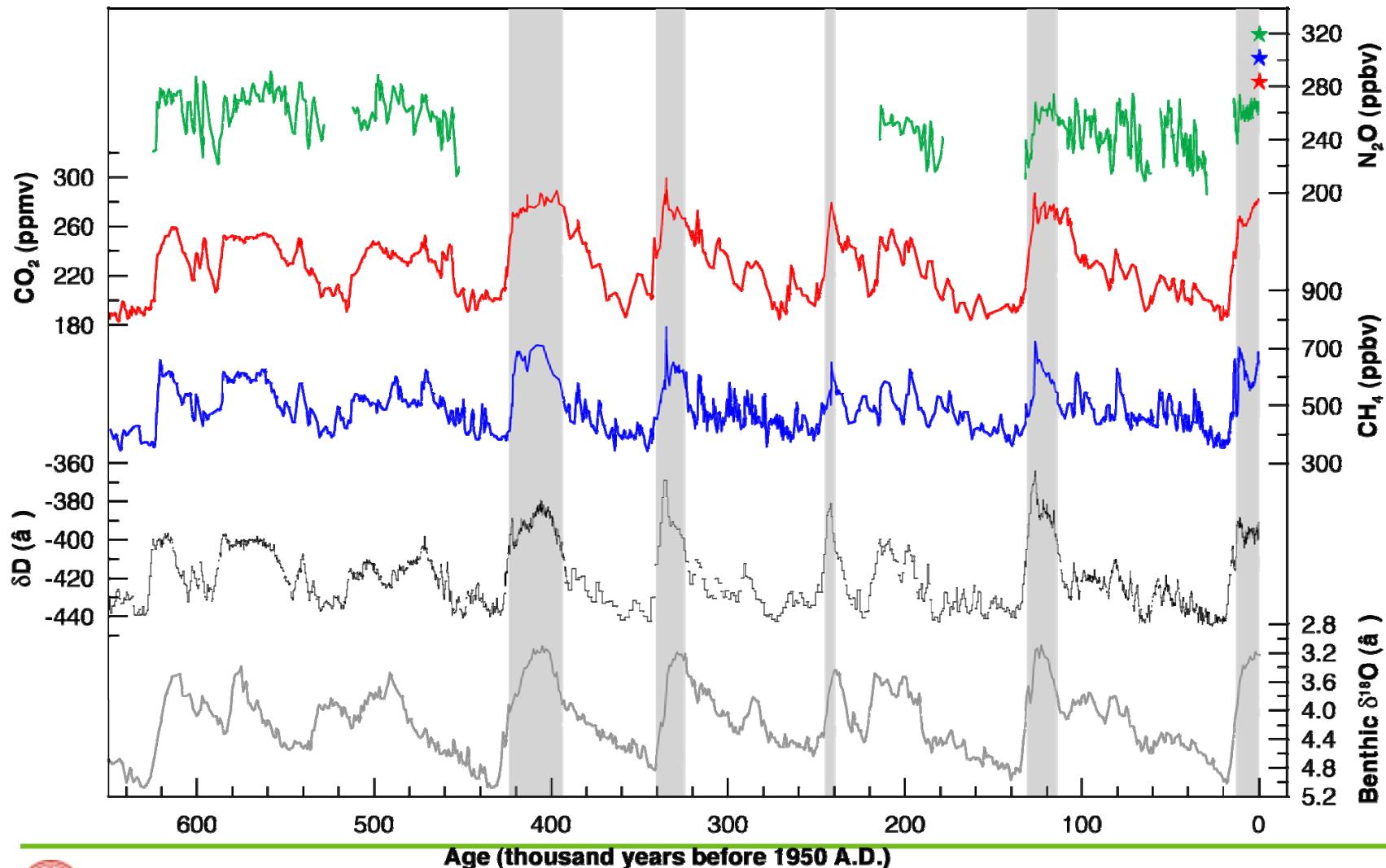

Carbon-climate feedbacks in the 21st century

Philippe Ciais

LSCE, Gif sur Yvette



The carbon cycle is coupled with the natural variations of climate

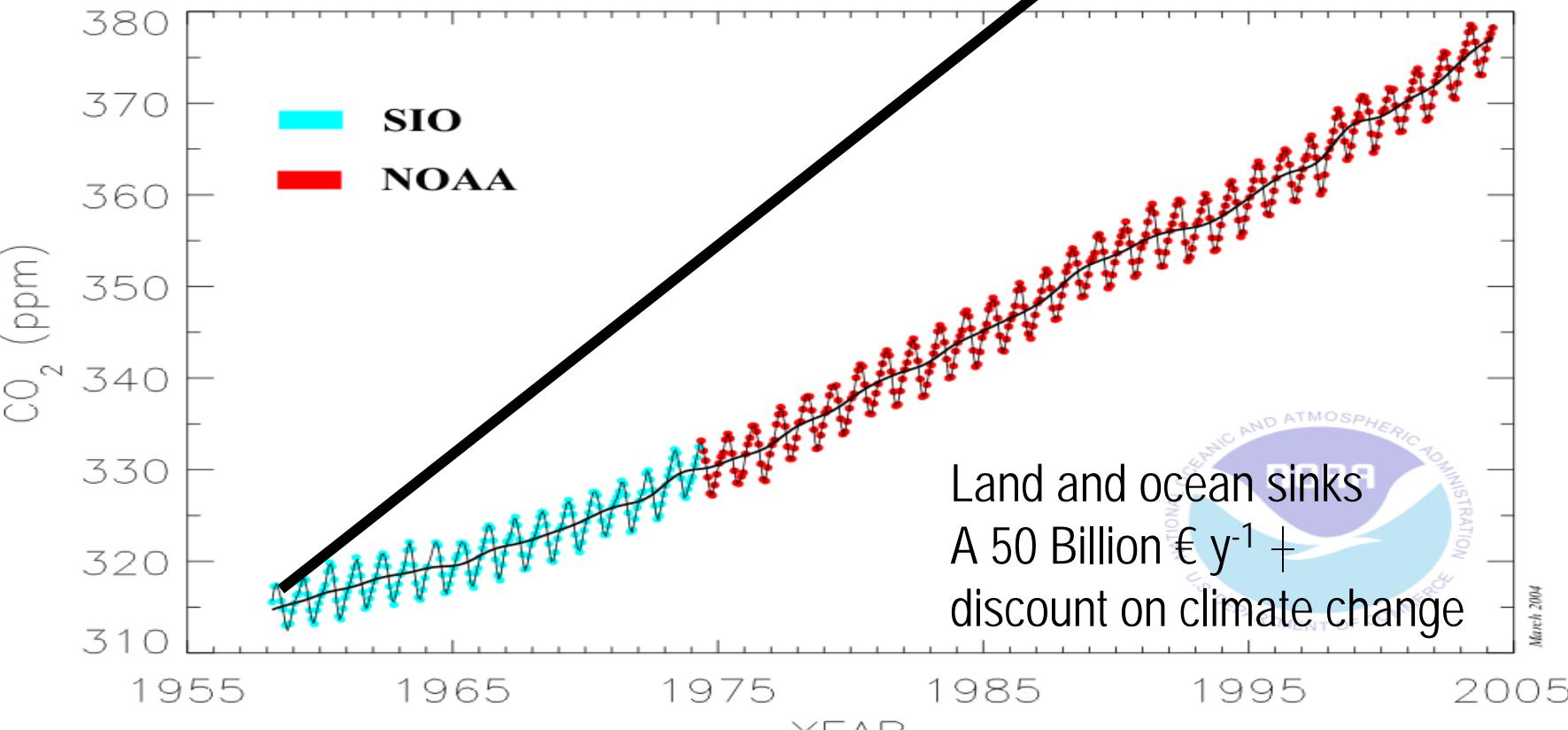


During the anthropocene, the carbon cycle is driven by fossil fuel emissions, and improved by sinks



