Permafrost Soil Warming Induced by Elevated CO_2-Physiological Forcing and Increased Summer Rainfall

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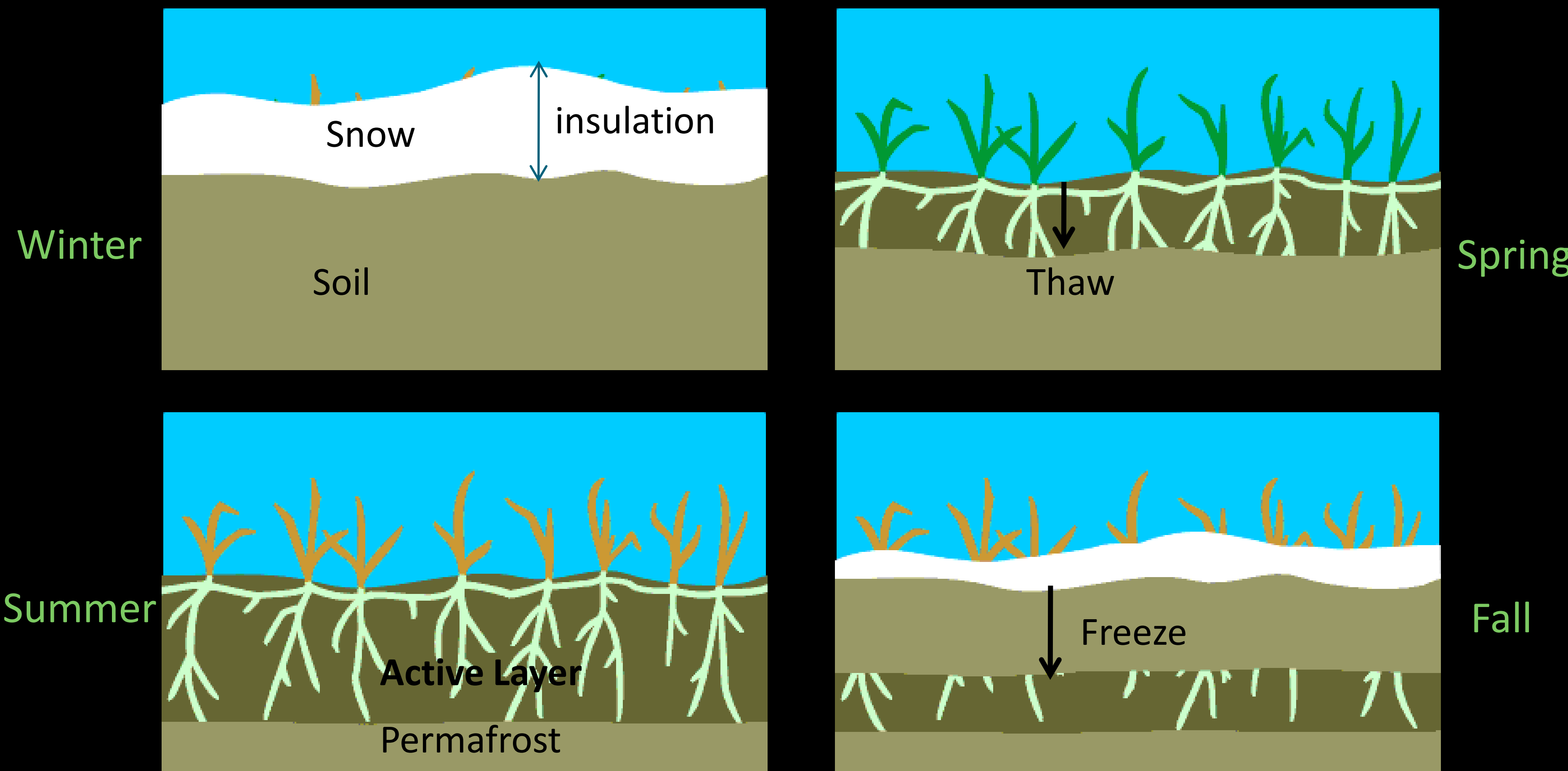
Permafrost Thermal Regime

