Understanding and Predicting Terrestrial High-Latitude Climate Change Feedbacks Using CCSM

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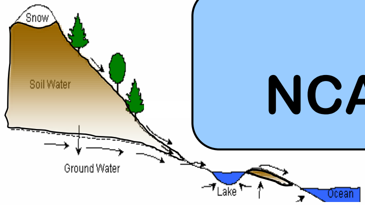
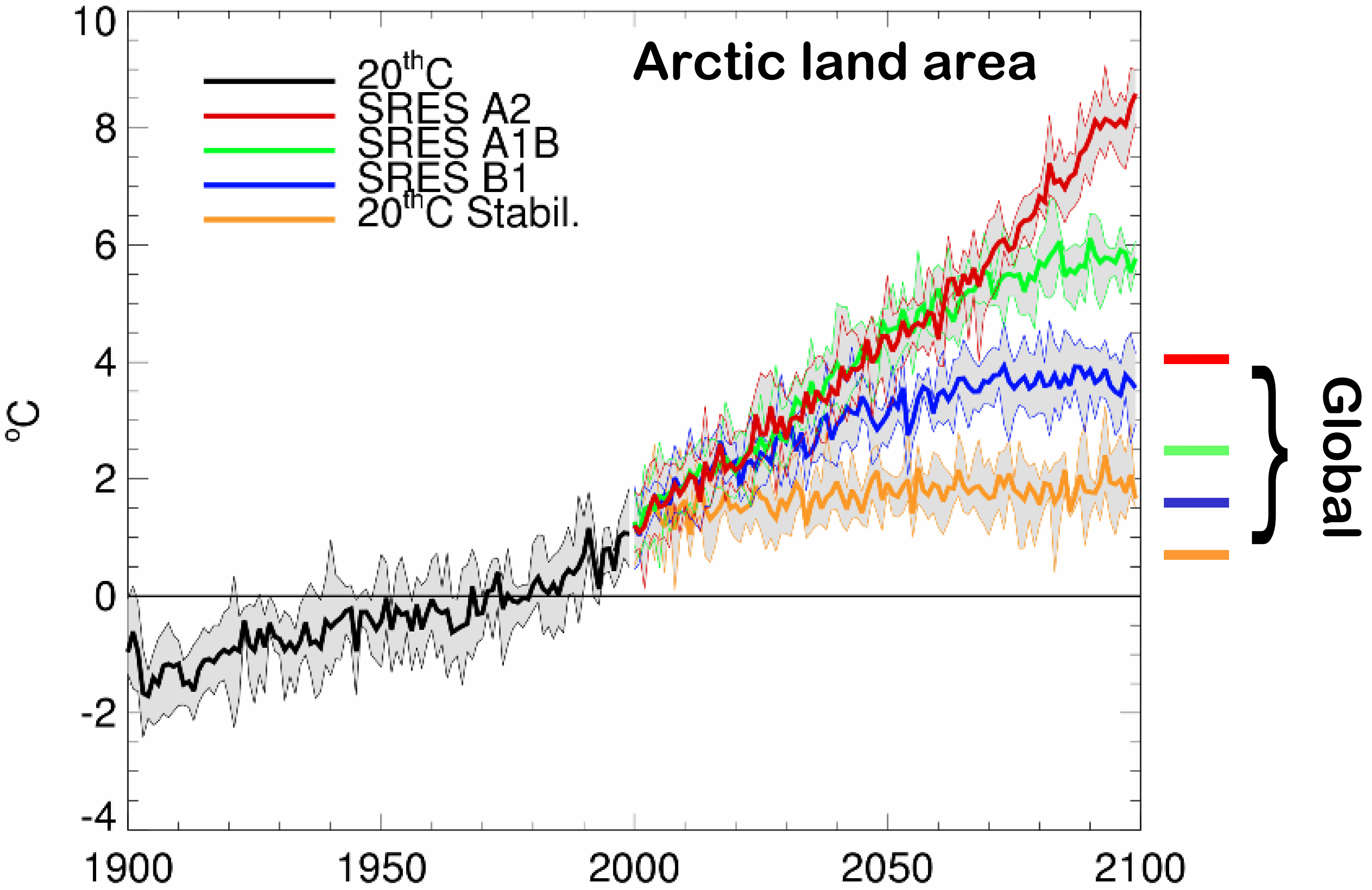
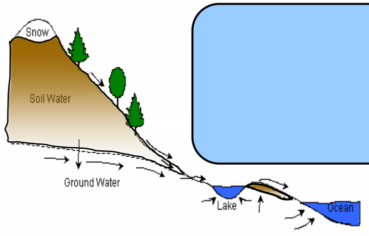
Surface air temperature change:
NCAR Community Climate System Model (CCSM3) projection





Hypothesized high-latitude terrestrial climate-change feedbacks



Global warming

Carbon sequester

Shrub growth

Radiative forcing of complete conversion tundra to shrubland 8.9W m^{-2} (4.2W m^{-2} GHG)

CO_2 efflux

CH_4 efflux

Permafrost warms and thaws

Microbial activity increases

Carbon stocks in permafrost soil

~ 200 – 800 PgC

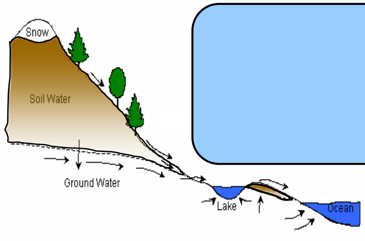
Atmos carbon content

~ 750 PgC + 8-9 PgC yr^{-1}

Arctic runoff increases

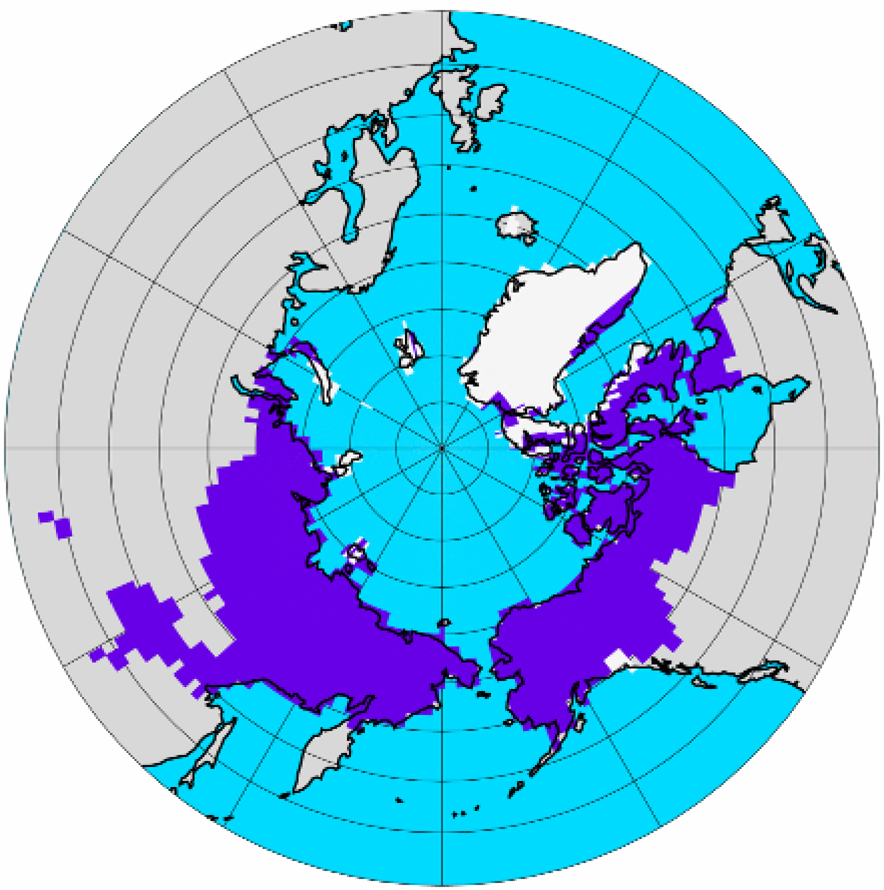
Thermohaline slows

McGuire et al., 2006

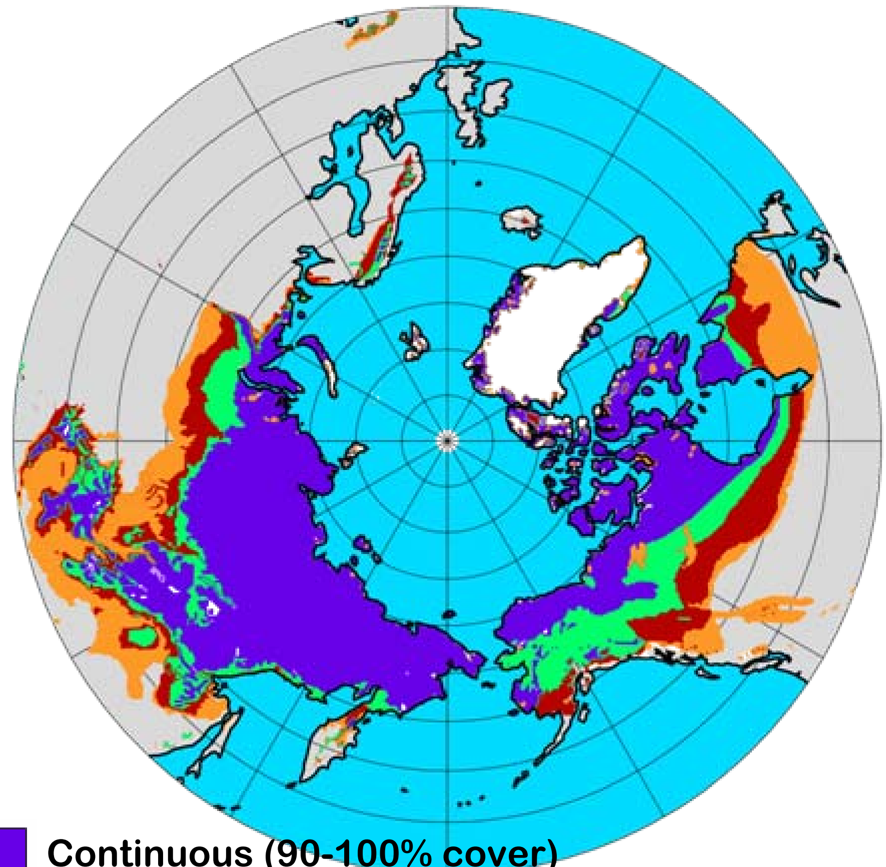


Near-surface permafrost in NCAR Community Climate System Model (CCSM3)

