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Life

SNOWCARBO

The terrestrial (high-latitude) carbon cycle

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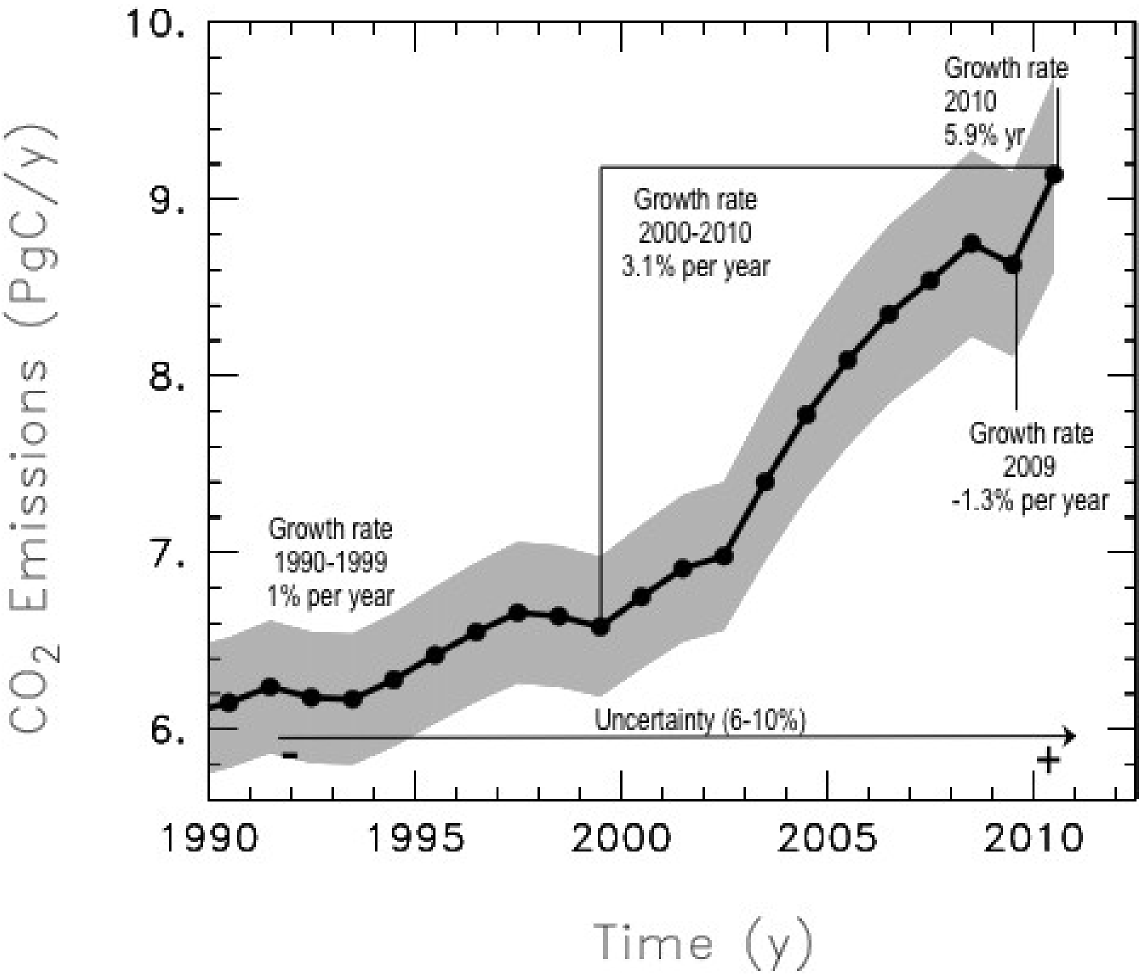
cnrs

université Joseph Fourier GRENOBLE

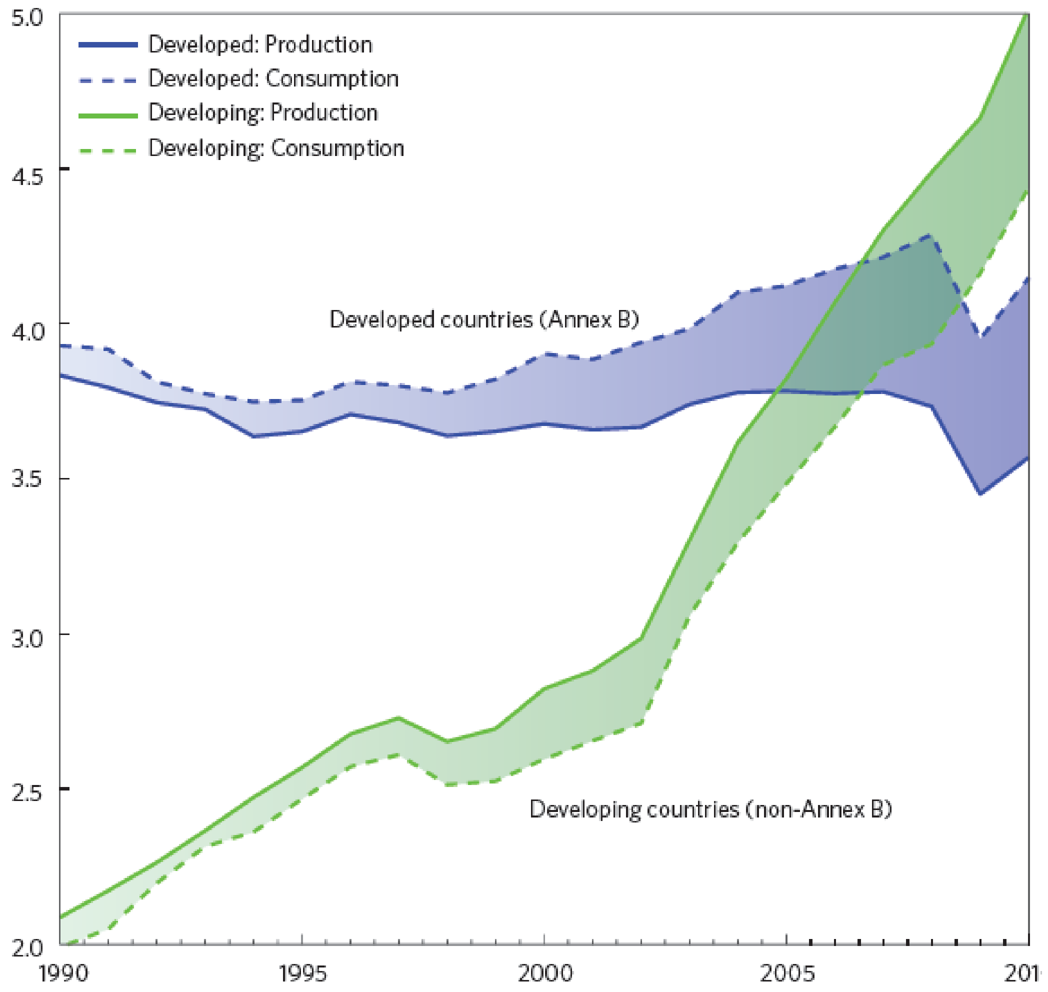
Thanks to : Philippe Ciais, Martin Menegoz, Isabelle Gouttevin, the Global Carbon Project

Fossil fuel & cement CO_2 emissions



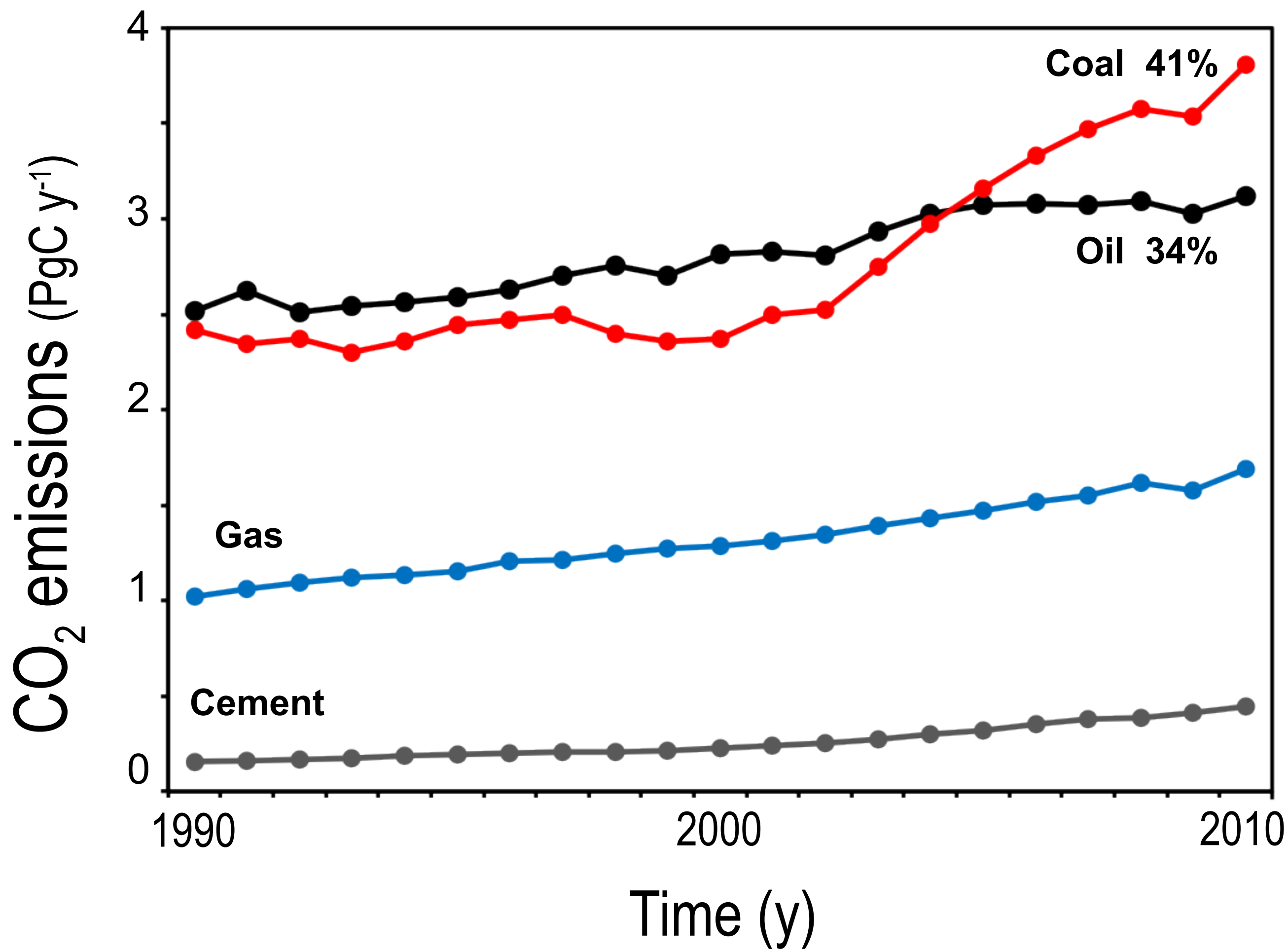
Peters et al. 2011, Nature CC; Data: Boden, Marland, Andres-CDIAC 2011; Marland et al. 2009

Fossil fuel & cement CO_2 emissions (territorial)



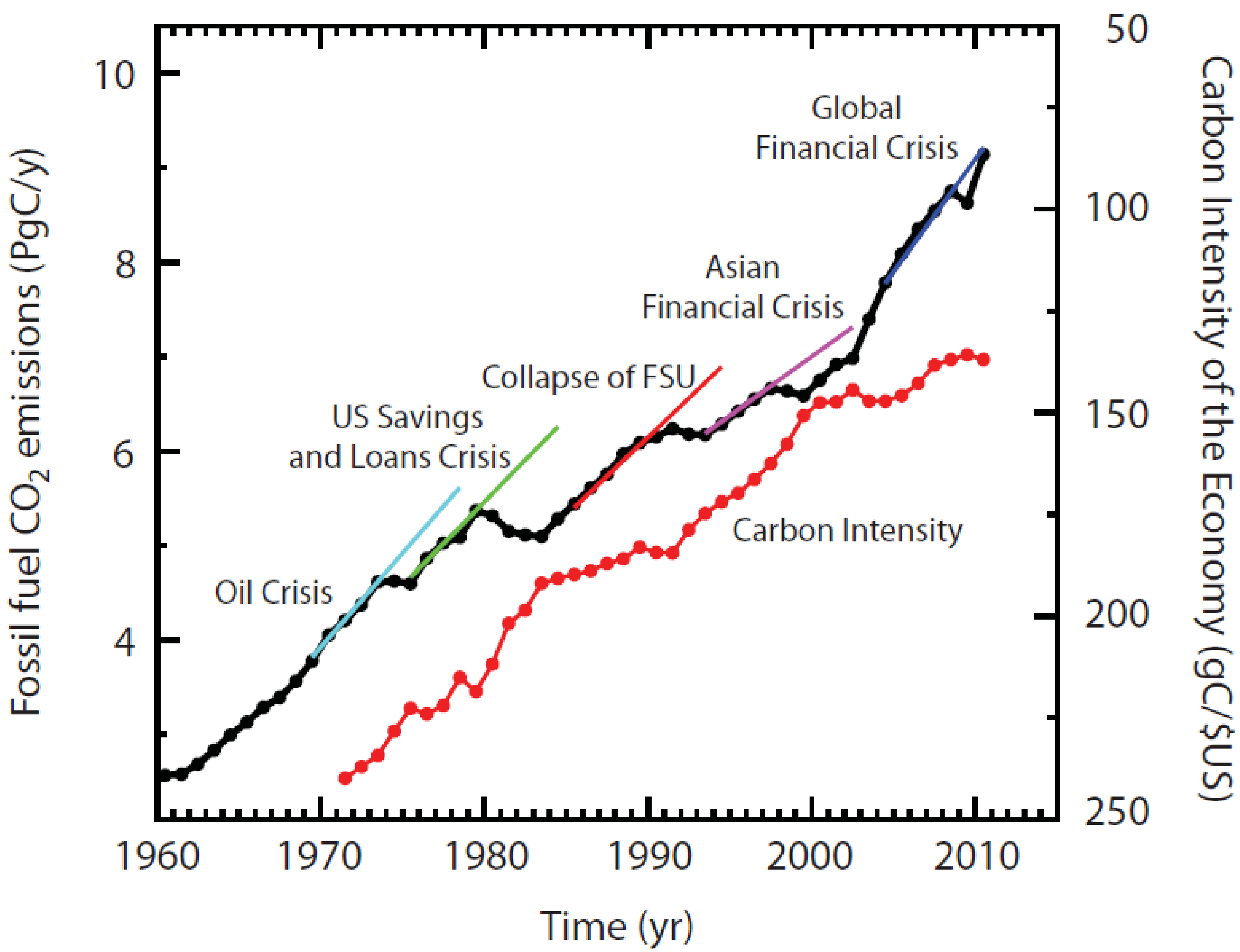
Peters et al. 2011, Nature CC

CO_2 emissions by fossil fuel type



Updated from Le Quéré et al. 2009, Nature Geoscience; Data: Boden, Marland, Andres-CDIAC 2011

Impact of economic crises on C emissions



Most of recent carbon intensity increase located in China

Peters et al. 2011, Nature CC

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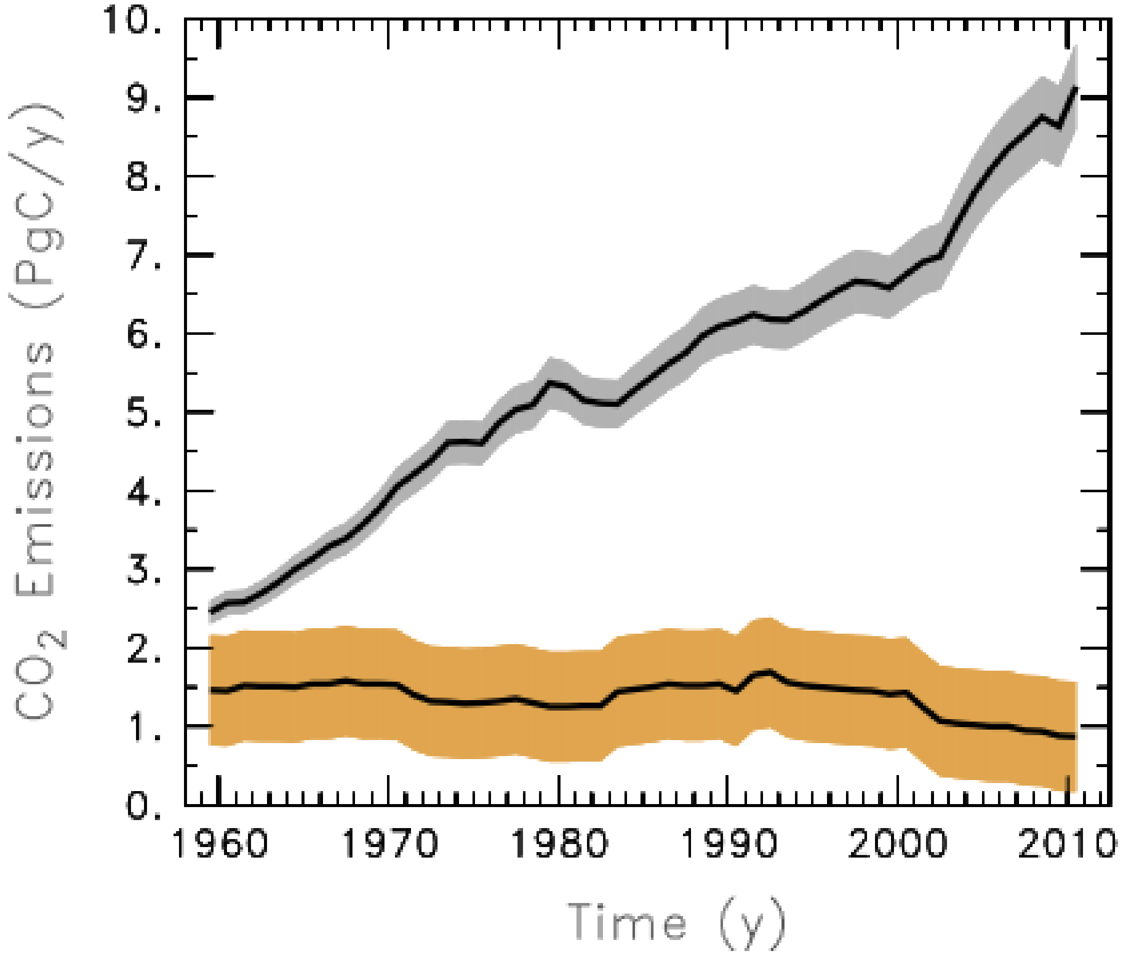
CO_2 emissions from FF and LUC (1960-2010)