Thaw advance depends on soil conductivity

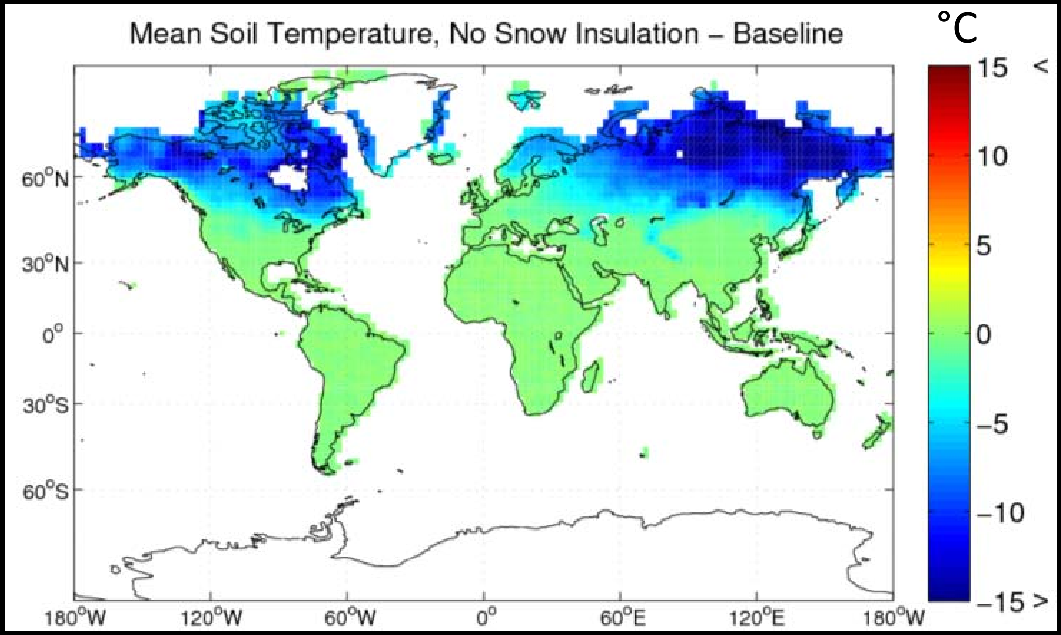


Freeze delayed by latent heat of fusion

Adapted from Arctic National Wildlife Refuge: http://arctic.fws.gov/activel.htm#animation

Snow Thermal Rectification Warms Permafrost Soils

- Examined by previous modeling and observational studies



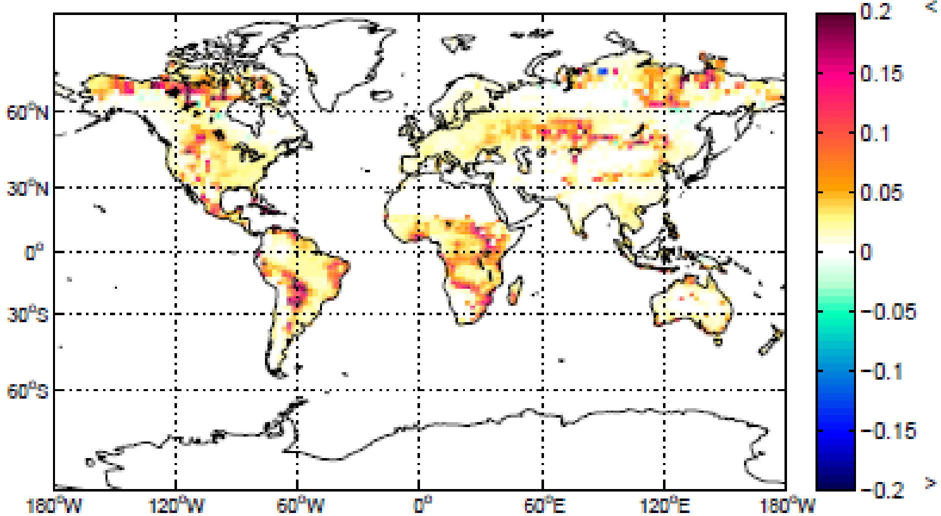
- Amplified by soil moisture
  - Not as widely recognized
- Can 21st century hydrological forcings interact with this effect?