The Earth
without
carbon
cycle

Mauna Loa Monthly Mean Carbon Dioxide



The Human Perturbation of the CO₂ Budget (2000-2009)

$7.7 \pm 0.5 \text{ PgC y}^{-1}$



$1.1 \pm 0.7 \text{ PgC y}^{-1}$ +



$4.1 \pm 0.1 \text{ PgC y}^{-1}$

47%



2.4 PgC y^{-1}

27%

Calculated as the residual

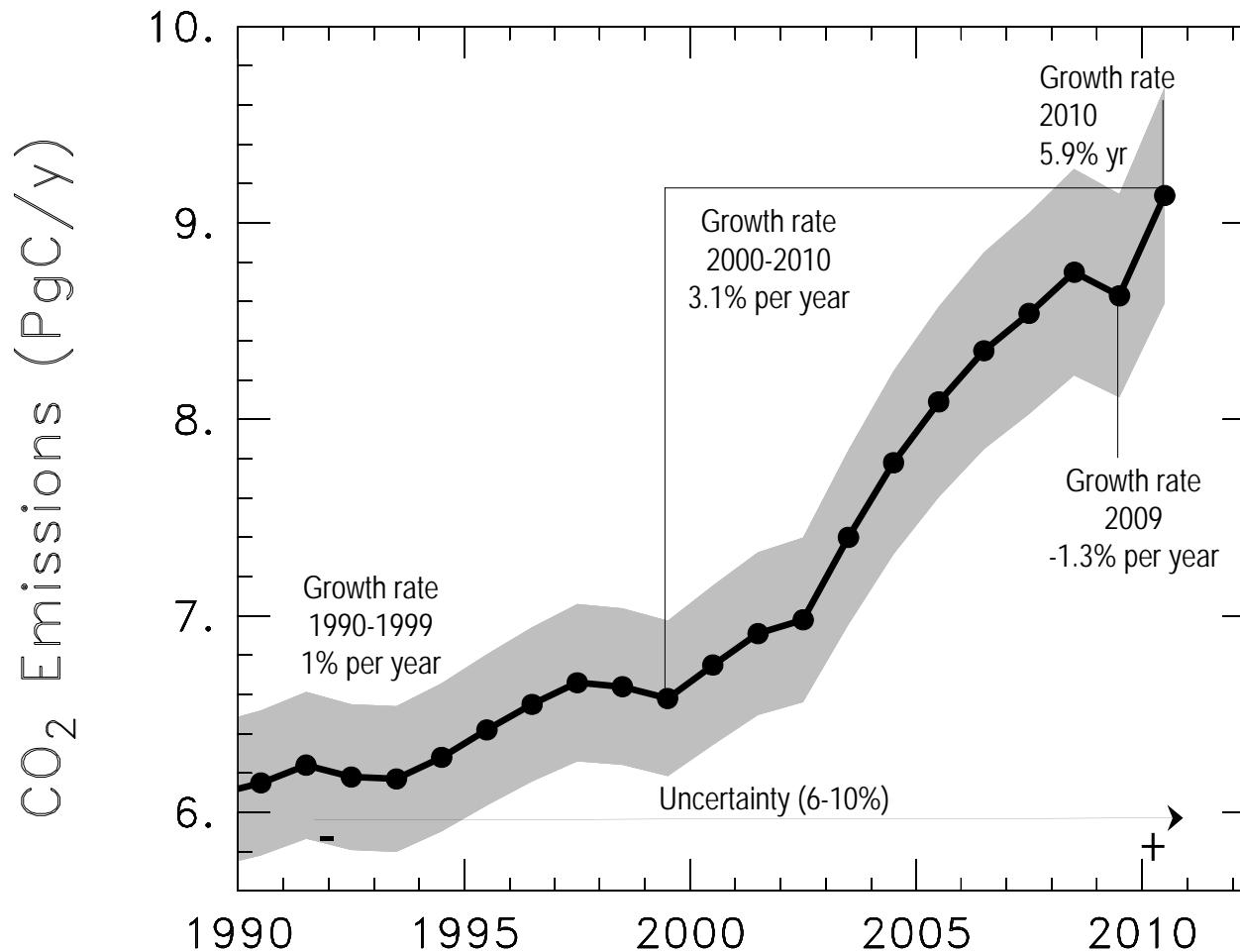


26%

$2.3 \pm 0.4 \text{ PgC y}^{-1}$

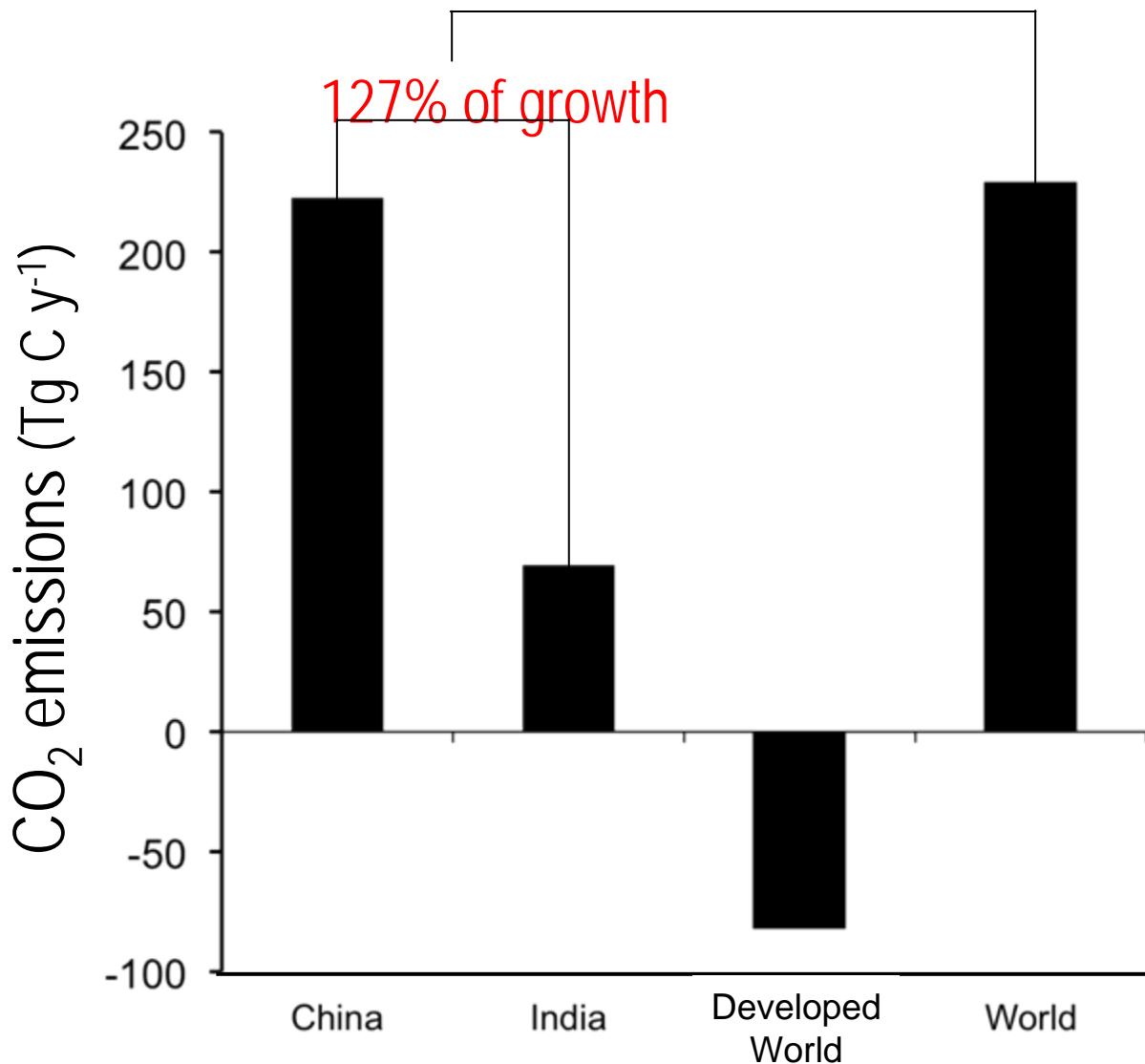


Fossil Fuel & Cement CO₂ Emissions

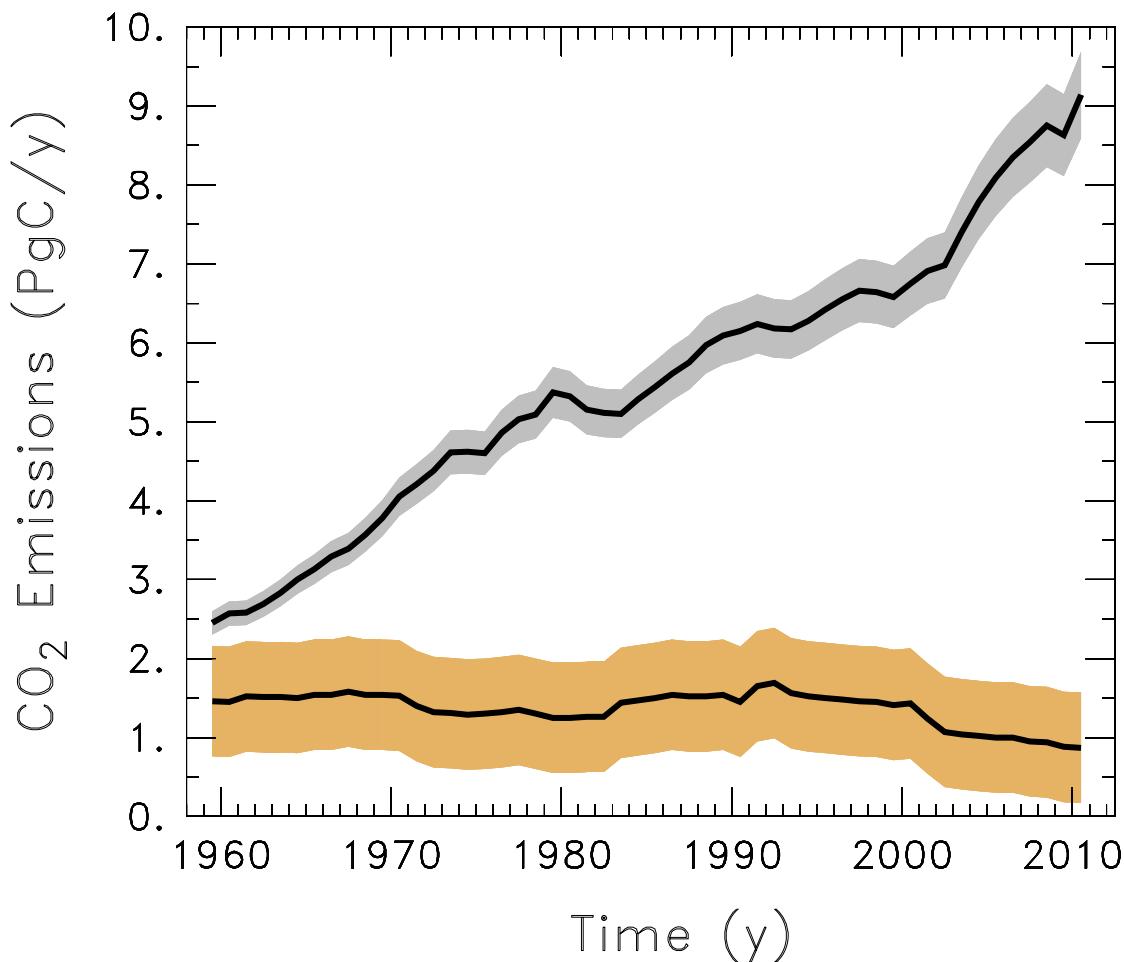


Fossil fuel emissions is an increasing forcing of the carbon cycle

Change in CO₂ Emissions from Coal (2008 to 2010)