Current LUC emissions
~10% of total CO_2 emissions

Updated from Le Quéré et al. 2009, Nature Geoscience

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Fate of anthropogenic CO_2 emissions (2010)

9.1±0.5 PgC y^{-1}

+

0.9±0.7 PgC y^{-1}

5.0±0.2 PgC y^{-1}

50%

2.6±1.0 PgC y^{-1}

26%

Calculated as the residual
of all other flux components

24%

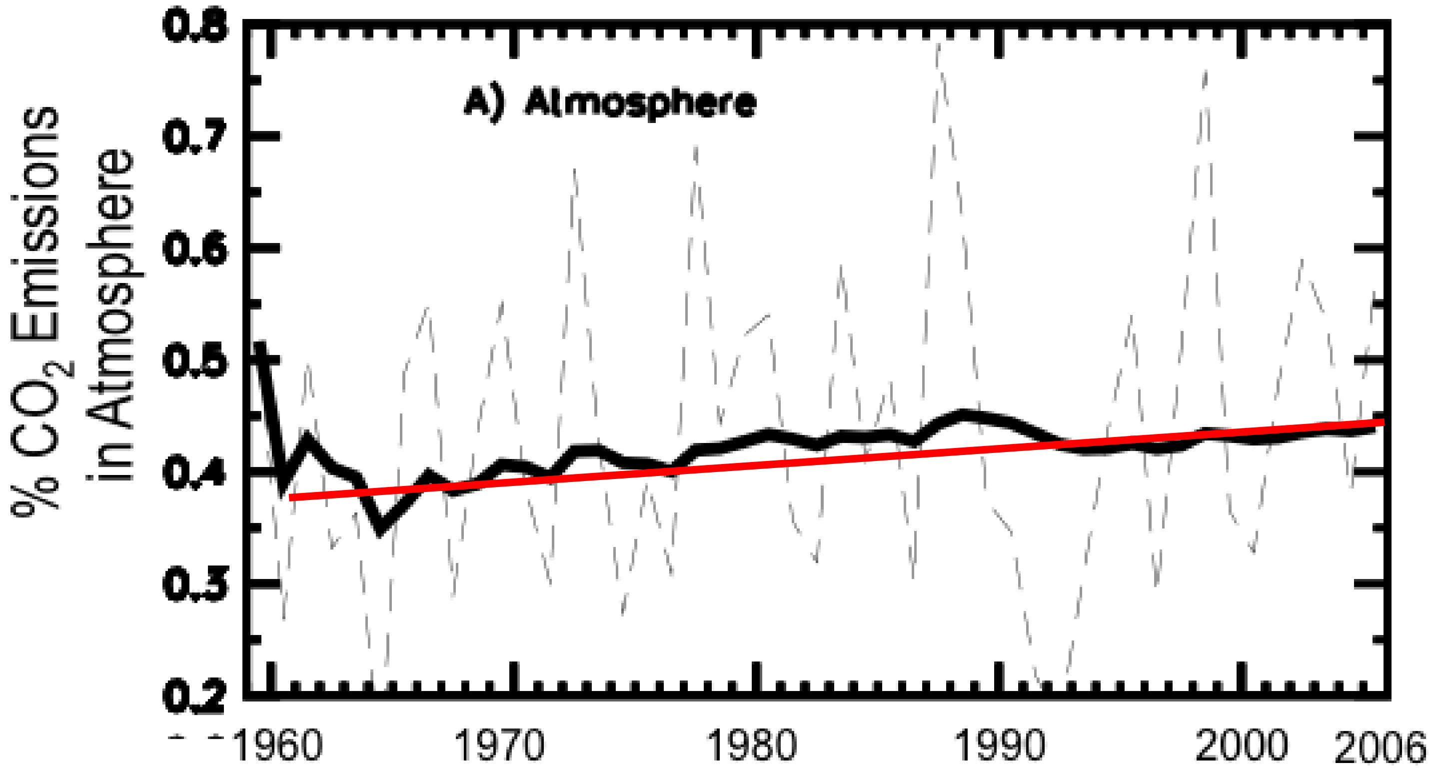
2.4±0.5 PgC y^{-1}

Average of 5 models

Global Carbon Project 2010; Updated from Le Quéré et al. 2009, Nature Geoscience; Canadell et al. 2007, PNAS

Decline in the efficiency of CO_2 natural sinks

Fraction of all anthropogenic emissions that stay in the atmosphere



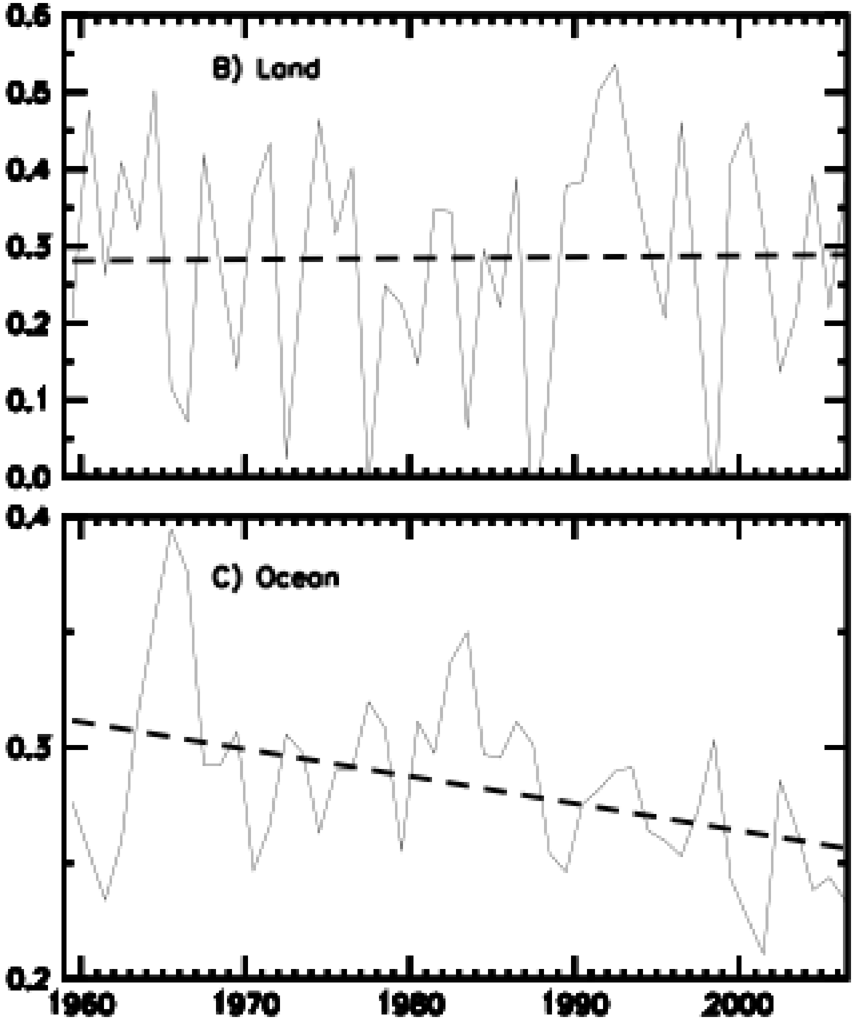
10% increase in atm fraction in 50 yrs

Canadell et al. 2007, PNAS

Efficiency of land vs ocean sinks

Land Fraction

Ocean Fraction



Canadell et al. 2007, PNAS

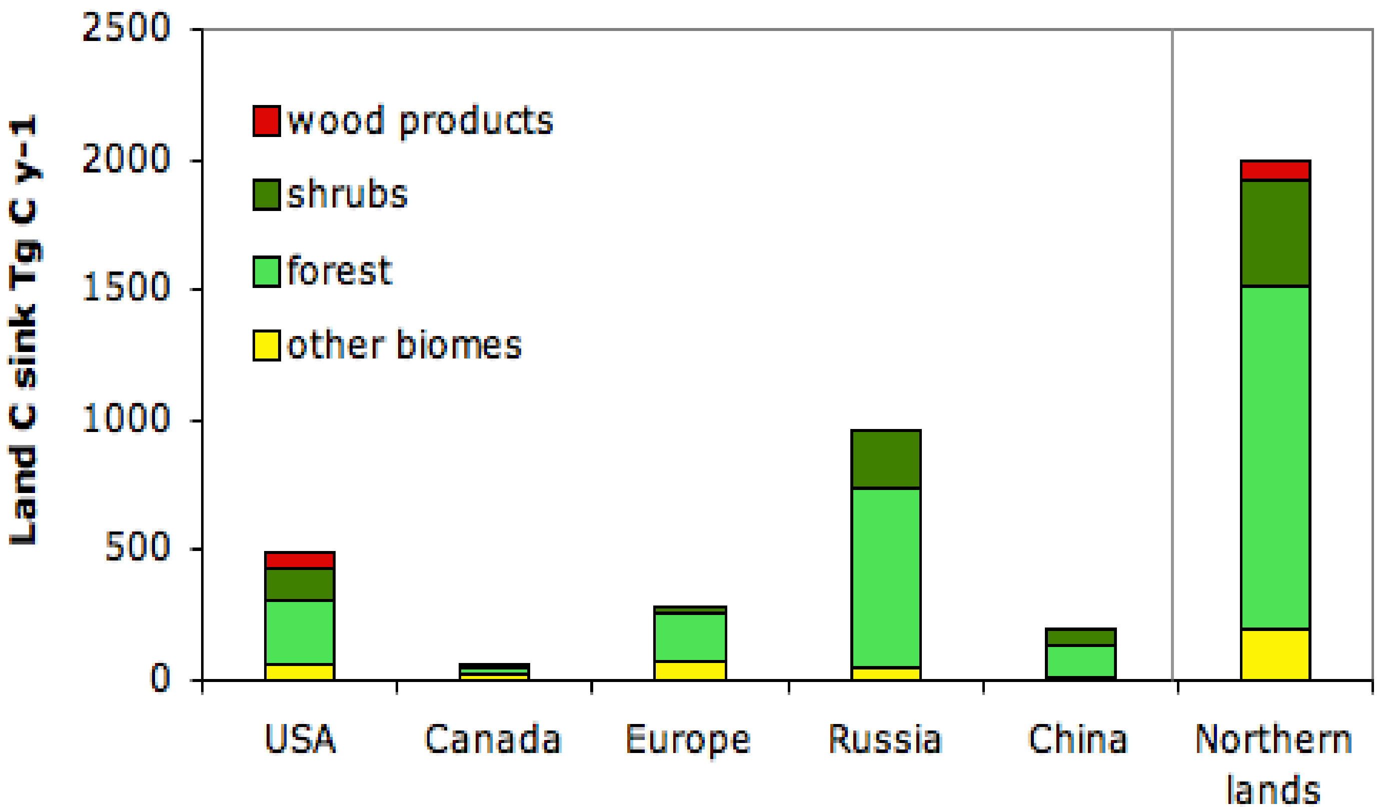
Declining efficiency of the ocean sink

Le Quéré et al. 2007, Science

- Part of the decline is attributed to up to 30% decrease in the efficiency of the Southern Ocean sink over the last 20 years.
- This sink removes annually 0.3±0.2 Pg of anthropogenic carbon.
- The decline is attributed to the strengthening of the winds around Antarctica which enhances ventilation of natural carbon-rich deep waters.
- The strengthening of the winds is attributed to global warming and the ozone hole.

Contribution of forests

More than 70% of the northern C sink is in forest



Unmanaged forests appear to be significant C sinks

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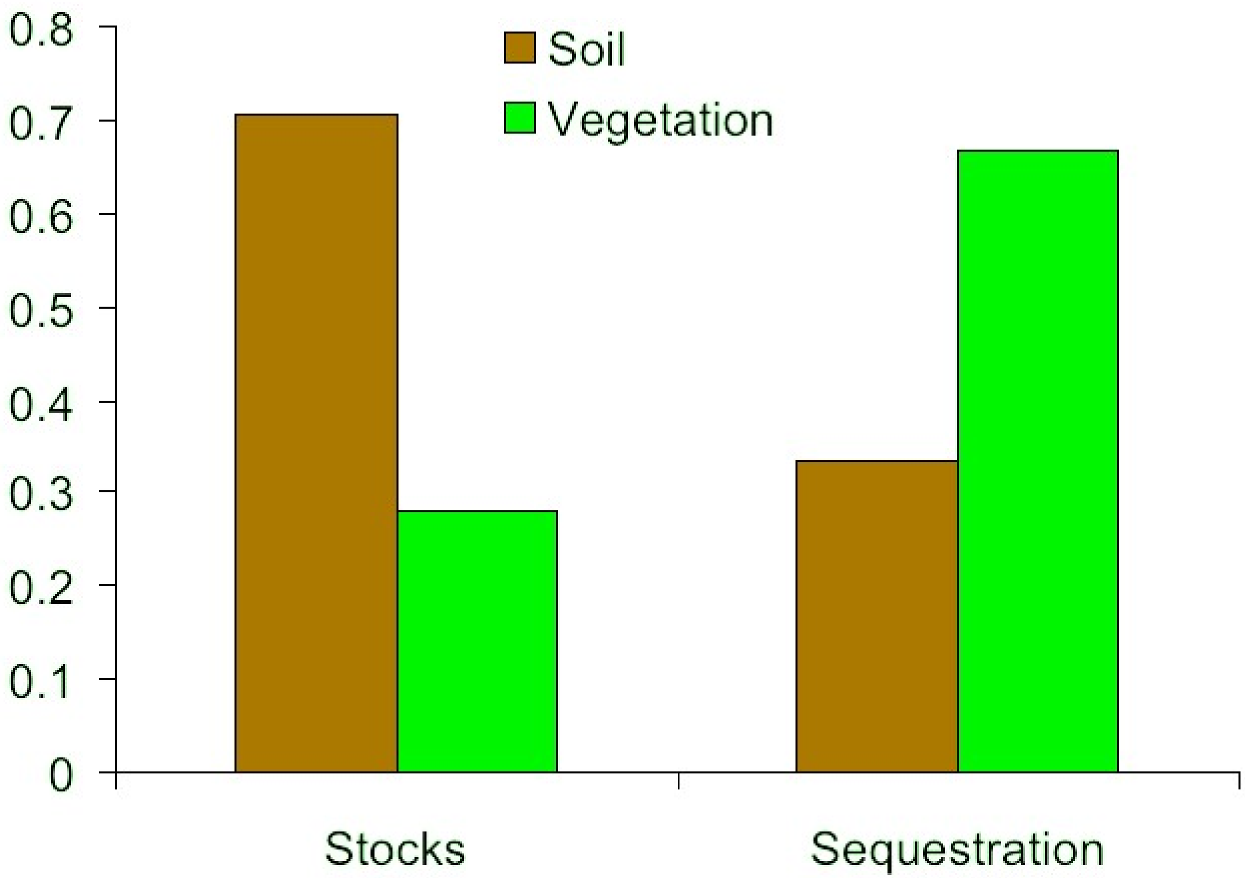
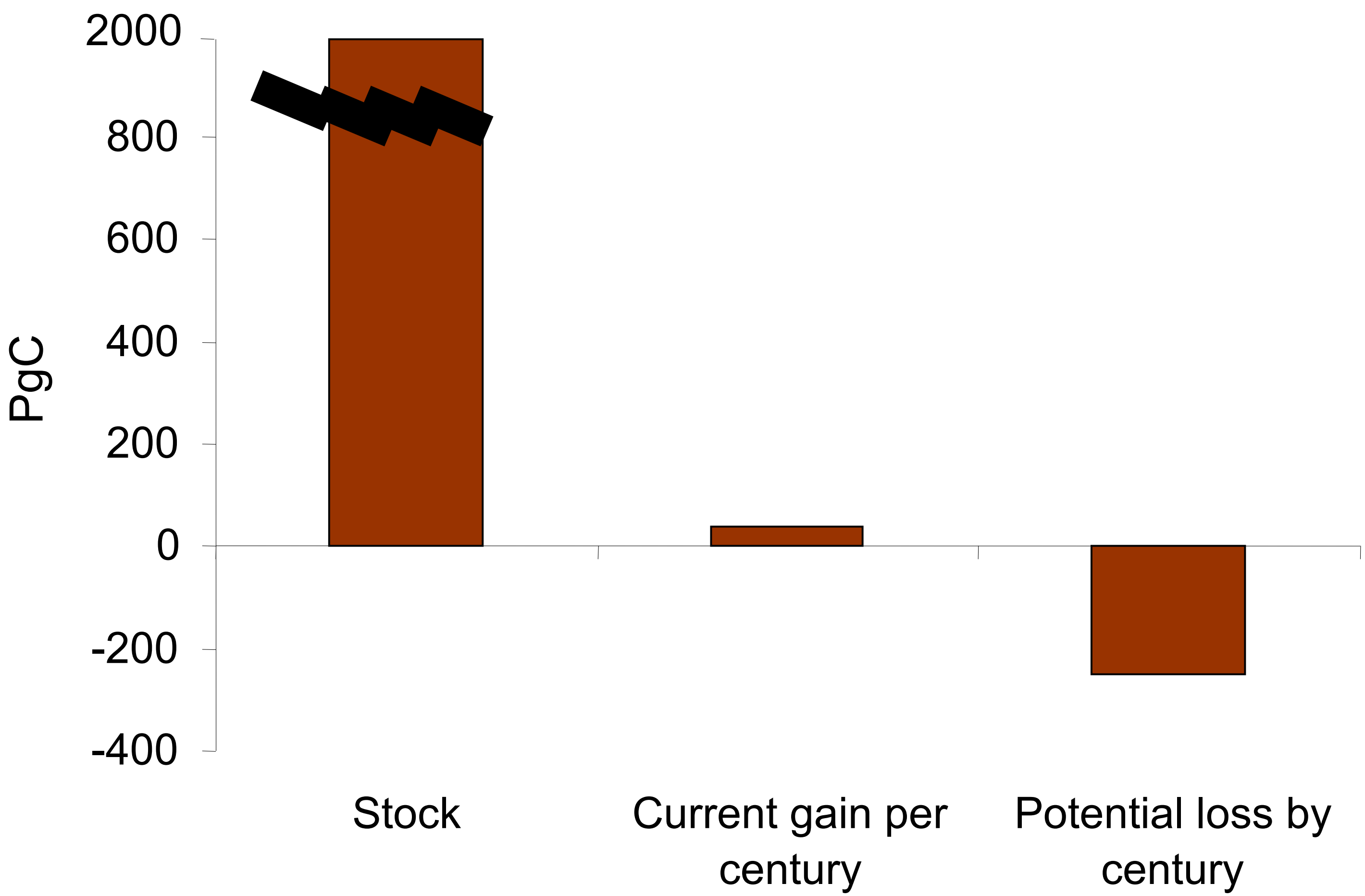
Stock vs. sequestration: partitioning between vegetation and soil