Experimental Design

- CLM4+
  - Frozen soil impedance from Sean and fibric-to-sapric peat transition from Dave
- Satellite phenology
- Offline 1850 conditions
  - 200 years for spinup
- Primary experiments
  - 857 ppm CO_2 (2100 A2 scenario) vs. 285 ppm
  - 125% vs. 100% JJAS unfrozen precip.
  - 100% vs. 75% JJAS unfrozen precip.
- Perturbed physics, prognostic phenology, and future experiments

21^{st} Century Anthropogenic Forcings May Increase Soil Moisture

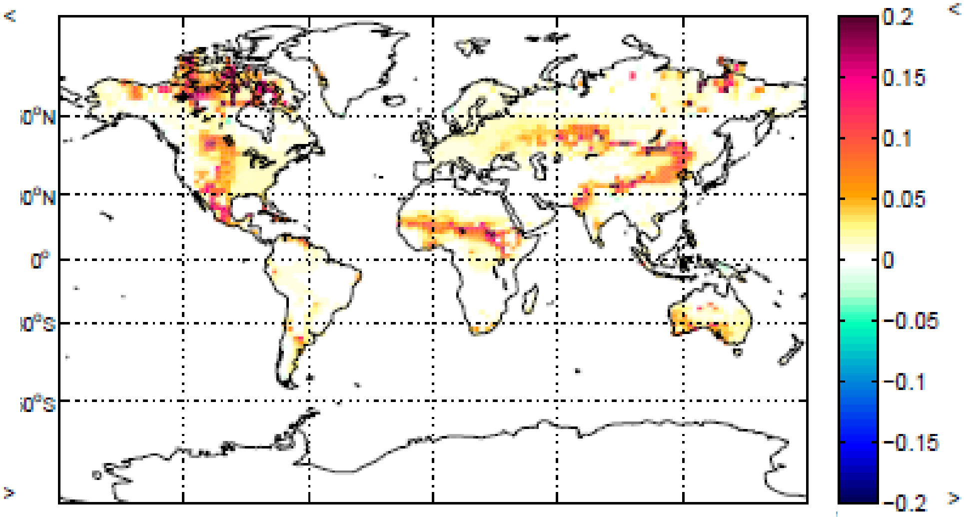
857 ppm CO_2 – 285 ppm CO_2



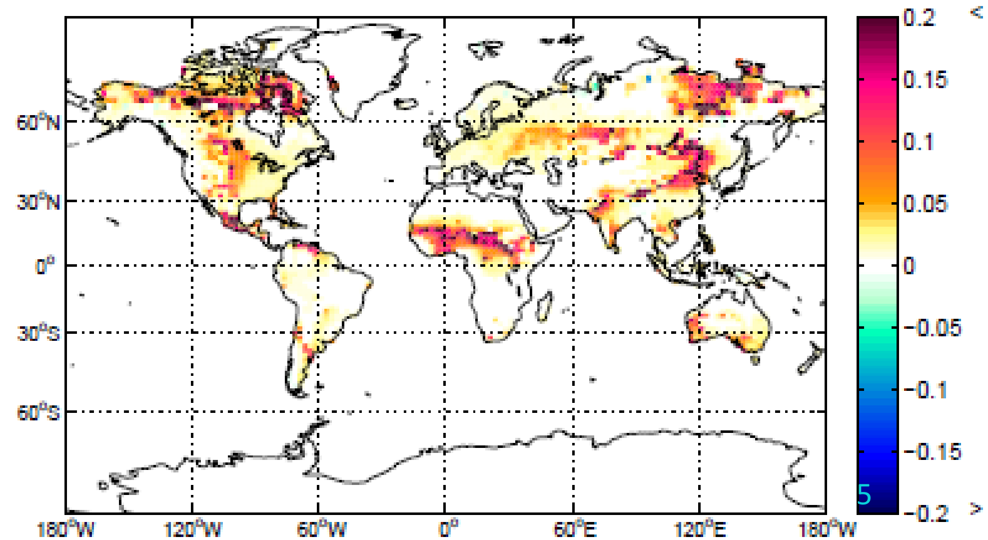
Transpiration decreases as in experimental syntheses

Mean Soil Moisture (-)