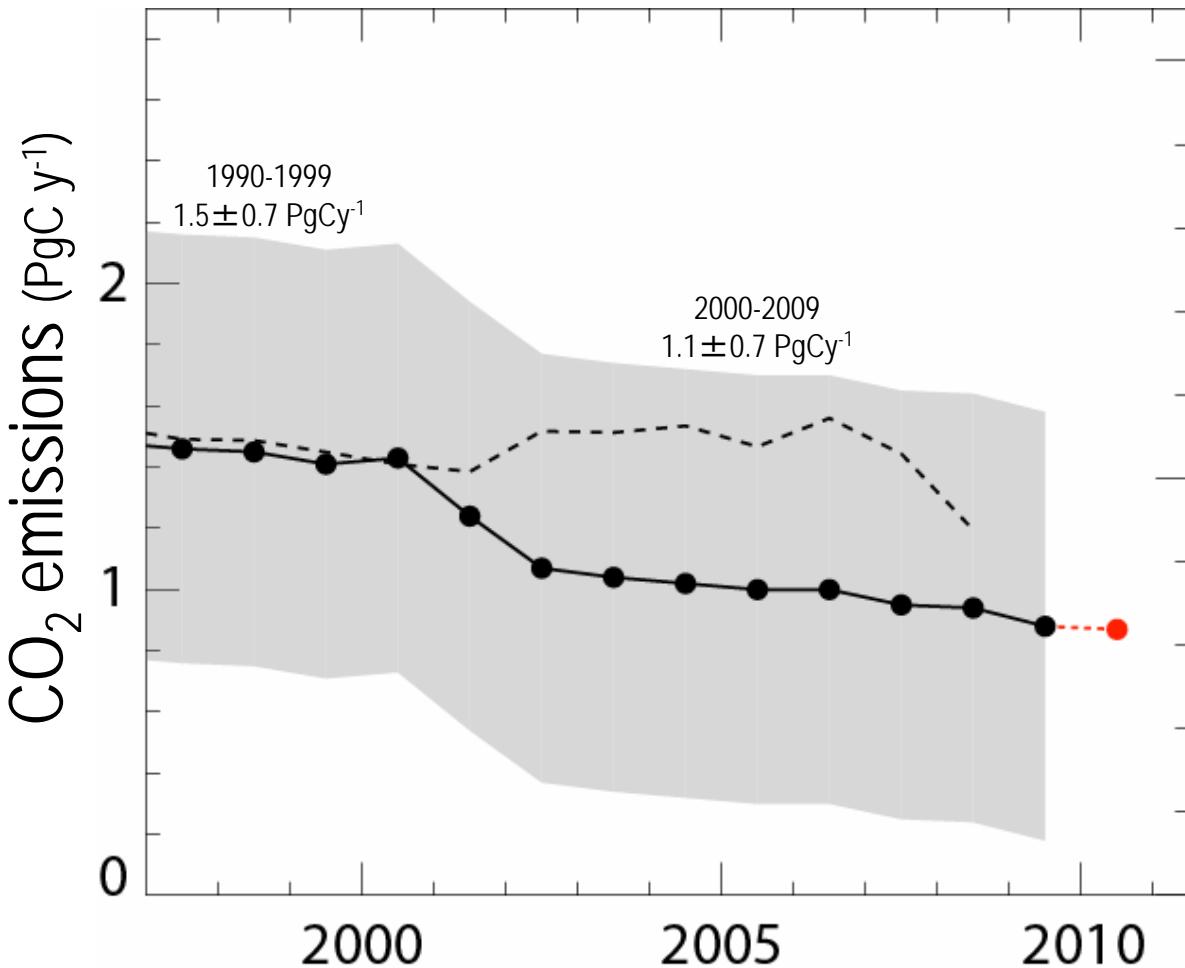
CO_2 Emissions from FF and LUC (1960-2010)



Current LUC emissions
~10% of total CO₂ emissions



CO₂ Emissions from Land Use Change



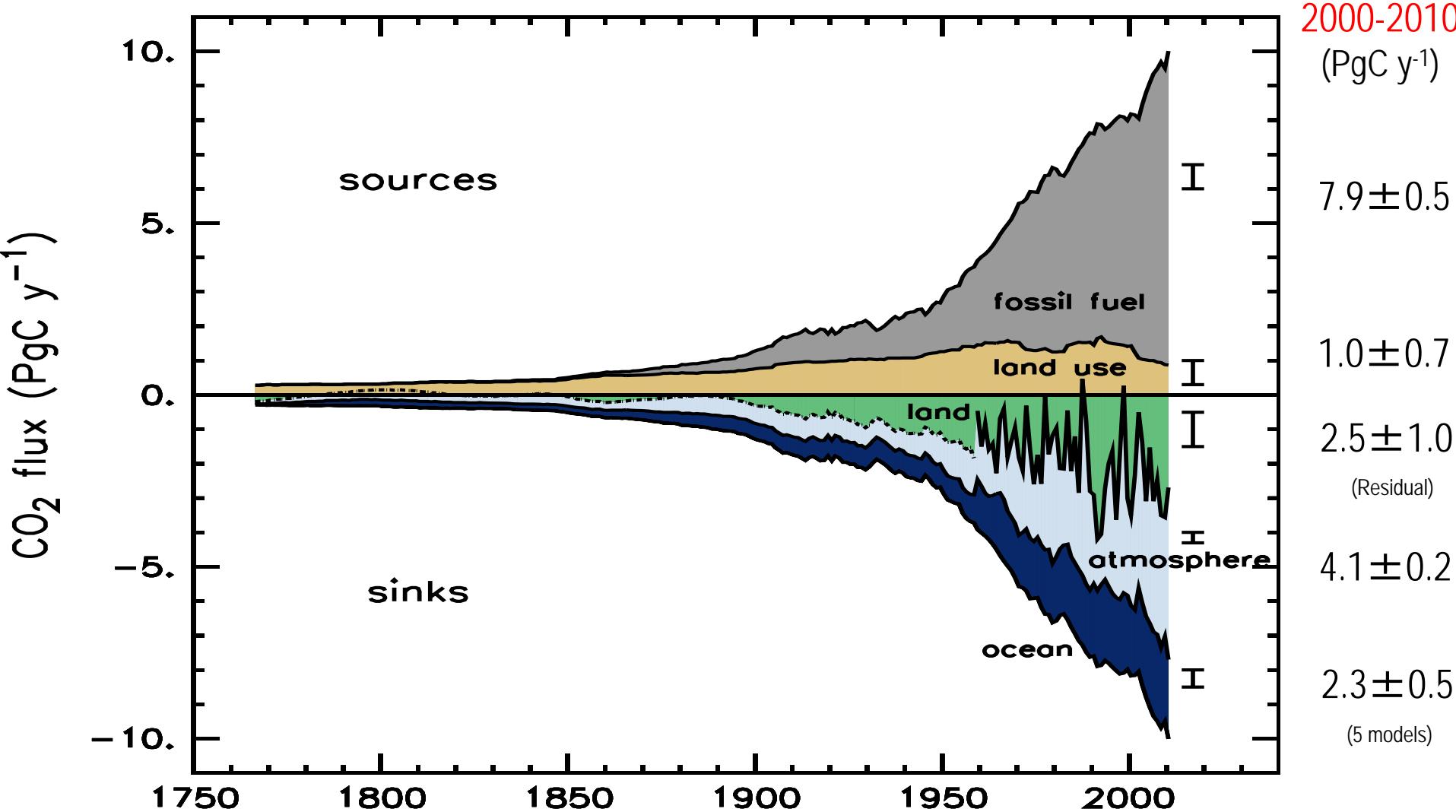
1990s
Emissions: $1.5 \pm 0.7 \text{ PgC}$

2000-2010
Emissions: $1.1 \pm 0.7 \text{ PgC}$

Dashed line – previous estimate.