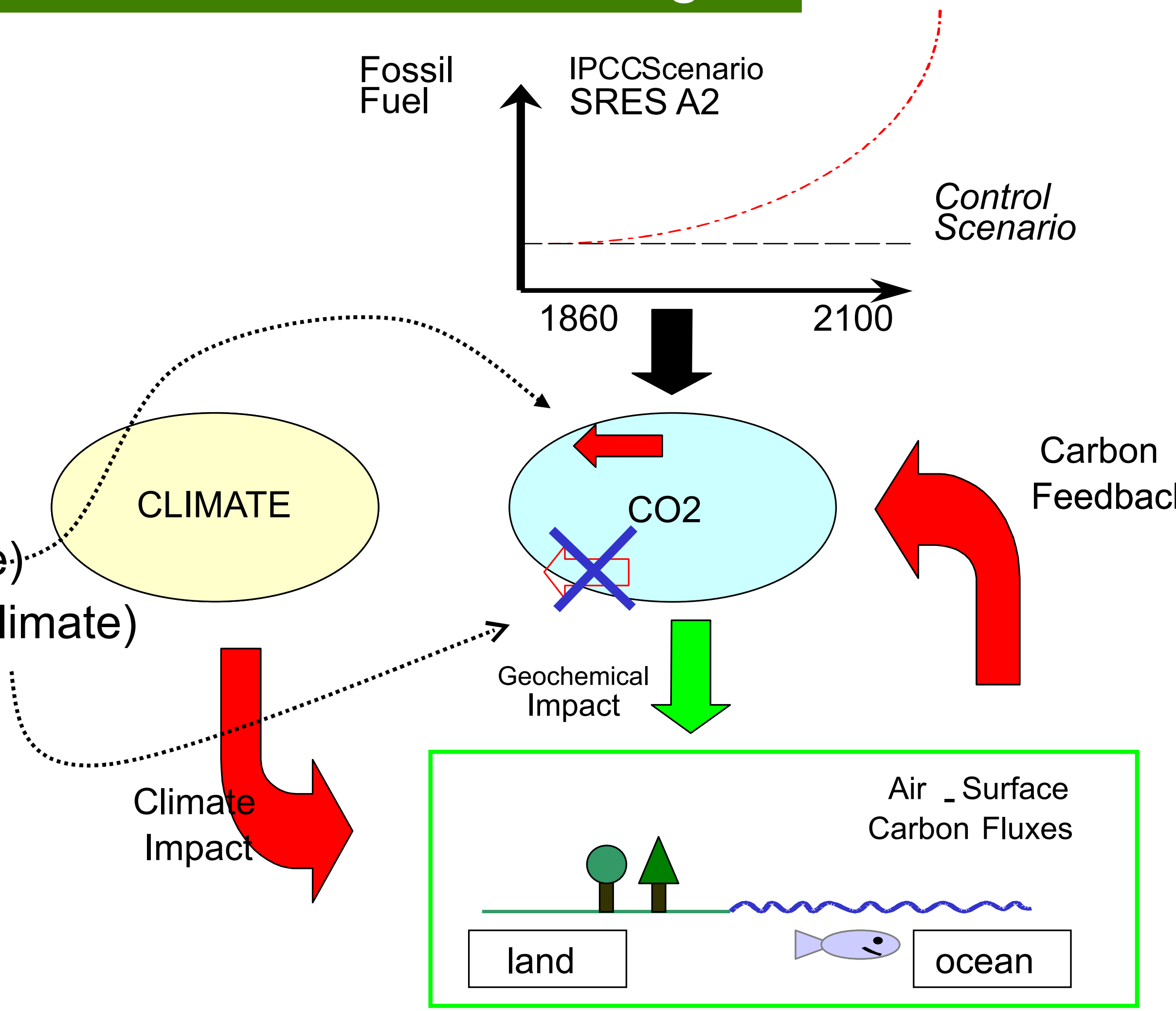


Soil carbon stock is large & vulnerable



after Davidson & Janssens 2006

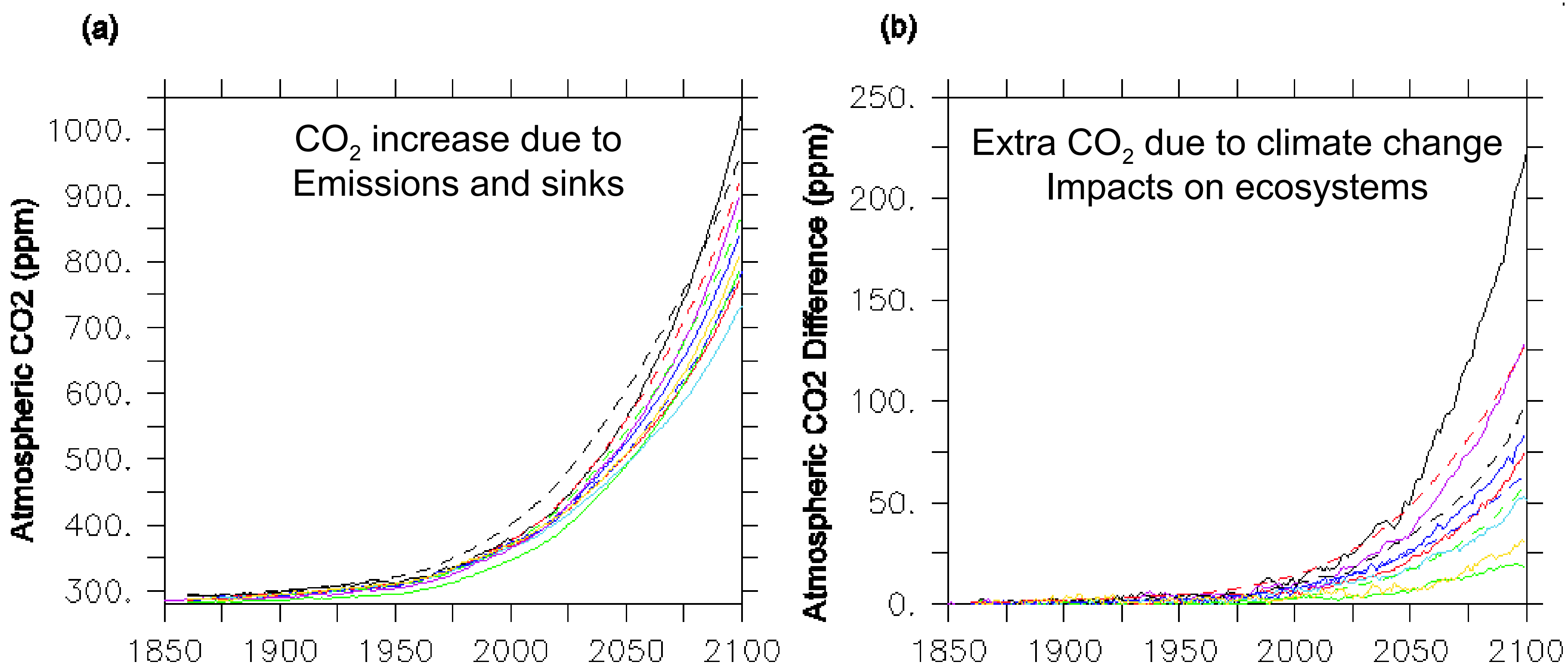
C^4MIP: Coupled carbon-climate simulation design



- Coupled (changing climate)
- Uncoupled run (constant climate)