125% - 100% JJAS Rain



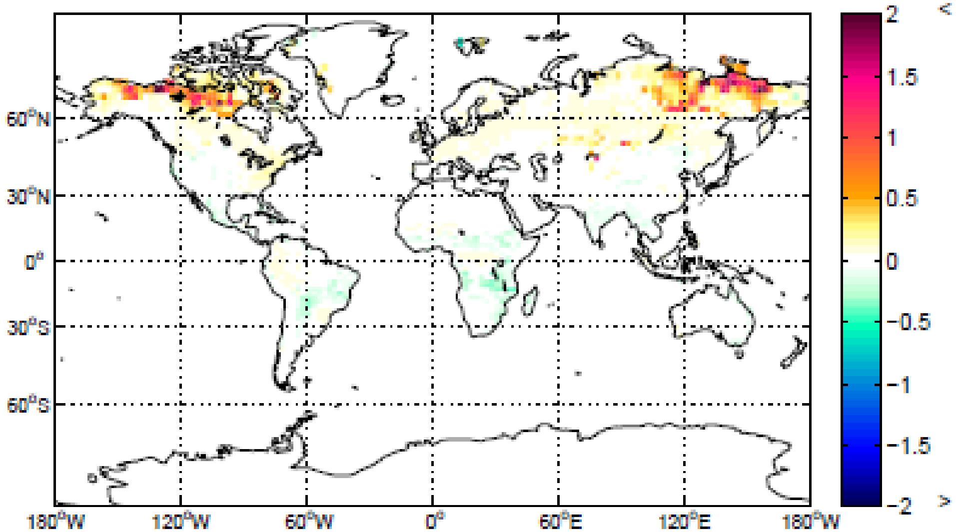
100% - 75% JJAS Rain



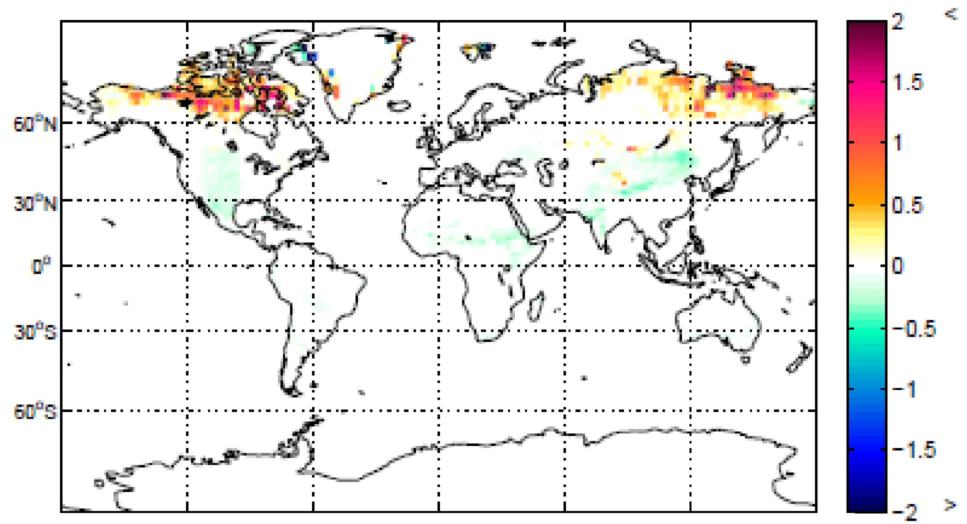
Moistening Causes Warming in Permafrost Soils

Mean Soil Temp (°C)

