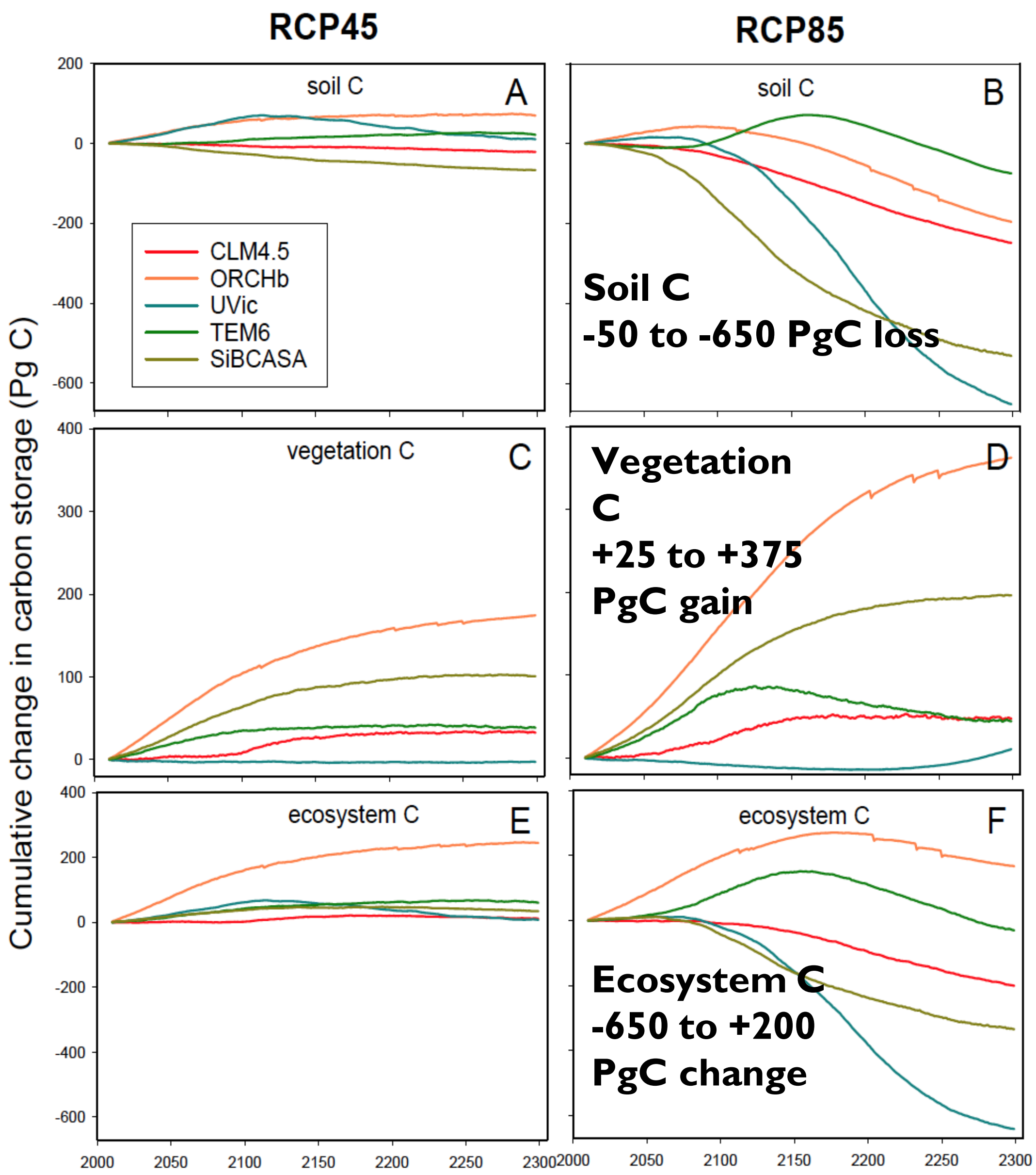
Land model features that are critical for baseline permafrost C projections

- 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, Burke et al. 2022)
- CH_4 emissions (Riley et al., 2013)





PCN: "Permafrost Model intercomparison" Diverse permafrost C loss predictions

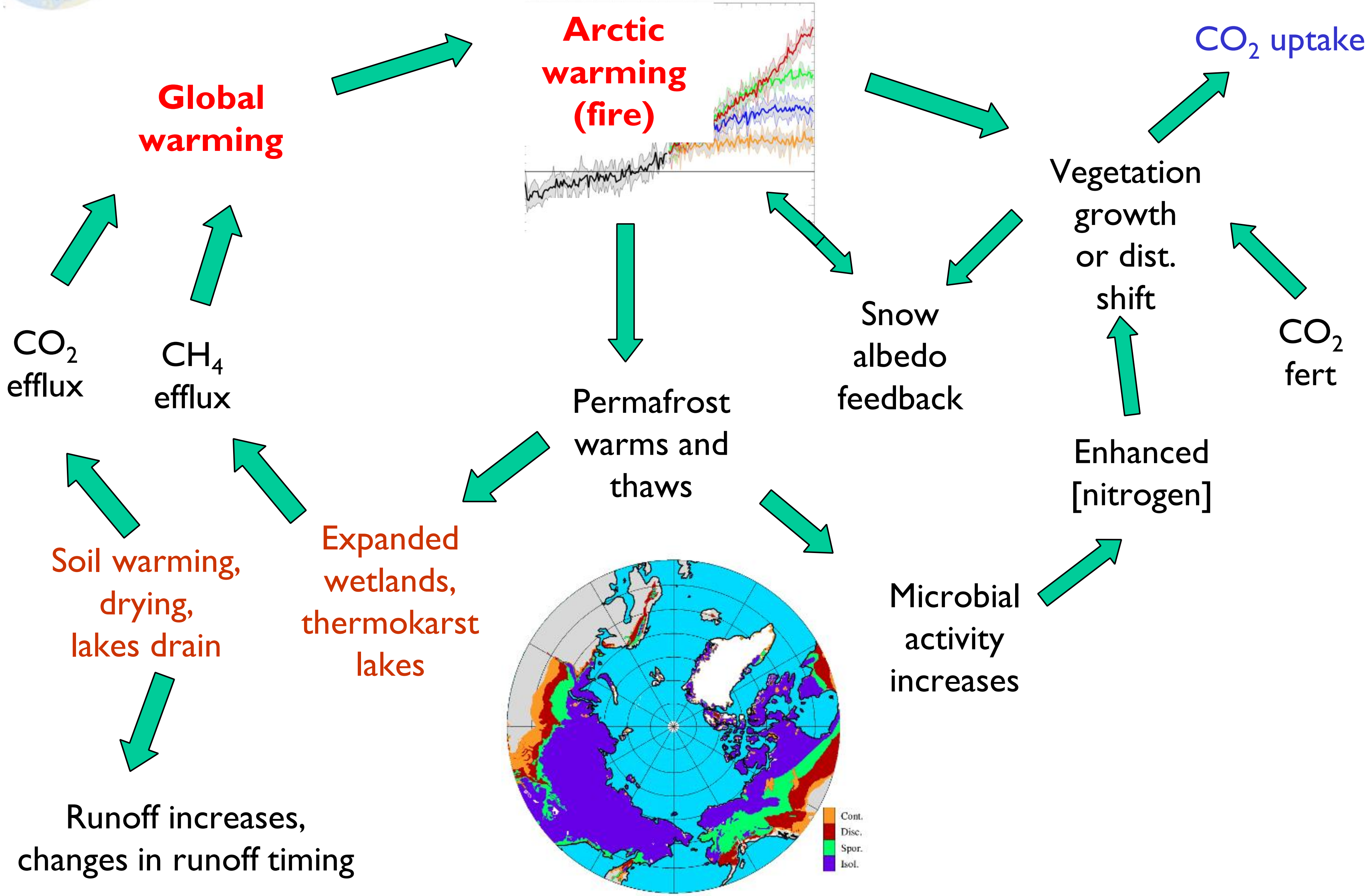


In a set of process-resolving 'permafrost-enabled' models, projections of Arctic ecosystem carbon loss differed sharply due in part to divergent

- vegetation C response to warming and CO2 fertilization
- soil moisture responses to active layer deepening