CCSM3 (1980 – 1999)

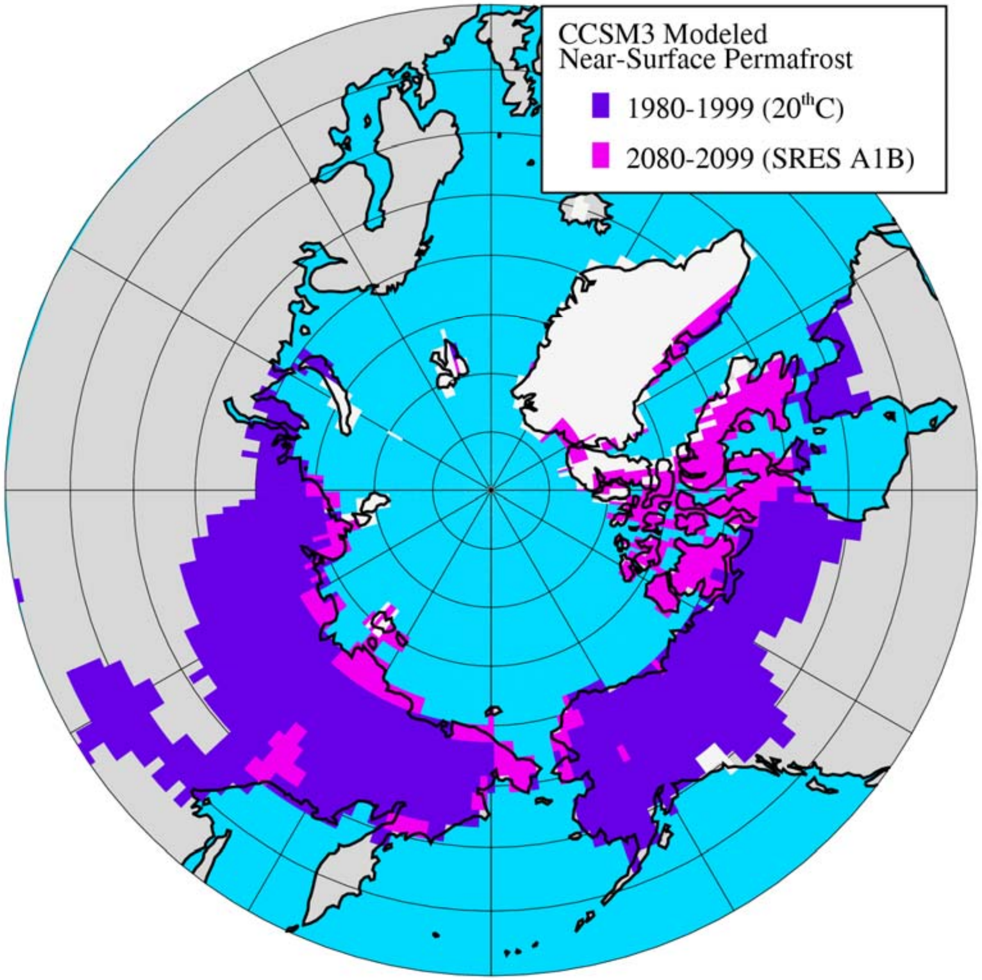


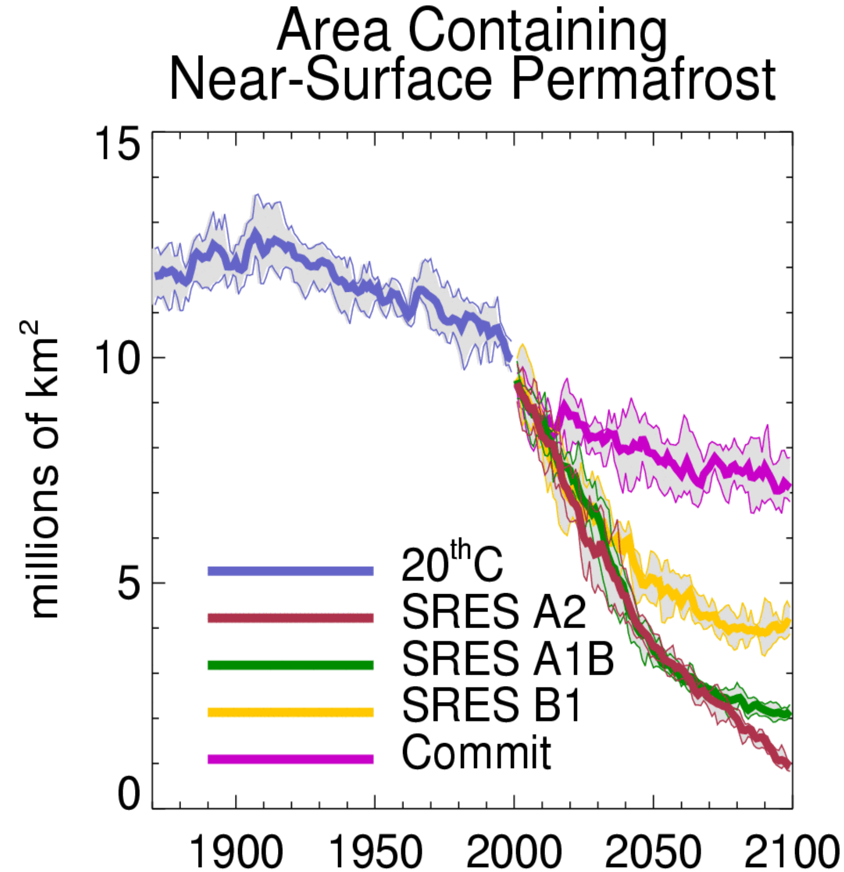
IPA Permafrost Distribution Map



Continuous (90-100% cover)
Discontinuous (50-90%)
Sporadic (10-50%)
Isolated (0-10%)

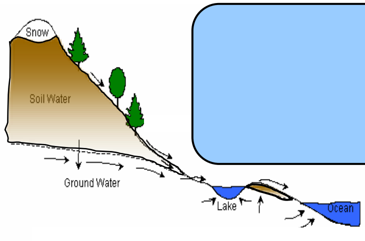
CCSM3 projections of degradation of near-surface permafrost



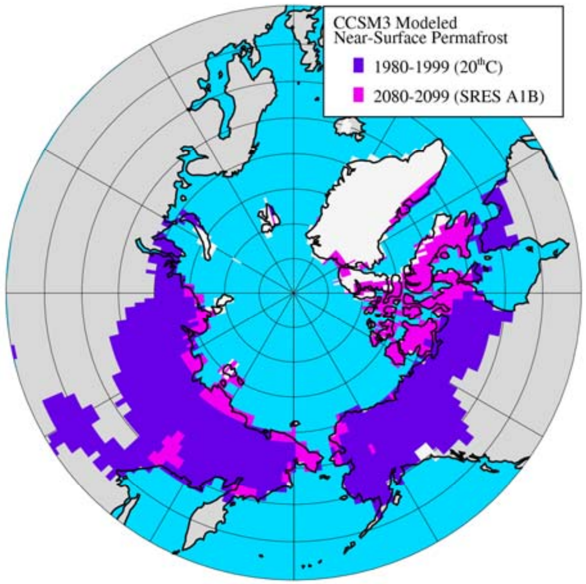


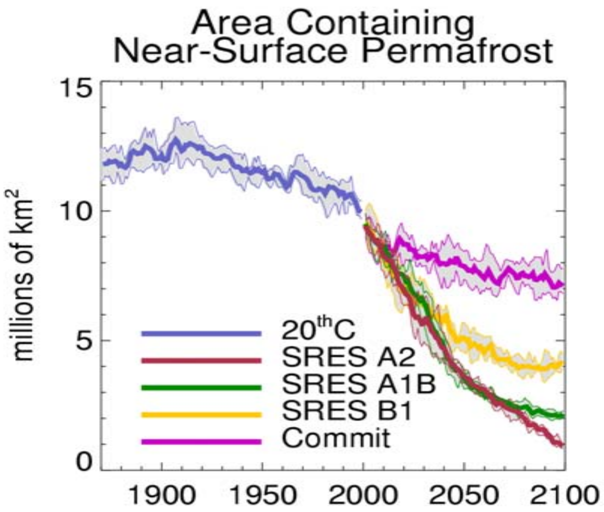
We define near-surface permafrost as perpetually frozen soil in upper 3.5m of soil

Lawrence and Slater, 2005



Are the CCSM3 Projections Plausible?

