Perfrost carbon climate feedbacks

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Frozen Carbon pools

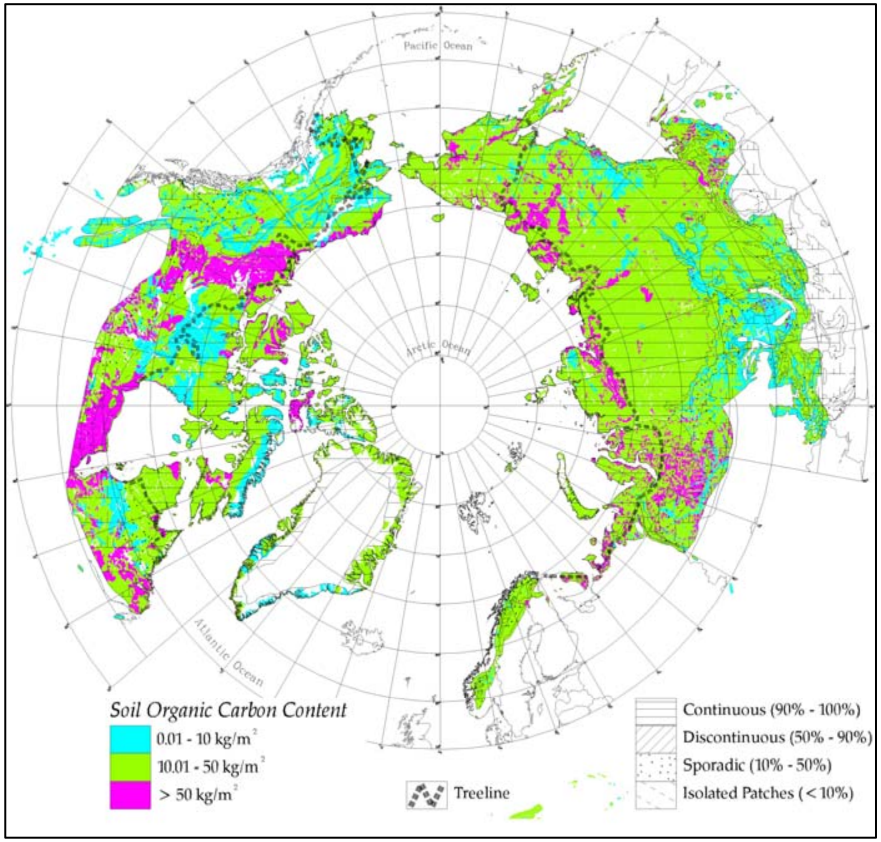
- Very thick soils (> 50 m in Yedoma)
- Carbon rich soils (30-50 Kg C m^{-2})
- Very old carbon (> 30,000 yrs)
- Labile carbon (burial of root biomass)
- Inbetween fossil and recent biospheric pools

These pools are ignored in carbon cycle models

Yedoma deposit of frozen C, Cherskii 68° N - 161° E

All pictures are courtesy of S. Zimov

Frozen carbon : a large global carbon pool

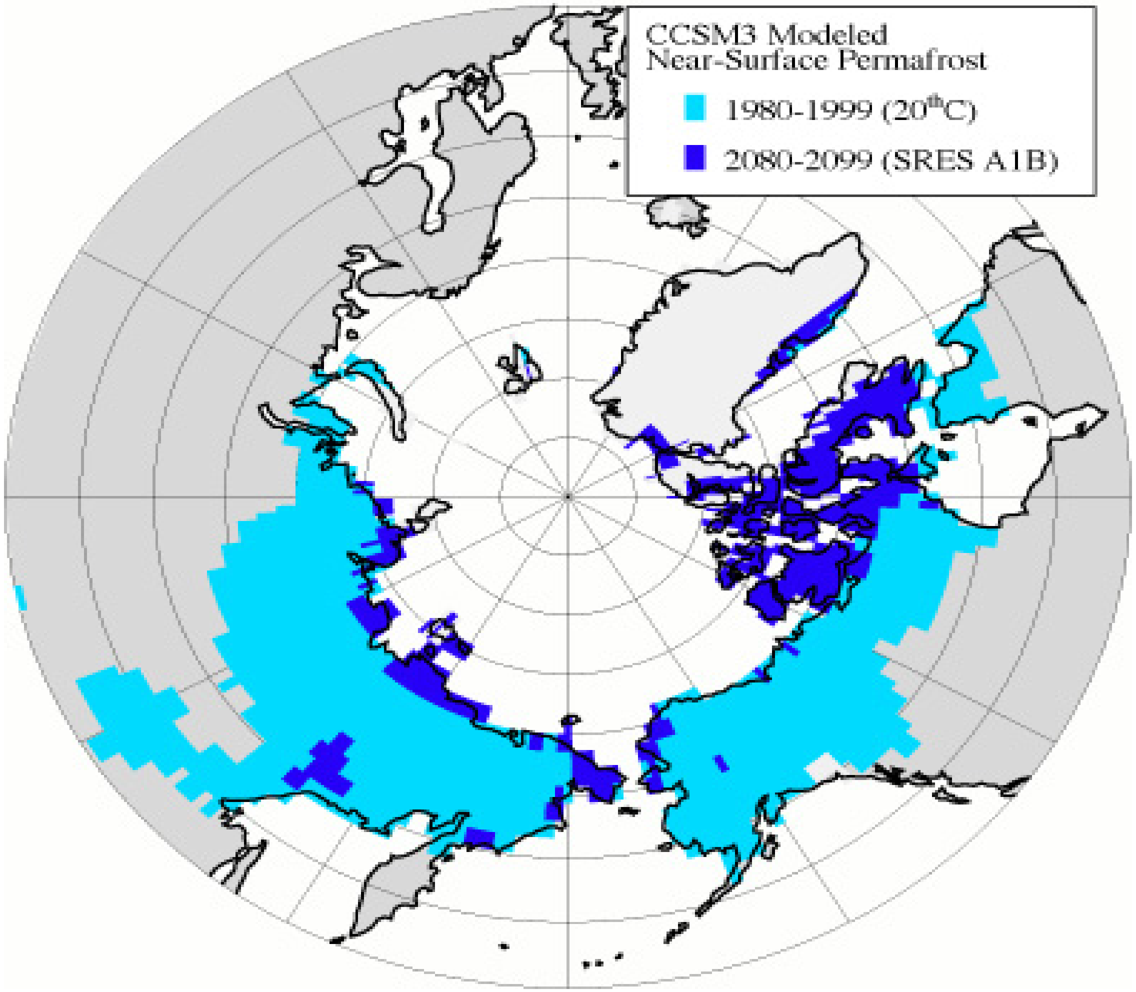


Permafrost zones	0-30 cm	0-100 cm
Continuous	110.38	298.75
Discontinuous	25.5	67.44
Sporadic	26.36	63.13
Isolated Patches	29.05	67.10
Total	**191.29**	**496.42**

Soil or deposit type	C stocks
Soils 0–300 cm	**1024**
Yedoma sediments	407
Deltaic deposits	241
Total	**1672**

Tarnocai et al. 2009

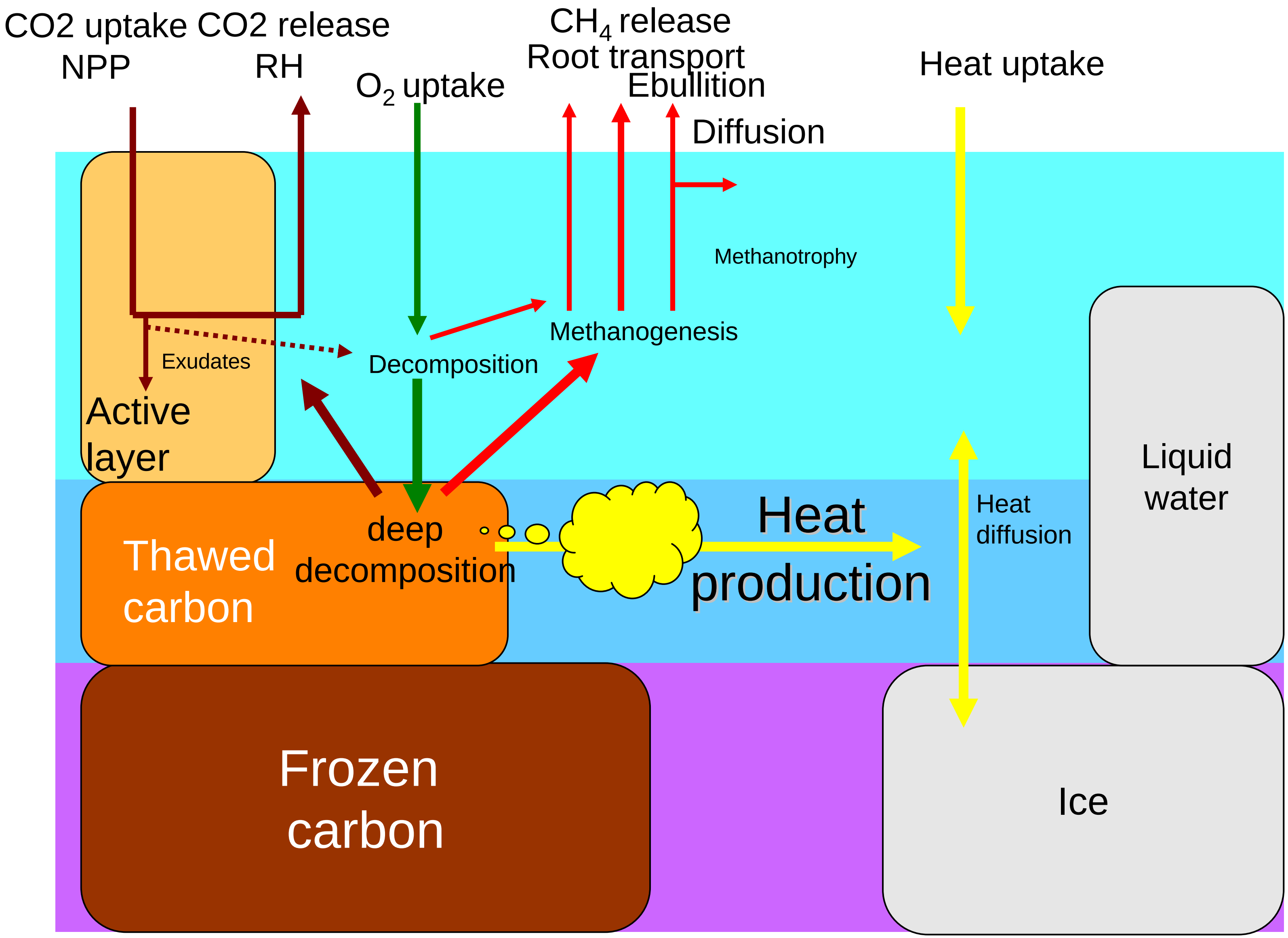
Permafrost covered areas
Today : 10.5 Mkm^2
By 2100 A2 scenario : 1 Mkm^2


CCSM3 Modeled
Near-Surface Permafrost
1980-1999 (20thC)
2080-2099 (SRES A1B)

Questions

- Can we model the current frozen C stocks ?
- Response of frozen soil C stocks to warming ?
- Are there non linearities and tipping points ?
- What are the uncertainties ?