Need to better constrain with observations

Arctic terrestrial climate-change feedbacks



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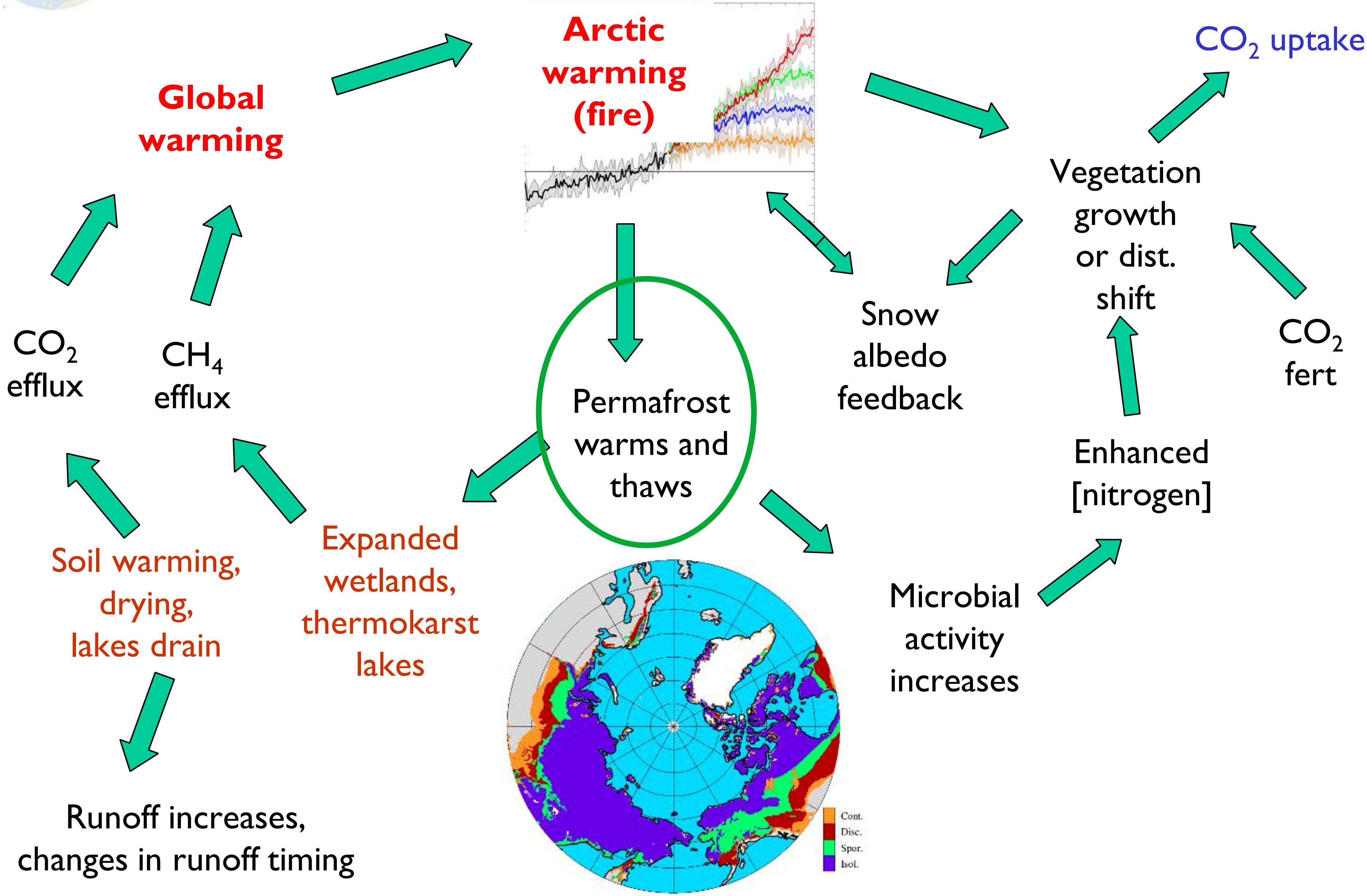

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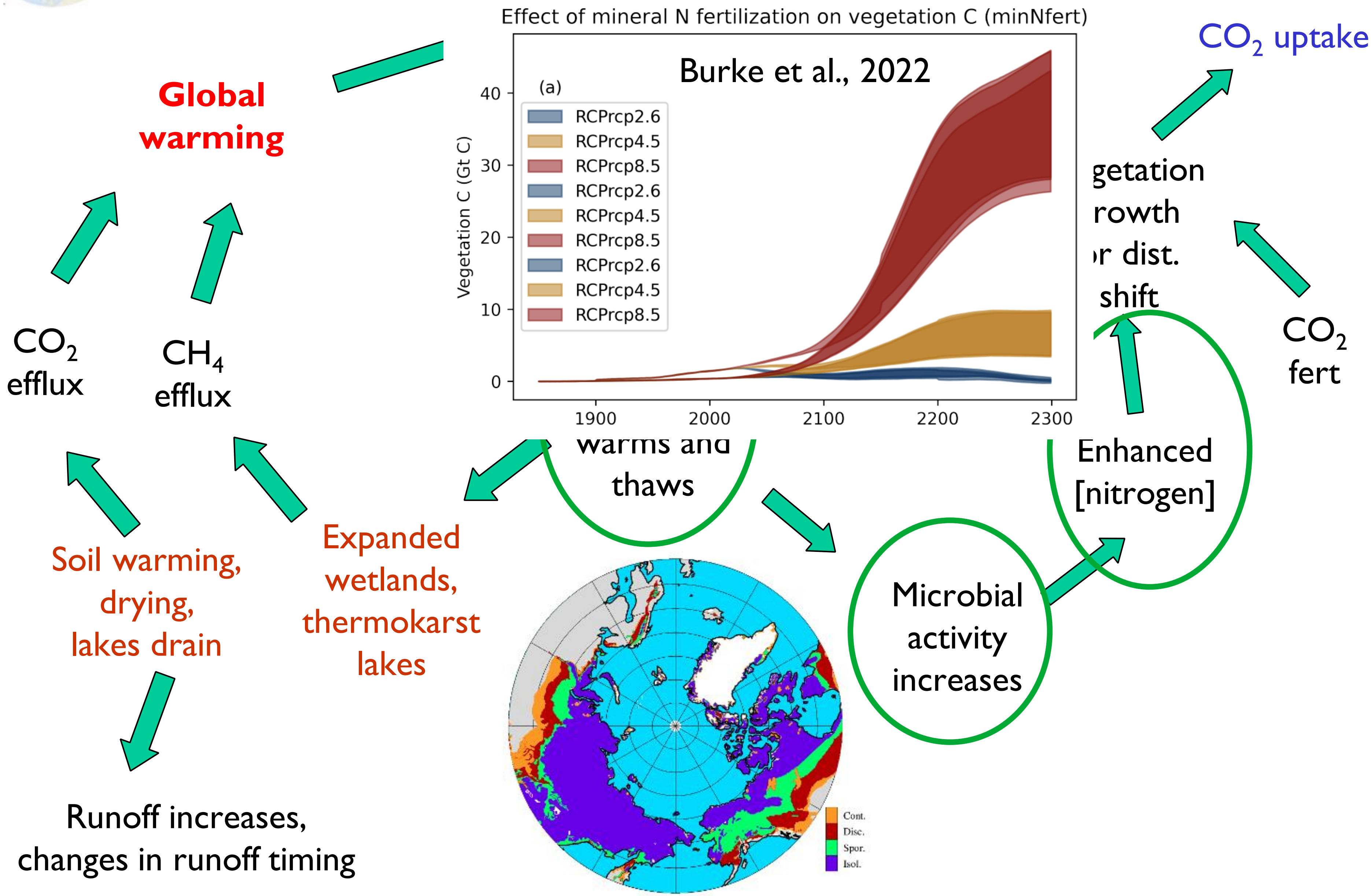