Land use emissions is a stable or decreasing forcing

Human Perturbation of the Global Carbon Budget



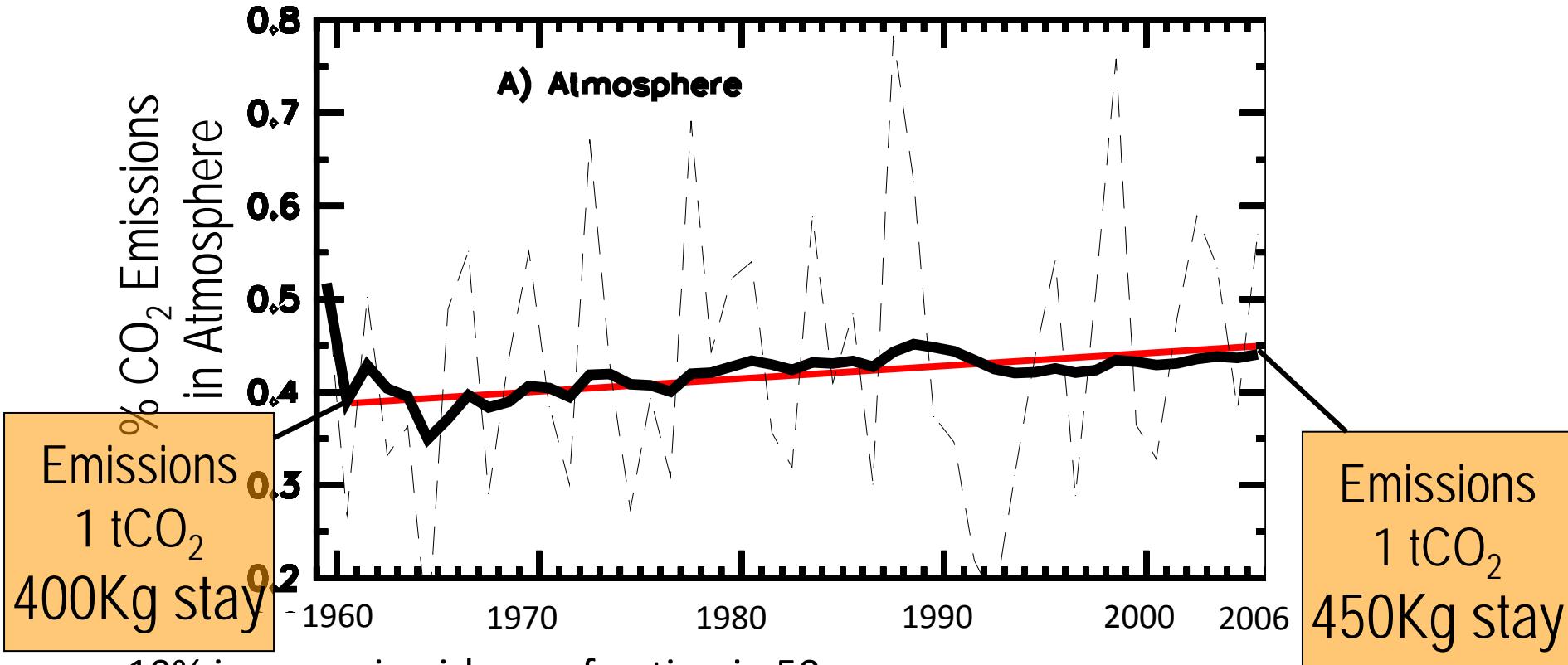
Remarkable linearity of sinks response to emissions forcing

Land sinks are sensitive to climate, at least on interannual time scale

Is there a decline in the efficiency of CO₂ Natural Sinks

Airborne Fraction :

Fraction of all anthropogenic emissions that stay in the atmosphere



10% increase in airborne fraction in 50 yrs

Not necessarily a decrease in sink processes (because different time constants of recent emission change and removal processes by sinks)

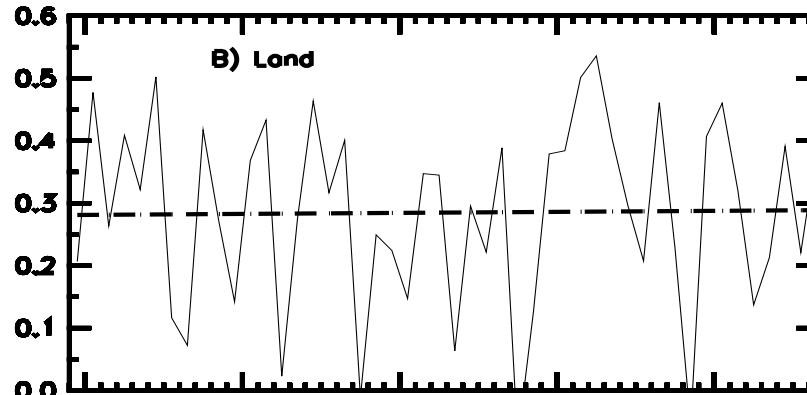
Ocean hypothesis to explain the decreasing sink efficiency



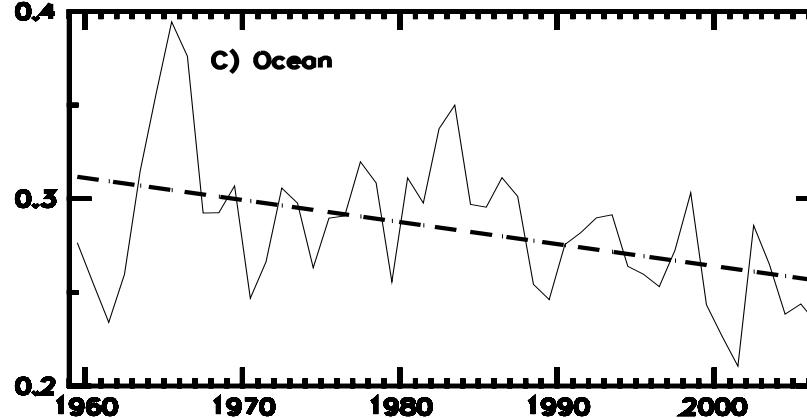
- Part of the decline is attributed to up to 30% decrease in the efficiency of the Southern Ocean sink over the last 20 years.
- This sink removes annually 0.3 ± 0.2 Pg of anthropogenic carbon.
- The decline is attributed to the strengthening of the winds around Antarctica which enhances ventilation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