1D Model of frozen carbon decomposition

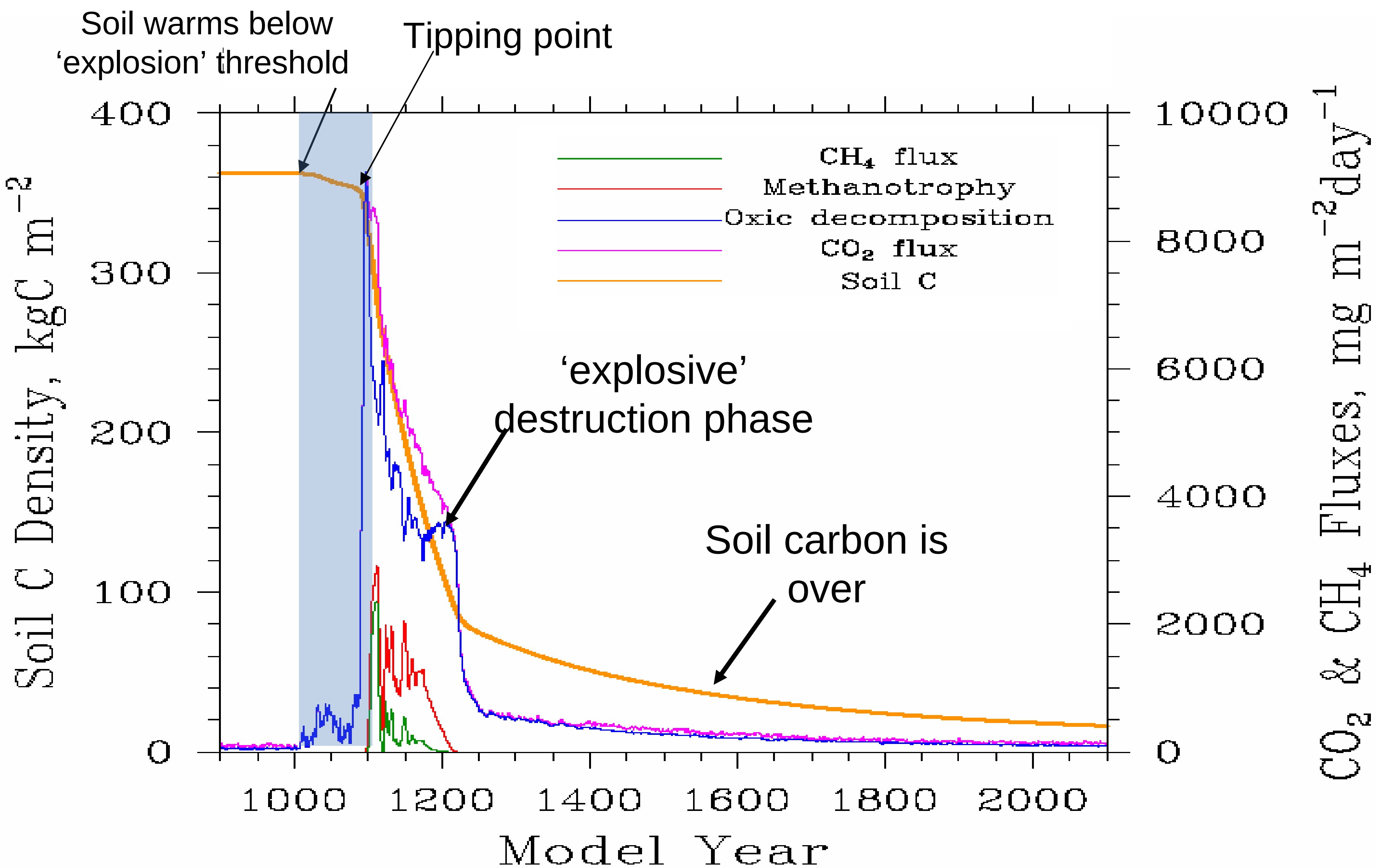


Khvorostyanov et al. , 2008ab

1D decomposition model

- Impact of heat released by exothermic decomposition reactions (Khvorostyanov et al. 2008a)
- inclusion of oxic and anoxic processes (Khvorostyanov et al. 2008a):
  - calculate diffusion of oxygen and methane in soil as function of soil water content
  - oxic respiration limited by oxygen availability; decomposition switches to methanogenesis where oxygen low
  - methanogenesis 10x slower than oxic decomposition
  - consumption of oxygen by oxic decomposition, methane production by methanogenesis and consumption by methanotrophy

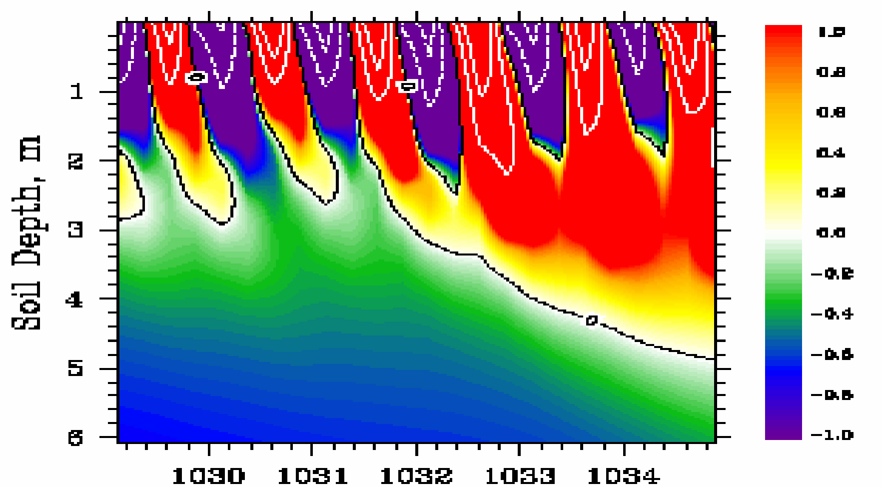
Point scale simulation (Yedoma area)



Response to a 100 yrs-long step warming of +3° C

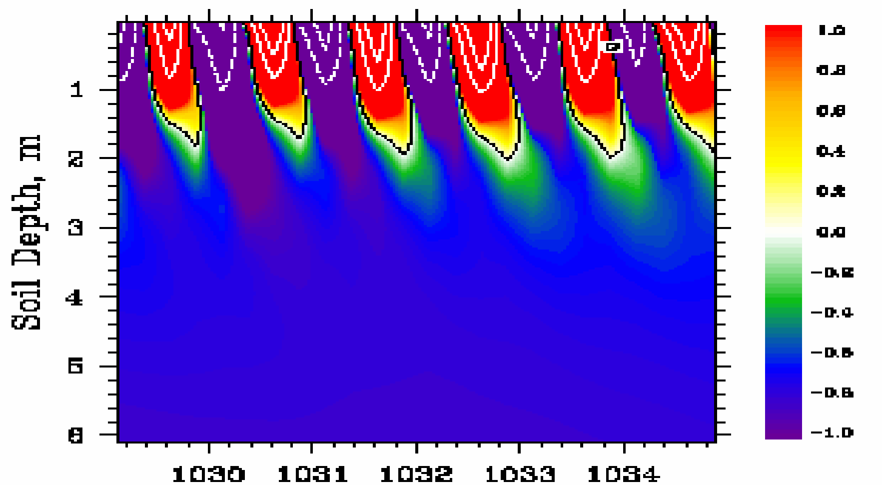
Clear threshold effect of bacterial heat production

Heat from Microbes



(a) Soil temperature (°C): talik formation when decomposition heat is 'On'. Contour interval is 4°C