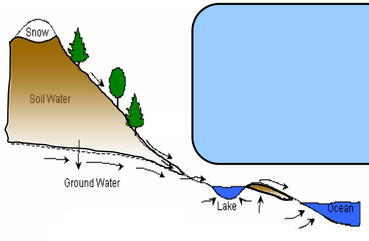


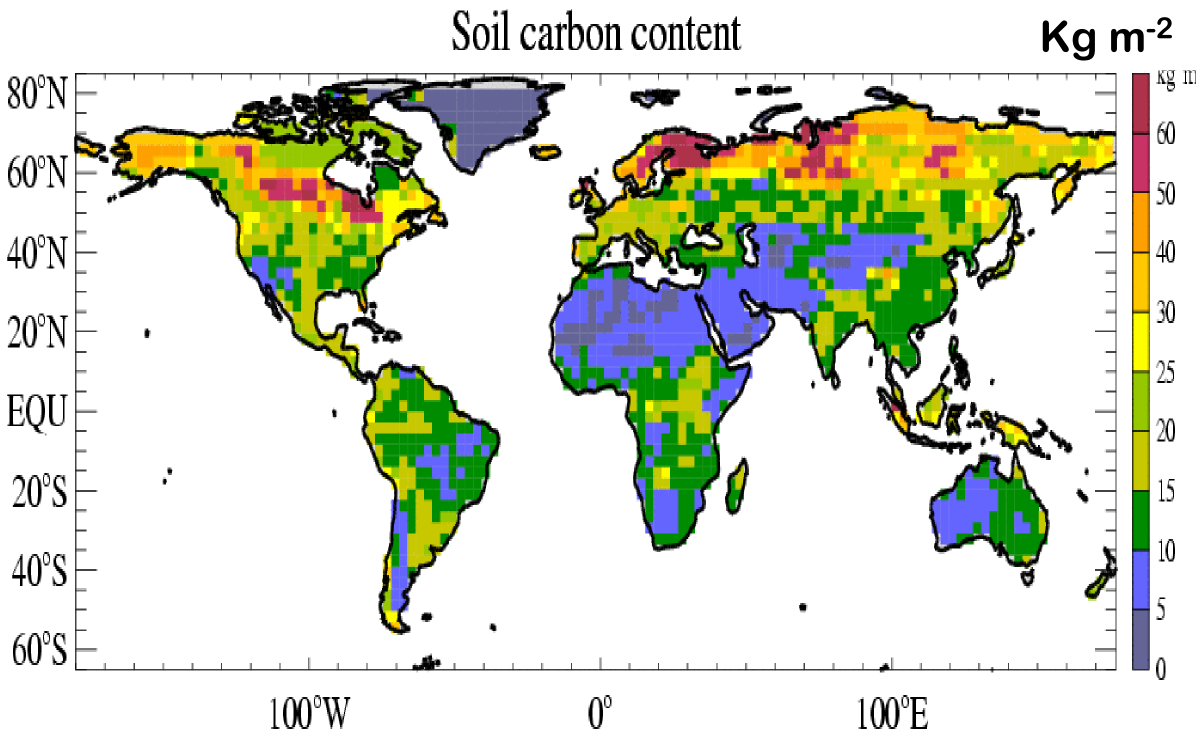


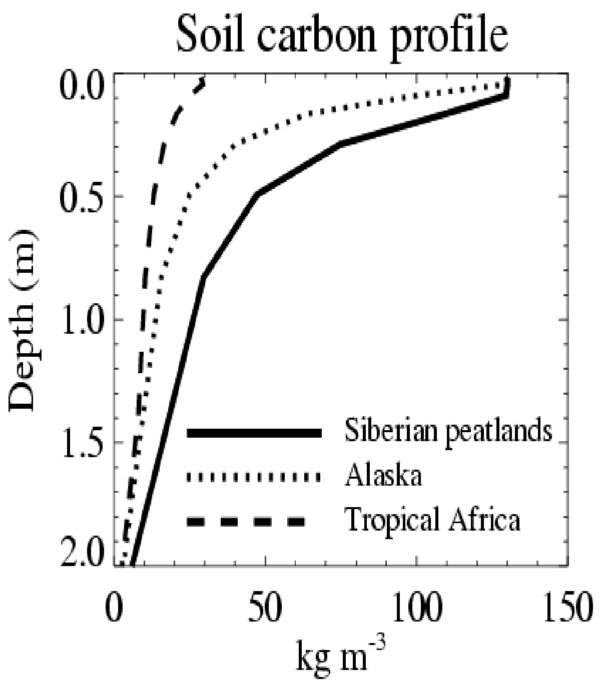
Need to ask:

- How bad are the biases in simulated climate?
  - T, snow, low clouds, circulation
- How complete is the representation of permafrost in CLM?
  - no organic soil (peatlands)
    - low thermal conductivity
    - high porosity
    - high hydraulic conductivity
  - soil column too shallow
    - thermal inertia provided by deep soil
  - no excess soil ice

CLM soil carbon density dataset
Source data from Global Soil Data Task

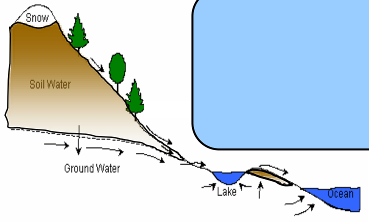






Calculate thermal and hydraulic soil parameters as a weighted combination of organic and mineral soil values

Lawrence and Slater, 2007, in press



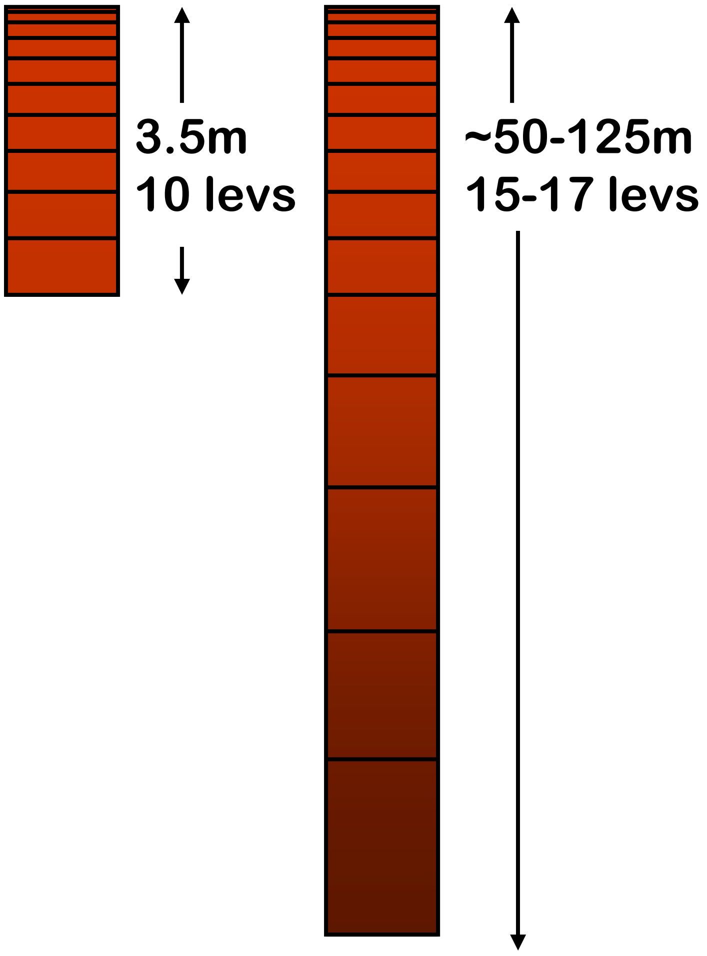
Deeper soil column

Motivation:

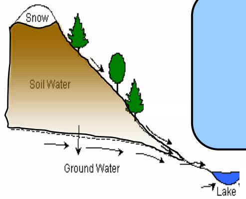
account for thermal inertia of deep soil layers

Solution:

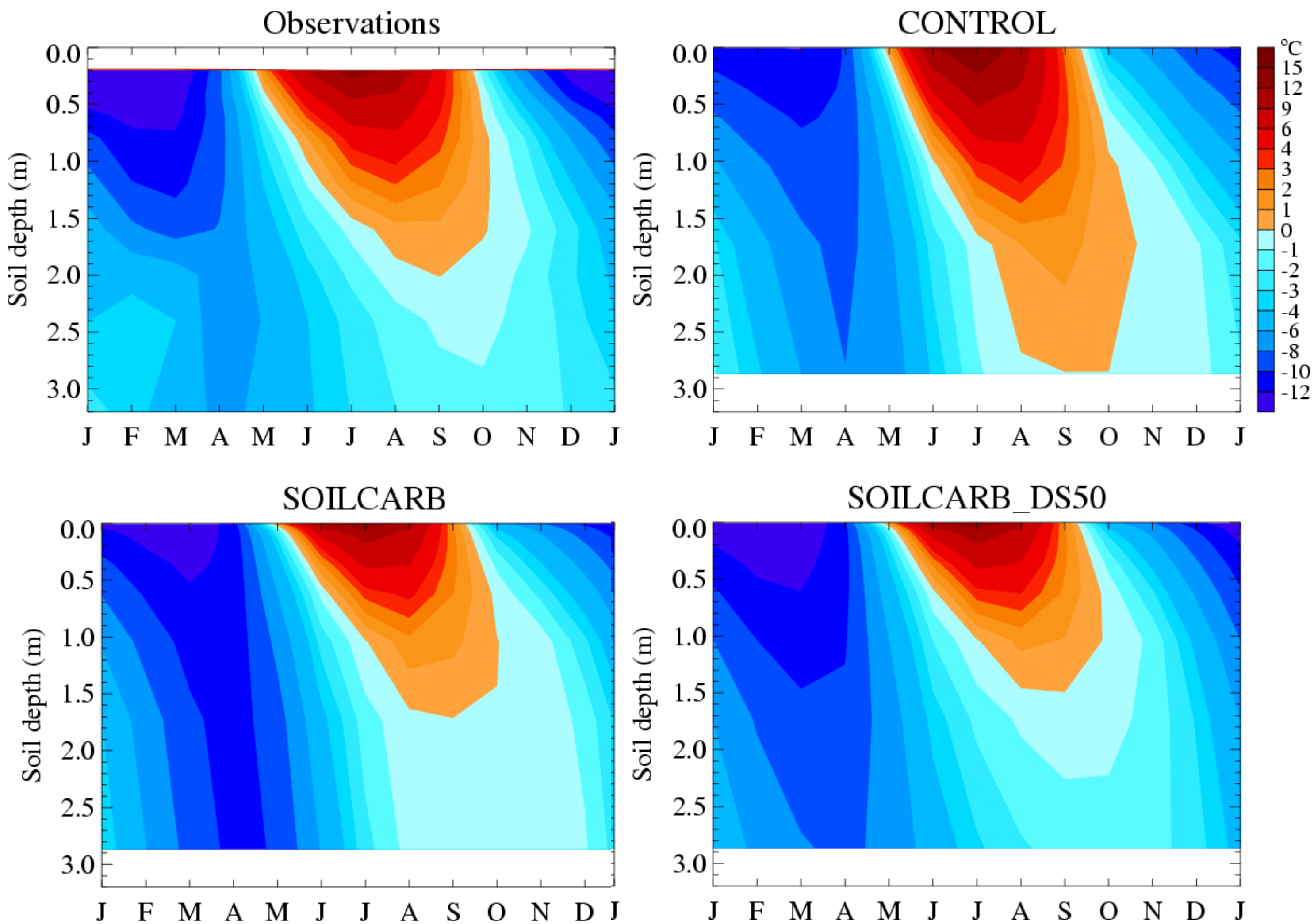
add additional layers, hydrologically inactive