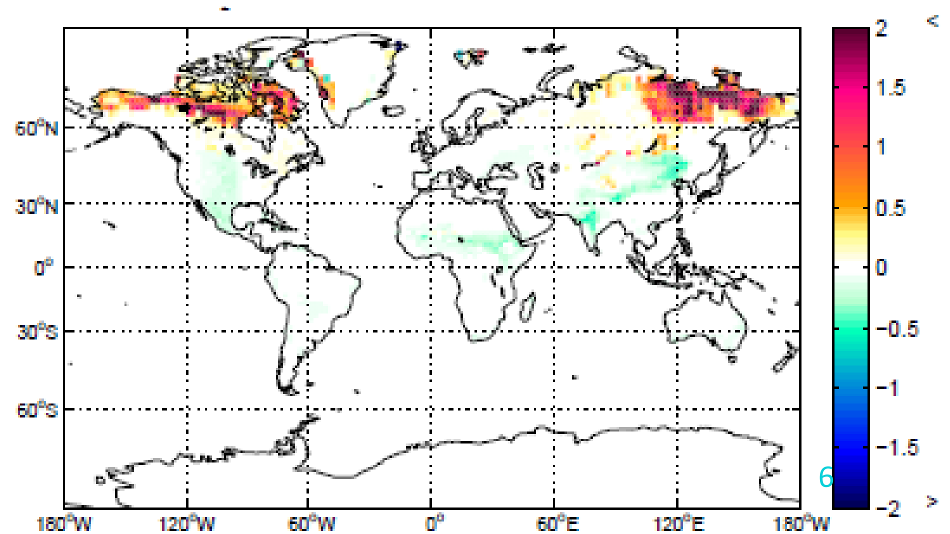
857 ppm CO_2 – 285 ppm CO_2



125% - 100% JJAS Rain



100% - 75% JJAS Rain

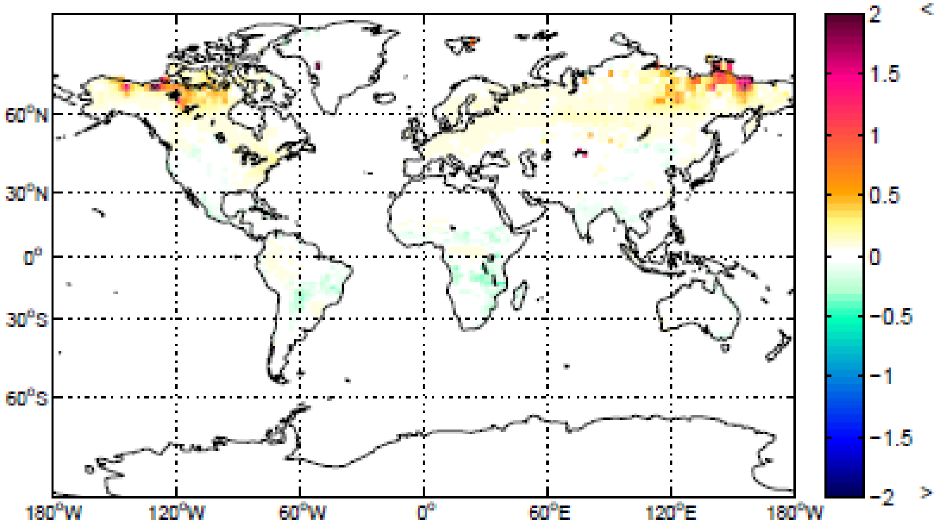


Analysis confirms warming is due to moisture increases.

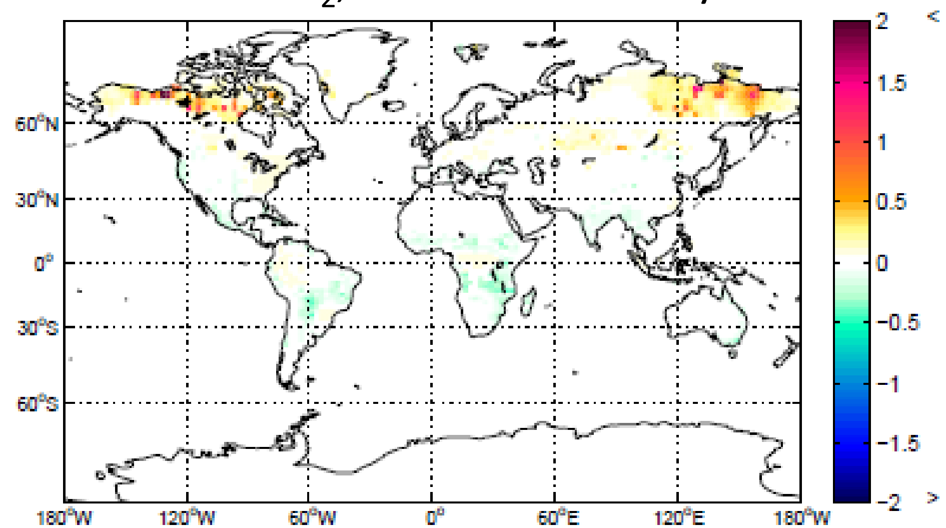
Perturbed Physics Illustrates 2 Mechanisms Linking Soil Moisture & Temperature