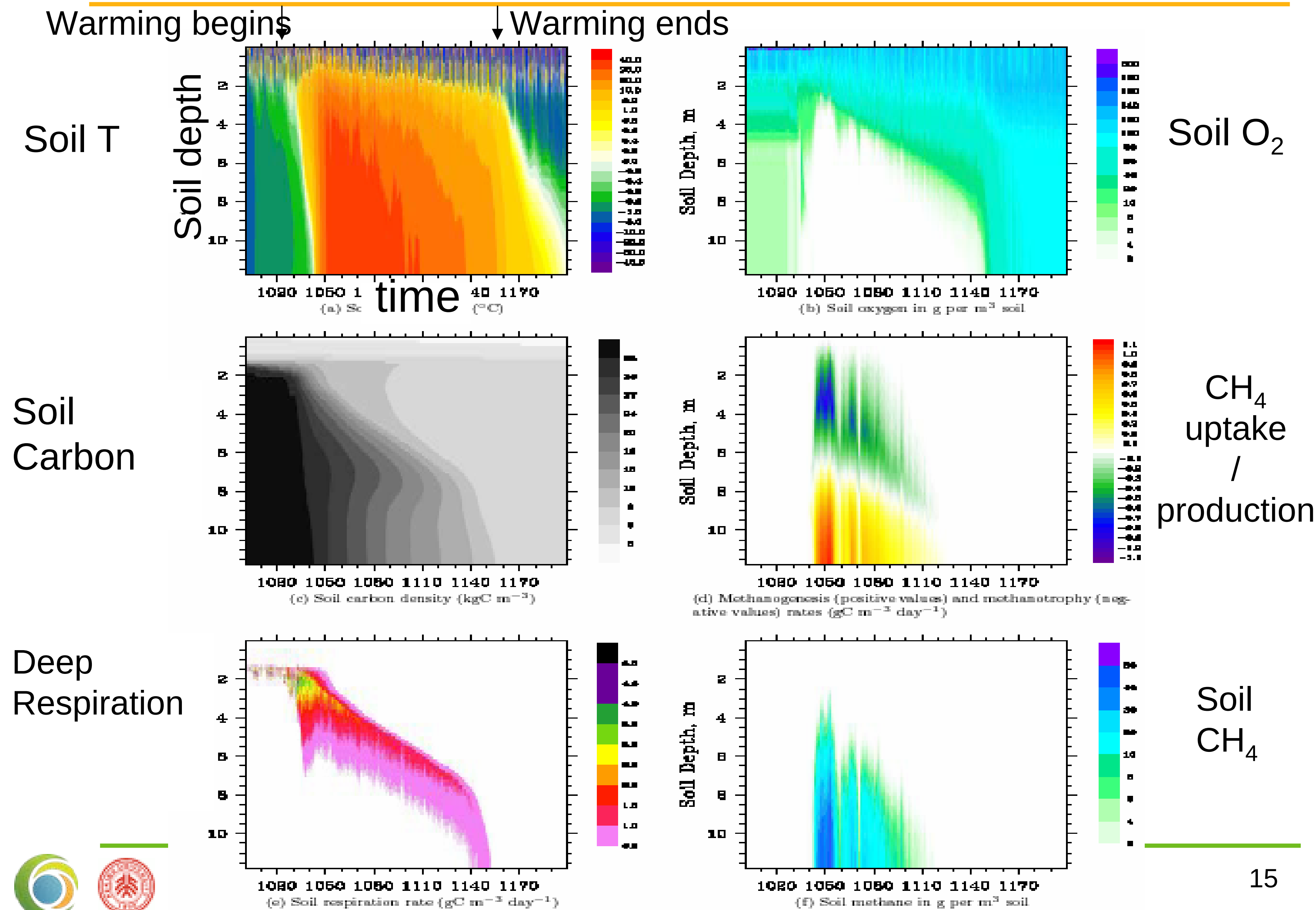
No heat



(c) Soil temperature (°C): no talik formation when decomposition heat is 'Off'. Contour interval is 4°C

Non-linear response to step warming is detectible after few years

Deep respiration and methane processes



(a) Soil temperature (°C)

(b) Soil oxygen in g per m³ soil

(c) Soil carbon density (kgC m⁻³)

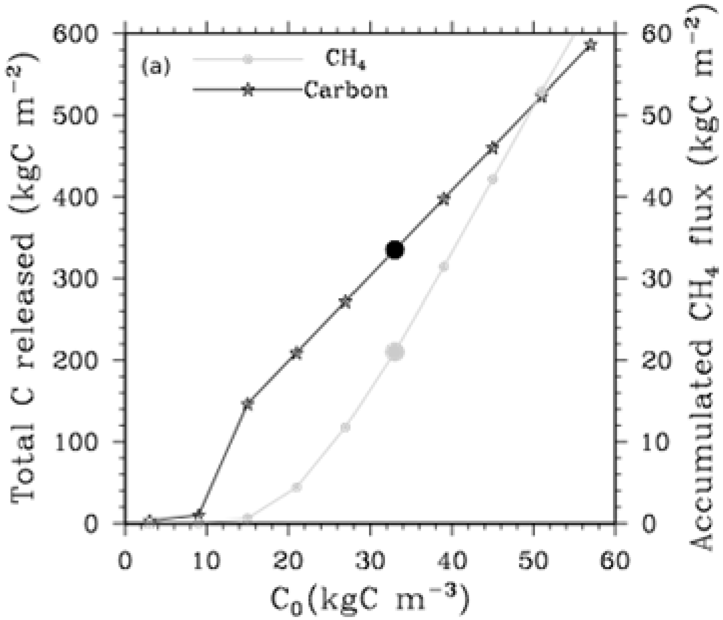
(d) Methanogenesis (positive values) and methanotrophy (negative values) rates (gC m⁻³ day⁻¹)

(e) Soil respiration rate (gC m⁻³ day⁻¹)

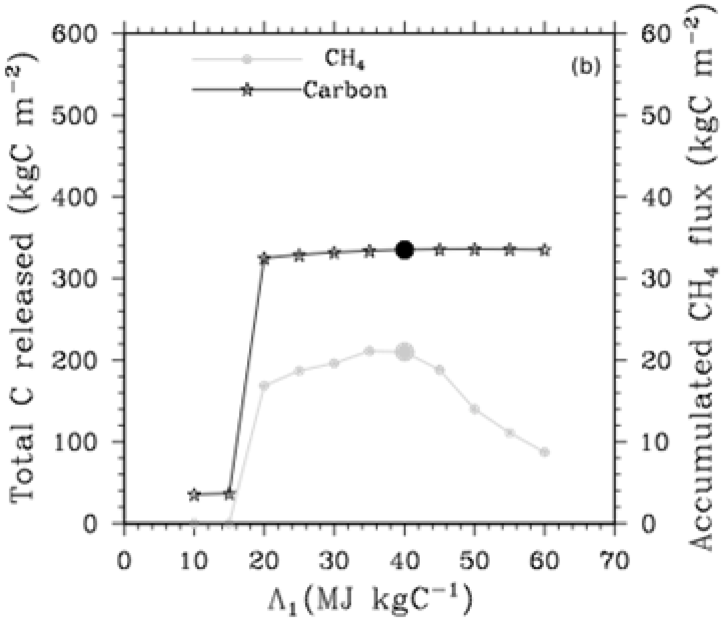
(f) Soil methane in g per m³ soil

Clear threshold response of total C release to parameters in 1-D model

Initial C concentration



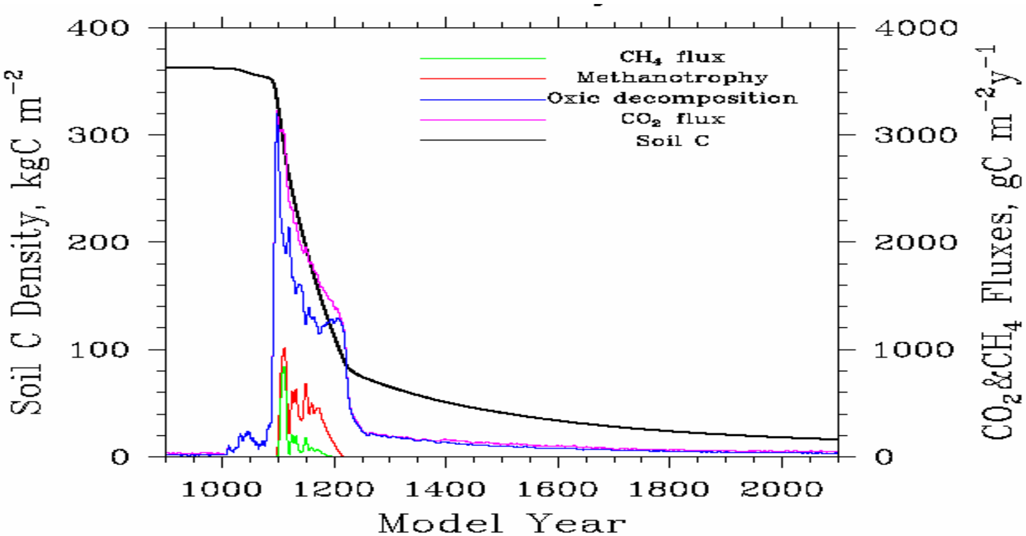
Microbial heat release

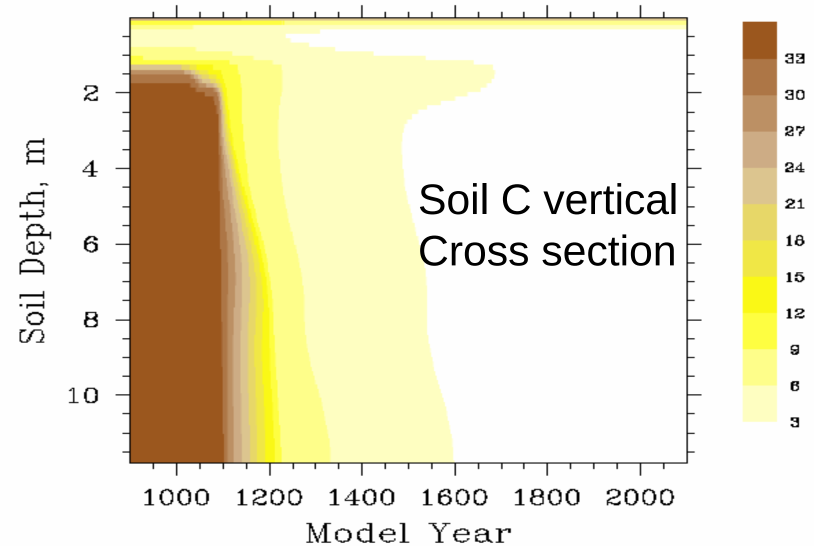


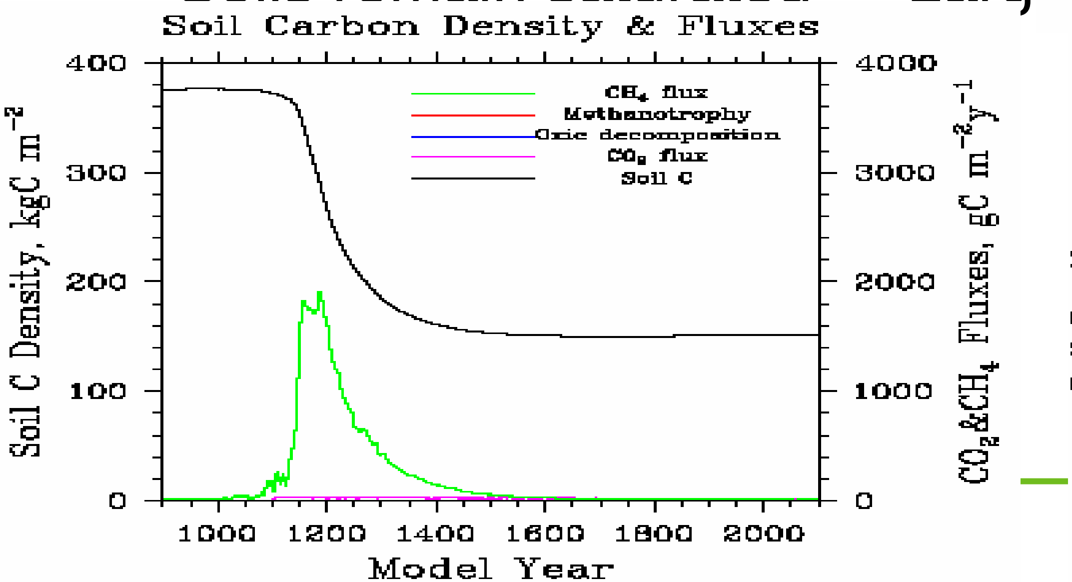
Khvorostyanov et al. (2008b)