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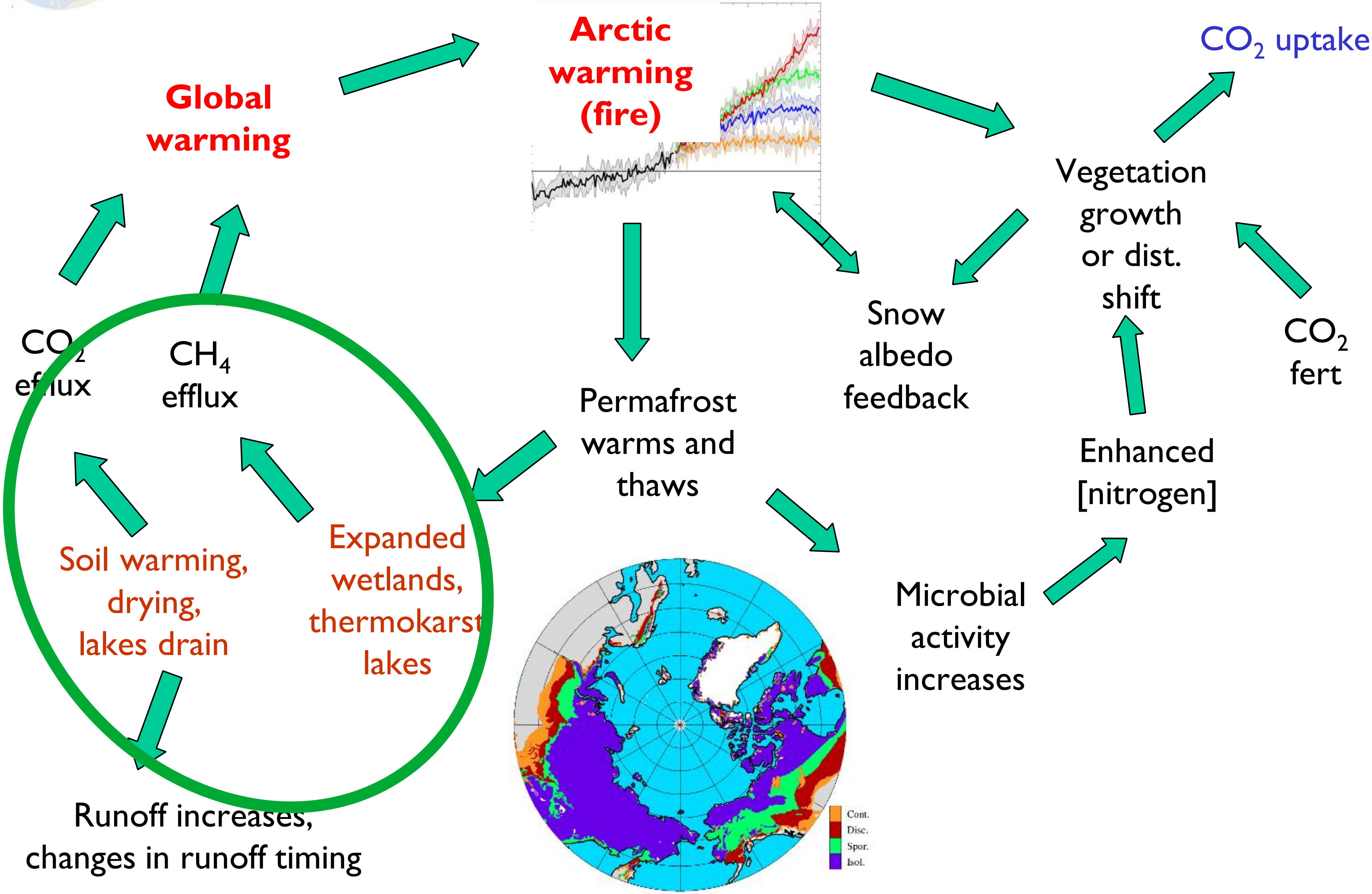
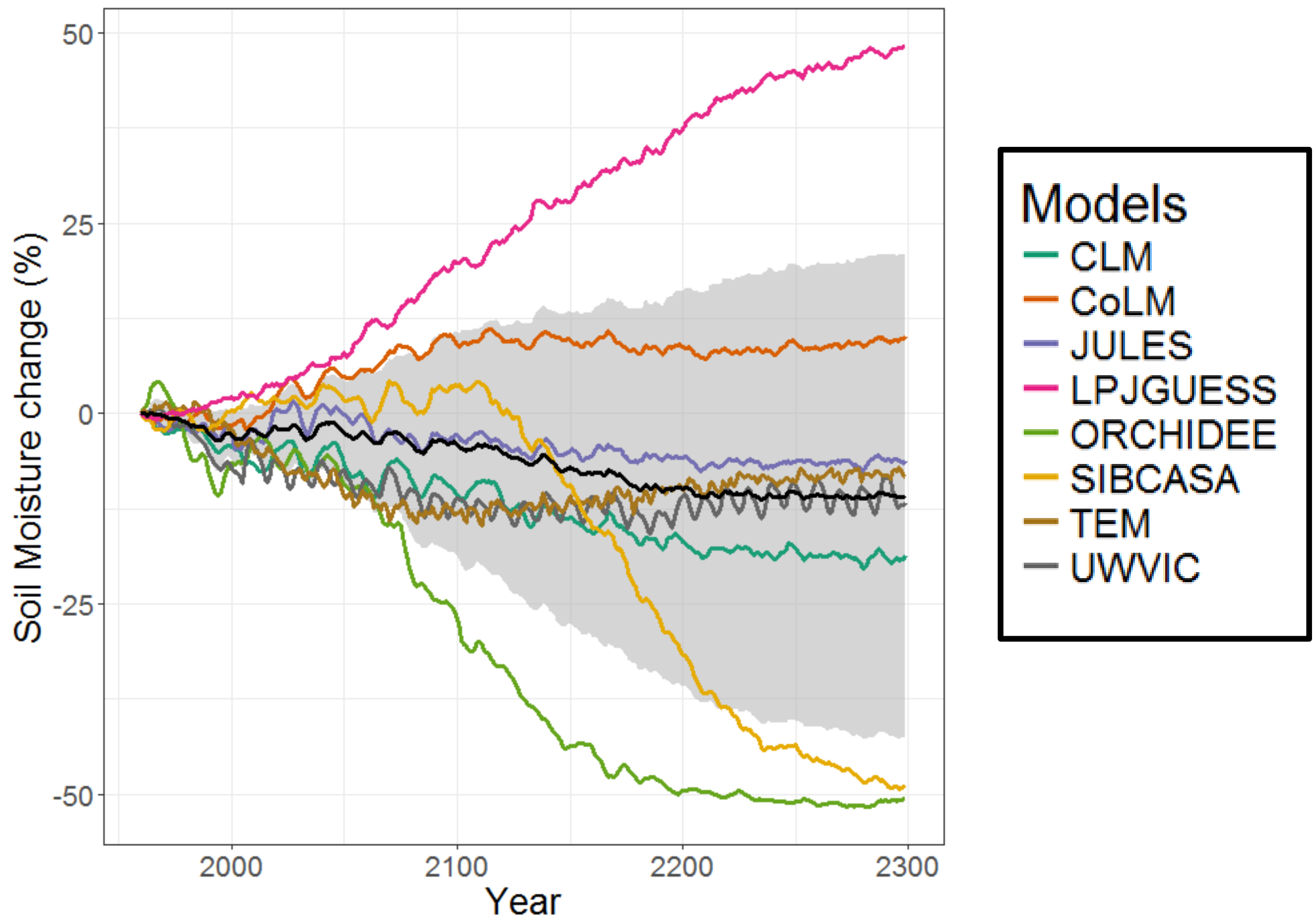
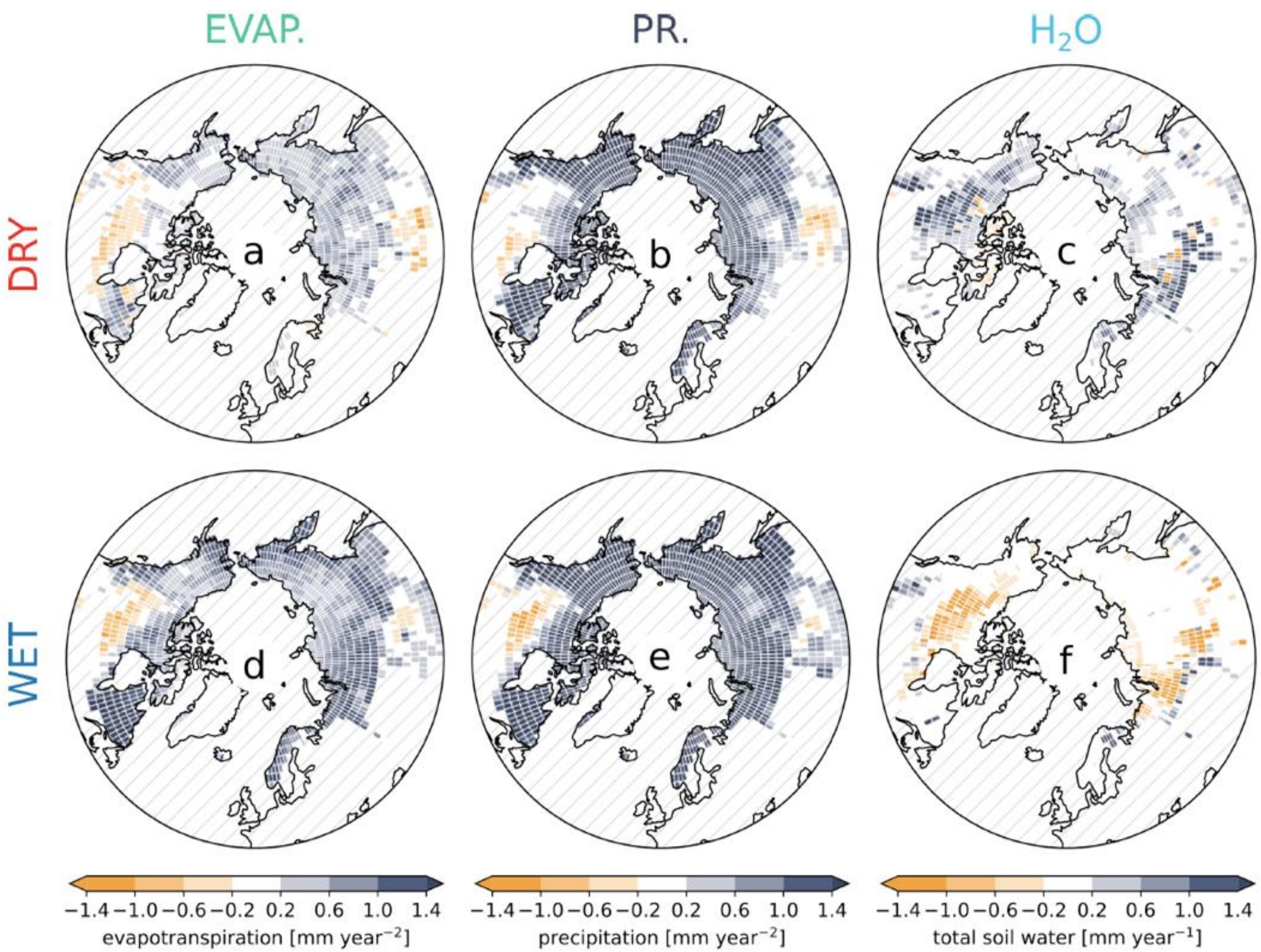


High uncertainty in permafrost-domain soil moisture projections in PCN models



Andresen et al., 2020

Will the Arctic be drier or wetter in the future?



Different Arctic futures. 21st century trends in evapotranspiration, precipitation and the total soil water (liquid soil moisture and ice) content in MPI-ESM RCP8.5 runs. a,b,c – the DRY simulation; d,e,f - the WET simulation. For details, see the poster by de Vrese et al.

de Vrese et al., TC Discuss., 2022

Where are we going?

Ongoing process development within land surface models (incomplete list)

- Enhanced sub-grid representation of hydrologic (e.g., representative hillslope), snow, and vegetation processes (many models)
- Moss, lichen (CLM; JULES; JSBACH)
- Snow redistribution and snow processes (CLM; JULES)
- Excess ice (CLM)
- Peat dynamics coupled to soil physics (JULES)
- ORCHIDEE: all sorts of things! DOC, yedoma, arctic veg.
- JSBACH: herbivory
- Parameter uncertainty quantification (CLM)

Where are we going?