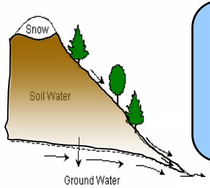


Ignore geothermal heat flux (up to ~0.1 W m^{-2})

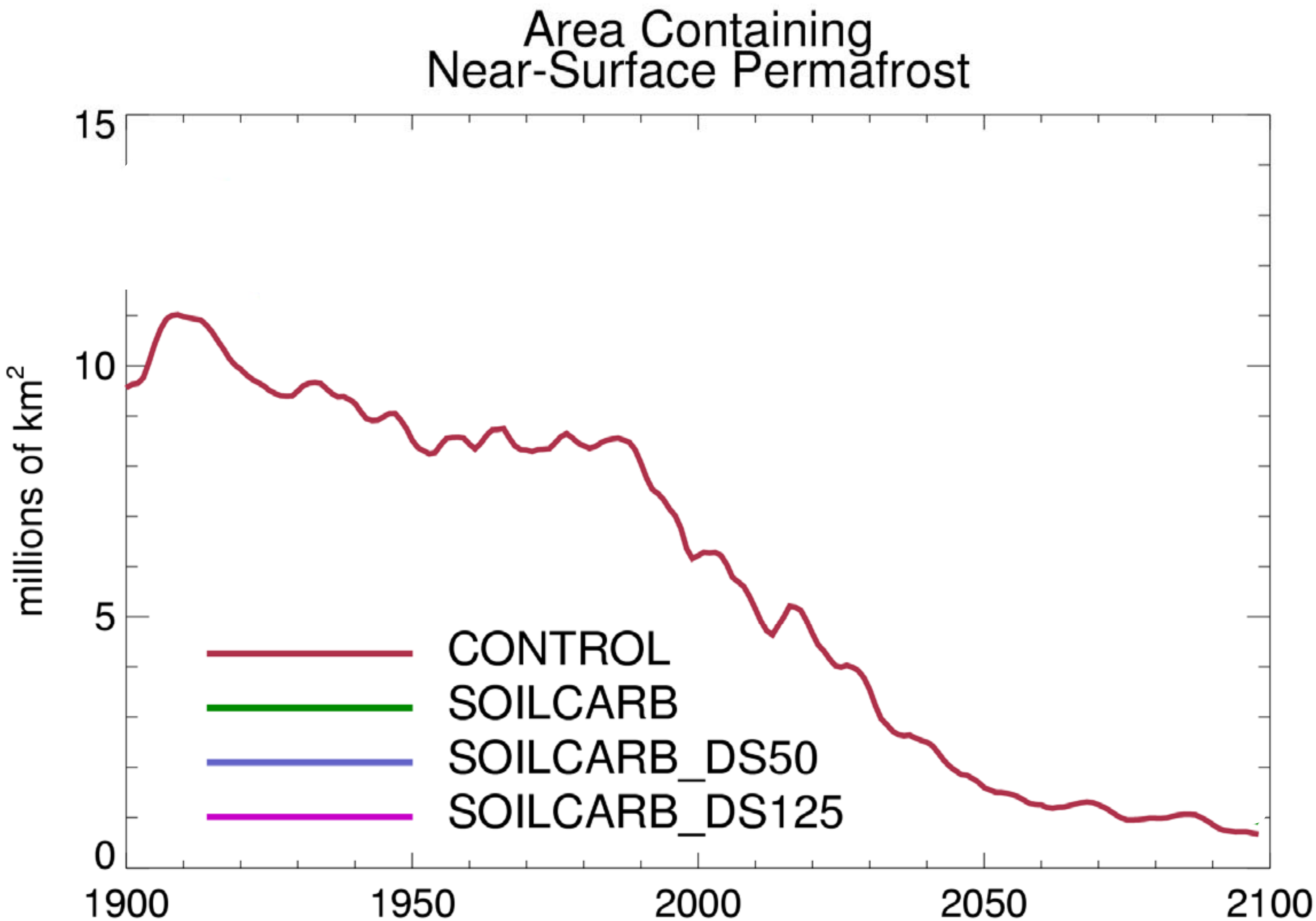


Annual cycle-depth soil temperature plots Siberia

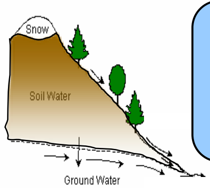




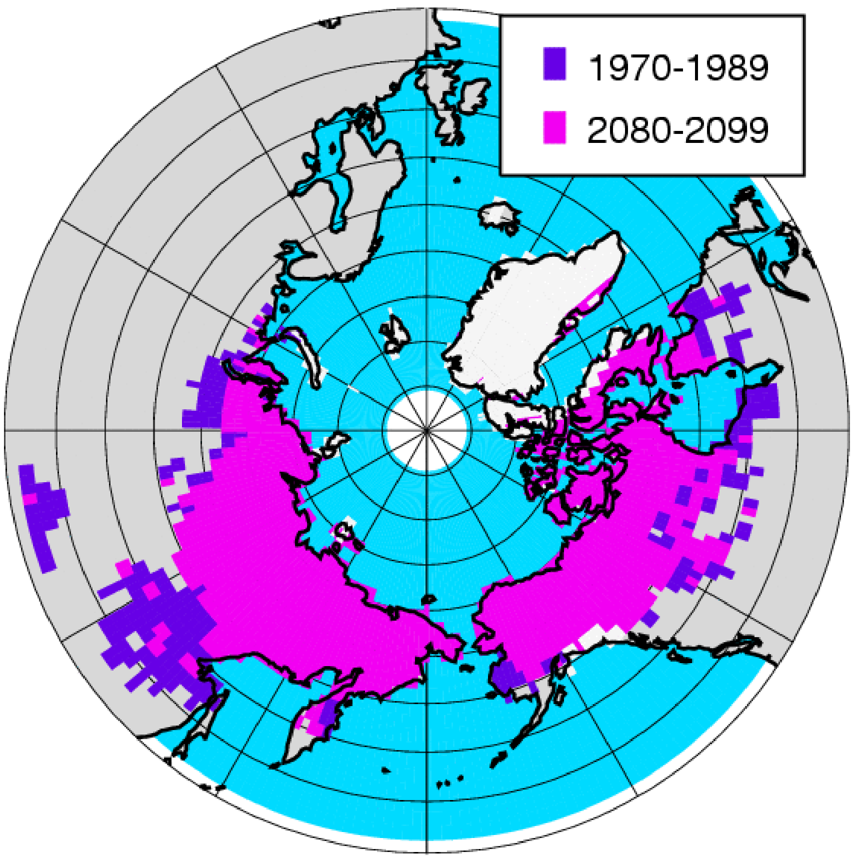
Near-surface permafrost degradation



Lawrence and Slater, 2007, in prep

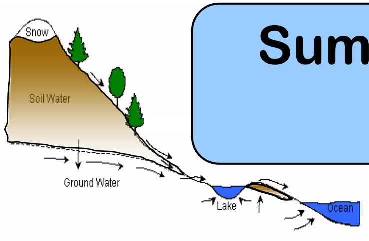


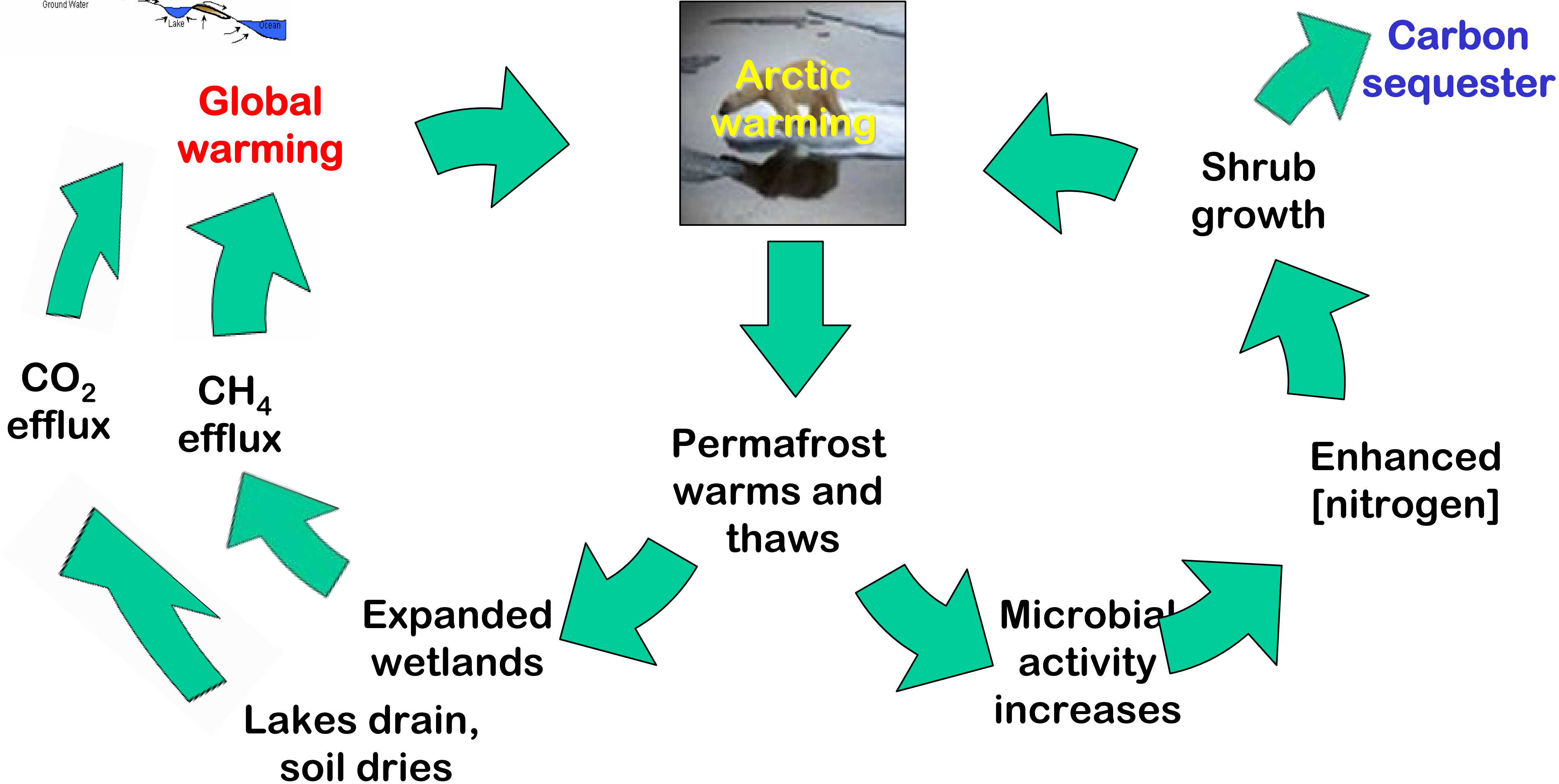
Deep permafrost (10-30m)