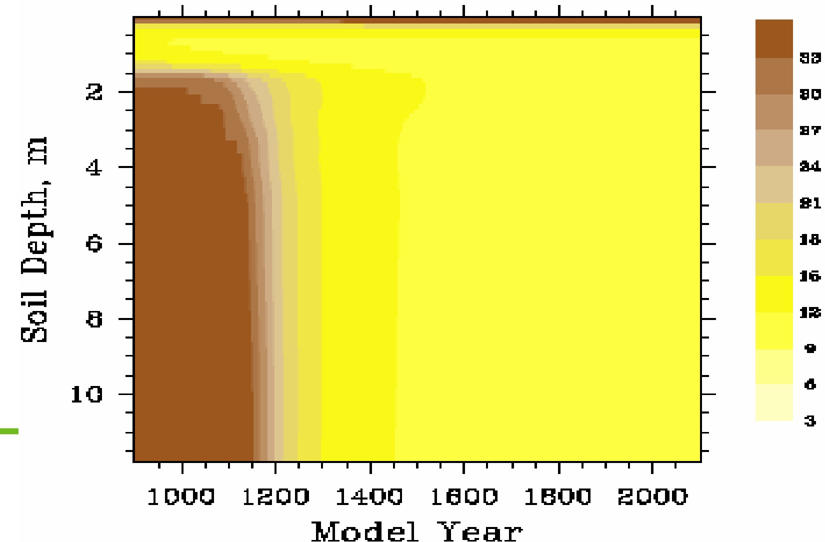
Results are sensitive to soil hydrology changes

Soils remain seasonally dry -> Large CO_2 respiration losses



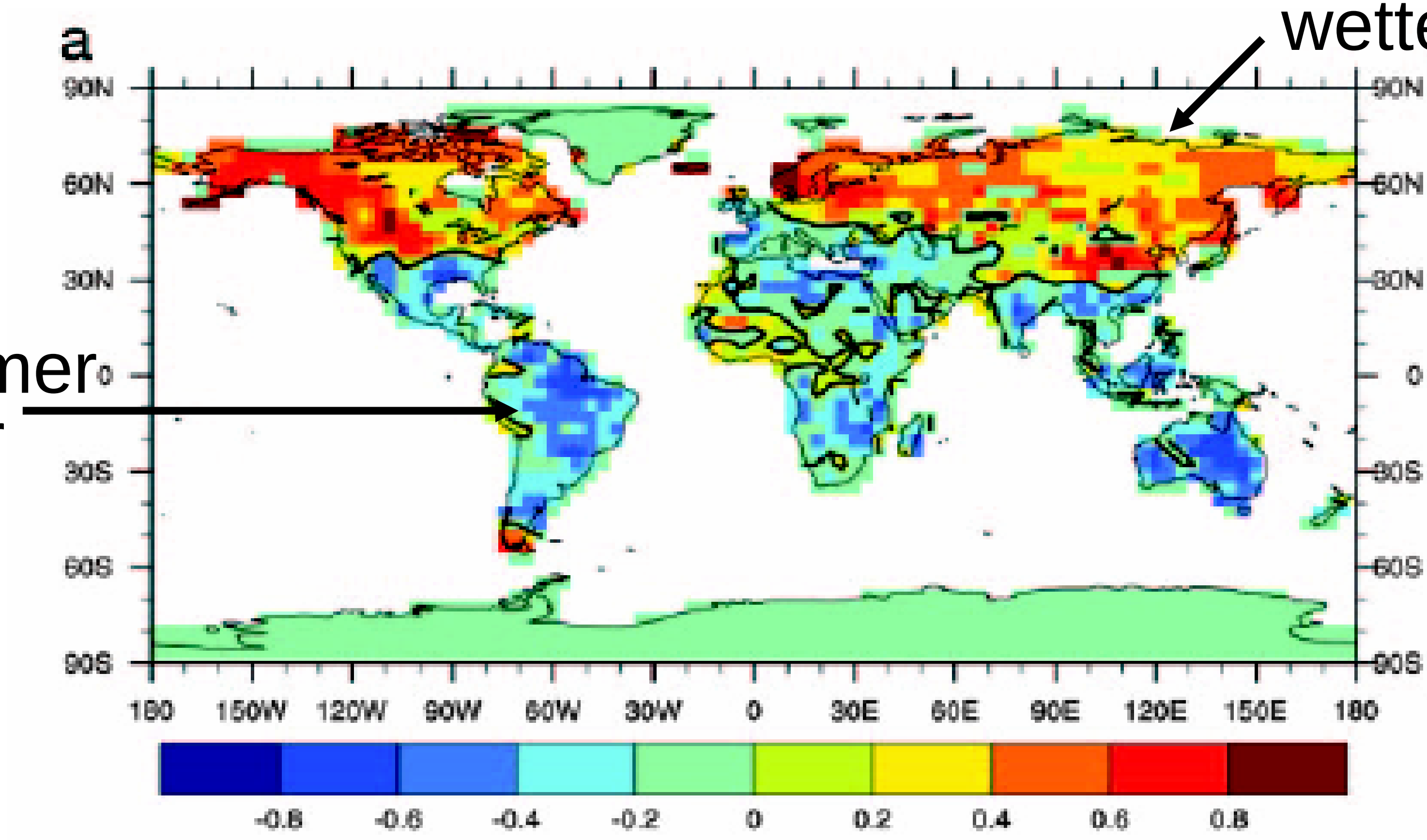






Tradeoffs between CO_2 and CH_4

Future high latitude climate likely warmer and wetter



Correlation between ΔT and ΔSoil Water Content (Fung et al. PN

Upscaling from point to pan-boreal region

Modifications of the ORCHIDEE global model relevant to permafrost regions

- soil hydrology and thermal diffusion based on Poutou et al. (2004)
  - take into account thermal effects of ice (latent heat, conductivity)
  - total soil column deepened to ~50m for thermal calculations
  - frozen soil initial ice content = 100% saturation
- soil carbon vertically discretized
  - carbon inputs integrated over plant rooting depth (Khvorostyanov et al. 2008b)
  - slow vertical diffusion through the active layer to account for mixing processes (cryoturbation, percolation)
- Feedback of soil carbon to soil temperature:
  - thermal insulation by soil organic matter (after Lawrence and Slater, 2008)

Koven et al. PNAS 2011

Vertical SOM mixing (cryoturbation)

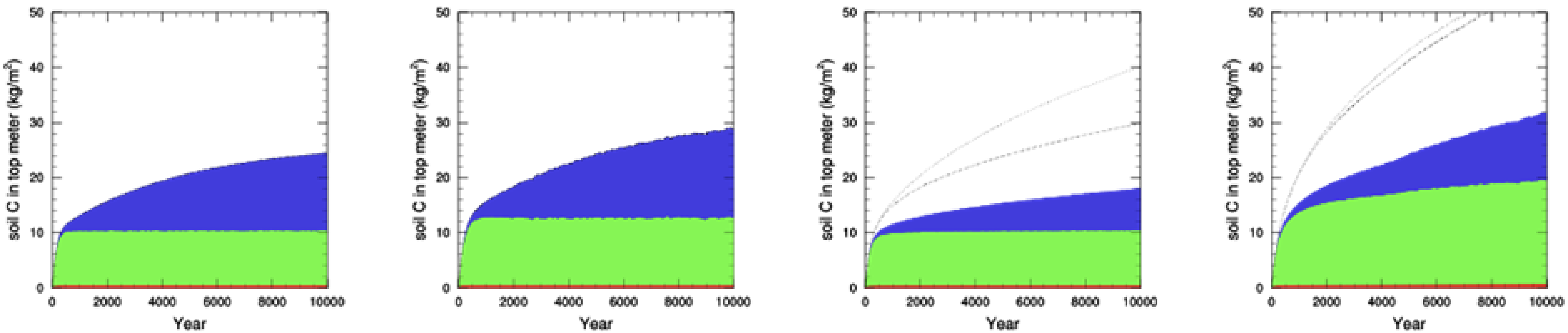
Parameterization

$$\frac{\partial C_i}{\partial t} = D\frac{\partial^2 C_i}{\partial z^2}$$

$$D = \begin{cases} D_0 & \text{for } z < z_{ALT} \\ D_0\left(1-\left(\frac{z-z_{ALT}}{2z_{ALT}}\right)\right) & \text{for } z_{ALT} < z < 3z_{ALT} \\ 0 & \text{for } z > 3z_{ALT} \end{cases}$$

- D_0, diffusion coefficient for active layer, is slow to allow mixing on century-millenial time scale: 10^{-3} m^2 yr^{-1}
- Mixing below active layer allows carbon to be subducted into upper permafrost

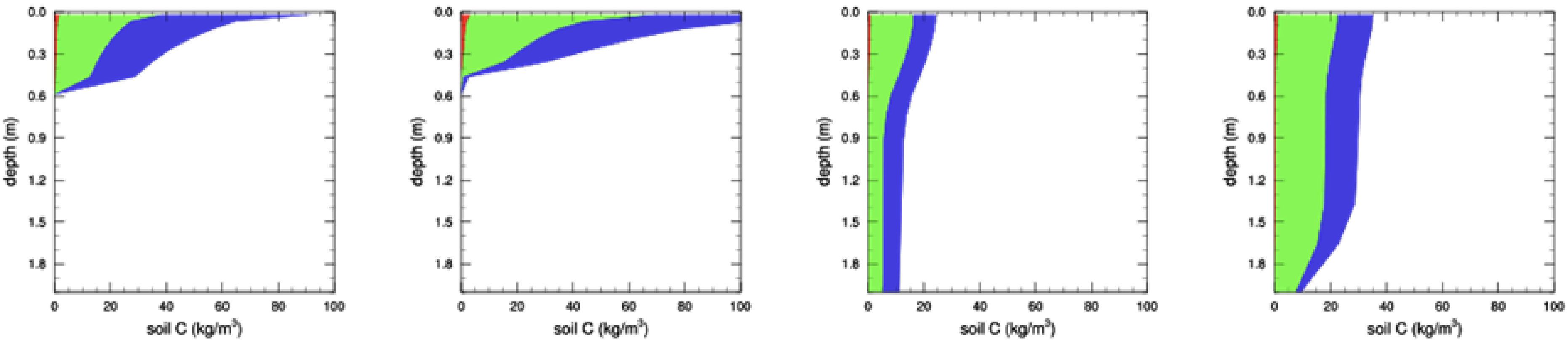
Combined effects of cryoturbation and insulation by SOM lead to large increases in modeled SOM



Control | SOM Insulation | Cryoturb. | Cryoturb + SOM Insul.