Key missing or underrepresented processes

- Abrupt thaw (thermokarst)
- Fire interaction with permafrost; organic layer burning
- Microbial dynamics

Key challenges

- Simulating existing processes more realistically
  - vegetation: community response to thaw-induced change, CO_2 fertilization
  - seasons snowpack evolution (depth hoar)
  - permafrost hydrology and response to thaw
- Spin up of soil carbon – different origins of permafrost carbon!
- Accounting for fine-scale heterogeneity

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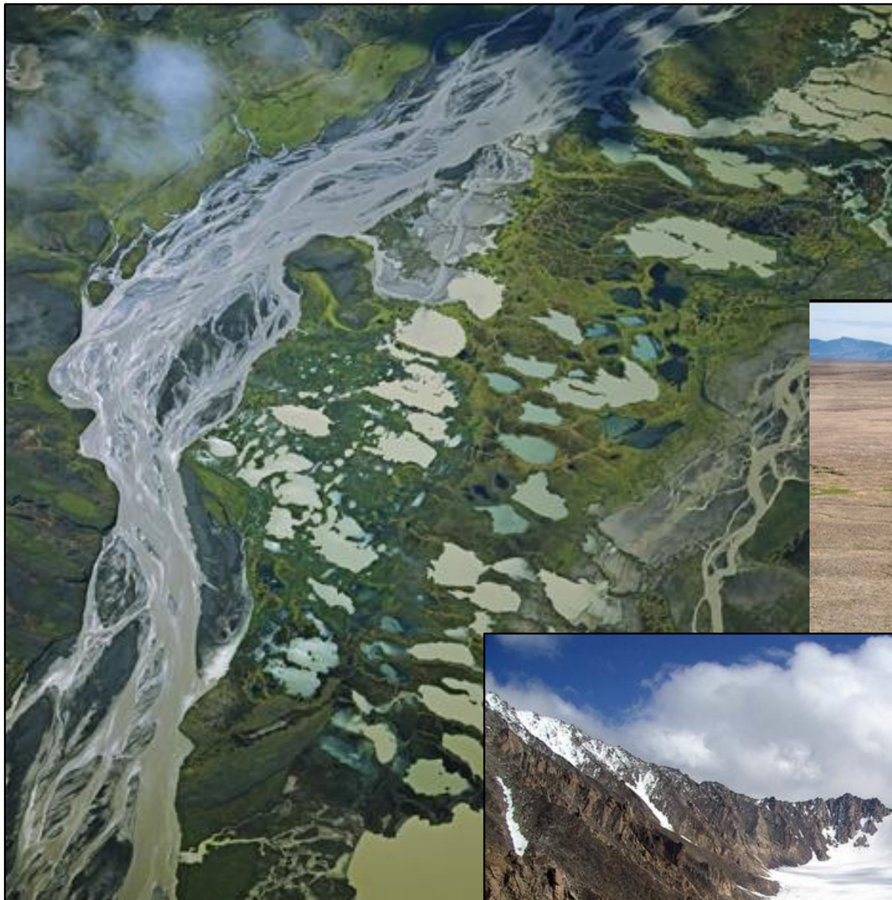
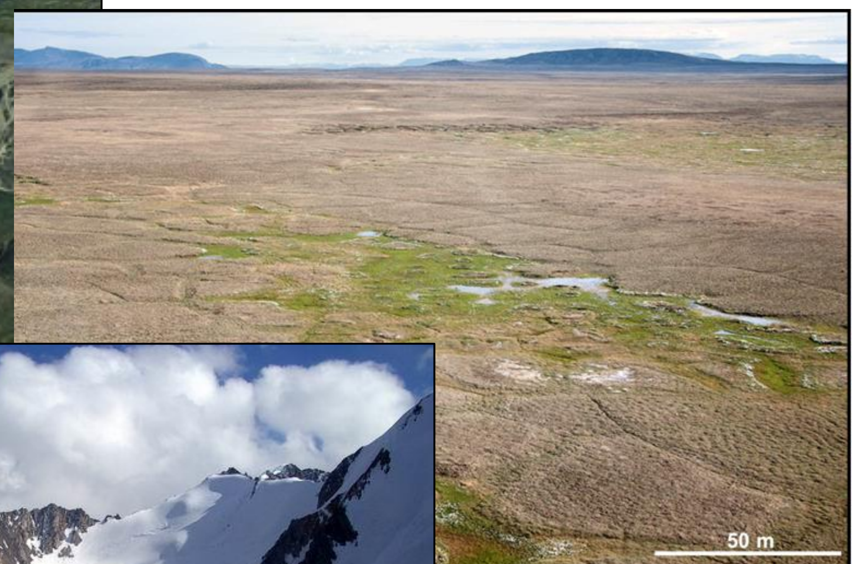
- Spin up of soil carbon – different origins of permafrost carbon!
- **Accounting for fine-scale heterogeneity**

Challenge of heterogeneity

To what extent do unrepresented heterogeneous land features, especially prevalent in permafrost domain, impact response to environmental change and affect the strength of the overall feedbacks?

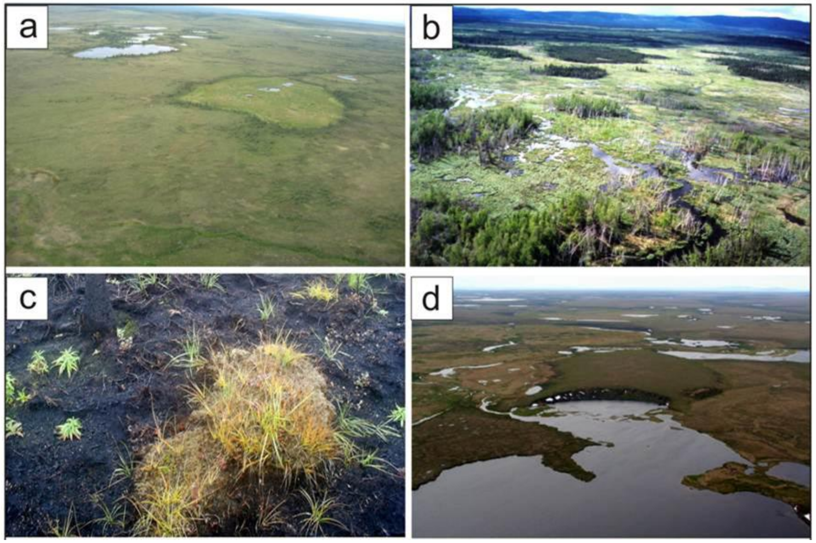




The challenge of heterogeneity
Example: Impact of thermokarst processes on permafrost C dynamics

Contrary to 'top-down' thaw, thermokarst processes can tap into deep permafrost C, resulting in rapid C release

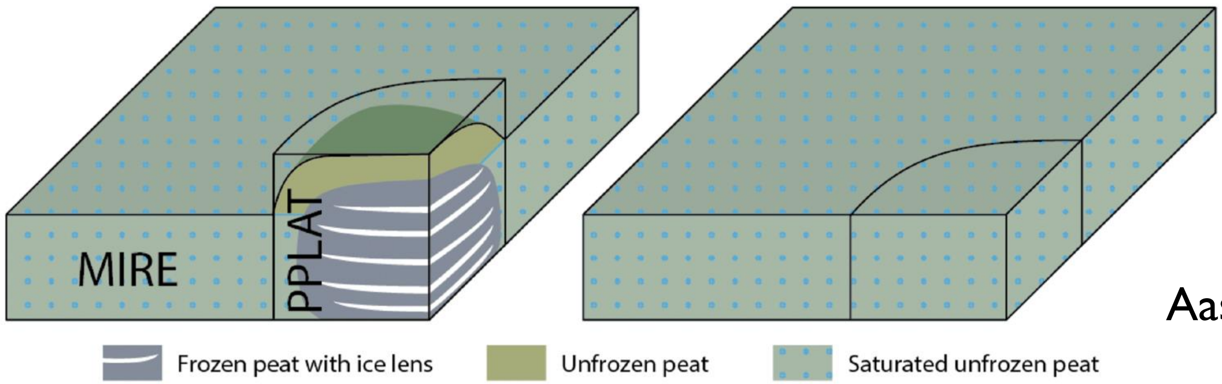
1) **Initial assessment using an inventory model suggests that thermokarst could amplify permafrost climate-carbon feedback by 50% or more (Turetsky et al., 2020)**