Mean Soil Temp (°C)

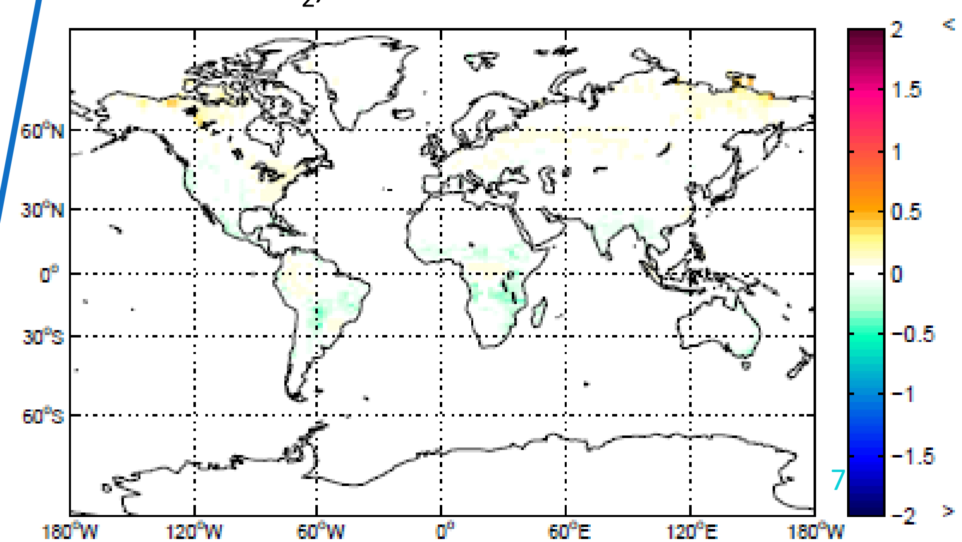
Elevated CO_2, No Heat of Fusion



Elevated CO_2, Fixed Conductivity



Elevated CO_2, Turn off Both Mechansims



- Additional moisture causes annual warming due to:
  - Increased soil diffusivity
  - Increased heat of fusion

Simplified Explanation

- +10 cm H_2O → 30 MJ m^{-2}
  - Frozen season = 1.5 x 10^6 s → 2 W m^{-2}
  - 20 cm of 0.2 W $m^{-1}K^{-1}$ snow → top soil temperature increases by 2 °C