SOM accumulation vs. time for spinup run under steady climate
Red: "fast" C pool, Green: "slow" C pool, Blue: "Passive" C pool in top meter
Dashed and dotted lines correspond to total carbon to 2m and 3m.

Vertical profiles of SOM after 10,000 years



Control

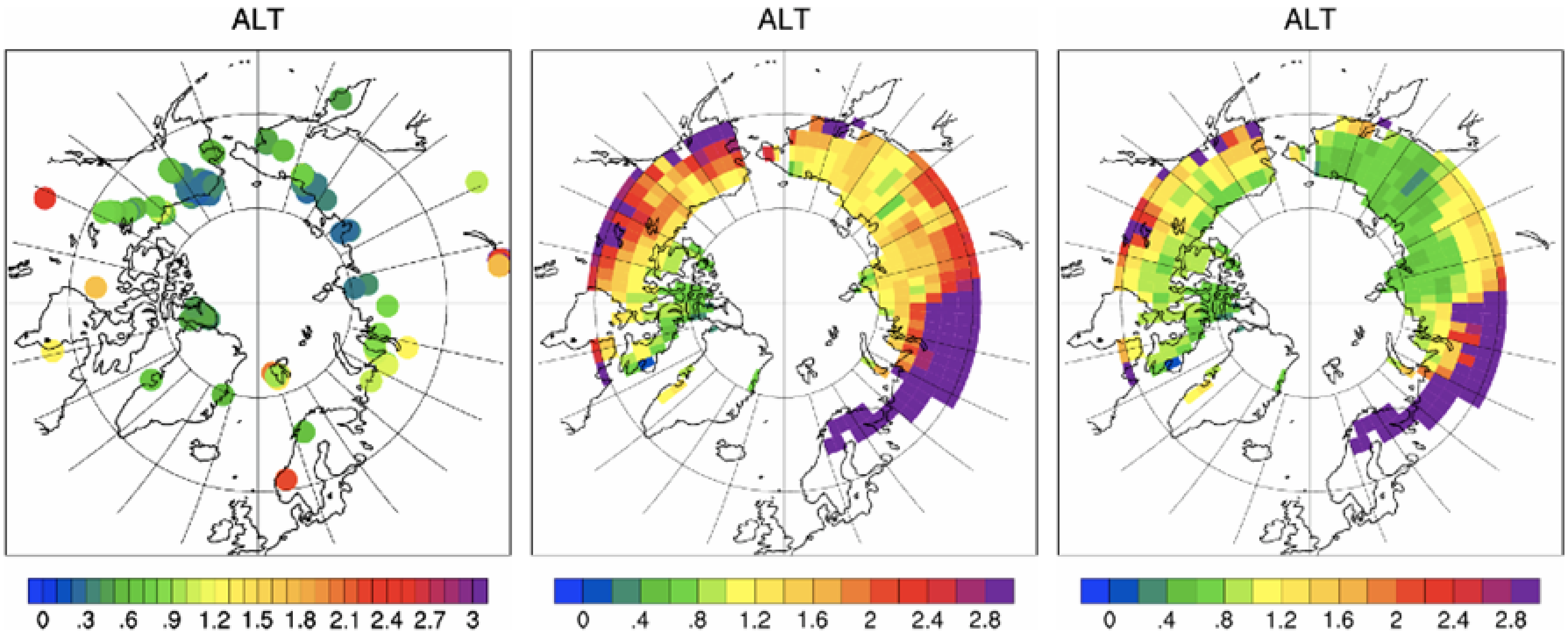
SOM Insulation

Cryoturb.

Cryoturb + SOM Insul.

Red: “fast” C pool, Green: “slow” C pool, Blue: “Passive” C pool

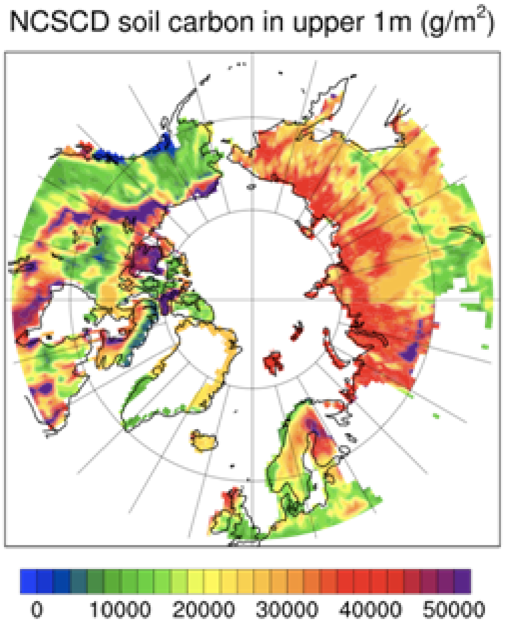
Effect of surface organic layer on modelled Active Layer Thickness



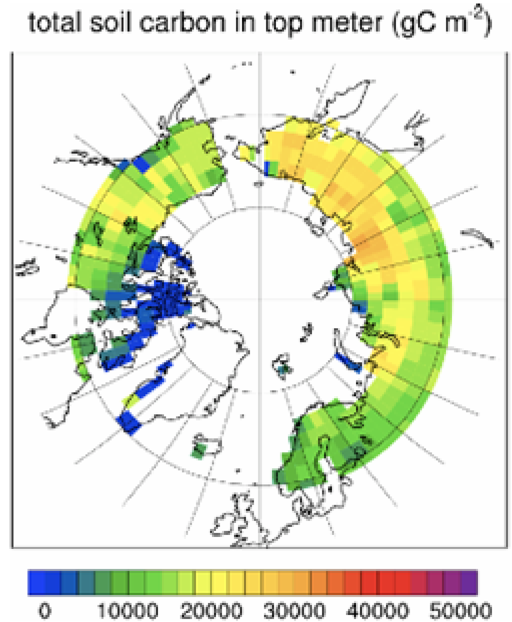
Observations: CALM (Brown et al. 2000) | ORCHIDEE no organic layer | ORCHIDEE with organic layer

Addition of organic layer leads to cooler summer soil T and reduces modeled active layer thickness, and generally improves match to observations, but still too deep in Northernmost Siberia and Alaska

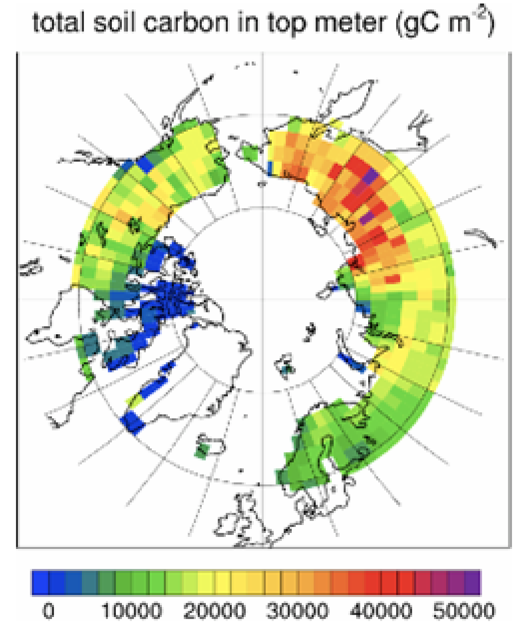
Insulating effect of soil carbon and cryoturbation creates a positive feedback for soil carbon accumulation



Observations from Northern Circumpolar Soil Carbon database (Tarnocai et al., 2007)



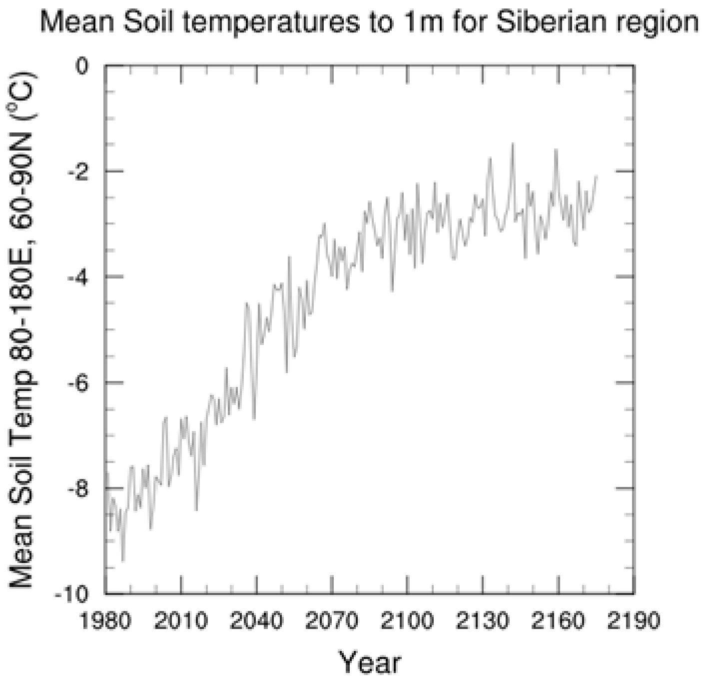
ORCHIDEE spinup for 10 000 years without soil carbon insulation or cryoturbation