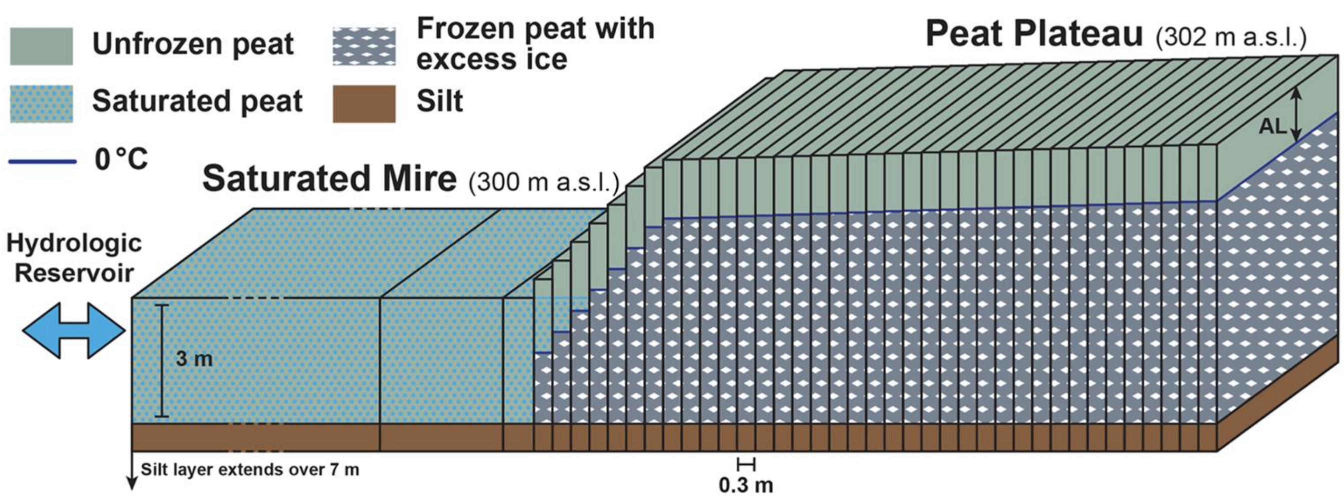
Thermokarst is subsidence of the surface that is caused by the melting of ground ice leading to fens/bogs, thermokarst lakes, thaw slumps, etc

Modeling heterogeneity and the associated feedbacks

2-tile vs 2D approaches



Aas et al., 2019

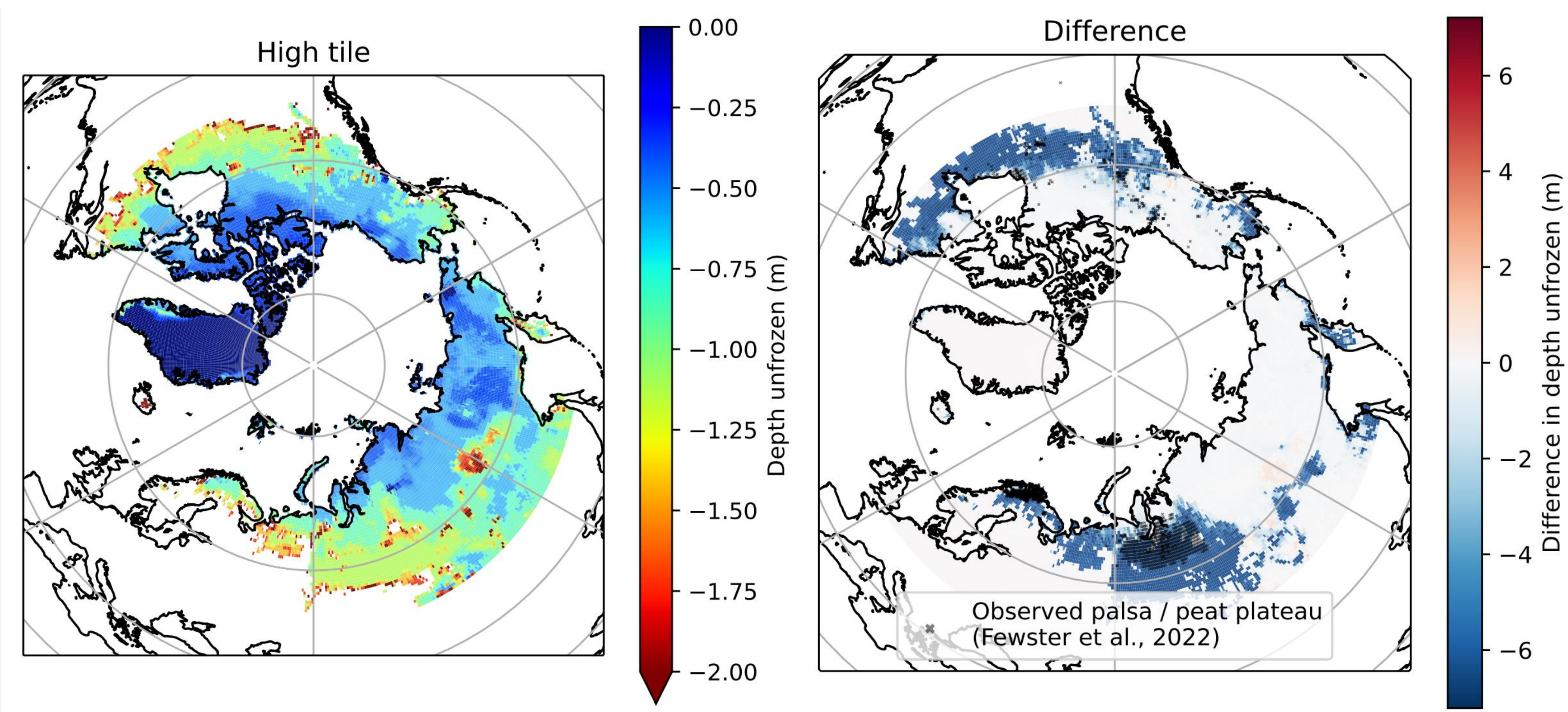


Martin et al., 2021

Modeling heterogeneity and the associated feedbacks

Currently trying hybrid approach with 2 tiles in JULES coupled to a 2D heat flow model to estimate lateral thaw rates.

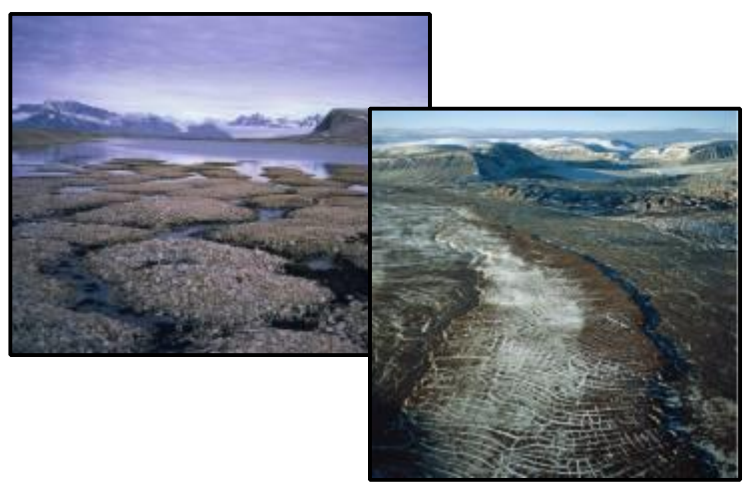
Distribution of palsas and peat plateaus is reasonable.



Smith et al., in prep

Paths forward for permafrost carbon-climate feedback modeling

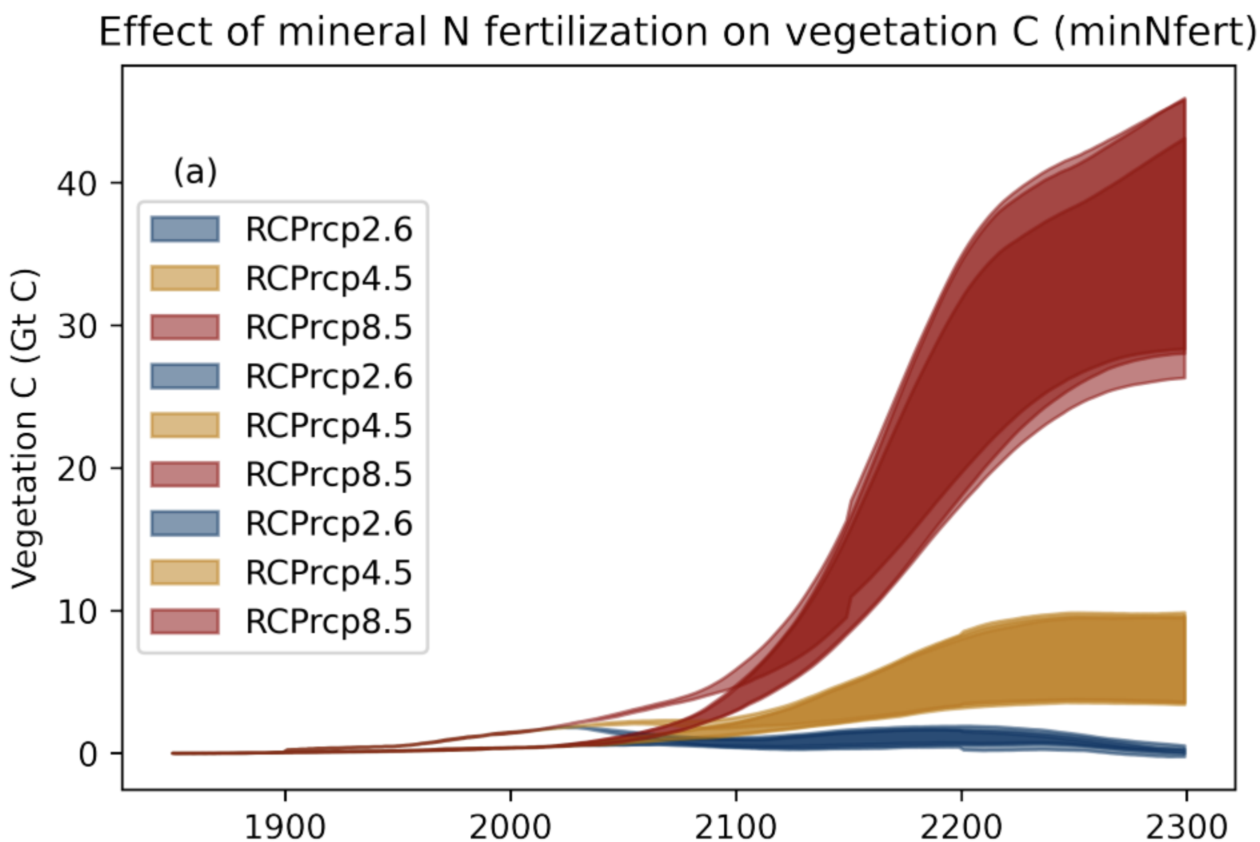
- Develop data sets and methodologies to constrain existing model processes (Permafrost Carbon Network, manipulation experiments, chronosequence)
- More permafrost-enabled ESMs; Implement “best” existing structural representations of permafrost and carbon from across LSMs
- Represent consequences of subgrid heterogeneity (e.g., abrupt thaw), fire, and other key processes
- Develop techniques to account for parameter and structural uncertainty in future projections