Efficiency of natural sinks

Land Fraction



Ocean Fraction



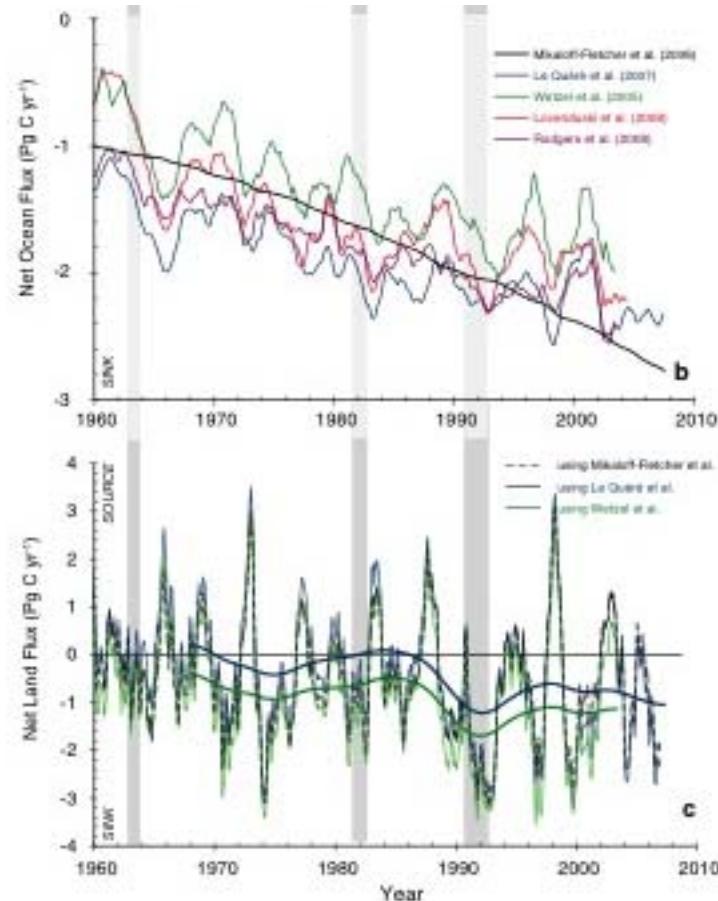
Suggests constant land sink efficiency globally

Needs to be looked at for each region using, e.g. inversions

Despite near-constant airborne fraction, the land sink increased in abruptly the late 1990's

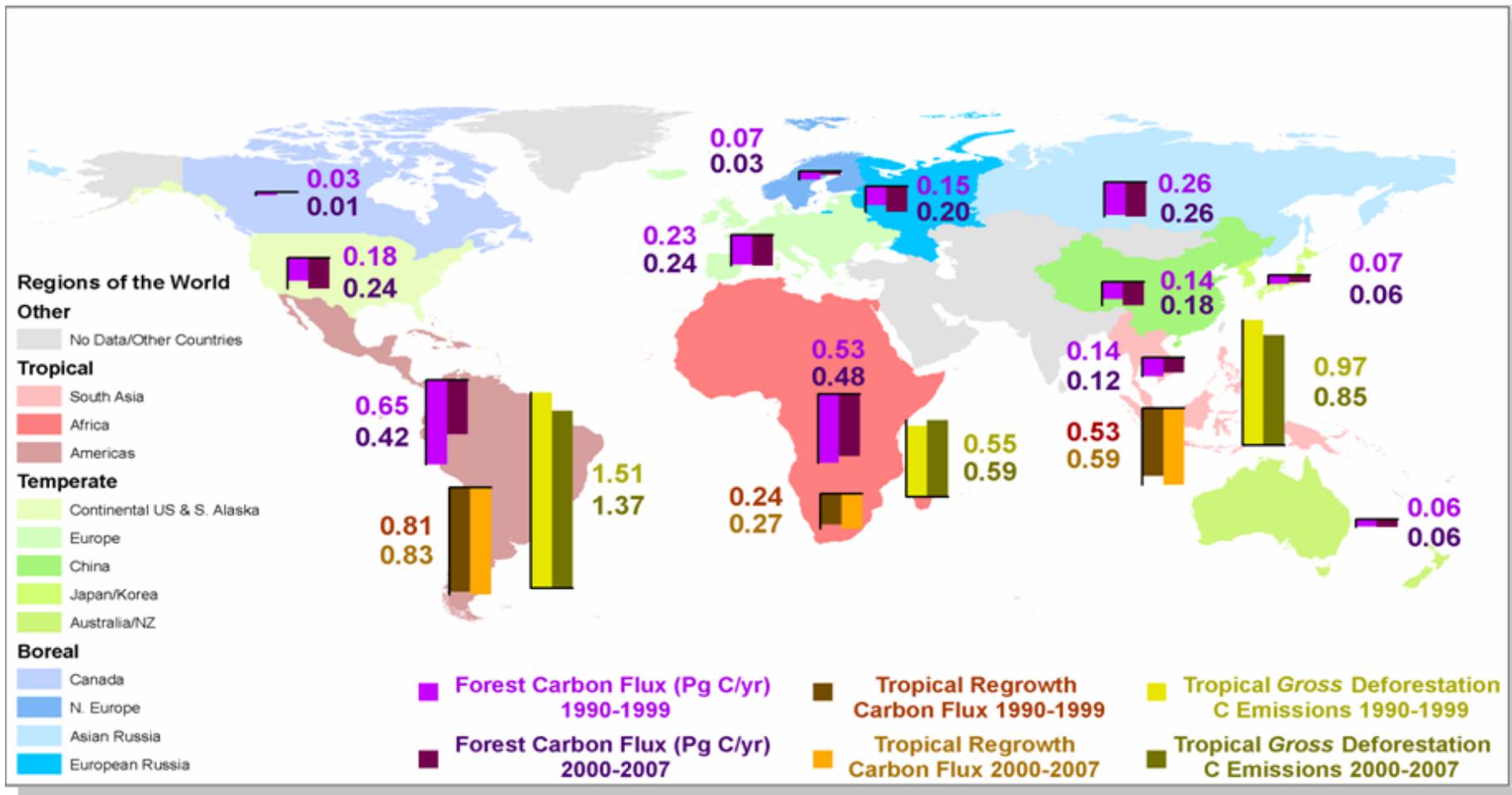
Ocean models sink suggest recent decline in efficiency

Net land sink almost constant ($0.27 \text{ Pg C yr}^{-1}$) between 1960 and 1988 abruptly increased around 1988 by $+0.88$ (0.77 to 1.04) Pg C yr^{-1}