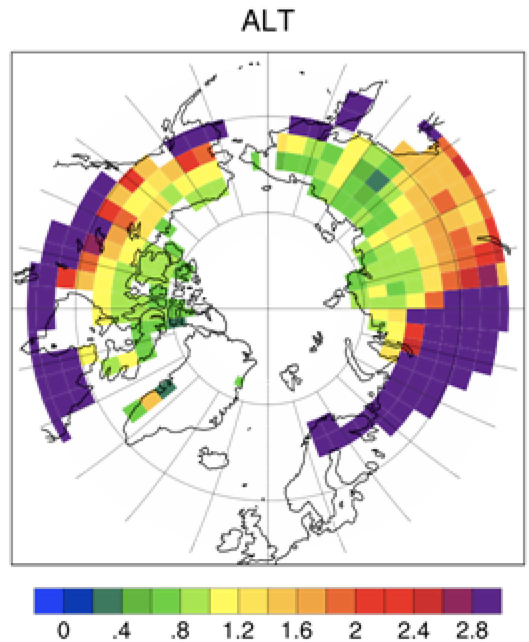


ORCHIDEE spinup for 10 000 years with soil carbon insulation and cryoturbation

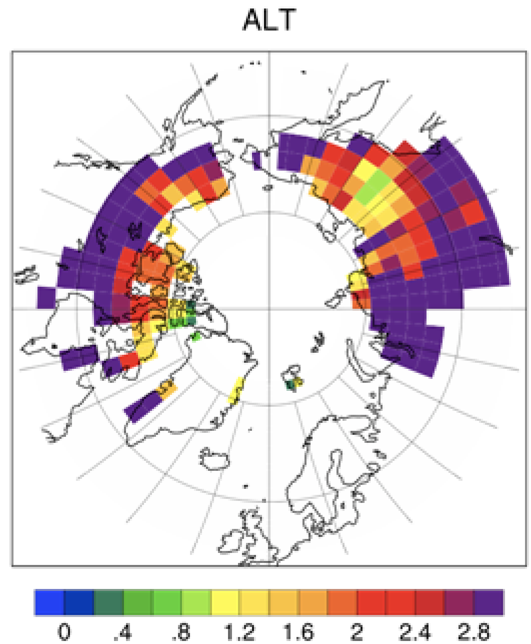
Model does reasonable job over eastern Siberia where decomposition is most limited by cold, but underestimates carbon in peatlands of western Siberia and Canada because there are no wetlands in current version of ORCHIDEE; also underestimates soil C in Alaska

Some results from model forced by future climate scenario: SRES A1B, with CO_2 stabilization at 720 ppm after 2100





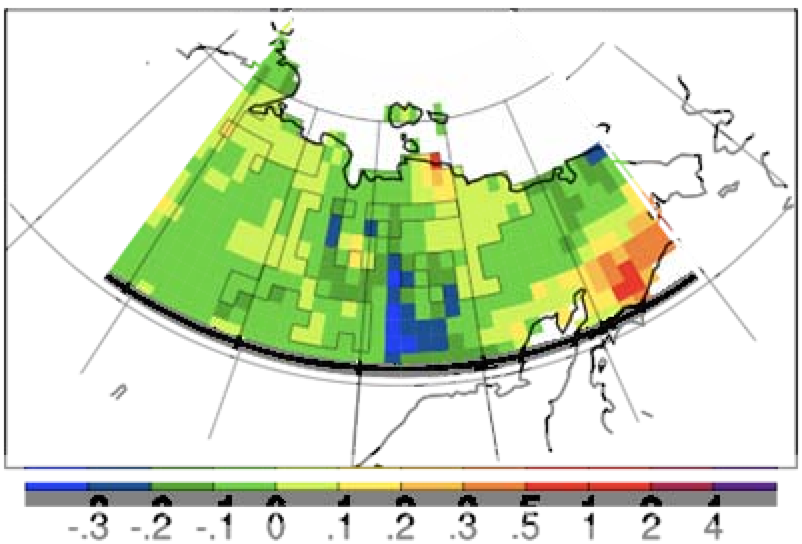
ALT 1990s

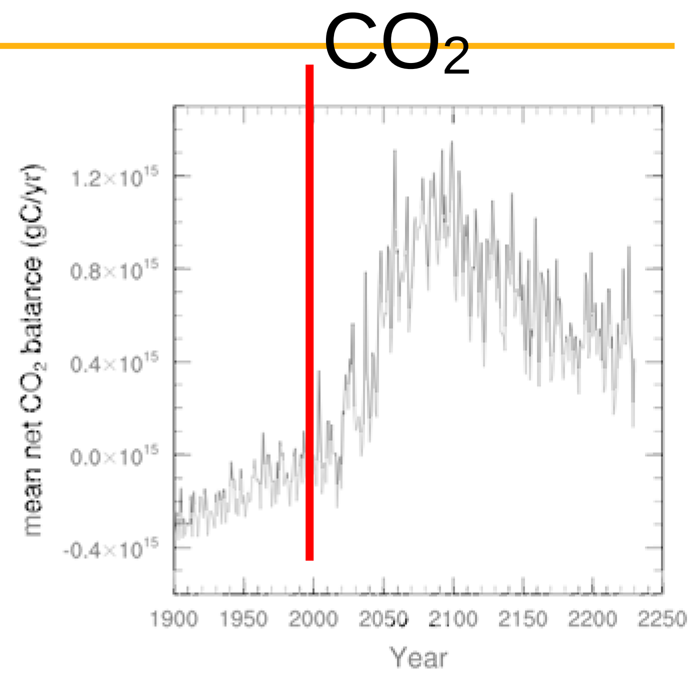


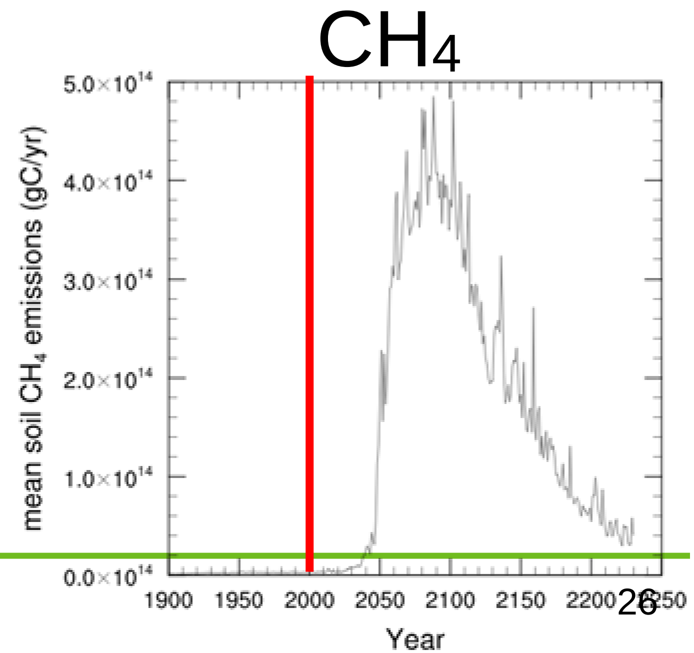
ALT 2090s

GHG emissions

mean CO2 flux for period 2000-2009 (gC m-2 day-1)



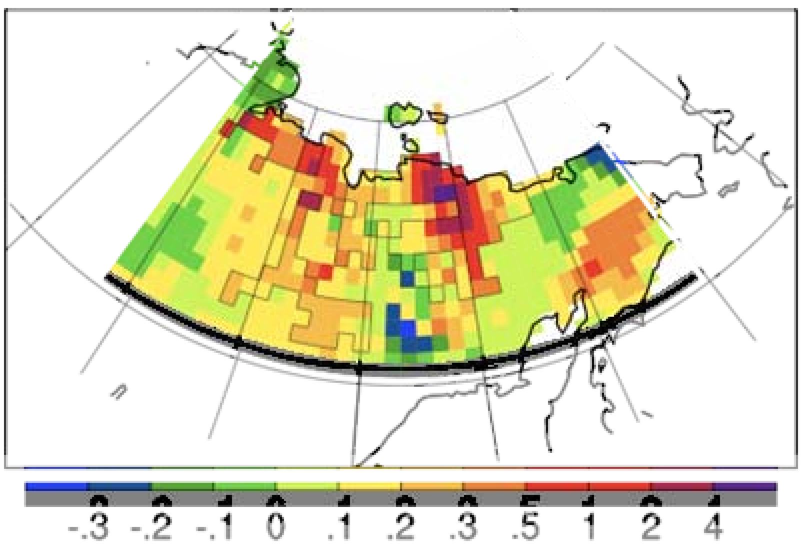




First areas to experience rapid Yedoma decomposition are those with high insulation at surface from surface soil organic carbon stocks.

GHG emissions

mean CO2 flux for period 2040-2049 (gC m^{-2} day^{-1})



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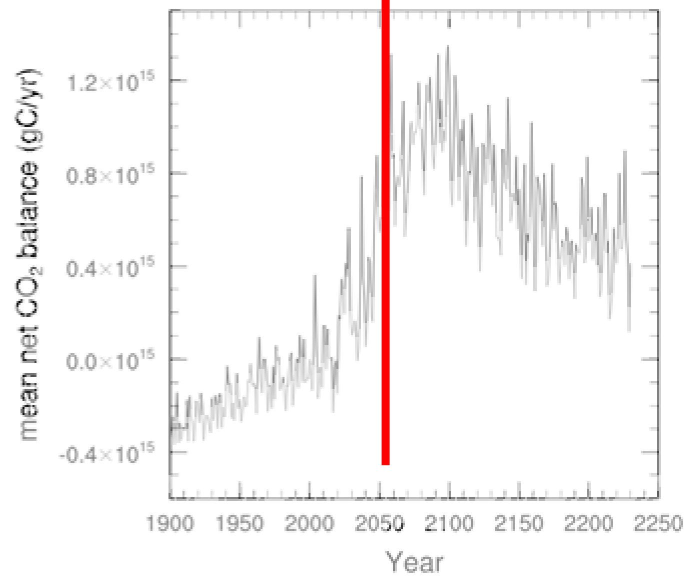
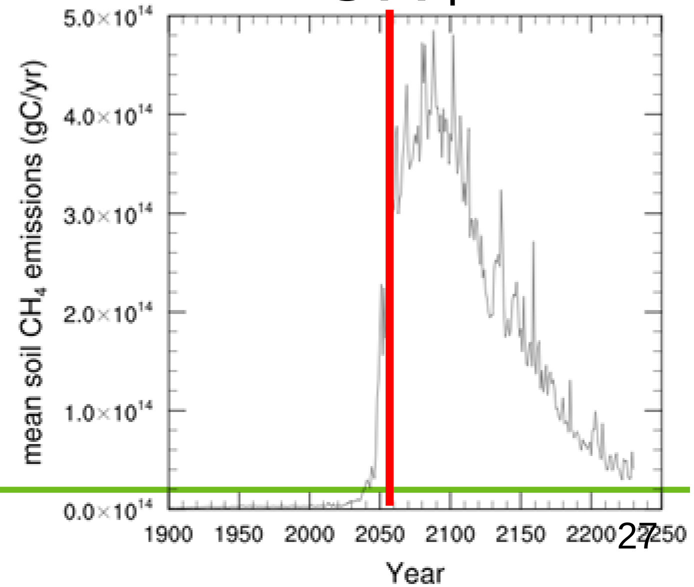
CO_2