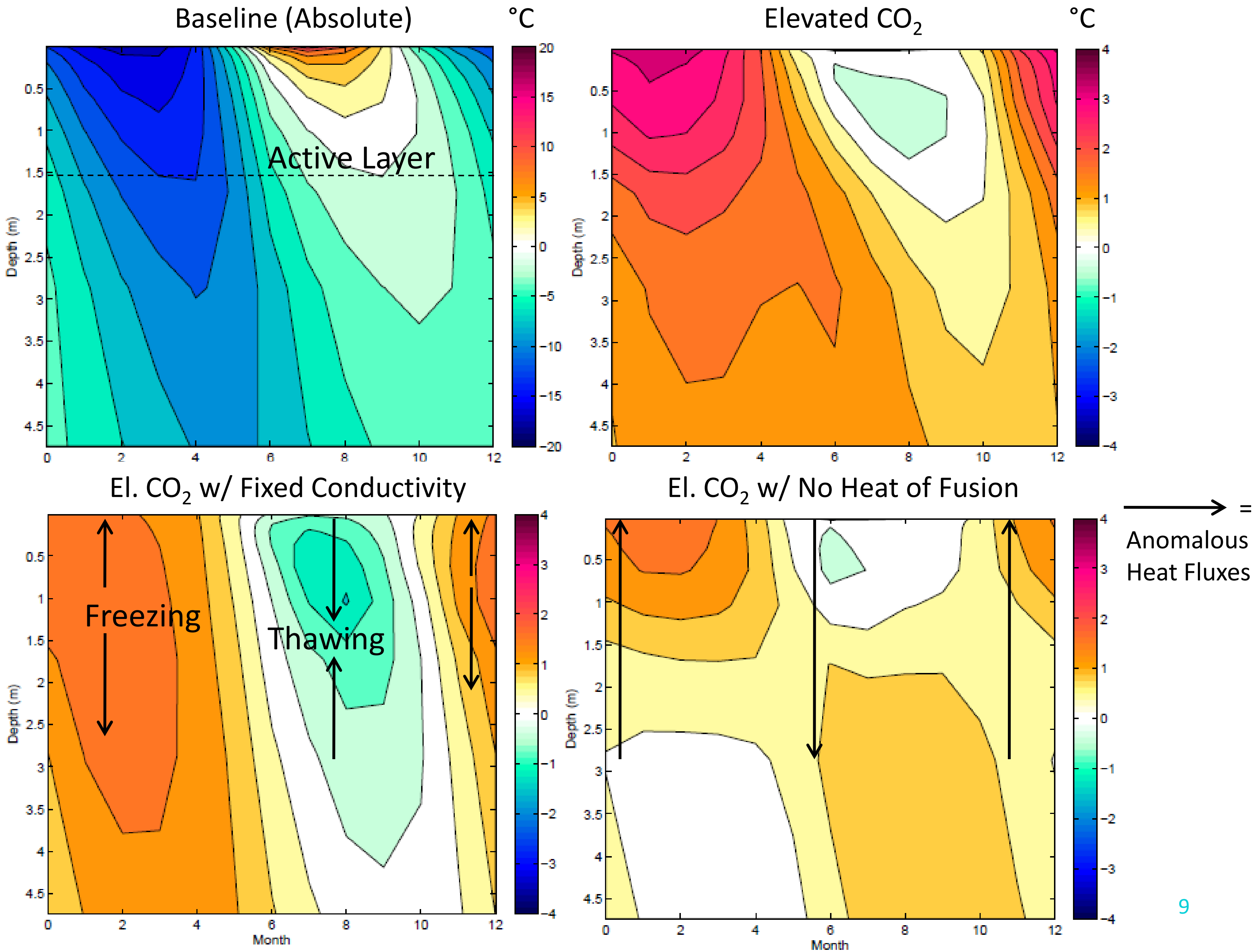
$$F = k \frac{\Delta T}{\Delta z}$$

- Similarly: increasing conductivity (~25%) increases summer heat absorption by 23 MJ m^{-2}

$$F \propto \sqrt{k} \Delta T$$

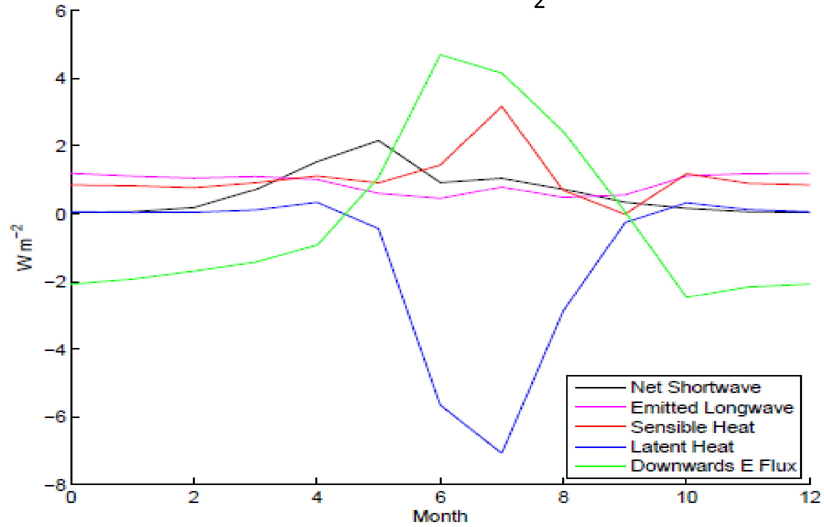
  - To balance annual energy budget in equilibrium, transporting this heat out in the winter requires similar top soil warming.