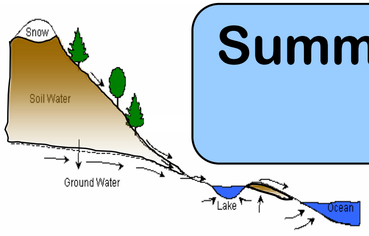


Most deep permafrost still exists at the end of the 21st century

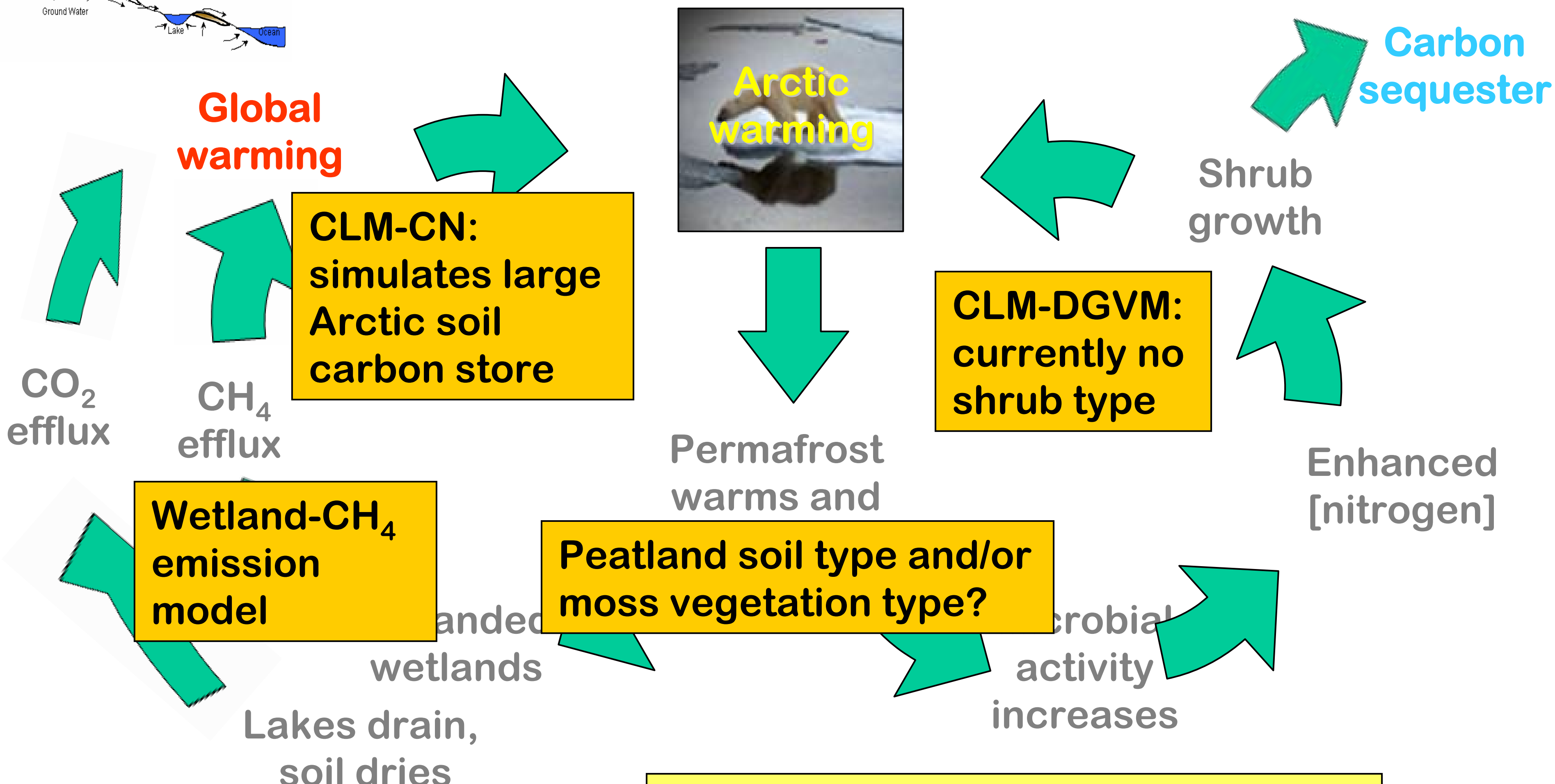
Summary: Towards simulating Arctic terrestrial high-latitude feedbacks in CCSM







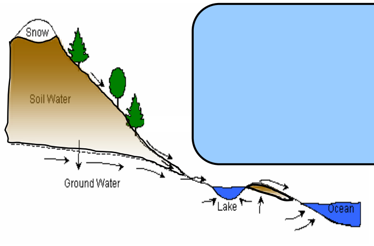
Summary: Towards simulating Arctic terrestrial feedbacks in an Earth System Model



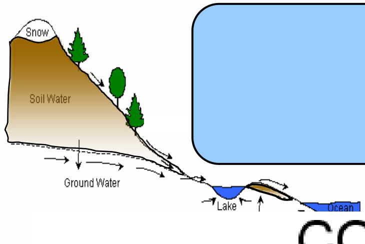
TOPMODEL based approach permits dynamic wetlands? Thermokarst?

Organic soil and deep soil column improve permafrost simulation

Large-scale degradation of near-surface permafrost likely



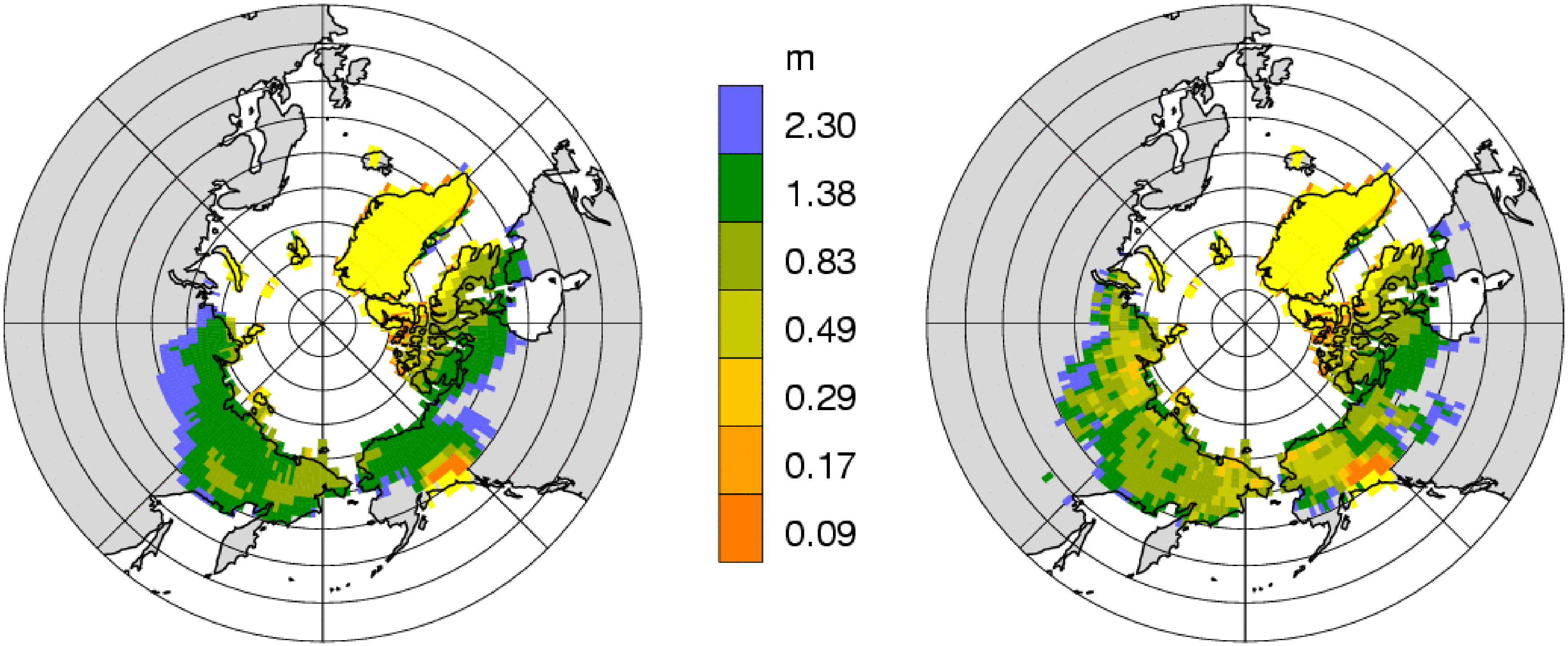
Extra slides



Near-surface permafrost extent and active layer thickness (1970-1990)