Allows to estimate
the feedback
on atmospheric CO_2

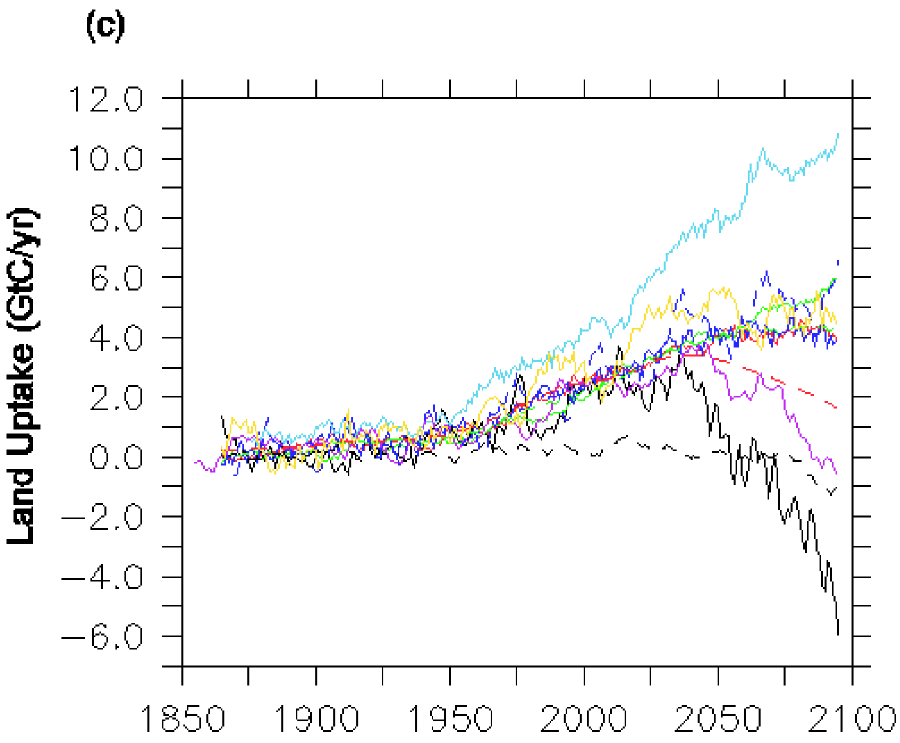
Simulated atmospheric CO_2

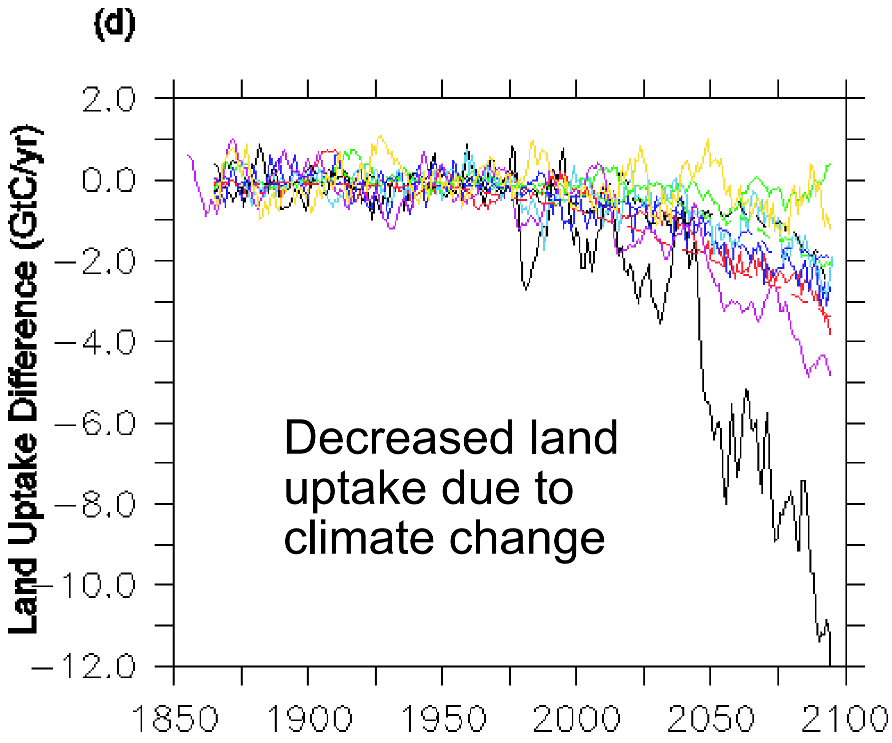


Always Positive Feedback
Large uncertainties

Friedlingstein et al., 2006

Simulated land fluxes

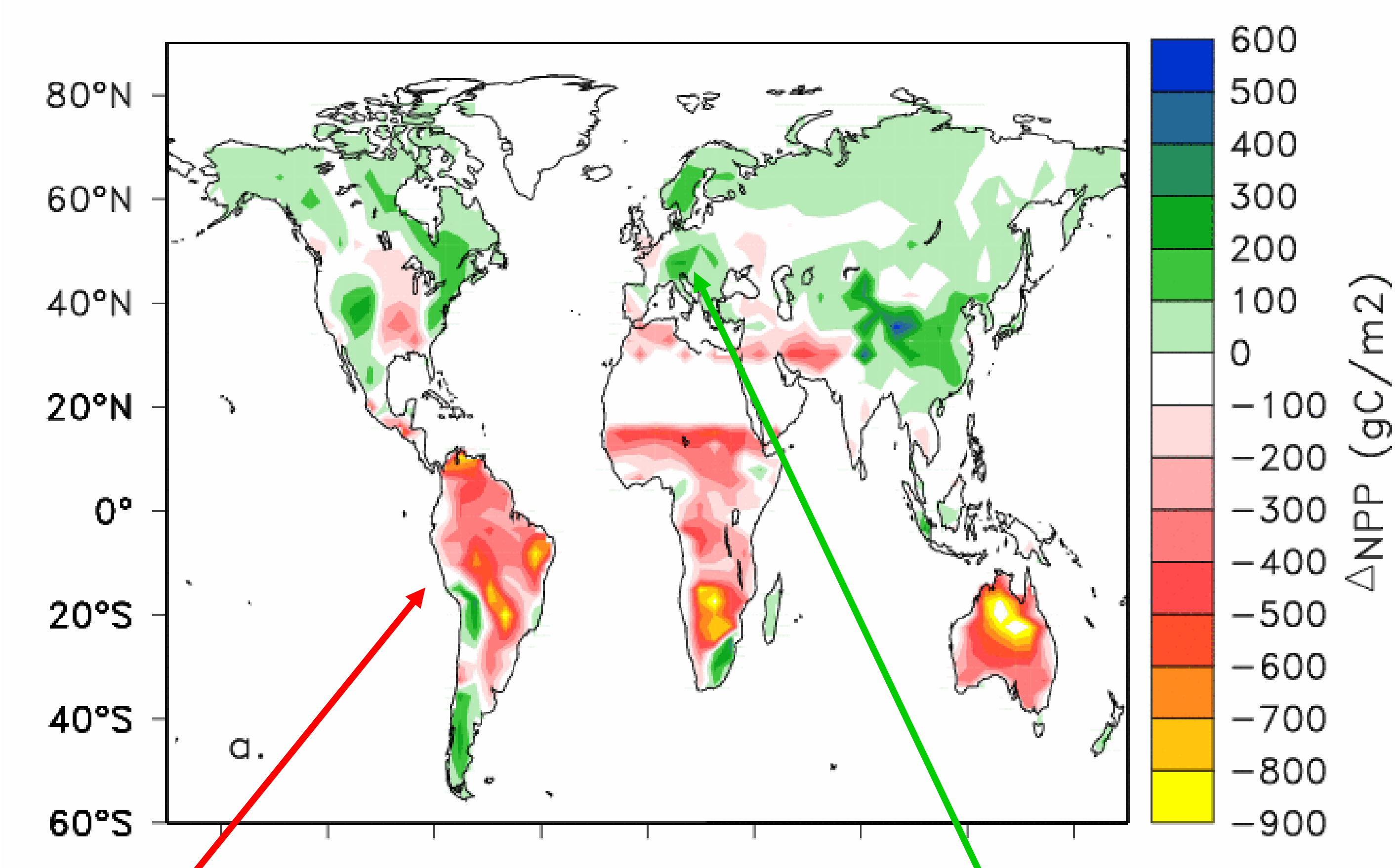




Globally a negative response

Friedlingstein et al., 2006

The land response

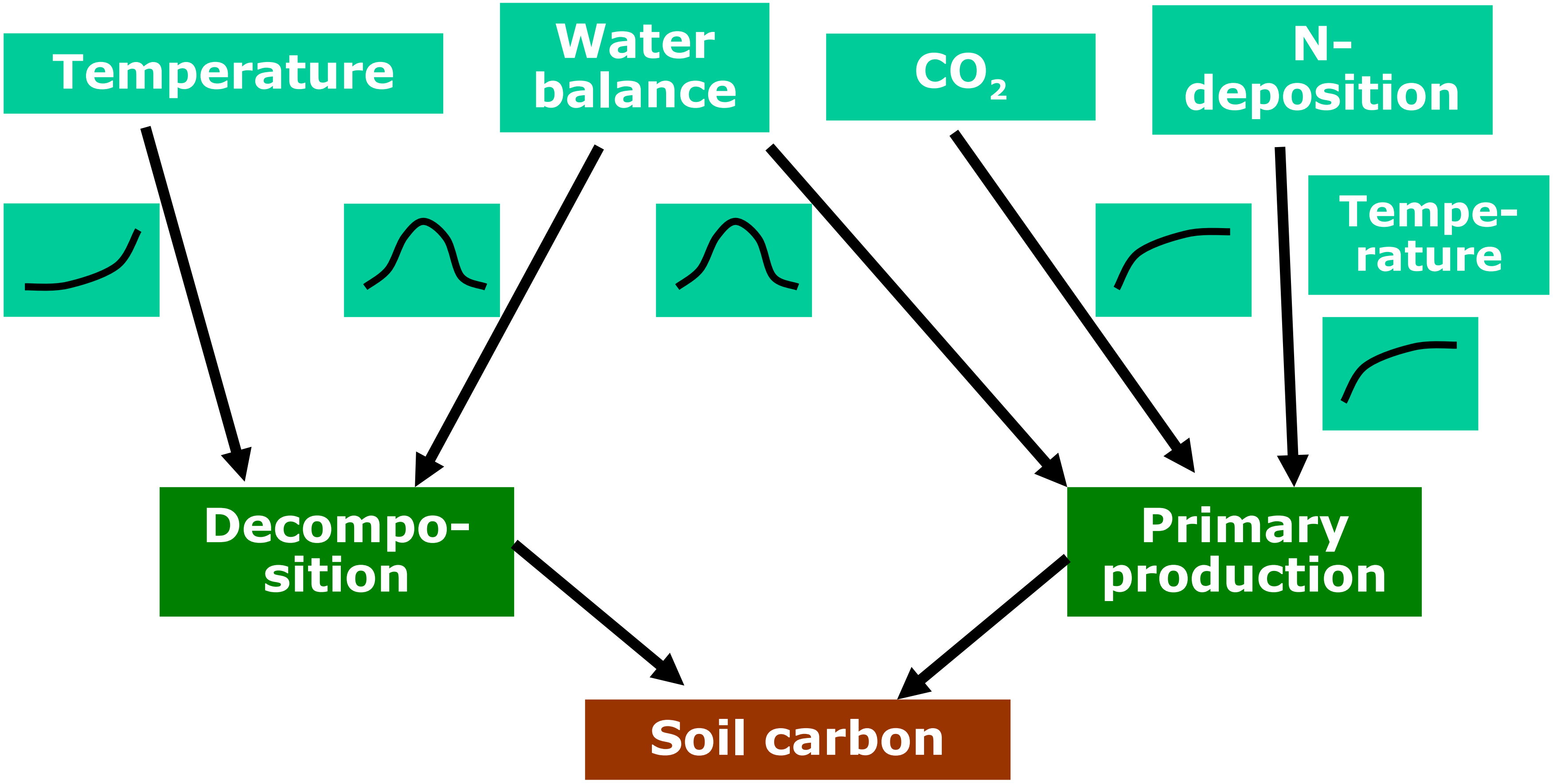


Increase in soil aridity

Extension of the growing season

Berthelot et al., 2002

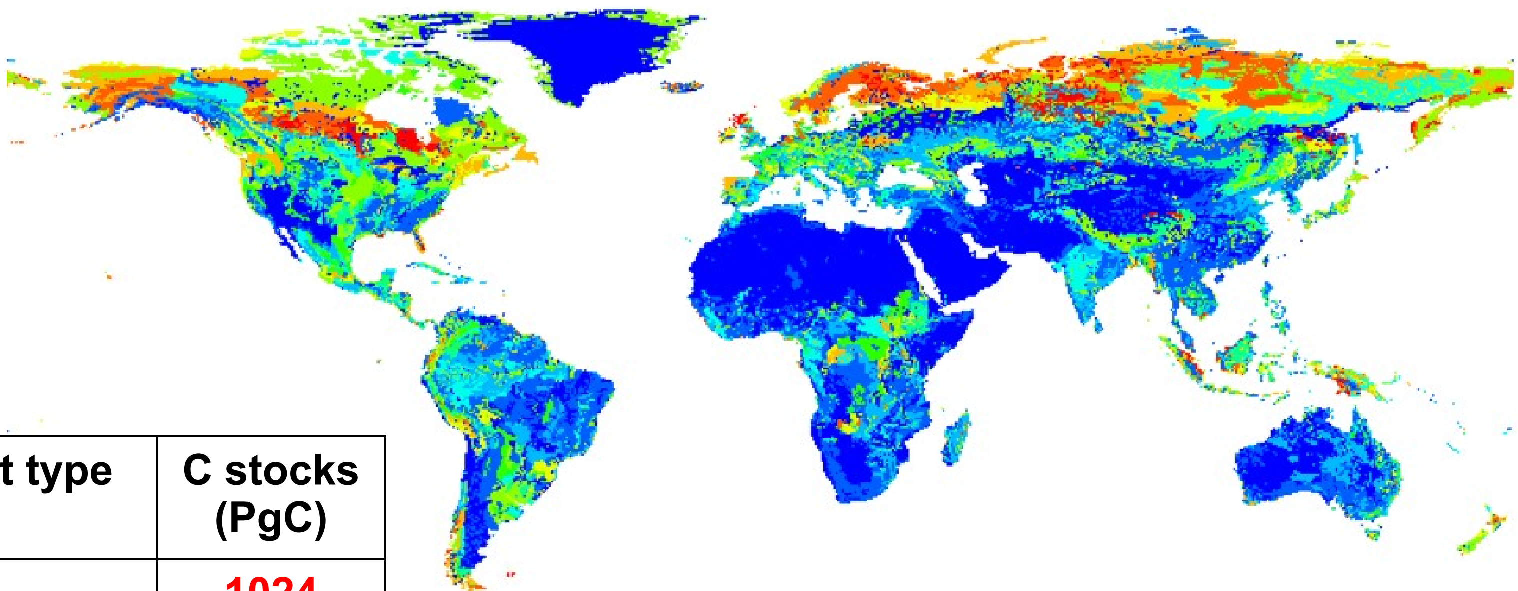
Climate factors affecting forest C balance (simplified)



Missing (or poor) representations in global models: e.g. fire

Twice the atmospheric C reservoir in permafrost region soils

- Tempting conclusion : Degassing under warming conditions
- Timescale ? Processes ?

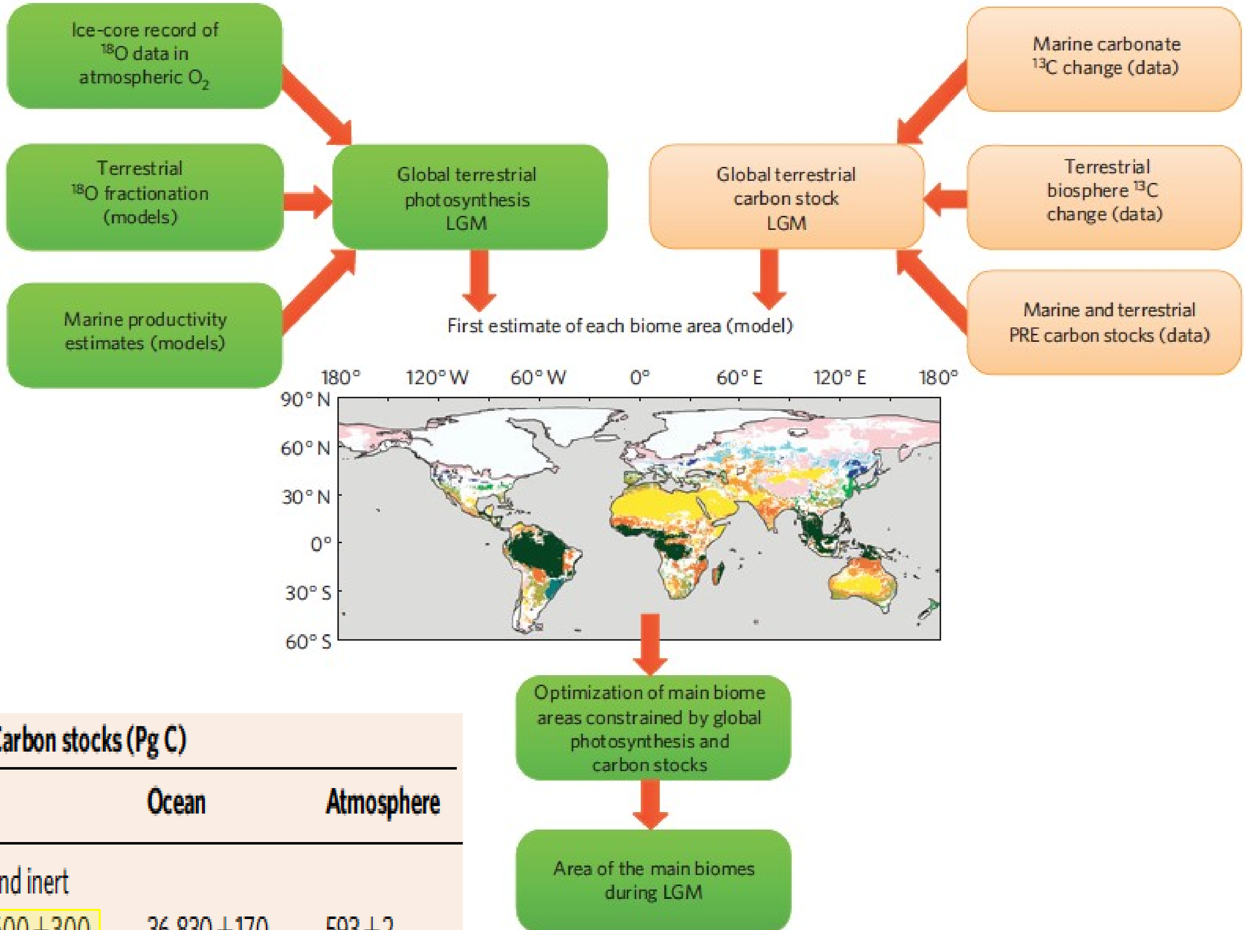


Top meter soil carbon density (IGBP-DIS)

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

Tarnocai et al., 2009

Permafrost carbon on glacial-interglacial time scales



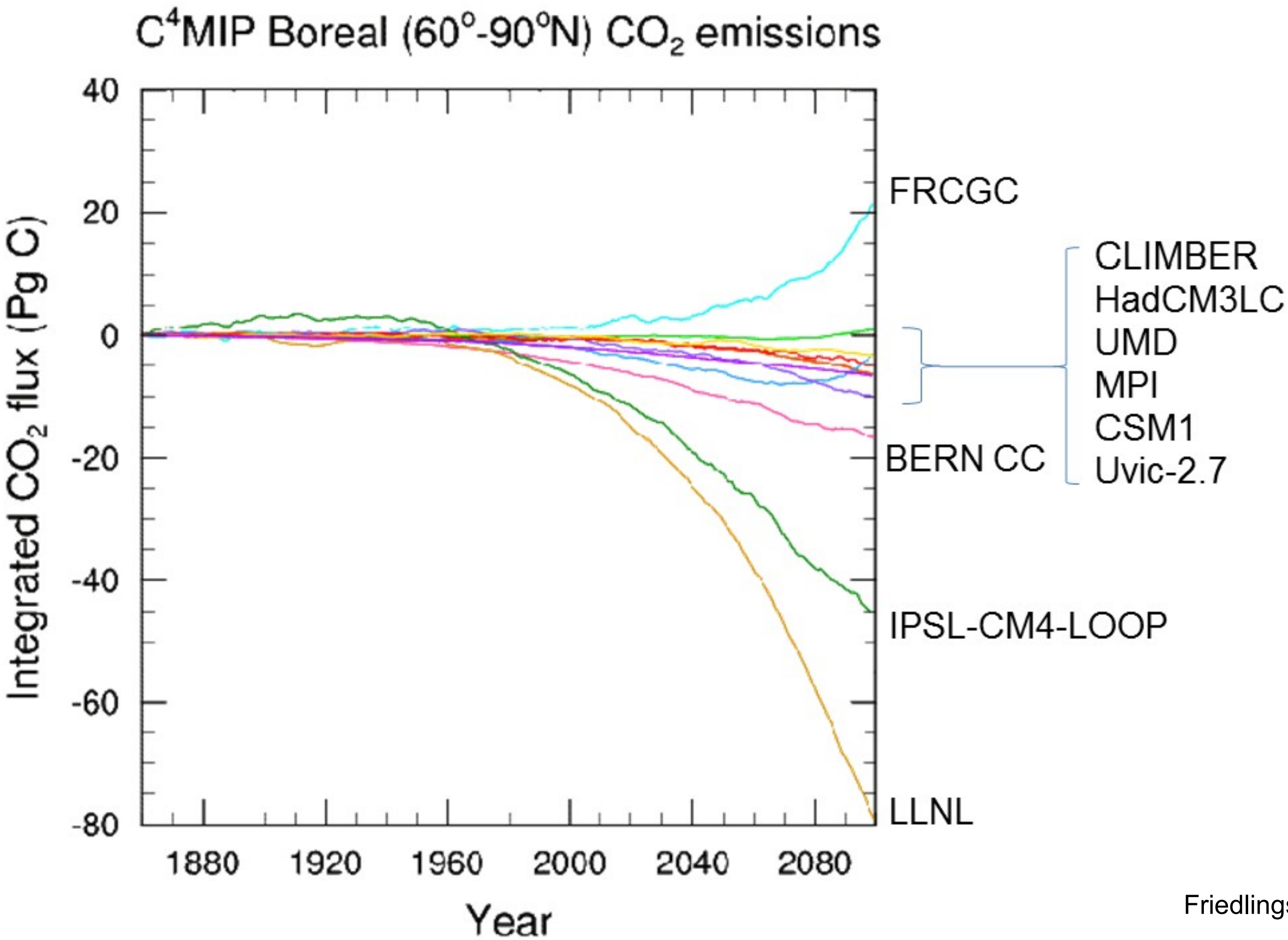
Large LGM inert terrestrial carbon pool inferred from measured air oxygen isotopes and carbon-cycle modelling: Permafrost?