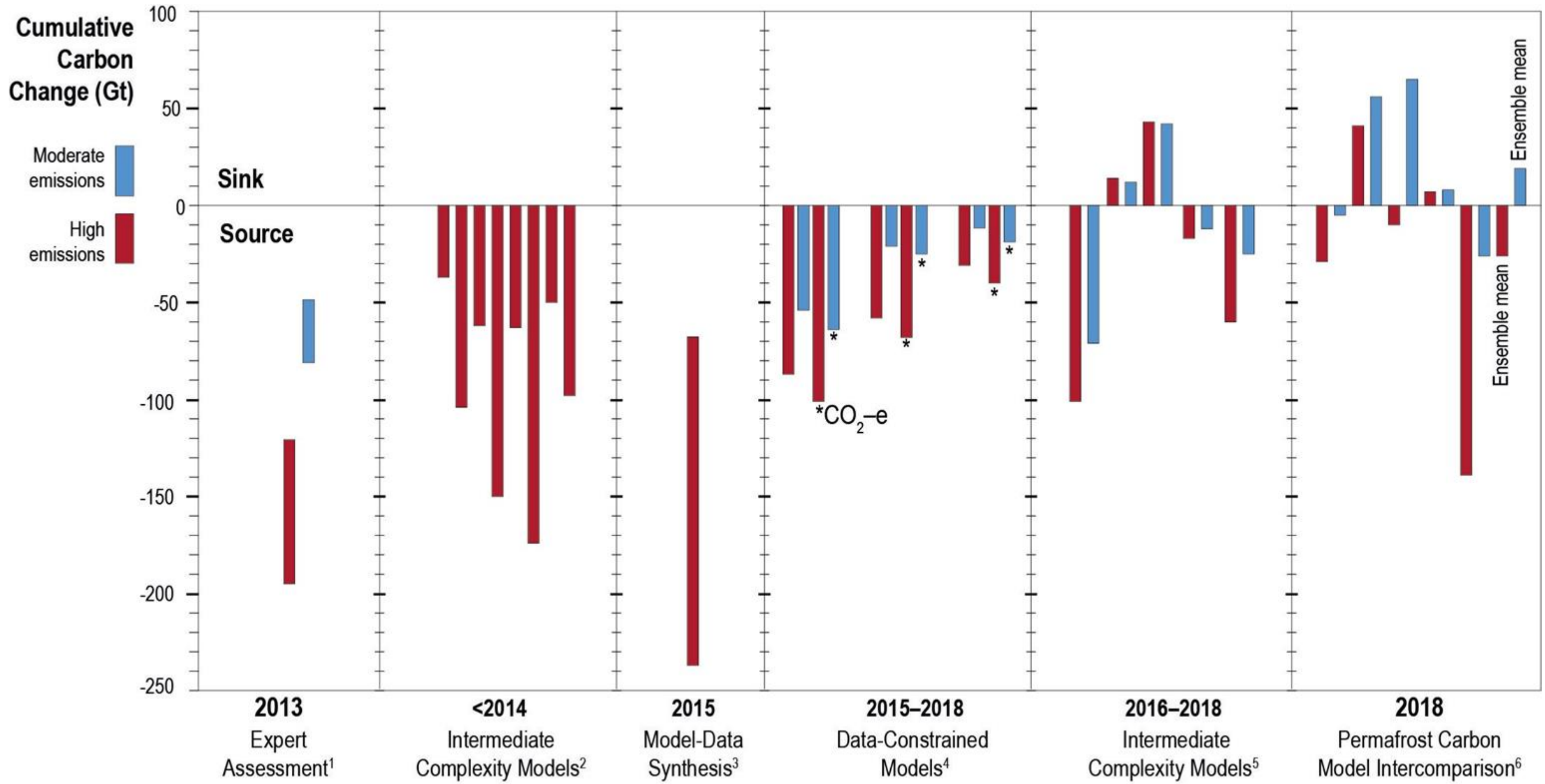
EXTRA SLIDES

Nitrogen feedback

Extra N from thawing permafrost: Burke et al 2022



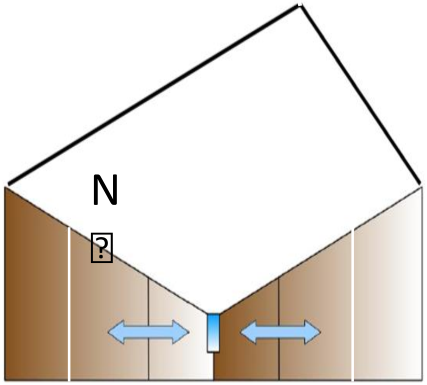
Permafrost carbon loss synthesis (IPCC SROCC)



Lateral soil water transport
Implementing concept of 'representative hillslopes' into CLM

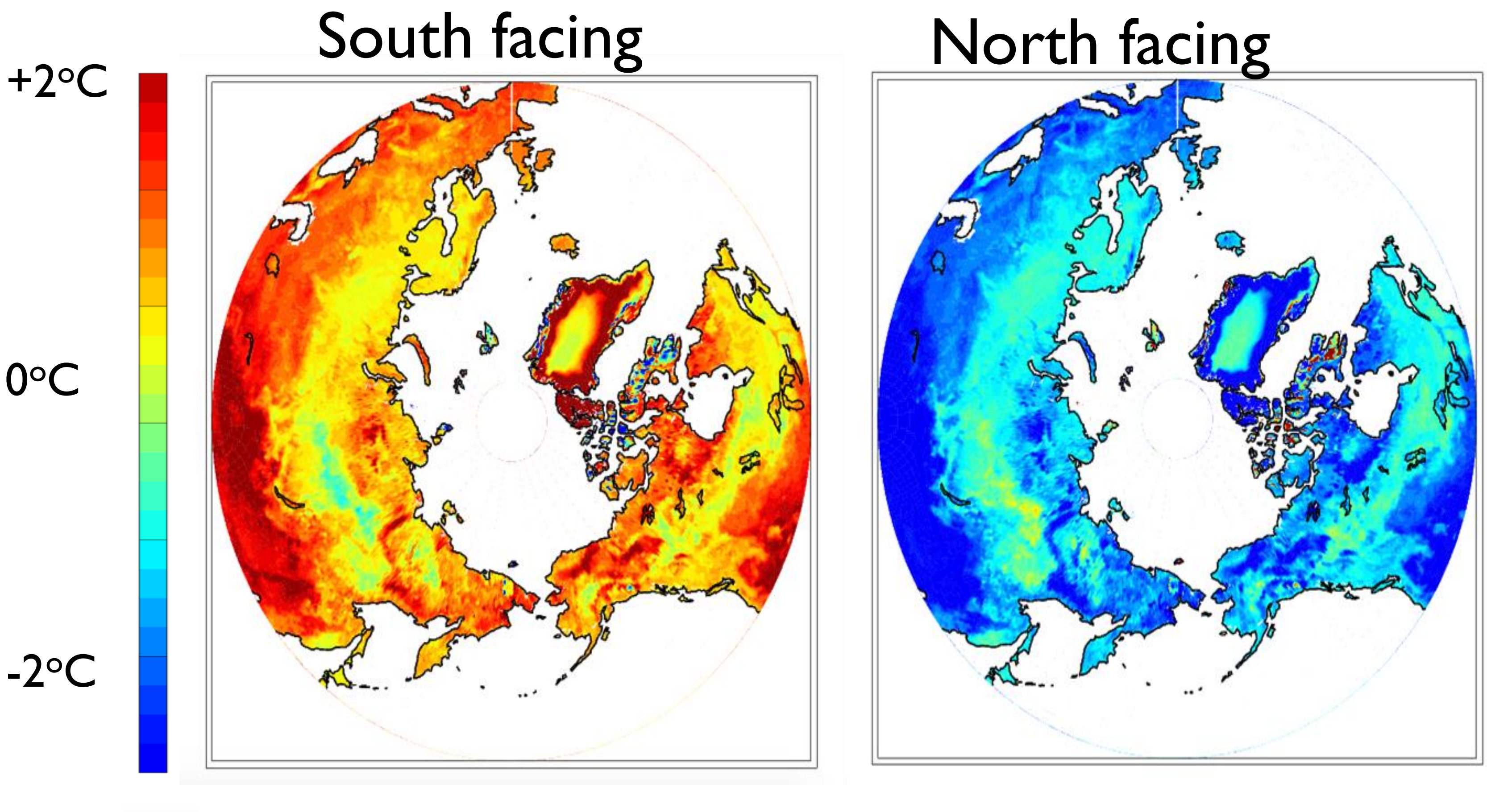
Observed vegetation patterns imply lateral movement of water and strong influences from slope, aspect, and elevation