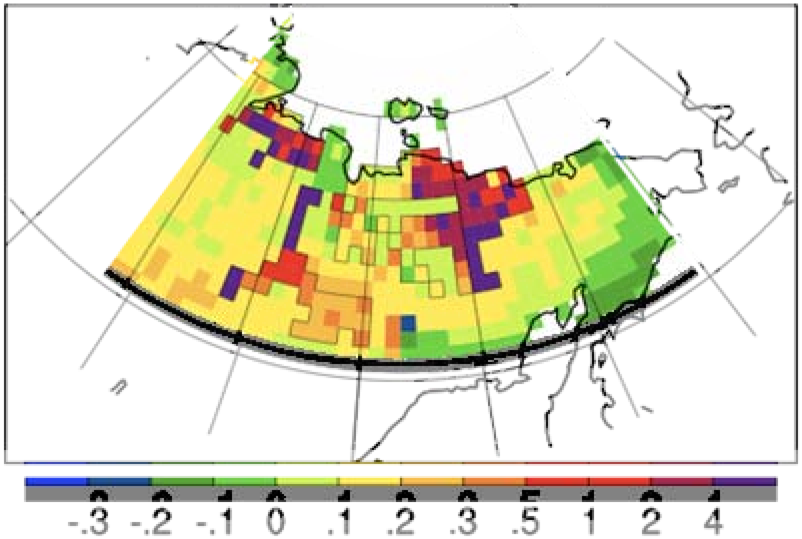


CH_4



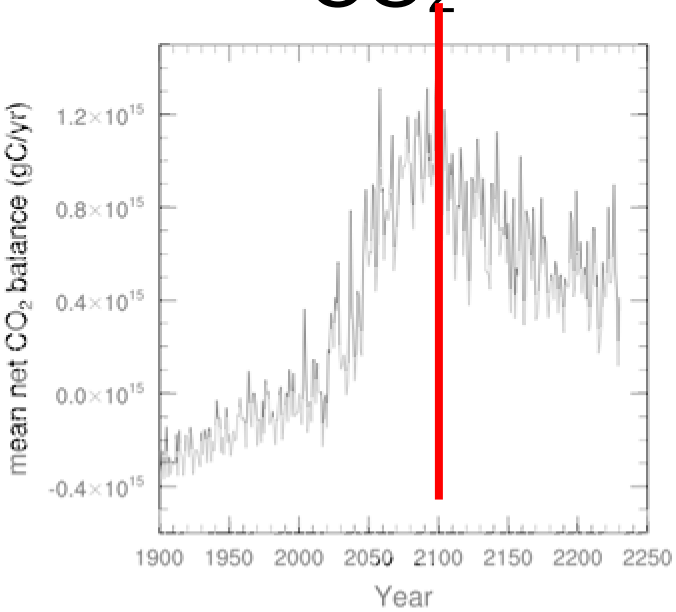
GHG emissions

mean CO2 flux for period 2100-2109 (gC m^{-2} day^{-1})

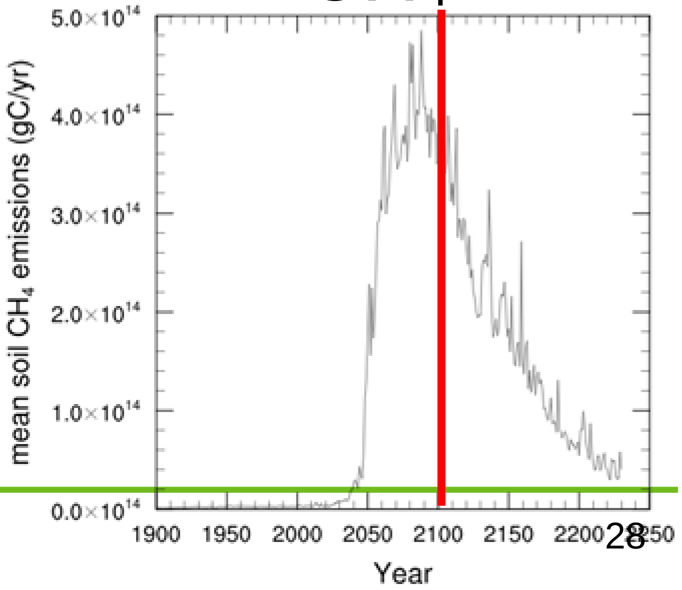


First areas to experience rapid Yedoma decomposition are those with high insulation at surface from surface soil organic carbon stocks.

CO_2



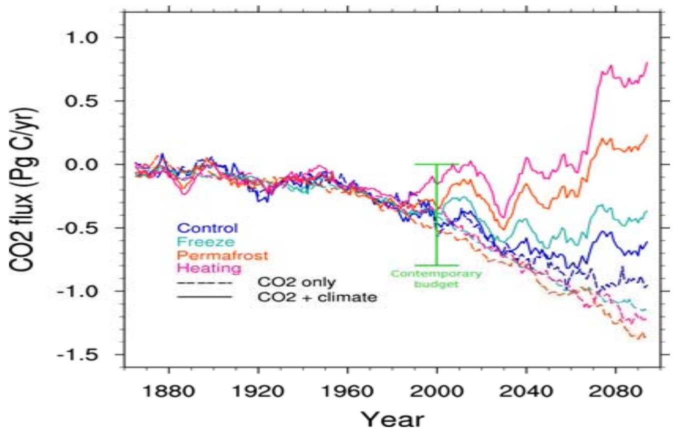
CH_4



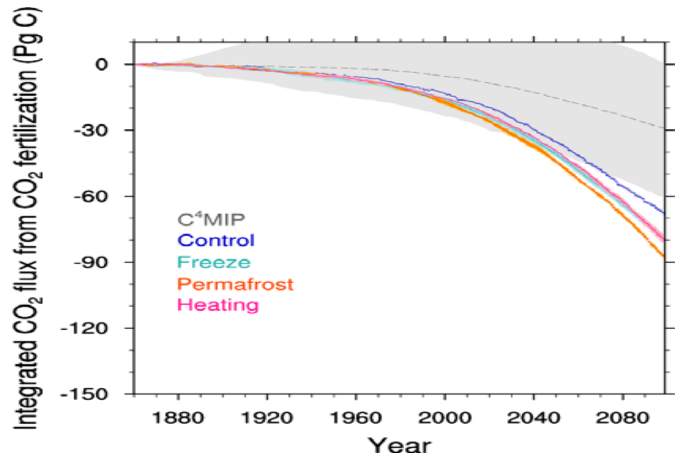
Sensitivity experiments to added processes incrementally (all forced by same climate scenario)

- Control
- Freeze (no sensitivity of soil resp > 0° C)
- Permafrost (added deep soil C and profile)
- Heating (bacterial heat release during decomposition – « Zimov effect »)
- CH_4 (interactive wetland area and climate dependent CH_4 emission rate)

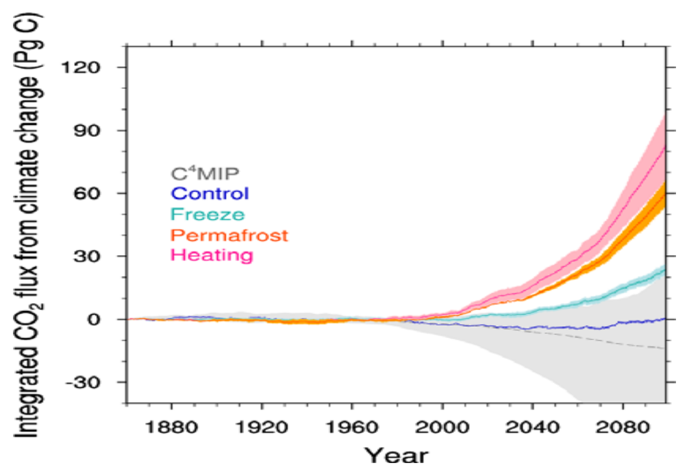
Future changes of high-latitude C balance due to CO_2 and climate change



(a)



(b)



(c)

Figure 2. Change in carbon fluxes over the model run. (a) mean fluxes over modelled period. Contemporary budget estimate from McGuire et al. [3] (b) integrated change in carbon balance due to rising CO_2 concentration alone. (c) integrated change in

Spatial patterns of CO2 fluxes due to climate change (different model proceses)