CONTROL

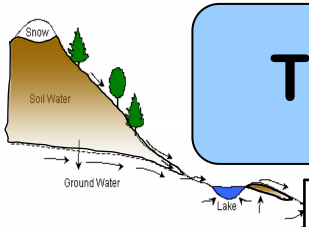
SOIL CARBON + DEEP SOIL



8.5 million km²

10.7 million km²

11.2 to13.5 million km² observed
Continuous + discontinuous



Thermal and hydraulic parameters for organic soil

Soil type	λ_{sat}	λ_{dry}	Θ_{sat}	k_{sat}
Sand	**3.12**	**0.27**	**0.37**	**0.023**
Clay	**1.78**	**0.20**	**0.46**	**0.002**
Peat	**0.55**	**0.05**[a]	**0.9**[a,b]	**0.100**[b]

$f_{sc,l} = \rho_{sc,i} / \rho_{peat}$ fraction of layer *i* that is organic matter

$$\Theta_{sat,i} = (1 - f_{sc,i})\ (\ 0.489 - 0.00126\ \%sand_i\ ) + f_{sc,i}\ \Theta_{sat,sc}$$

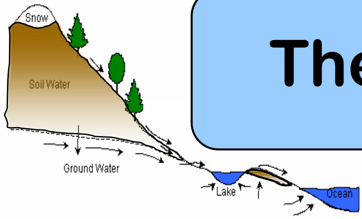
λ_{sat} sat. thermal conductivity

λ_{dry} dry thermal conductivity

Θ_{sat} volumetric water at saturation

k_{sat} sat. hydraulic conductivity

[a] Farouki (1981), [b] Letts et al. (2000)



Thermal and hydraulic parameters for organic soil

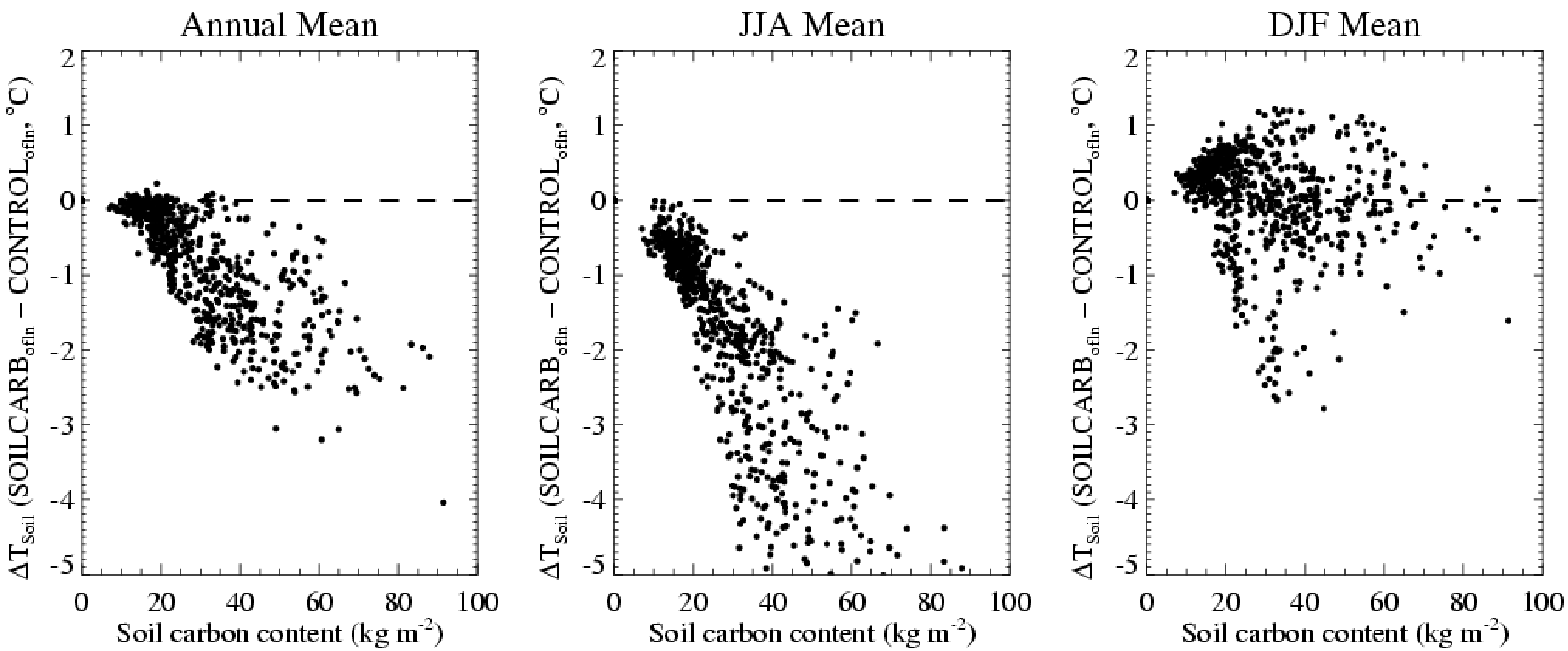
Soil type	λ_s W m^{-1} K^{-1}	λ_{sat} W m^{-1} K^{-1}	λ_{dry} W m^{-1} K^{-1}	c_s J m^{-3} K^{-1}x10^6	Θ_{sat}	k_{sat} m s^{-1}x10^{-3}	Ψ_{sat} mm	b
Sand	**8.61**	**3.12**	**0.27**	**2.14**	**0.37**	**0.023**	**-47.3**	**3.4**
Clay	**4.54**	**1.78**	**0.20**	**2.31**	**0.46**	**0.002**	**-633.0**	**12.1**
Peat	**0.25**[a]	**0.55**	**0.05**[a]	**2.5**[a]	**0.9**[a,b]	**0.100**[b]	**-10.3**[b]	**2.7**[b]

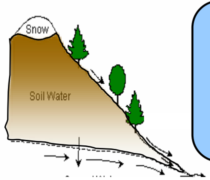
λ_s soil solid thermal conductivity
λ_{sat} saturated thermal conductivity
λ_{dry} dry thermal conducitivity
c_s heat capacity

Θ_{sat} volumetric water at saturation
k_{sat} saturated hydraulic conductivity
Ψ_{sat} saturated matric potential
b Clapp and Hornberger parameter

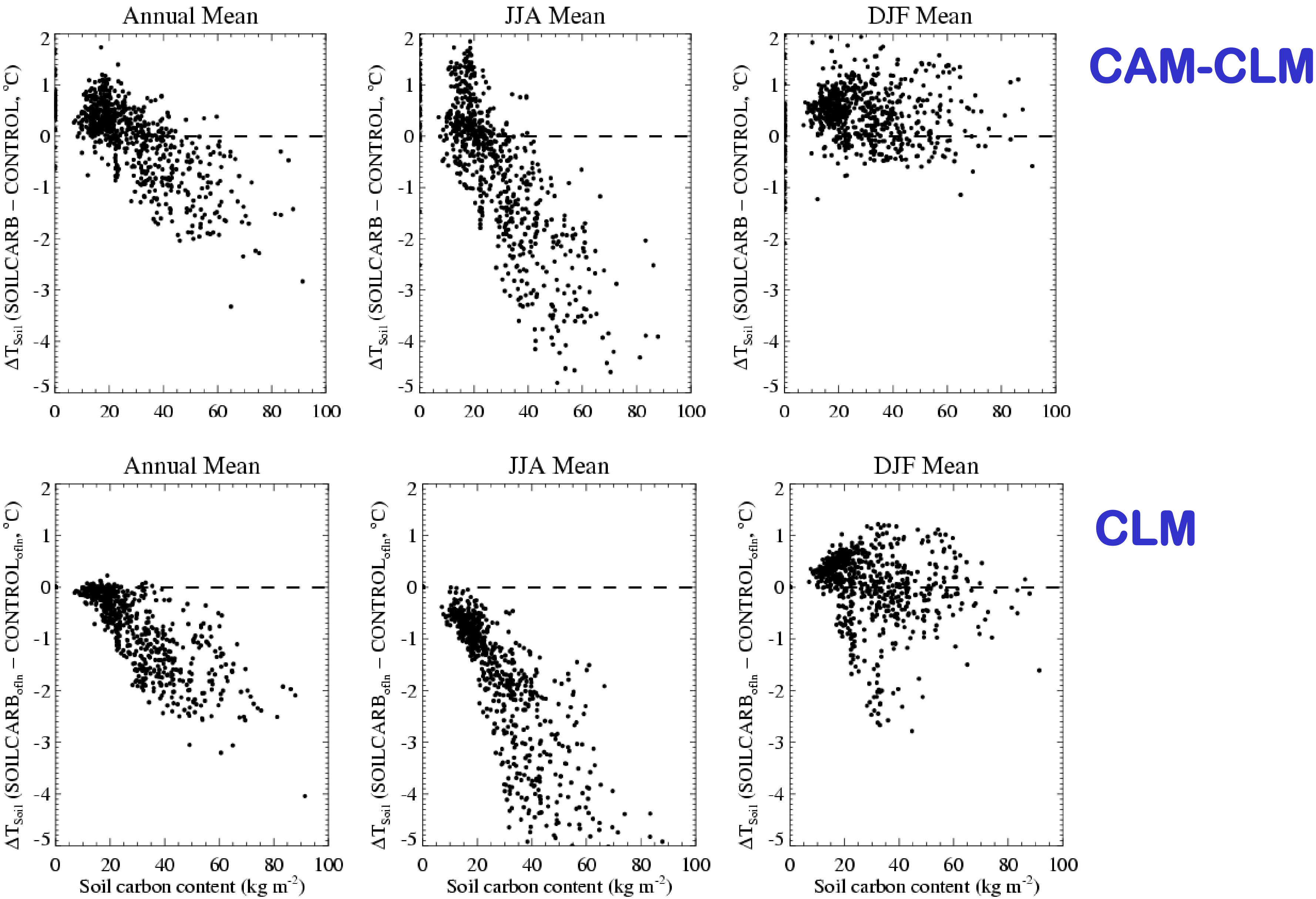
[a] Farouki (1981), [b] Letts et al. (2000)