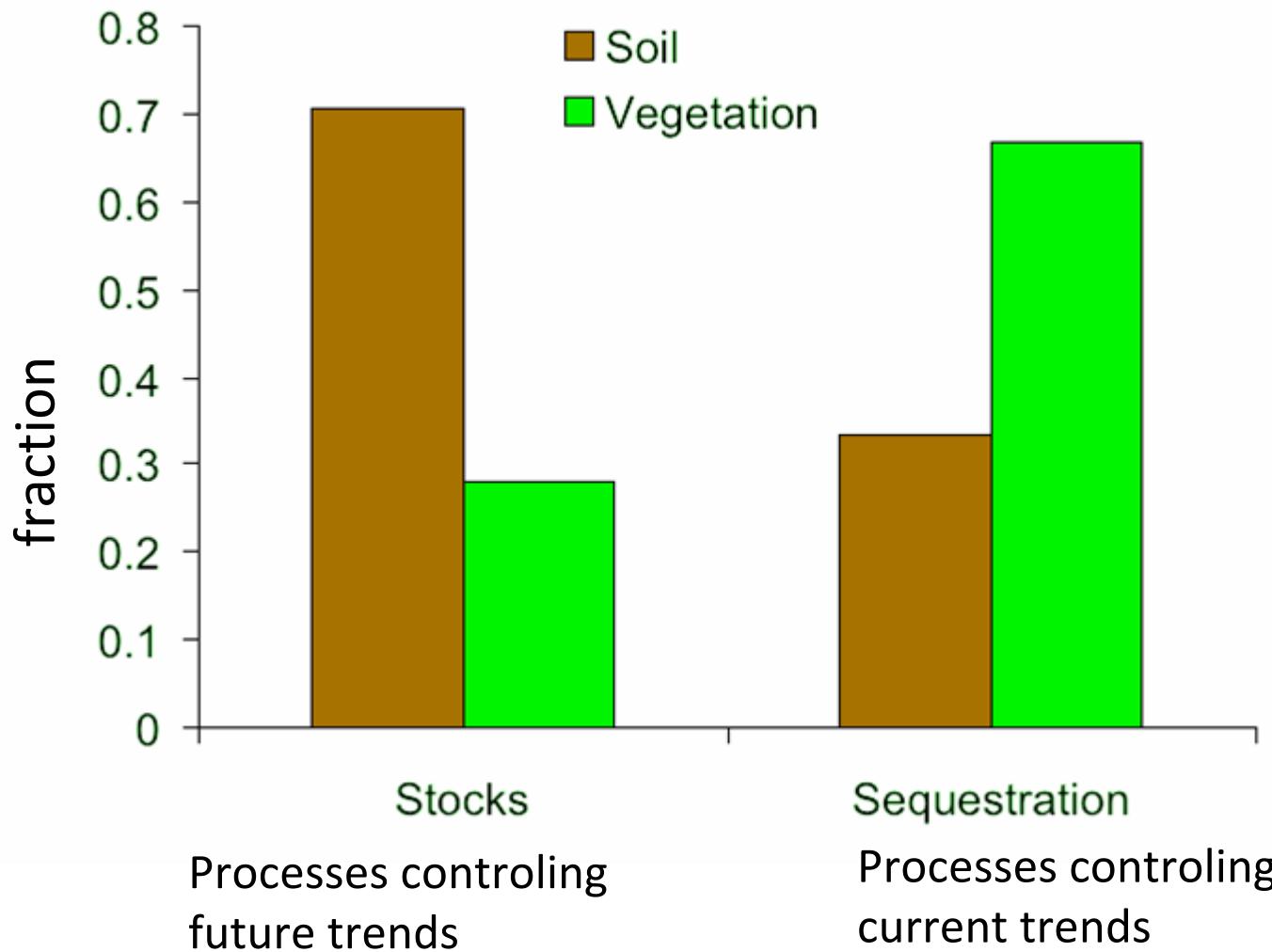
Large and Consistent Global Forest Carbon Sink

Increasing in the North, decreasing in Tropics

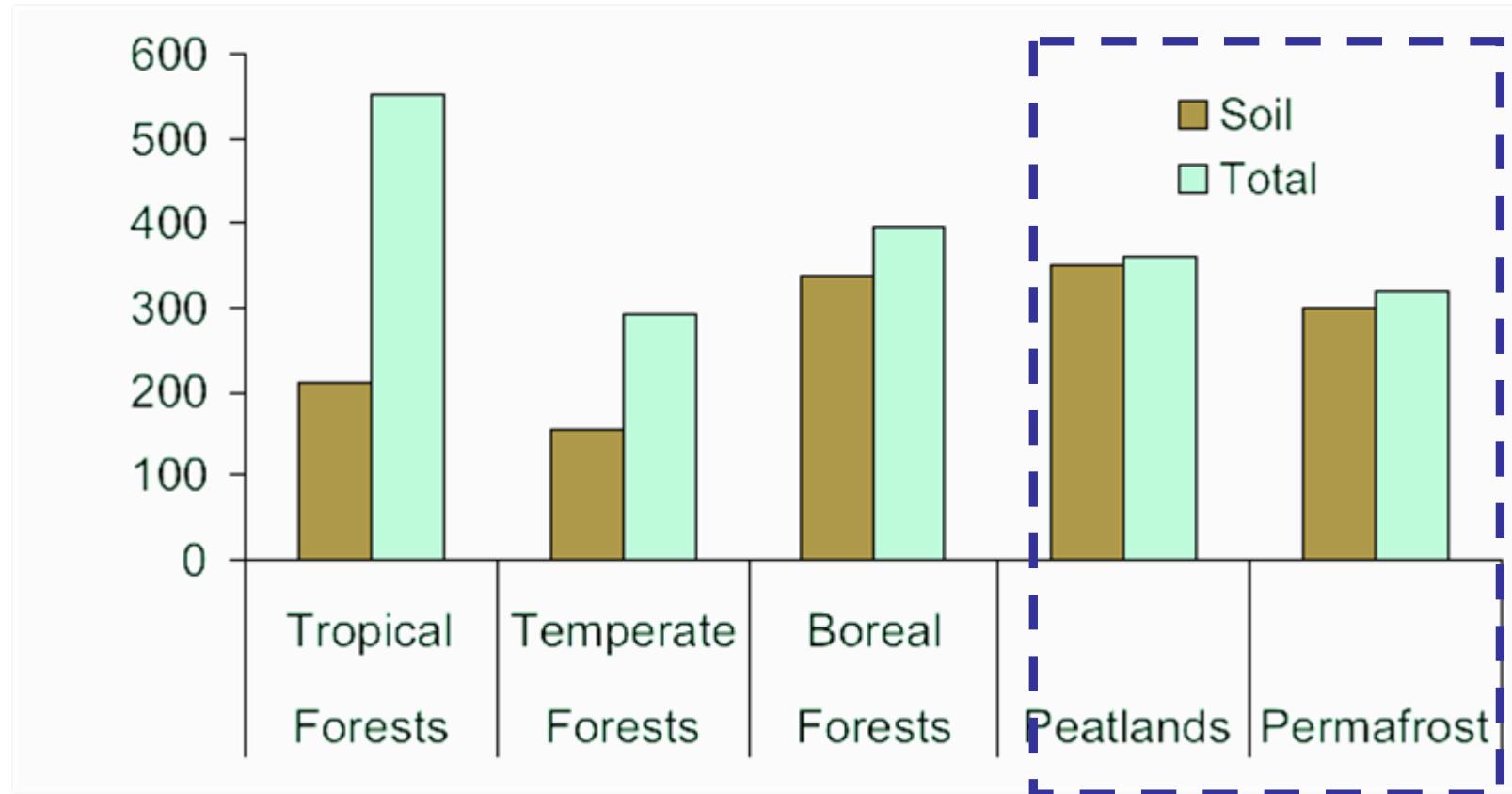


What are the implications of these trends for the future ?