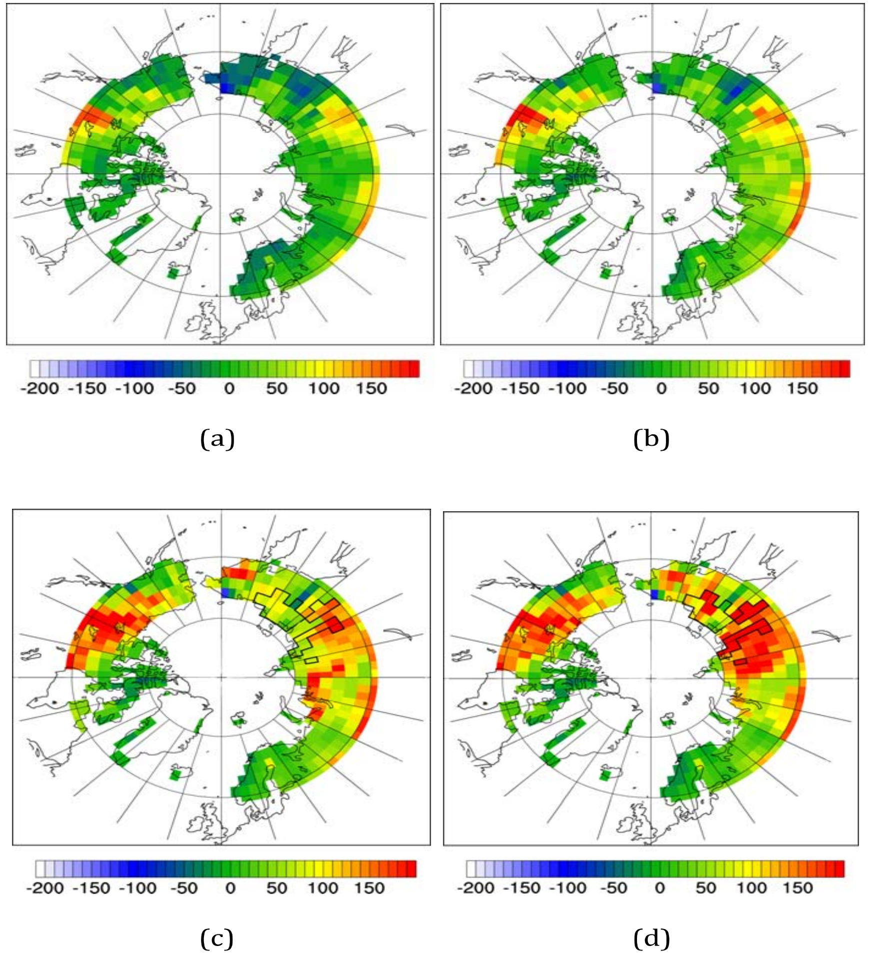


Figure 3. Spatial patterns of net CO_2 fluxes due to climate change at end of 21st century, for (a) Control (b) Freeze (c) Permafrost (d) Heating experiments. Units are in gC/m2/yr. Outlined cells are initialized as containing deep Yedoma carbon.

Modeled CH4 emissions

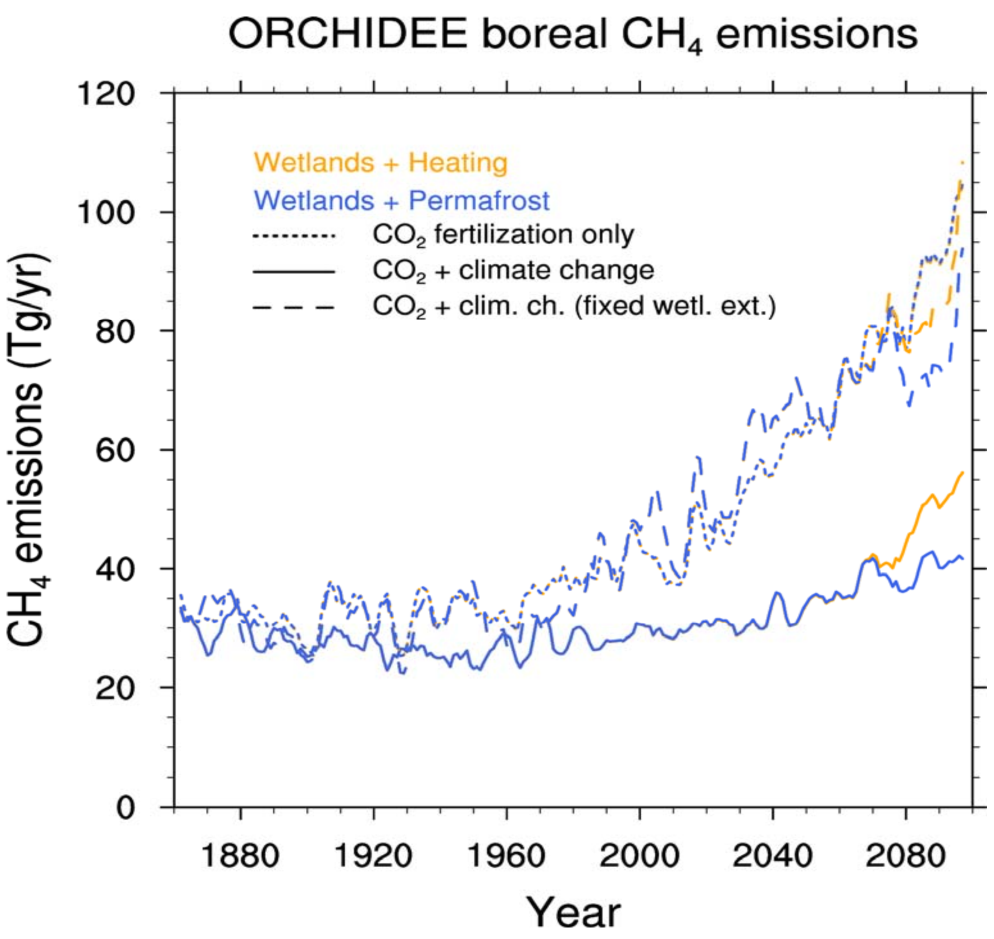
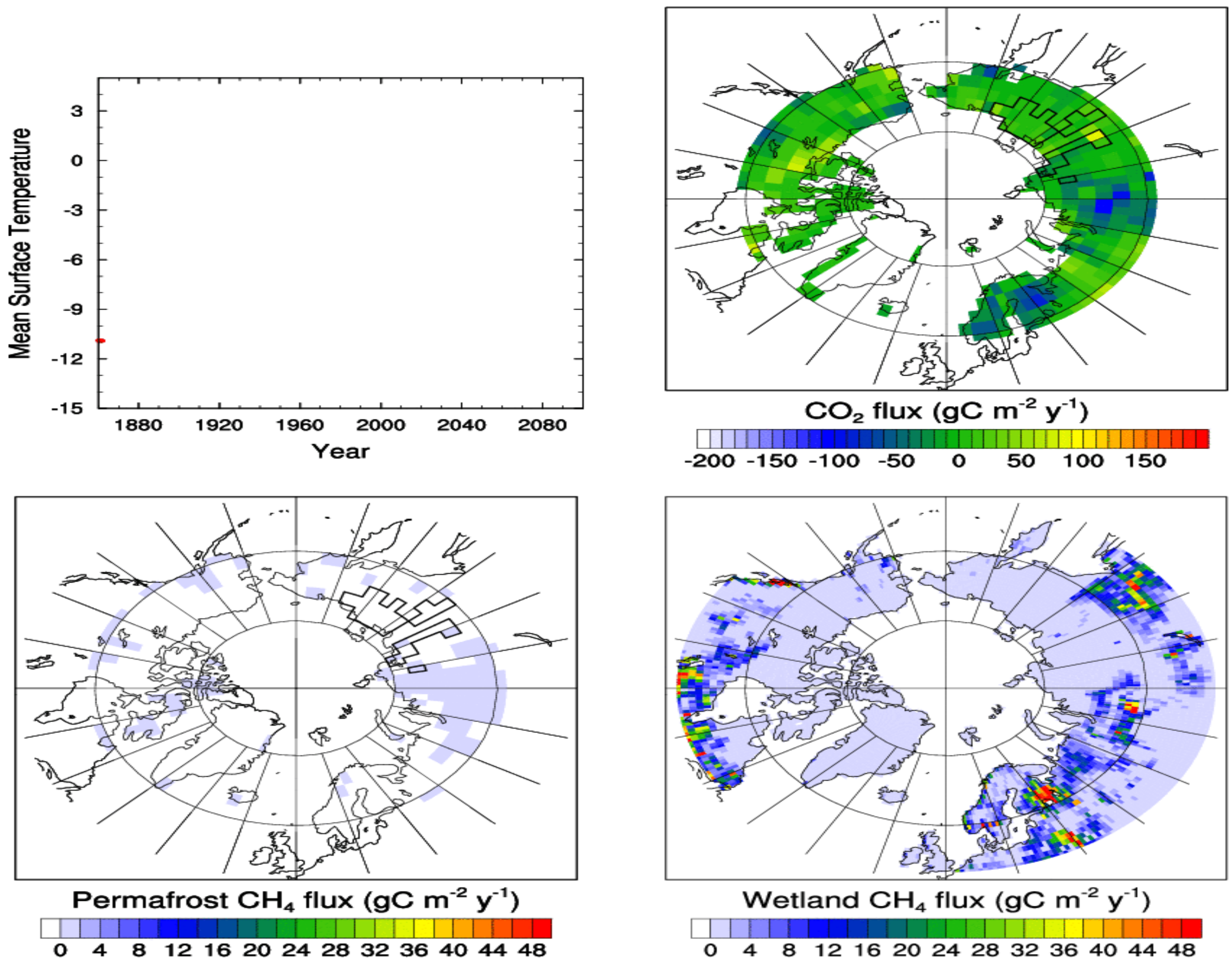


Figure 4. CH_4 fluxes from high-latitude region over model runs (Tg CH_4). Dotted lines: CO2 effect only; solid lines: CO2 and climate change, wetland extent held fixed; dashed lines: CO2 and climate change, with varying wetland extent. The line colors correspond to which permafrost extent was used: blue includes the "Permafrost" experiment, orange includes the "Heating" experiment, in which some methane is released from thawing of deeper permafrost soils.


Mean Surface Temperature
3
0
-3
-6
-9
-12
-15
1880
1920
1960
2000
2040
2080
Year
CO2 flux (gC m-2 y-1)
-200 -150 -100 -50 0 50 100 150
Permafrost CH4 flux (gC m-2 y-1)
0 4 8 12 16 20 24 28 32 36 40 44 48
Wetland CH4 flux (gC m-2 y-1)
0 4 8 12 16 20 24 28 32 36 40 44 48

Conclusions

- For carbon accumulation experiments, vertical mixing of and thermal insulation by SOM lead to large increases in the SOM content.
- Adding these processes gives better agreement with SOM and ALT maps.
- For future scenarios with microbial heat release, model predicts significant emissions of CO_2 and CH_4 from rapid Yedoma thaw due to local feedback processes within late 21st century under SRES scenario A1B.
- Modelled permafrost melt is extremely sensitive to parameters:
  - initial carbon concentration in deep Yedoma layers, where present
  - insulation by surface carbon layers
  - carbon lability and variation with depth
  - heat released per unit carbon respired
- CH_4 emissions most sensitive and least-constrained variable.

Major mechanisms missing from model relevant to permafrost thaw and C balance

- Lateral heat transport by conduction
- Lateral and vertical heat transport by soil moisture
- Poor knowledge on what the amount of heat production is
- Poor knowledge on what the soil moisture is after thawing
- Ice wedges and thermokarst
- Vertical heterogeneity in Yedoma SOM content
- Changes in vegetation / fires
- Changes in nitrogen cycling