Time period	Carbon stocks (Pg C)					
	Land				Ocean	Atmosphere
	Sum of:	Land active	+	Land inert		
PRE	3,970±325	2,370±125	+	1,600±300	36,830±170	593±2
LGM	3,640±400	1,340±500	+	2,300±300	37,350±400	399±2
LGM minus PRE	−330	−1,030	+	700	520	−194

Ciais et al., 2011

Representation in recent coupled carbon-climate models

Future CO_2 balance : Northern land areas = Large sink because of vegetation growth



Friedlingstein et al., 2006

Many permafrost-related processes not or poorly represented

- Soil freezing
- Impact of soil freezing on hydrology
- Thermokarst
- Peat accumulation
- Snow-vegetation interactions
- Cryoturbation
- Thermal insulation by organic surface layer
- …

In the following:

Cold region and permafrost-related processes in the ORCHIDEE land-surface model, effect on C reservoir dynamics

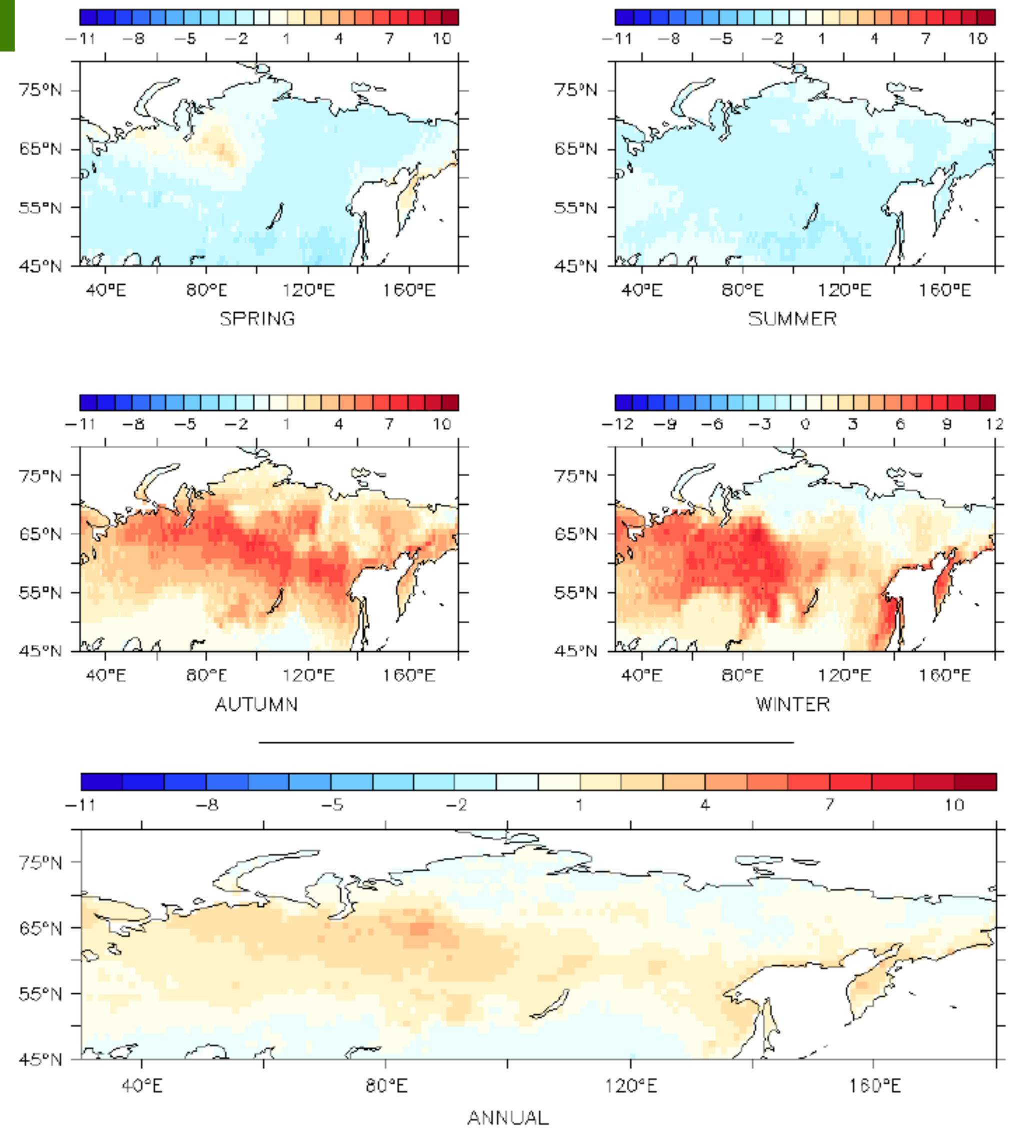
ORCHIDEE

Basic version (Krinner et al., GBC, 2005)

- Land surface component of the IPSL-CM5 coupled climate model
- IPSL-CM5: Part of current CMIP5 – IPCC climate projection exercise
- Land-surface component of an AOGCM, but also stand-alone land-surface model
- Dynamic vegetation model (LPJ)
- Carbon cycle, including soil carbon (CENTURY)

Soil hydrology and freezing

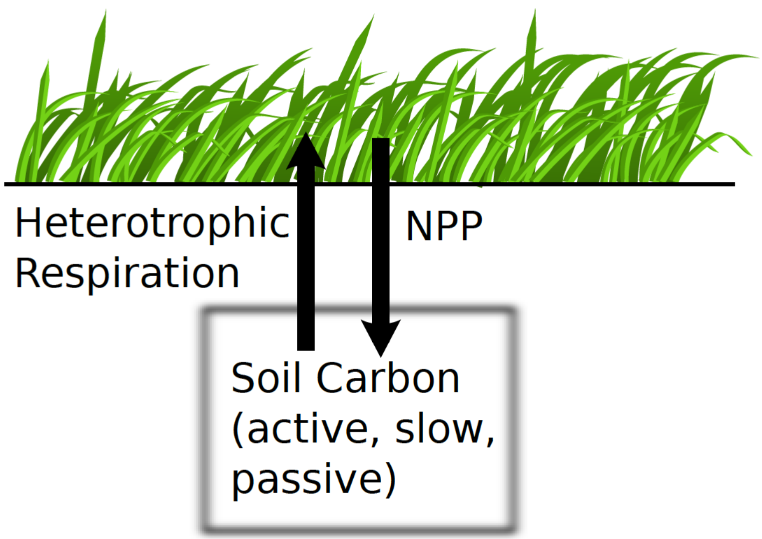
Multi-level hydrology with freezing : thermal & hydrological effects
(Gouttevin et al., The Cryosphere, submitted)

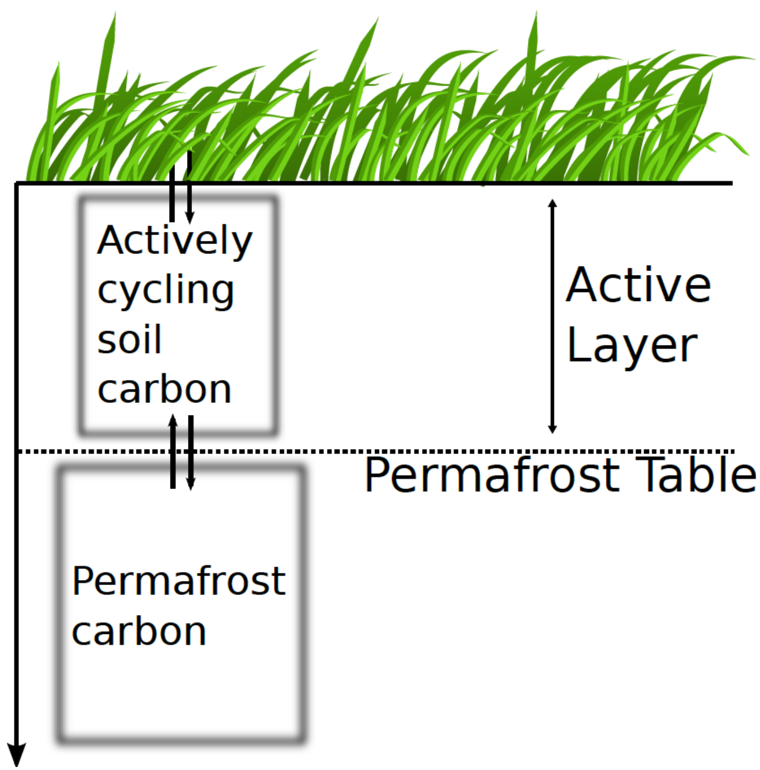


Thermal effect of soil freeze and thaw at 20 cm depth

Carbon cycle without and with soil freezing/permafrost

Active layer vs. permafrost : Part of the carbon essentially locked away





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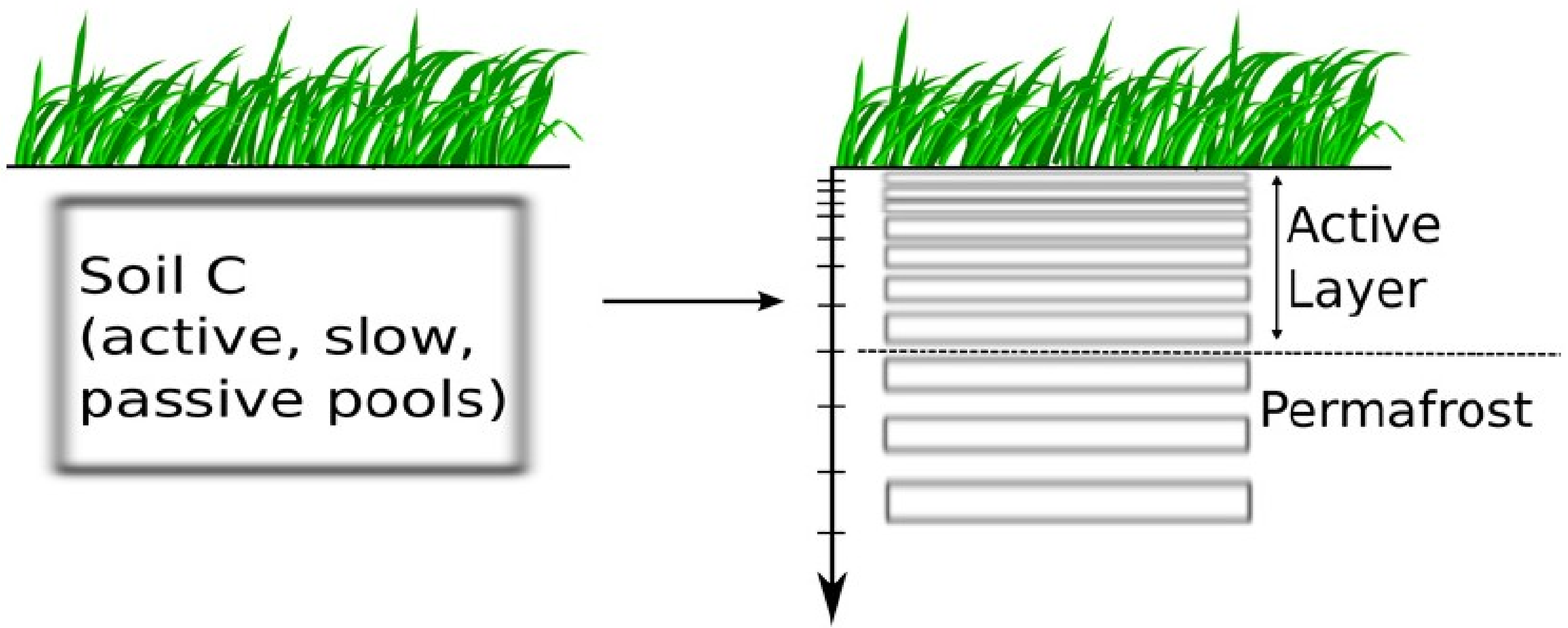
Active layer vs. permafrost : Need vertically resolved carbon distribution

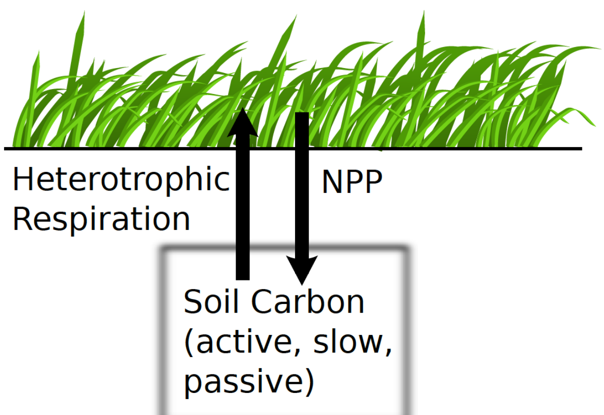


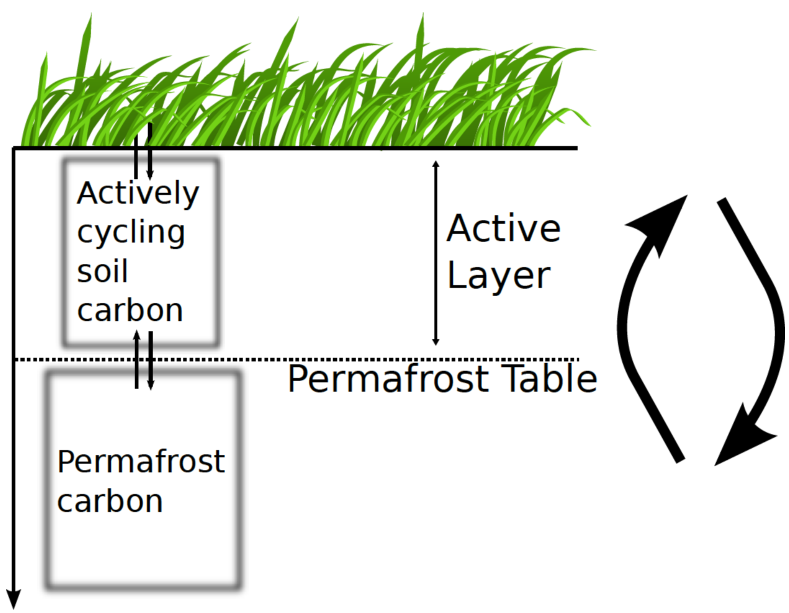
Cryoturbation

Treated by a simple diffusion scheme without advection *(Koven et al., 2009)*

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

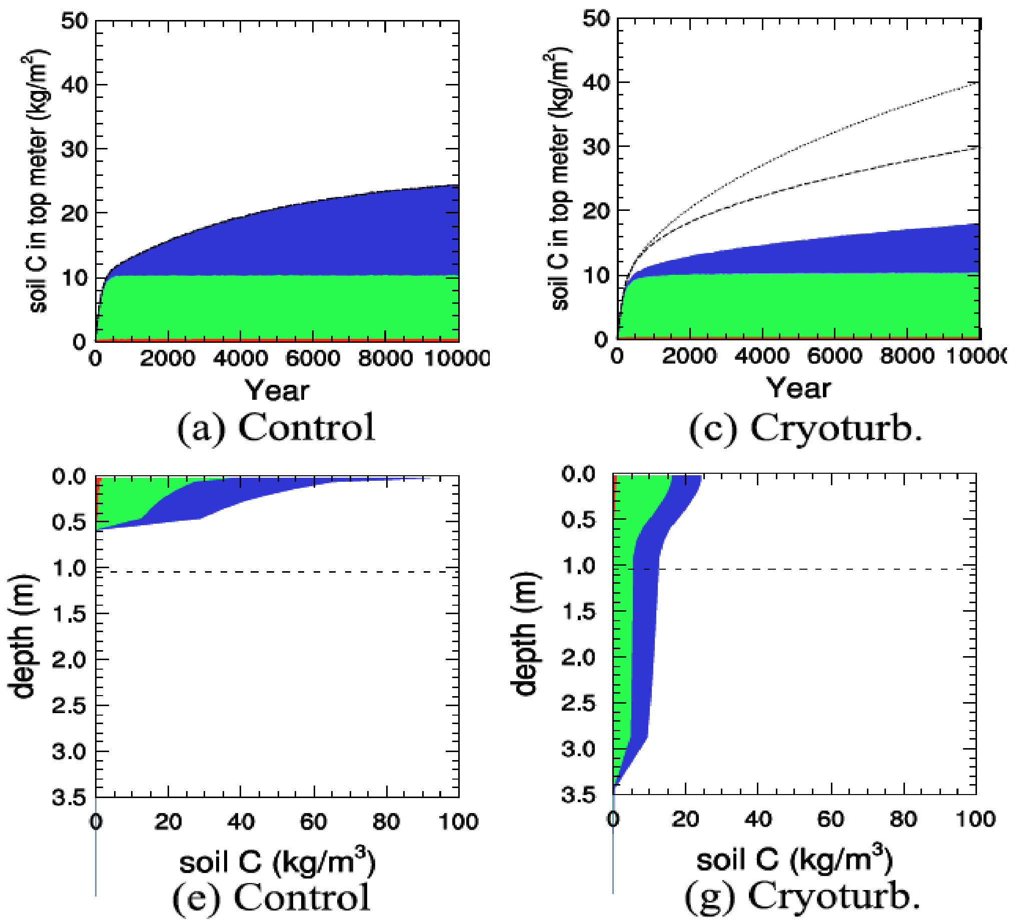
$$D = \begin{cases} D_0 & \text{for } z < z_{ALT} \\ D_0\left(1 - \left(\frac{z - z_{ALT}}{(k-1)z_{ALT}}\right)\right) & \text{for } z_{ALT} < z < kz_{ALT} \\ 0 & \text{for } z > kz_{ALT} \end{cases}$$