CLM grid cell (~1°x1°)

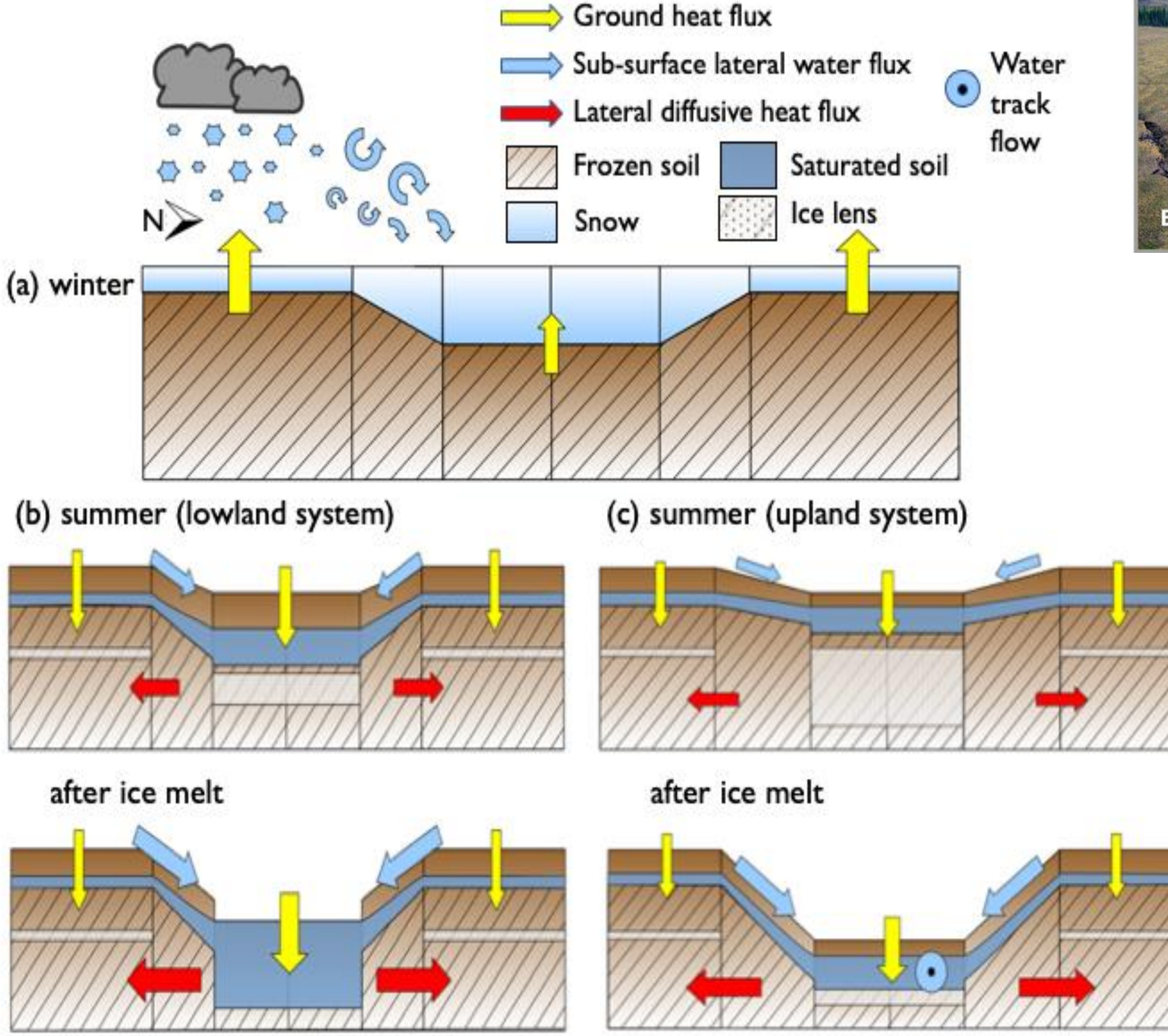


Accounting for sub-grid variations: representing slope and aspect

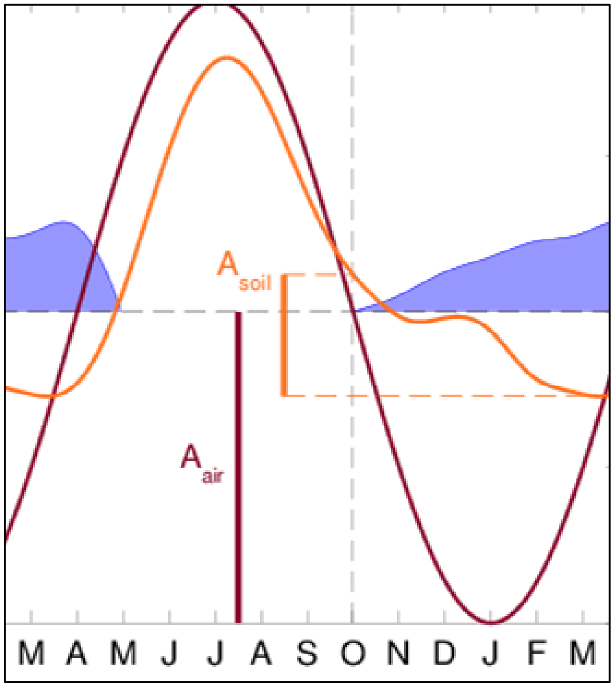
Soil Temperature (1m)

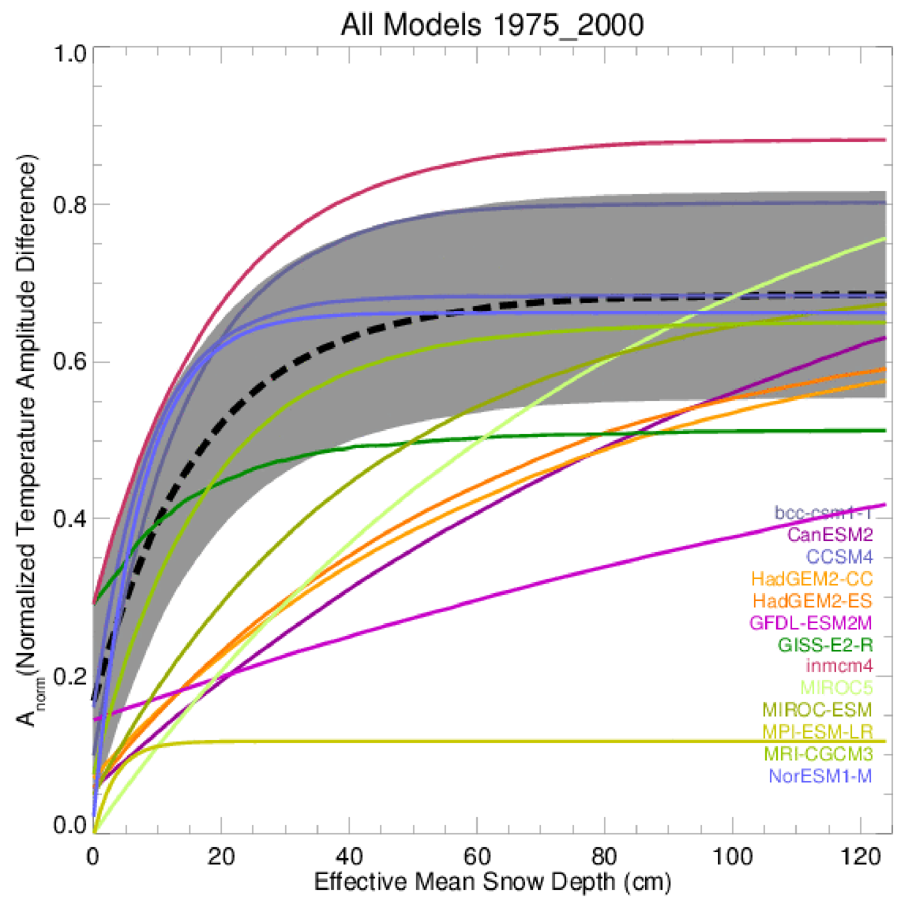


Possible future permafrost developments
Representative hillslopes with subsidence