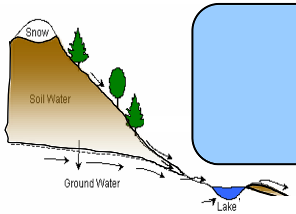
Impact on soil temperature



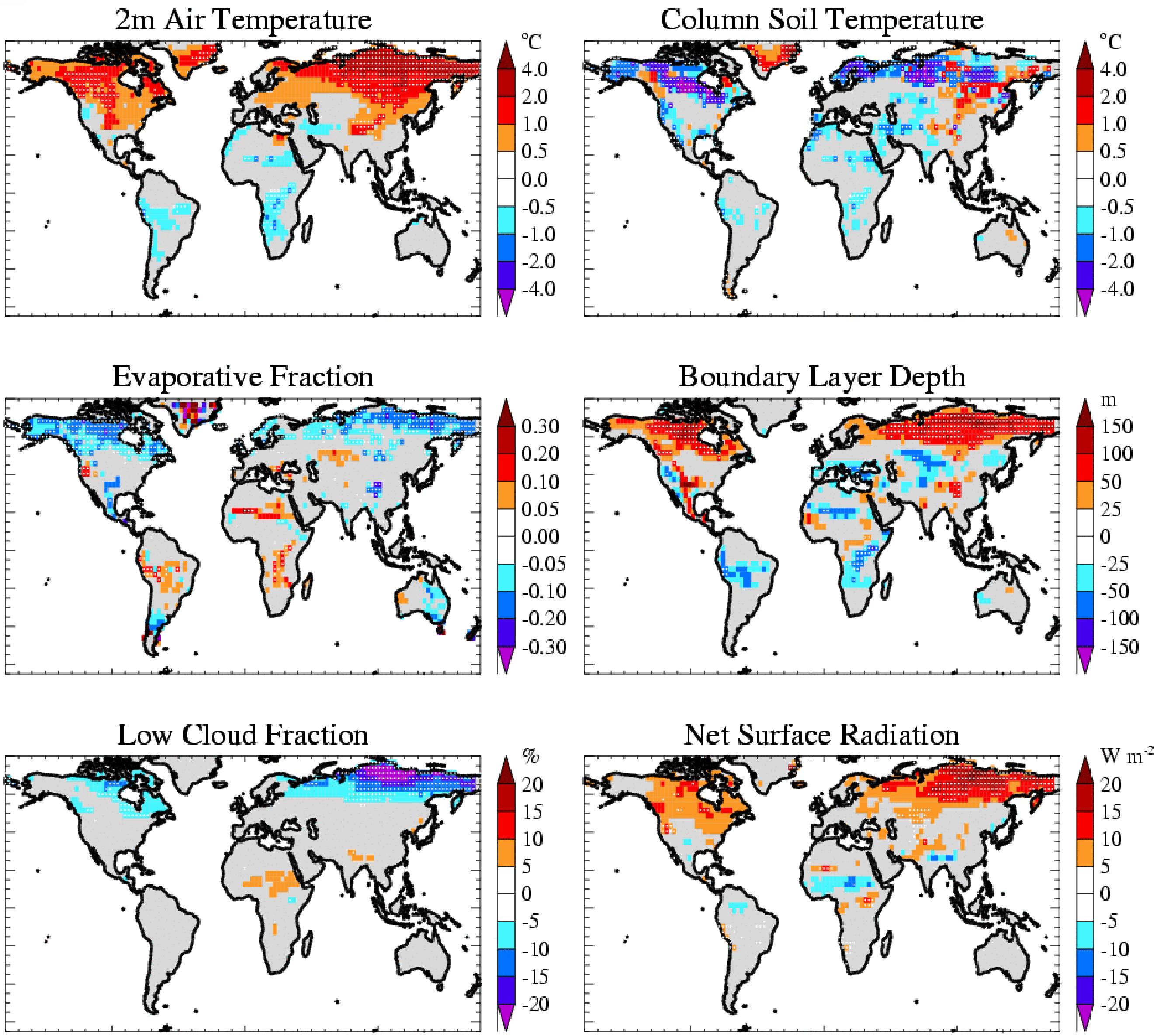


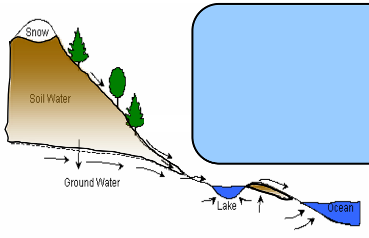
Impacts on climate





SOILCARB – CONTROL (JJA)





Arctic Shrub Expansion

Climate impact is complicated:

- more snow drifting - warmer winter soil temperature
- lower albedo, earlier snowmelt
- more summer shading - cooler soil temperature
- carbon sink … or source??
  - increase above ground biomass but greater loss of soil organic material

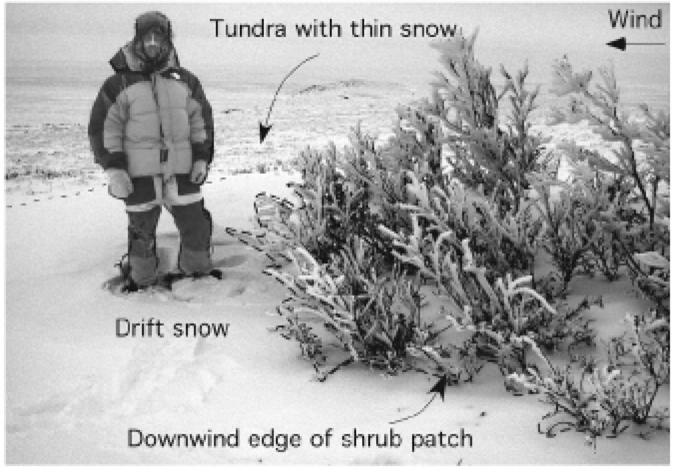
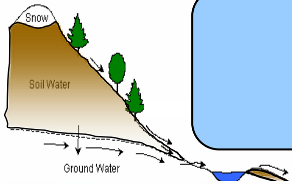
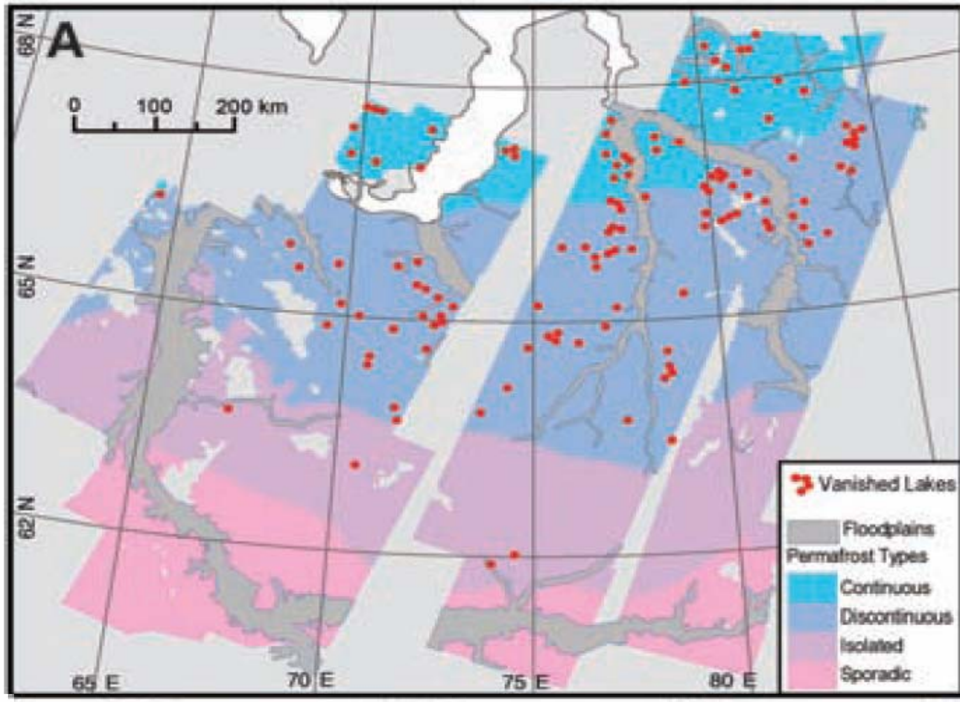