Effect of cryoturbation on simulated soil carbon at Tcherskii

Carbon content in top m decreases, buried below

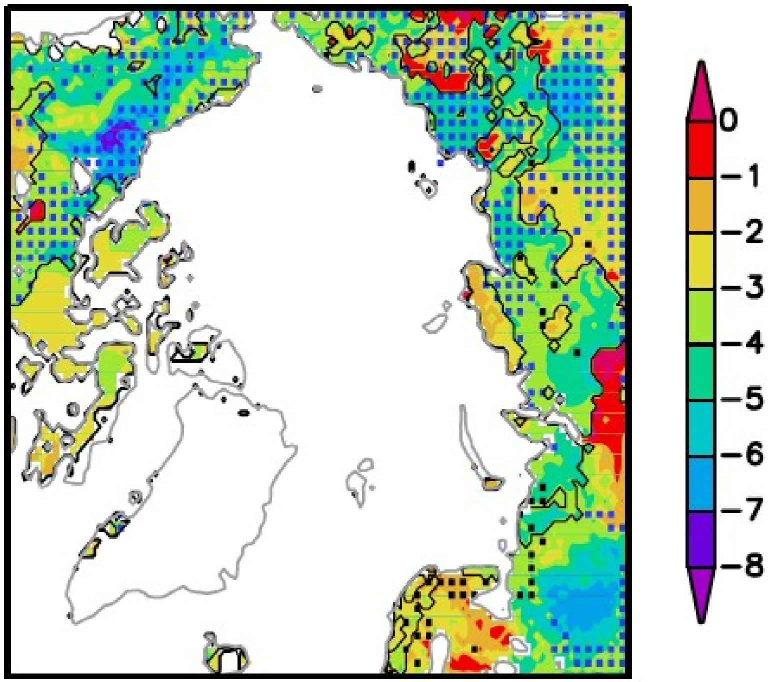


(Koven et al., GRL, 2009)

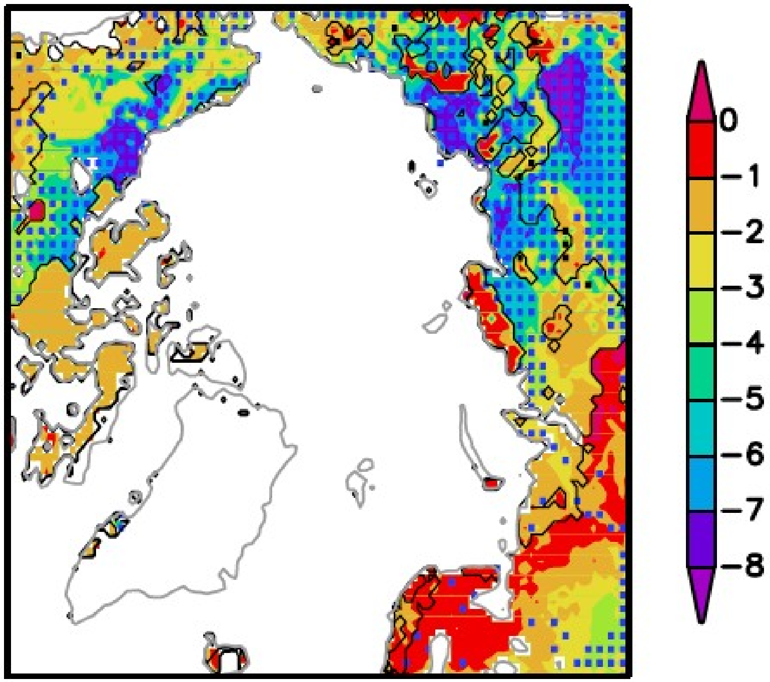
Thermal insulation by organic surface layer

Strong effect on soil thermal profiles shown before : dampening of the annual temperature cycle below the surface

TG at 50cm, summer



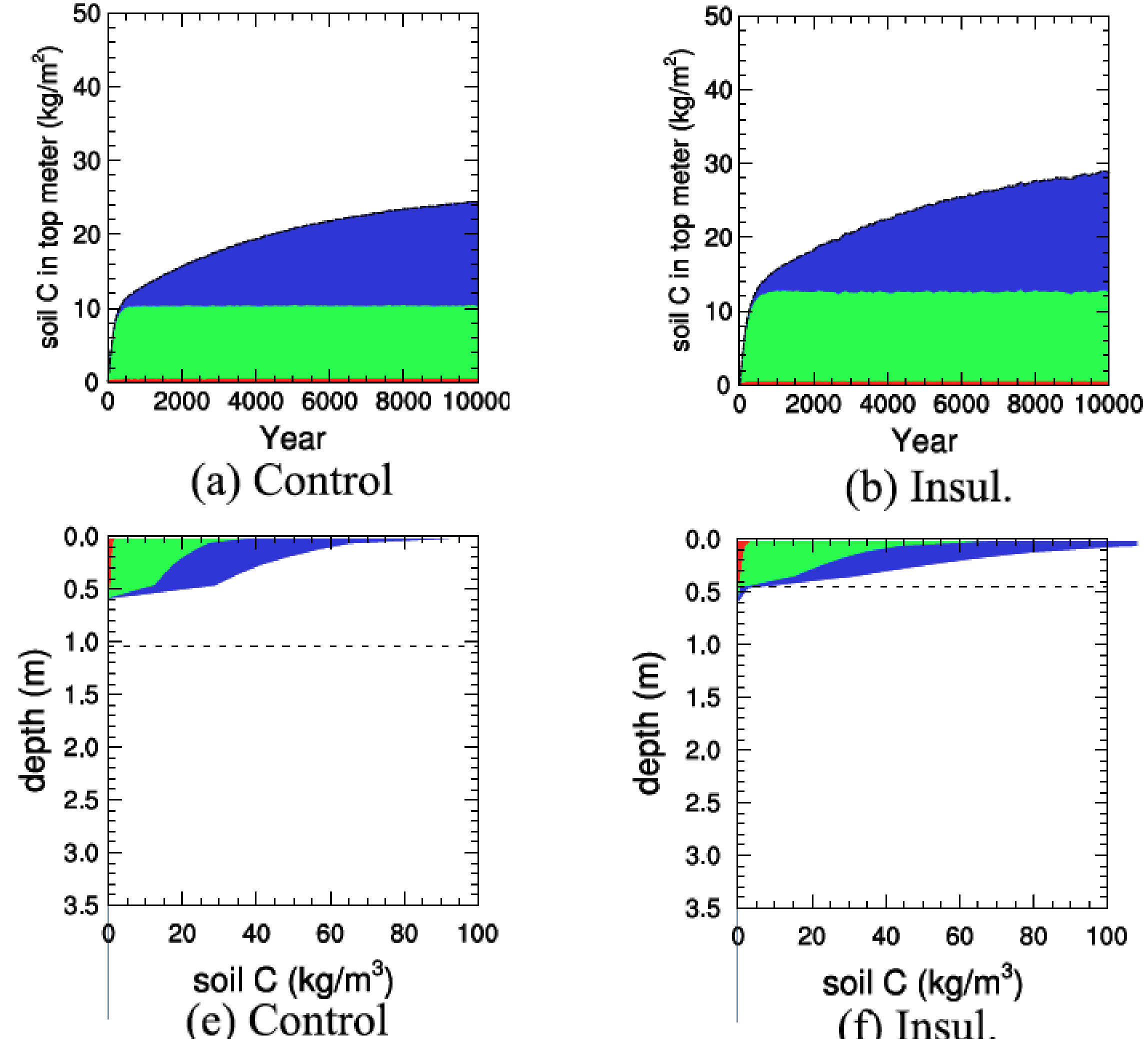
TG at 230cm, summer



(Rinke et al., GRL, 2008)

Effect of thermal insulation on simulated soil carbon at Tcherskii

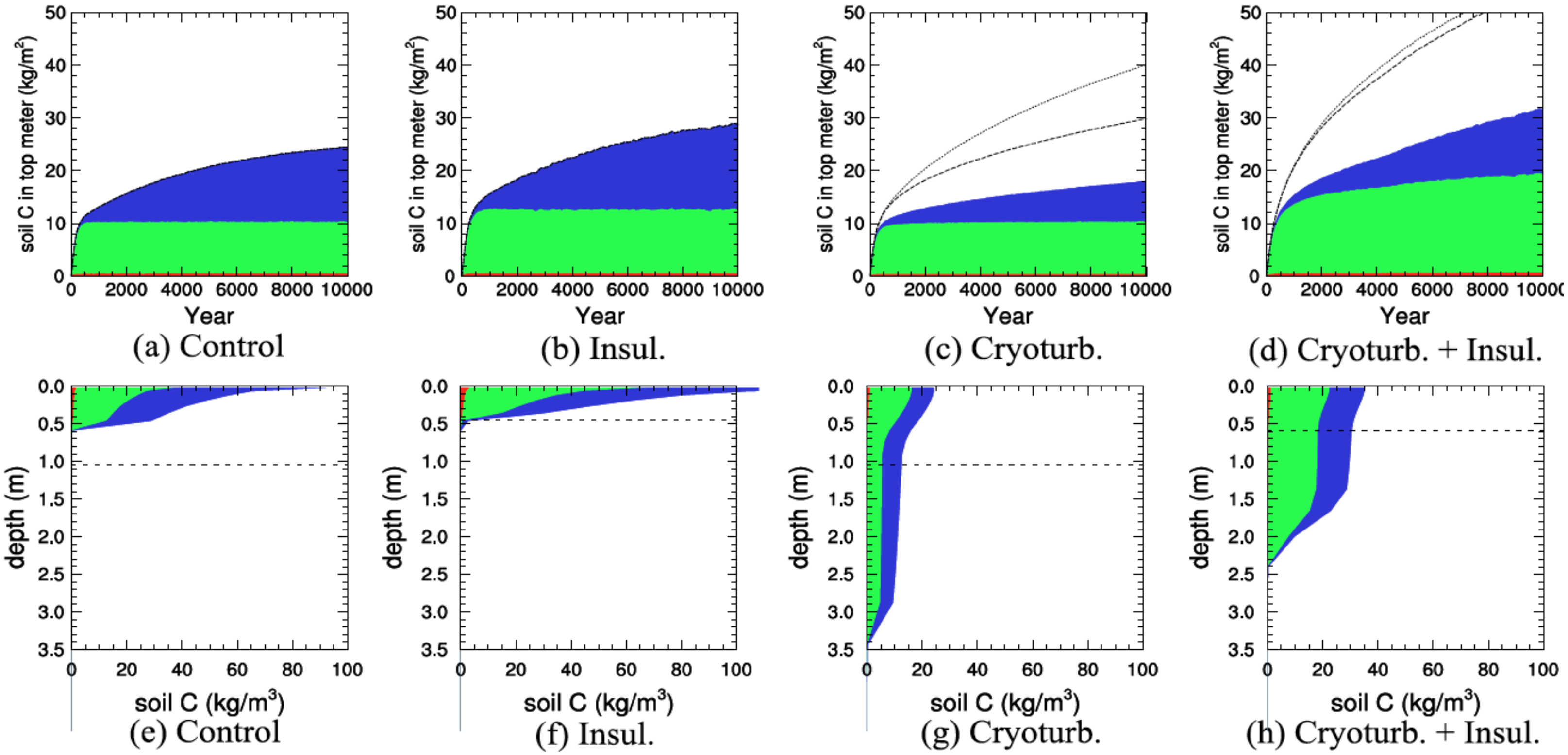
Cooler soil in summer : slower decomposition



(Koven et al., GRL, 2009)

Cryoturbation + thermal insulation

- Positive feedback: more soil carbon, more insulation
- Even top m not in equilibrium after 10000 years



(Koven et al., GRL, 2009)

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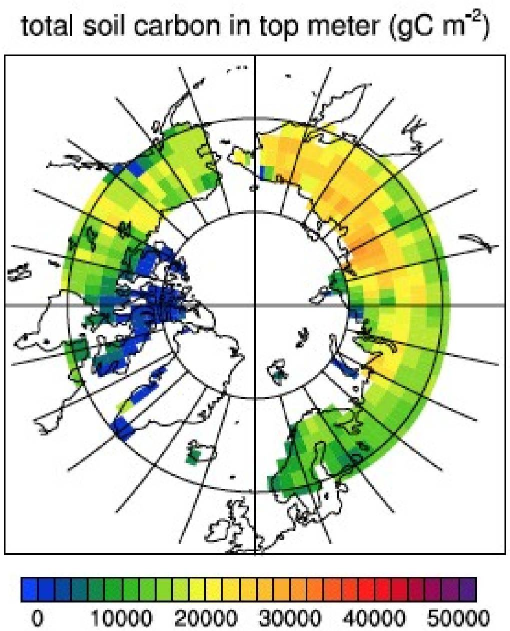
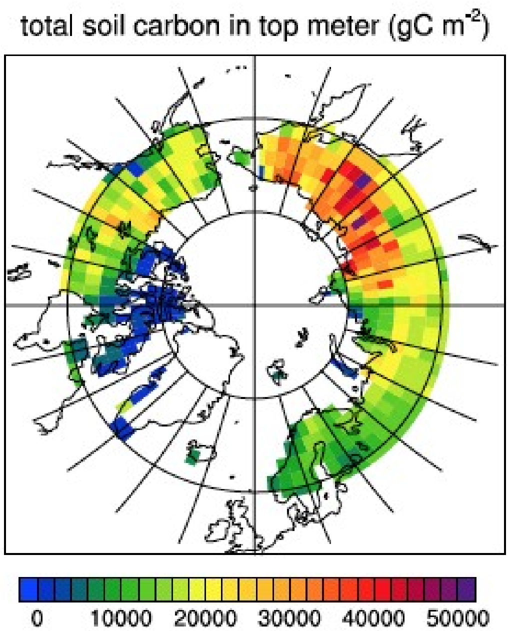
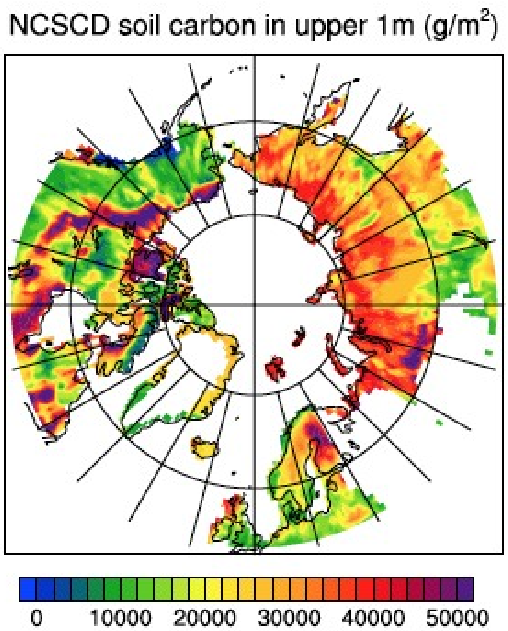
Better simulation of top m organic soil carbon after 10000 yrs spinup