A snow heat transfer metric





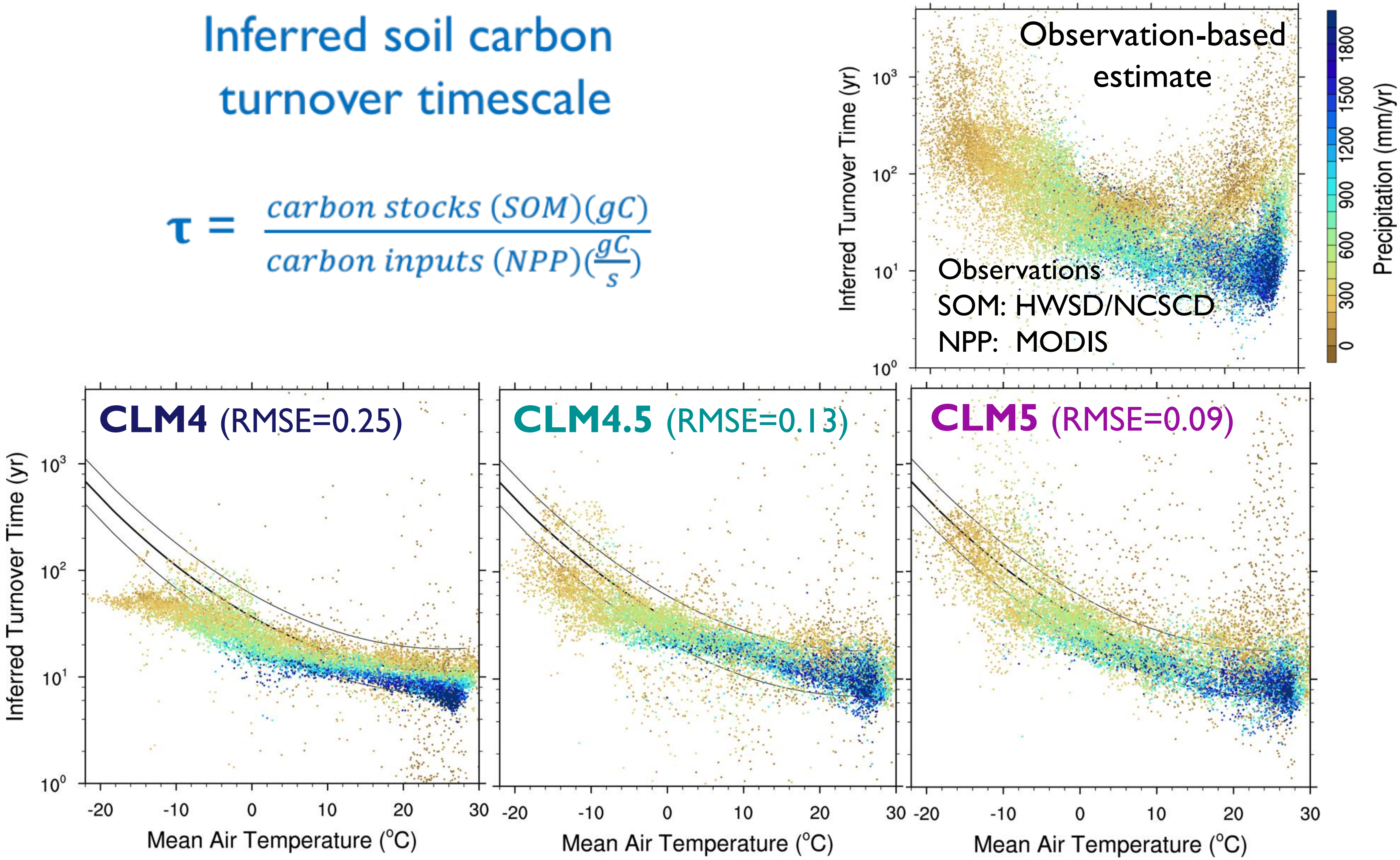
Many models do not correctly represent snow insulation
Lack of representation of depth hoar is a significant problem

Slater et al. 2017

timescale

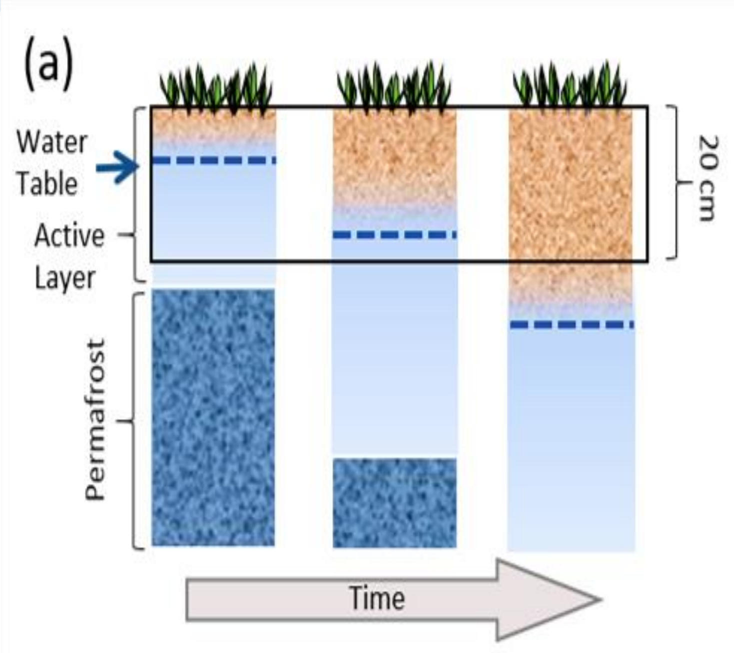
Inferred soil carbon turnover timescale

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

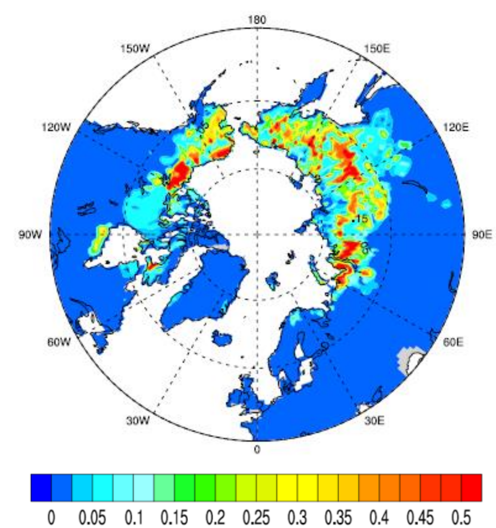


Koven, Hugelius, Lawrence, and Wieder, NCC, 201

Active layer deepening and soil subsidence



CLM projection of subsidence by 2100



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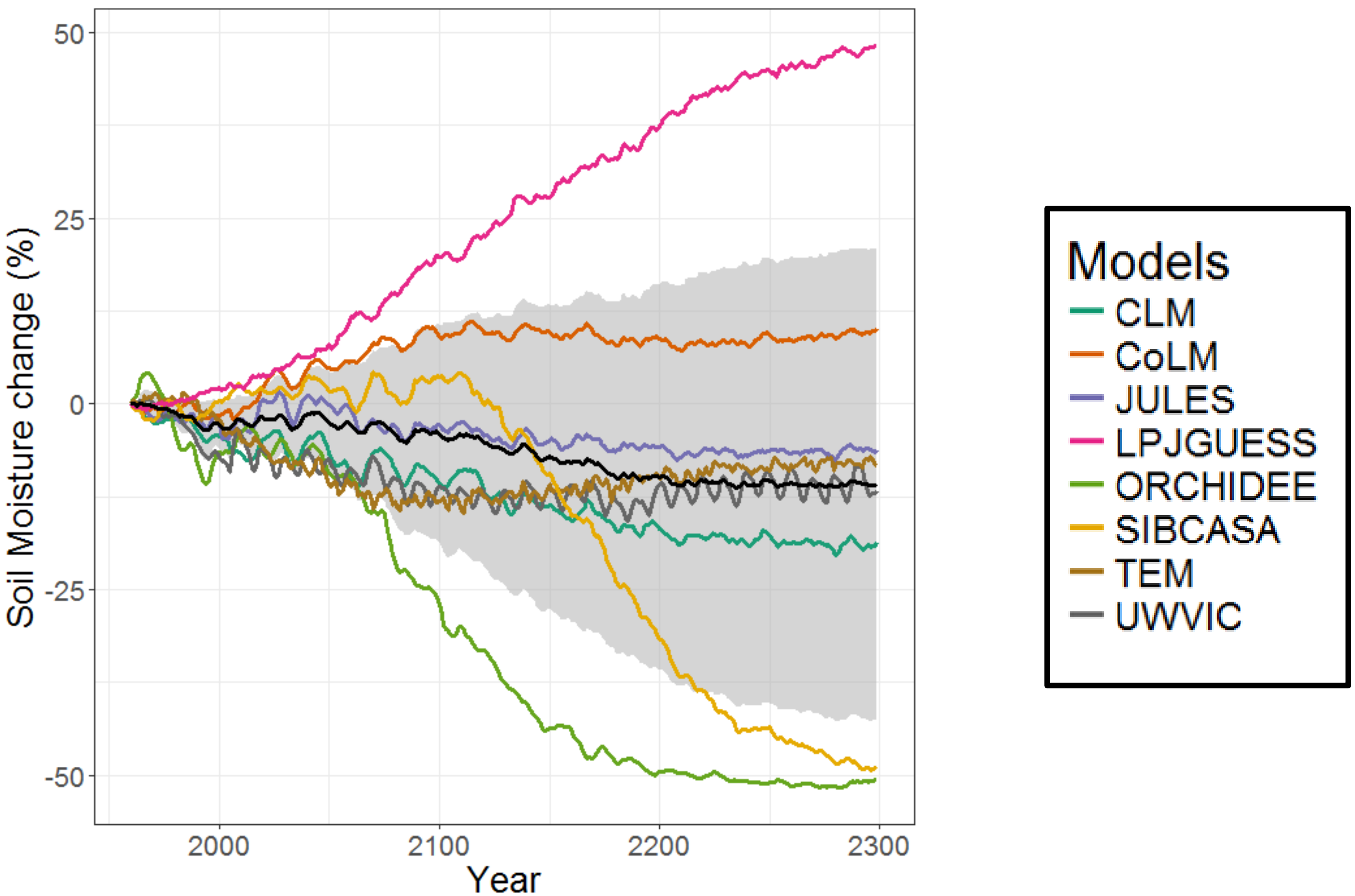

Andresen et al., in prep