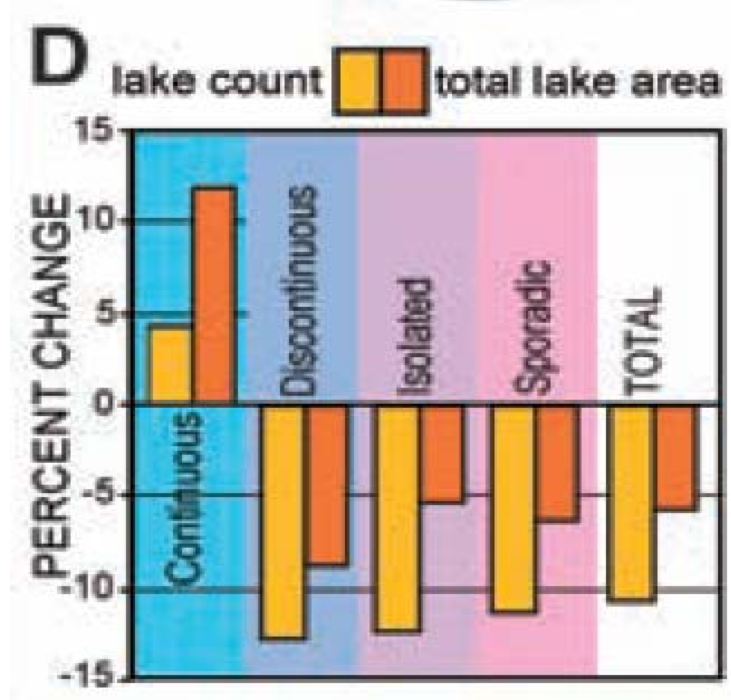
Photo by M. Sturm

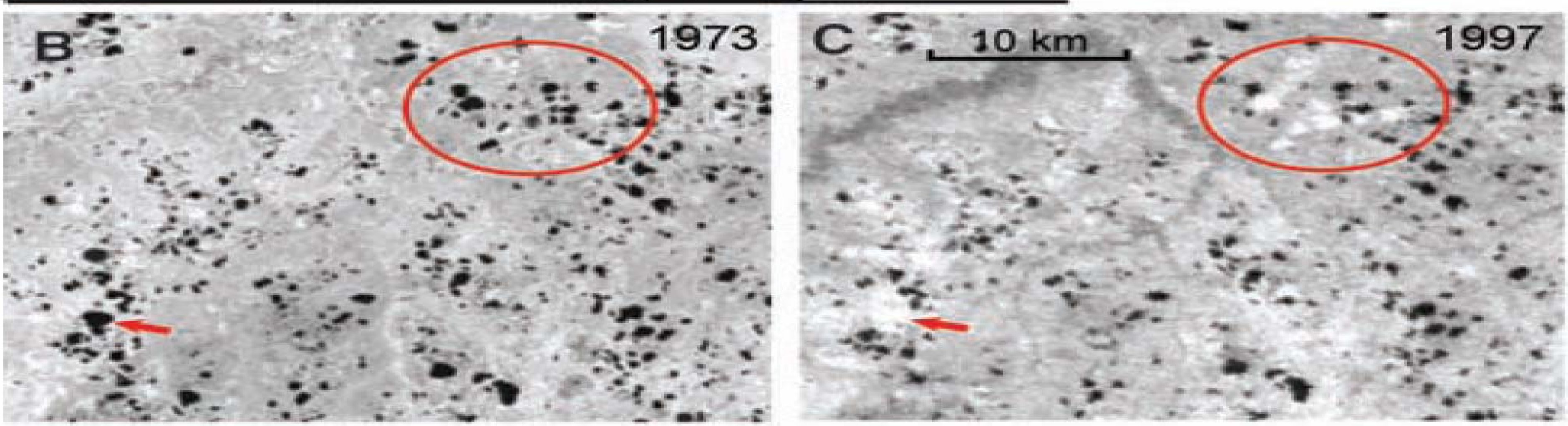
NCAR Dynamic Global Vegetation Model cannot currently simulate shrub cover expansion

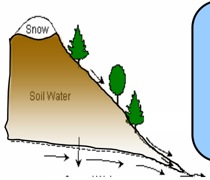


Appearing and Disappearing Lakes in Siberia
(Smith et al. 2005)

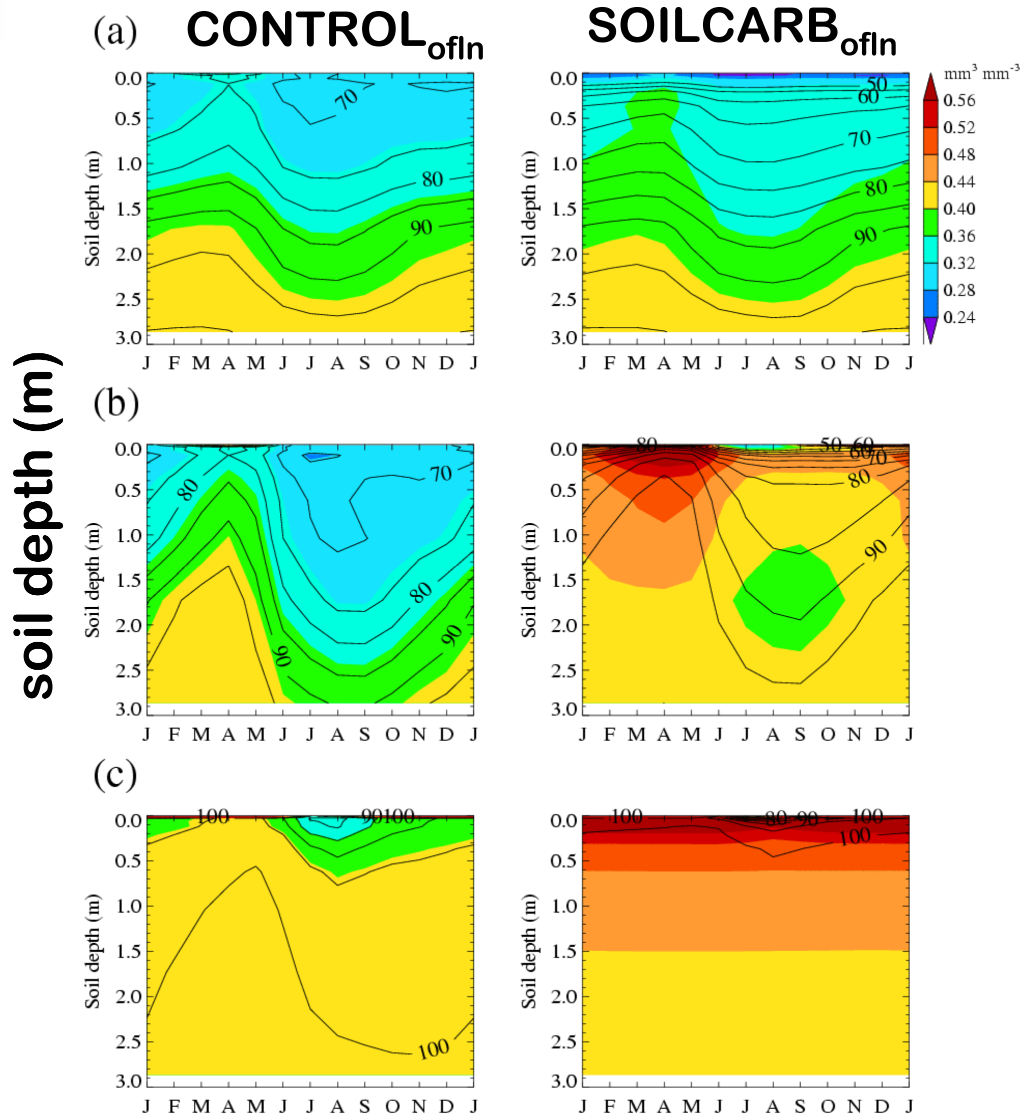








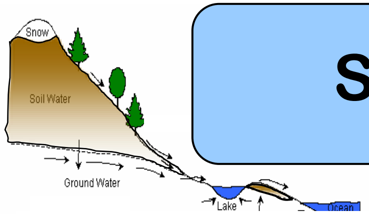
Impact on soil hydrology (volumetric soil water, % saturation)



(a) No perpetually frozen layer in either simulation

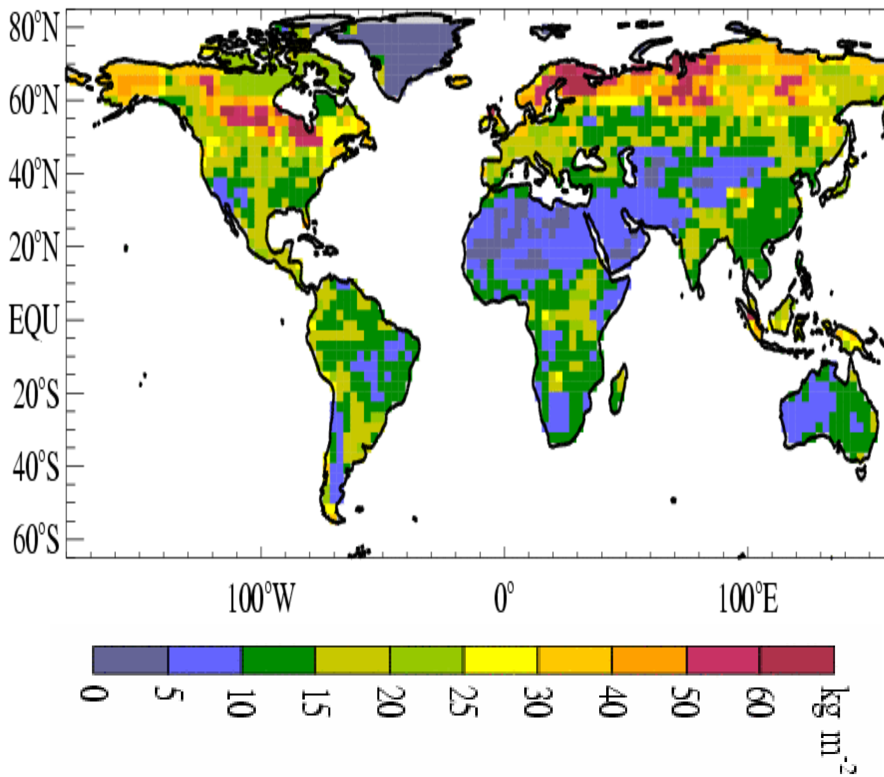
(b) Perpetually frozen layer in $\text{SOILCARB}_{\text{ofln}}$ but not in $\text{CONTROL}_{\text{ofln}}$

(c) At least one perpetually frozen soil layer in both experiments



Soil carbon in CLM-Carbon/nitrogen (CLM-CN)

Soil carbon content: Obs



Soil carbon content: CLM-CN