Average Soil T. Anomalies For Gridcells Showing > 1°C Warming

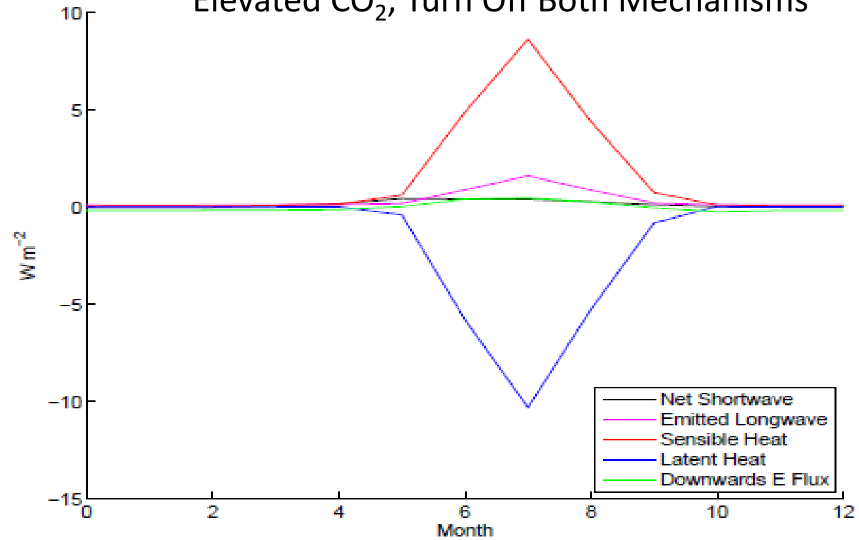


Surface Flux Anomalies

Elevated CO_2

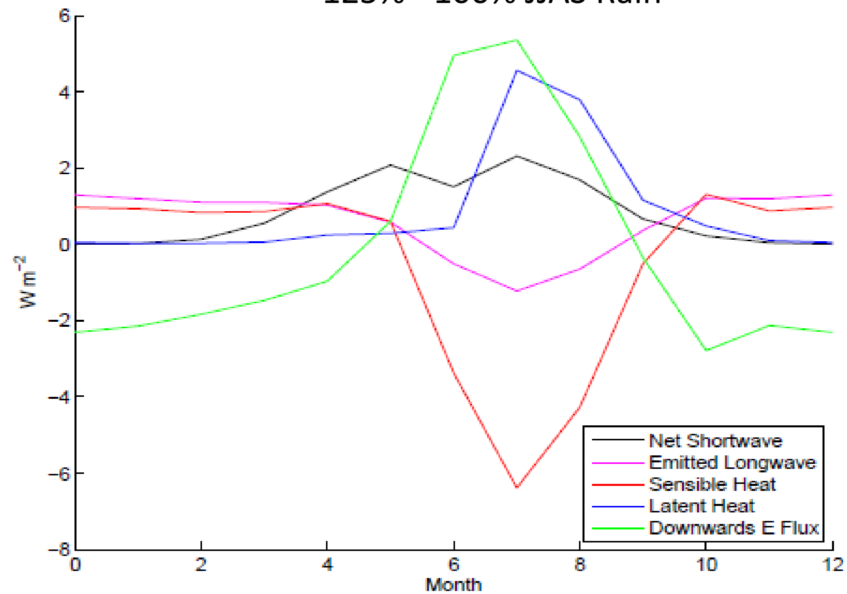


Elevated CO_2, Turn Off Both Mechanisms



- Increased moisture increases seasonal flux exchange.
- Summer Bowen ratio has little effect on soil temperature (offline).

125% - 100% JJAS Rain



Additional Experiments / Discussion

- Responsive LAI
  - Lower soil moisture increase
  - Enhanced snow-albedo feedback
- Future climate
- BGC interactions?
  - Changes in vegetation
  - Changes in soil organic matter
  - Effects on GHG fluxes

Snow-Covered Boreal Forest (BBC):
http://www.bbc.co.uk/programmes/p00382g0

CO_2

Sphagnum moss
(wikipedia)

Carex sedge
(wikipedia)

Conclusions & Future Work

- Vertically resolved modeling of soils, including phase change and snow dynamics, is necessary for predicting high-latitude terrestrial climate feedbacks.
- Anthropogenic forcings which increase permafrost zone soil moisture by ~10-20% have the potential to cause soil warming of ~ 1-2°C.
- Experiments are needed to confirm this mechanism.
- More comprehensive observations of current soil moisture are needed to predict vulnerability.

Acknowledgements

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