(a) ORCHIDEE control SOM

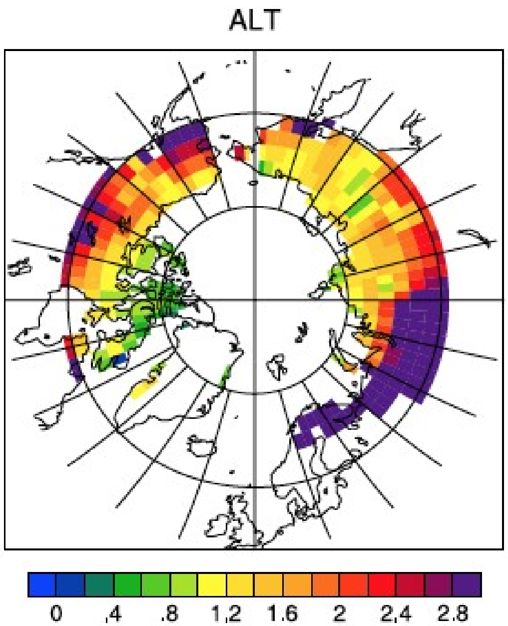


(b) ORCHIDEE exp. SOM

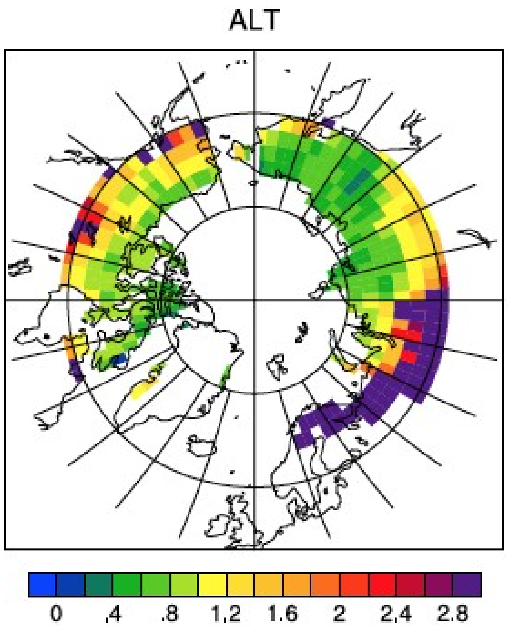


(c) NCSCD SOM

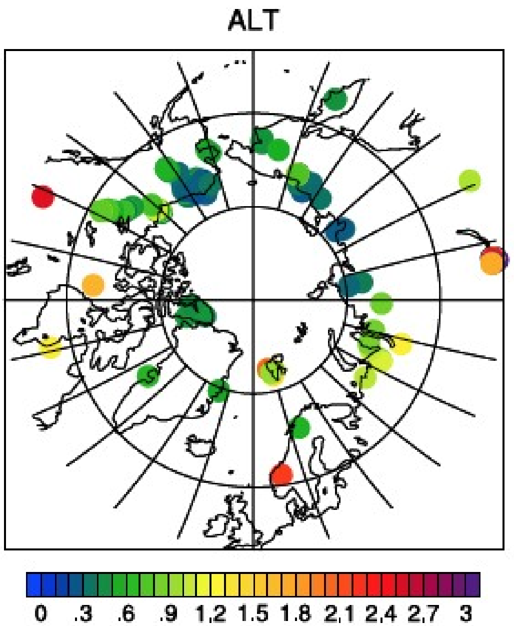
Better simulation of active layer thickness



(e) ORCHIDEE control ALT



(f) ORCHIDEE exp. ALT

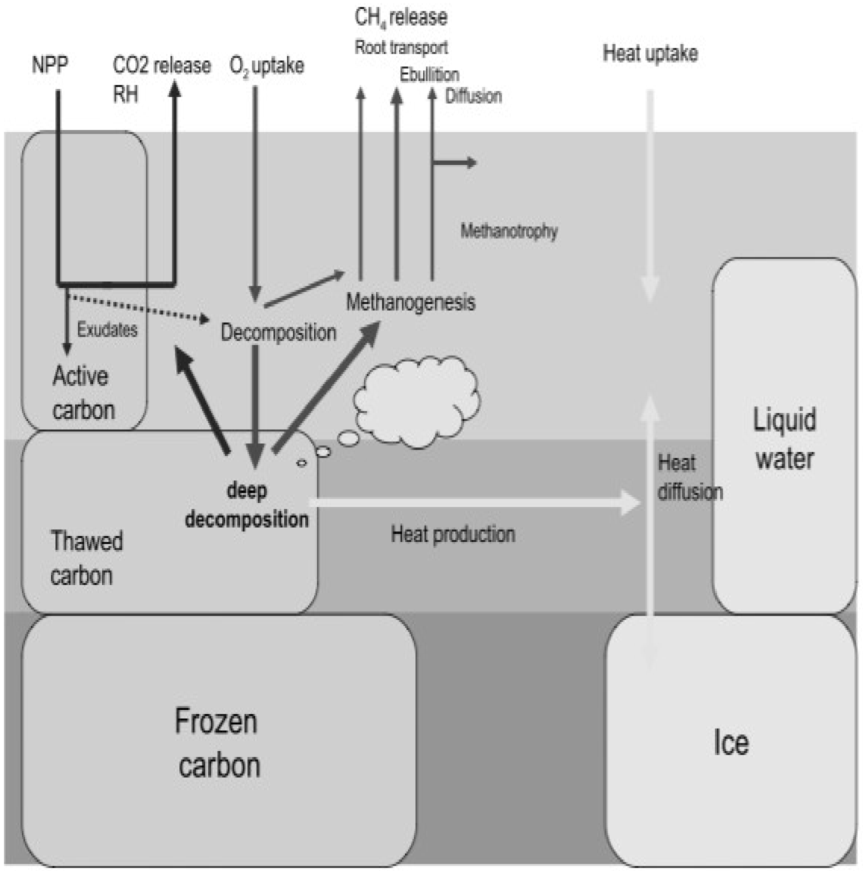


(g) CALM active layer thickness

Microbial heat generation

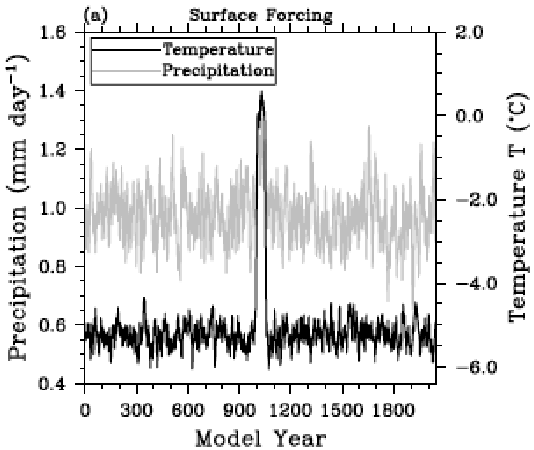
"Compost bomb" ? Positive feedback between soil temperature and microbial activity

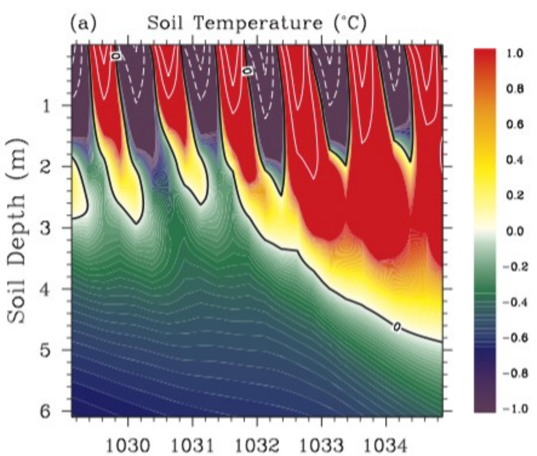
Condition : Heat in deep soil generated more quickly than heat diffuses vertically, very high carbon content

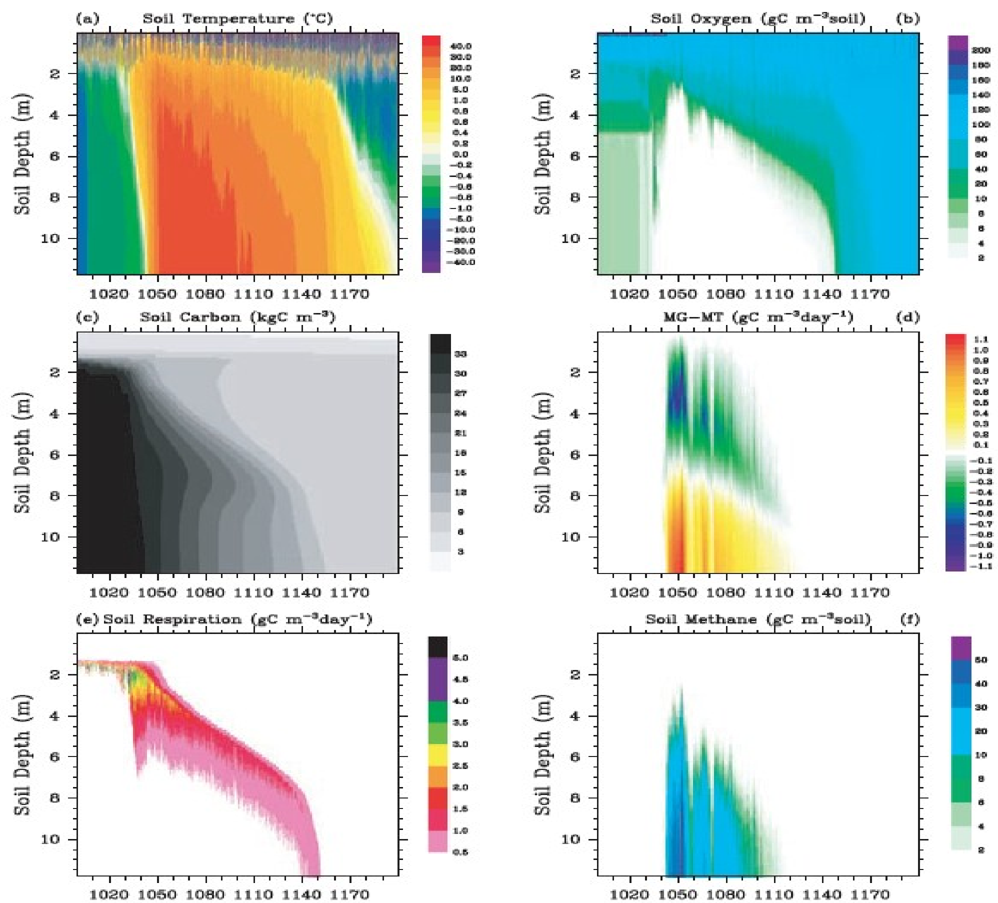


S. Zimov in front of a Yedoma section near the Kolyma river

(Khvorostiyanov et al., Tellus 2008a,b; GRL 2008c)







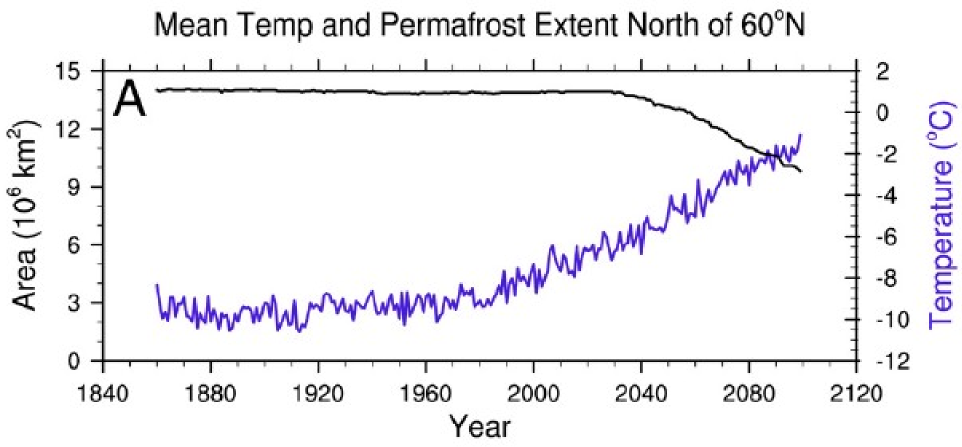
(Khvorostiyanov et al., Tellus 2008a)

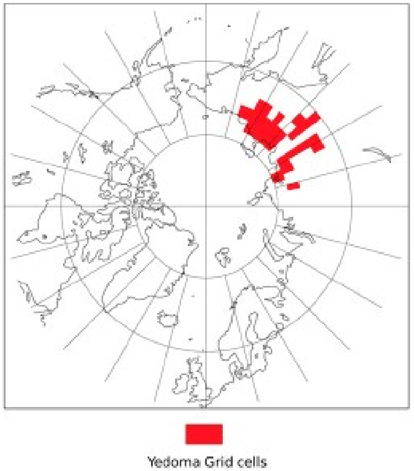
Yedoma : 2 GT/yr during 100 yrs in extreme (unrealistic) warming scenario

Possible neglected limitation: nutrient availability

Projections of the 21st century boreal carbon balance

- Different soil freezing/permafrost processes activated
- Topmodel and methane emission model for CH_4 fluxes from wetlands *(Beven and Kirkby, 1979; Walter et al., 2001; Ringeval et al., 2010)*
- 10,000 yrs initialization with 20th century climate
- Yedoma: initialized with estimated present carbon density prior to 10,000 yr spinup
- Suppose SRES A2 scenario warming from IPSL-CM4 CMIP4 run
- Anomaly method used

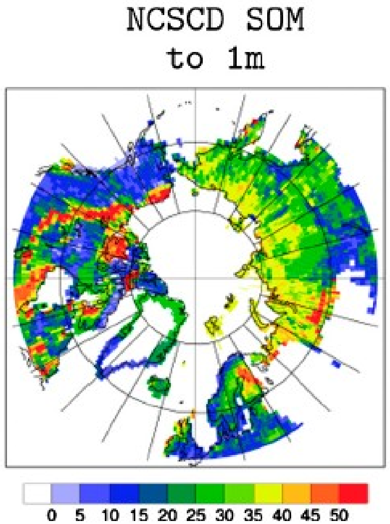


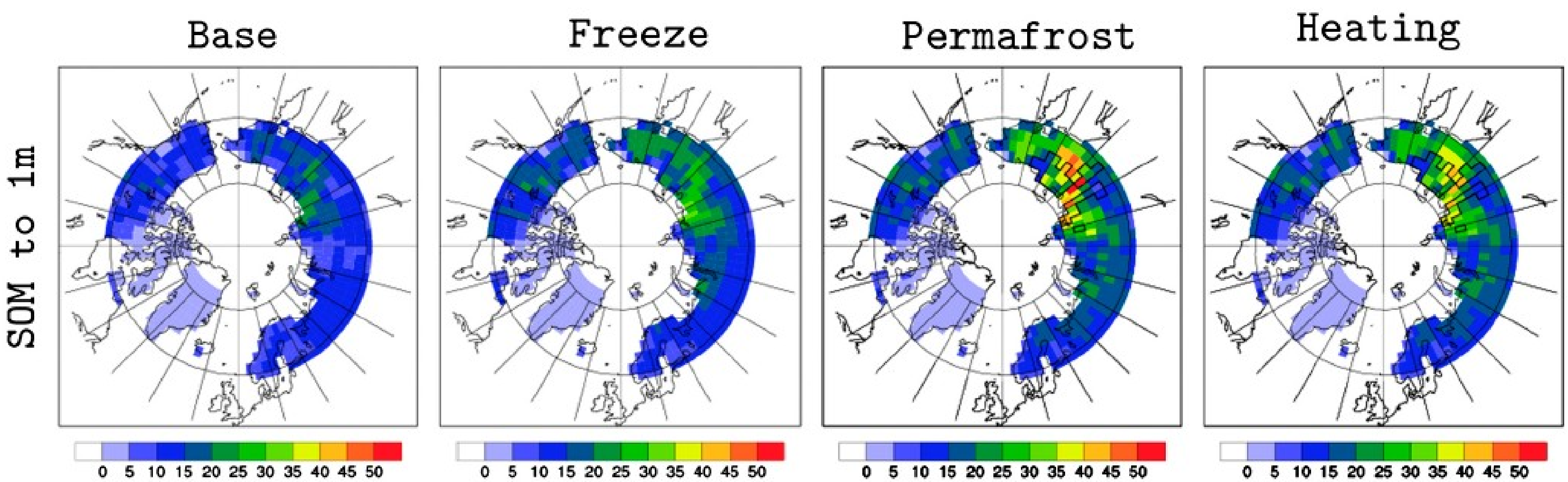


(Koven et al., PNAS, 2011)

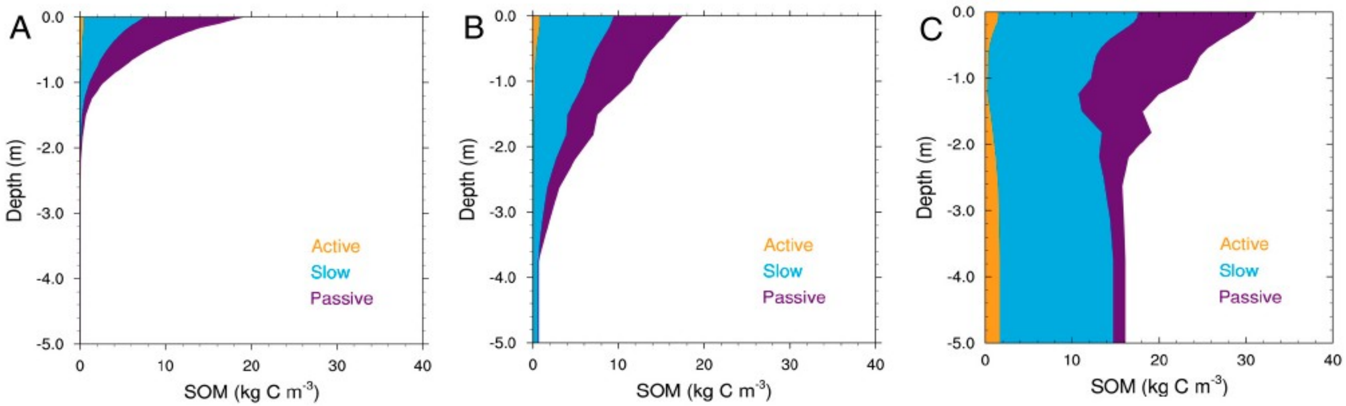
Experiments

- Base : No permafrost
- Freeze = Base + Frozen soil carbon
- Permafrost = Freeze + permafrost-specific processes (cryoturbation, insulation)
- Heat = Permafrost + Microbial heating





Simulated average soil carbon profile



Freeze case, permafrost grid cells

Permafrost case, permafrost grid cells

Permafrost case, Yedoma grid cells

Experiments :

- Base : No permafrost
- Freeze = Base + Frozen soil carbon
- Permafrost = Freeze + permafrost-specific processes (cryoturbation, insulation)
- Heat = Permafrost + Microbial heating

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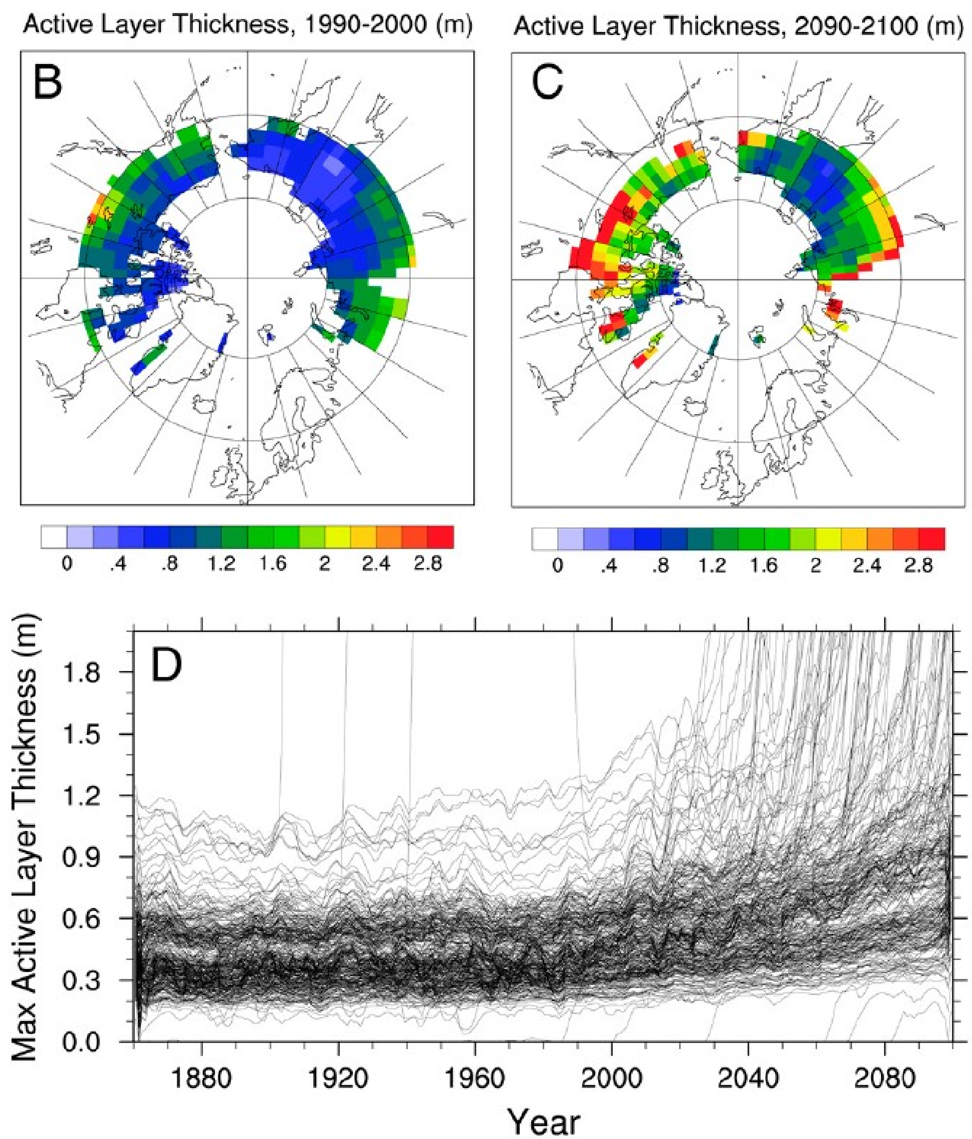
Simulated permafrost changes



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Simulated carbon fluxes

- Change from sink to source during the 21[st] century when permafrost processes are taken into account
- Difference between Permafrost and Control simulation at the of the 21[st] century: 61 PgC

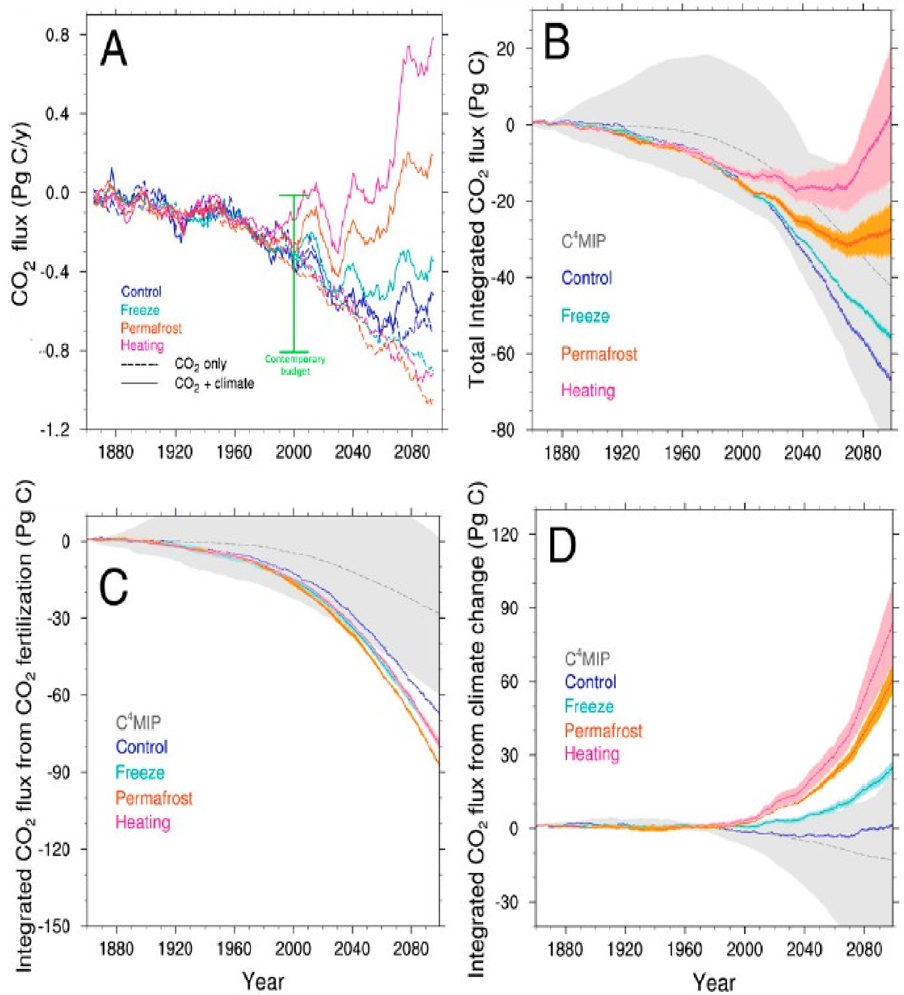
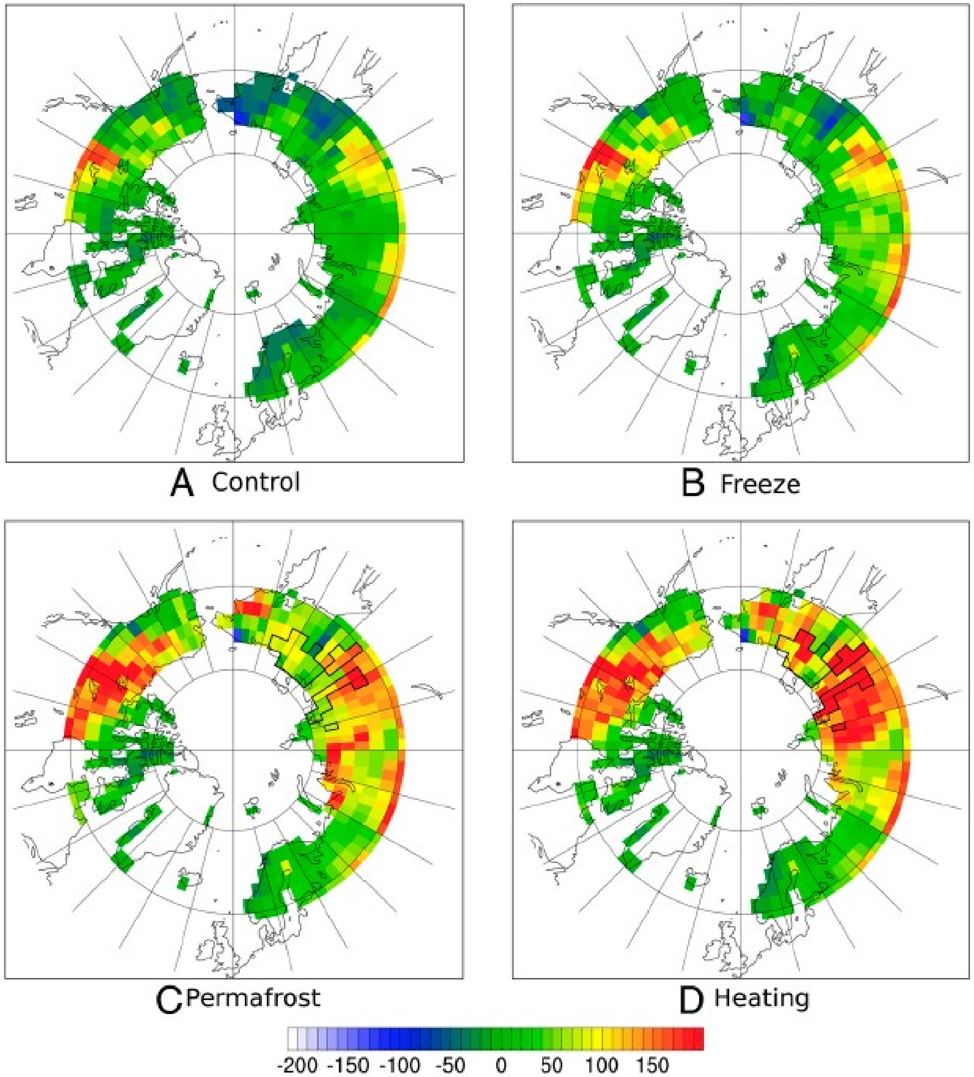


Fig. 2. Change in carbon fluxes over the model run. (*A*) Mean fluxes over modeled period. Contemporary budget estimate from McGuire et al. (1) (*B*) integrated changes. (*C*) Integrated changes in carbon balance due to rising CO_2 concentration alone. (*D*) Integrated change in carbon balance due to climate change alone (difference between CO_2-only and CO_2+climate change).

Large fluxes from Yedoma area if microbial heating is taken into account

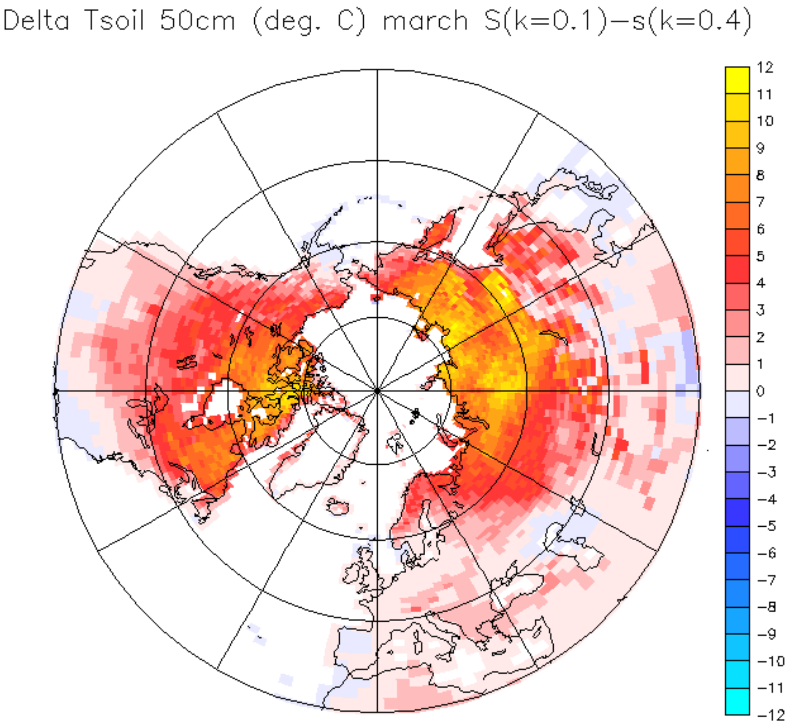


Net CO_2 fluxes due to climate change at the end of the 21st century, gC/m²/yr

Snow - soil carbon interactions: thermal insulation

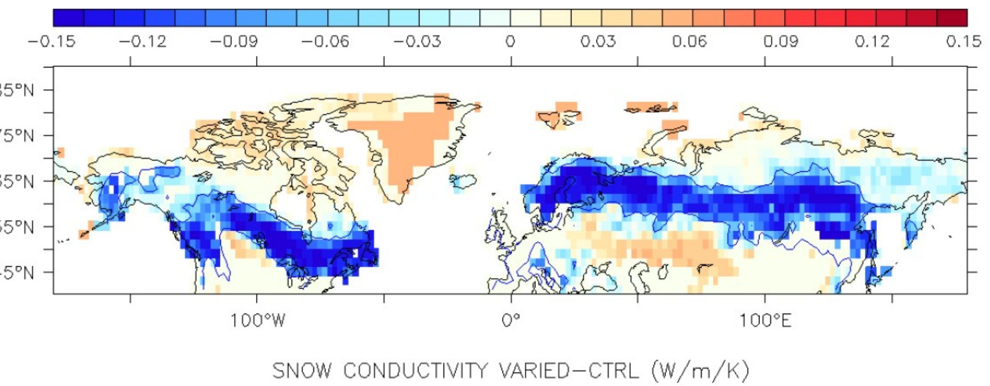
Taiga snow conductivity observed : k=~0.1 $W.m^{-1}.K^{-1}$

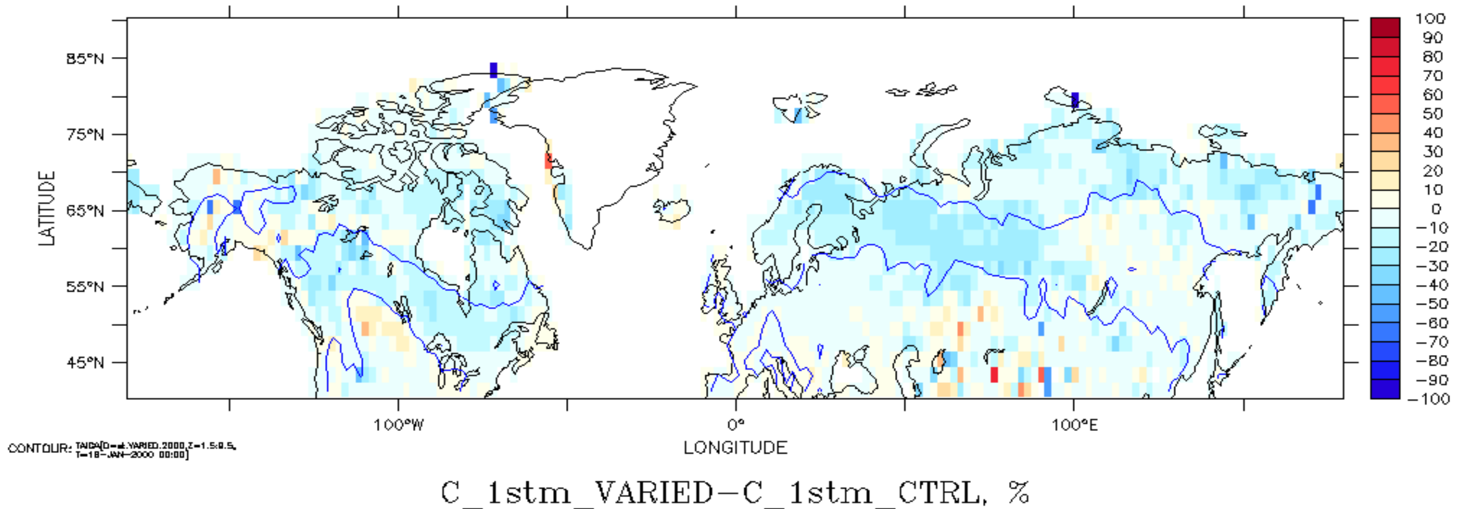
Tundra snow conductivity observed : k=~0.3 to 0.4 $W.m^{-1}.K^{-1}$



50 cm depth soil temperature difference between two simulations performed with k=0.1 and k=0.4

Lower snow conductivity prescribed in the boreal forest





Consequence: Less soil carbon in the boreal forest belt

(Gouttevin, Menegoz et al., JGR, submitted)