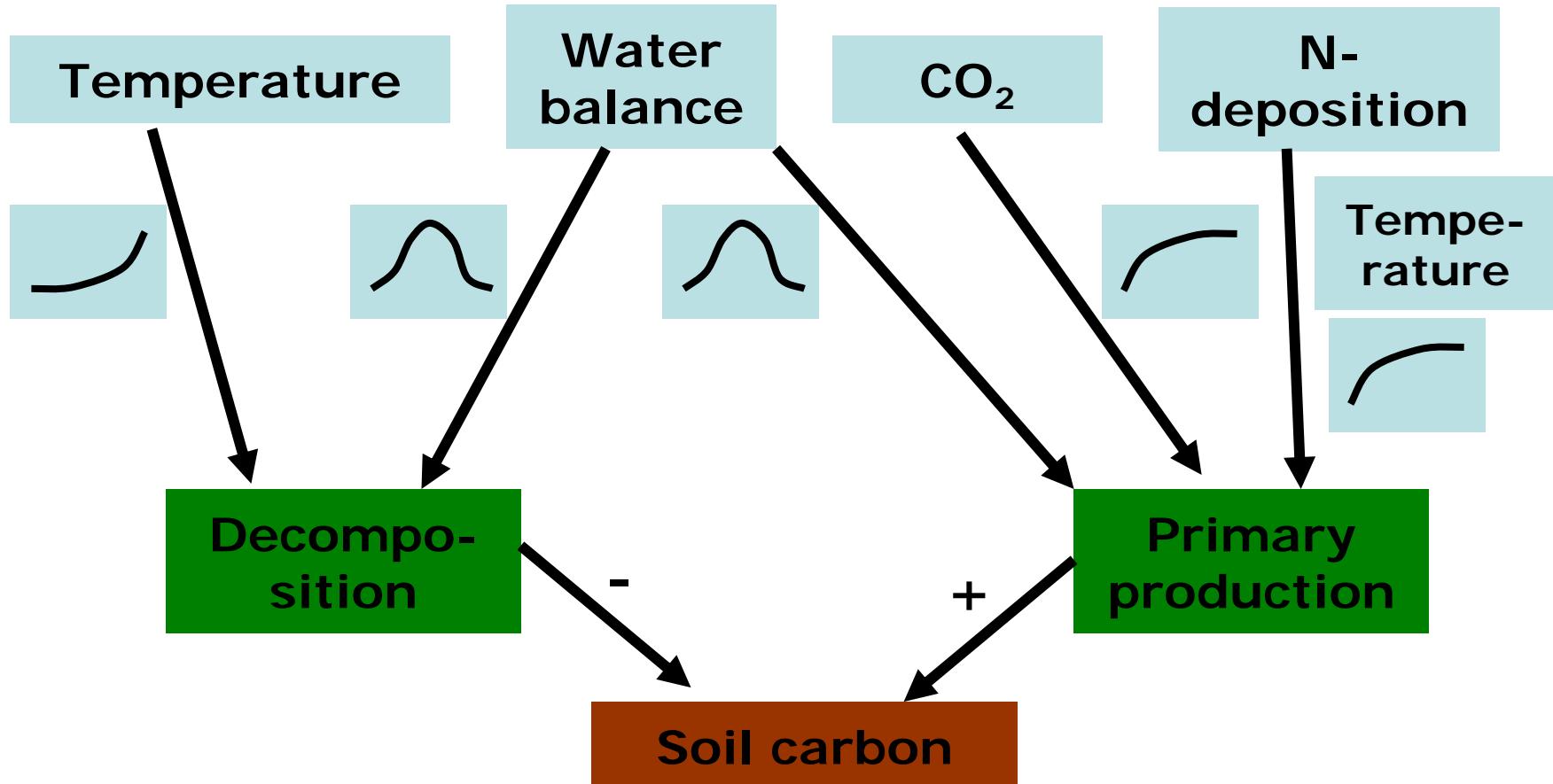
Stock vs. sequestration: partitioning between vegetation and soil



Global carbon stocks in ecosystems



Climate factors affecting soil C balance (simplified)

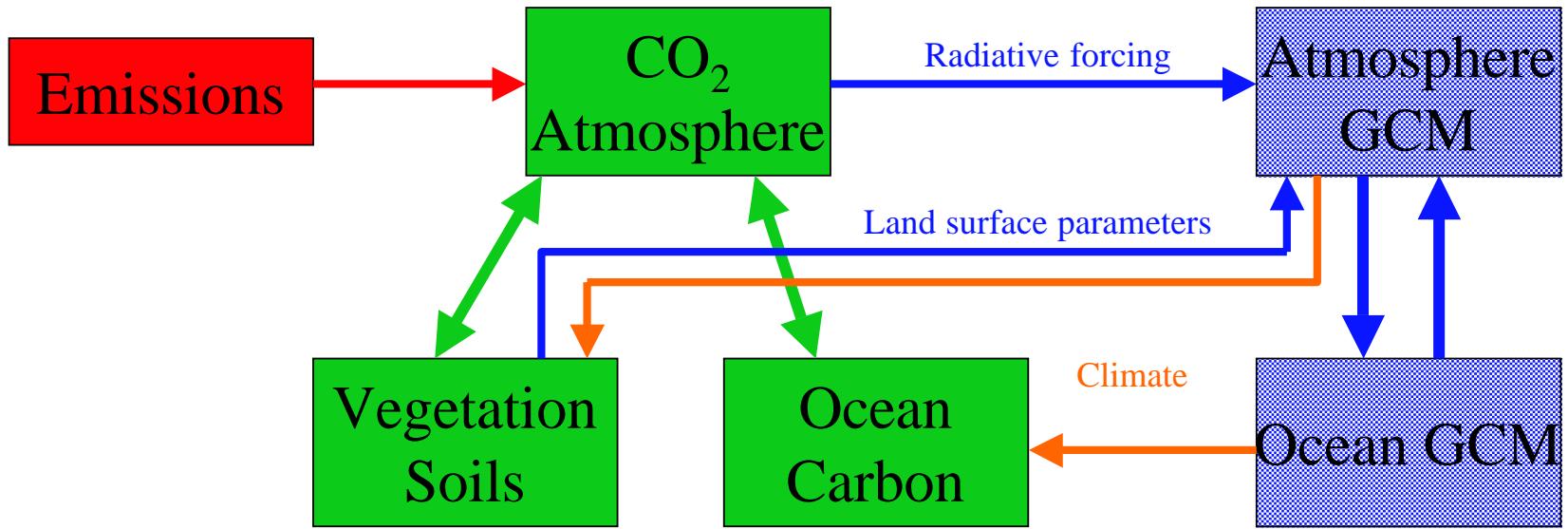


Not tractable with analytical, simple theory



Need spatially explicit models to tackle the problem

Coupled carbon-climate simulation design



Carbon Cycle Model

Climate Model

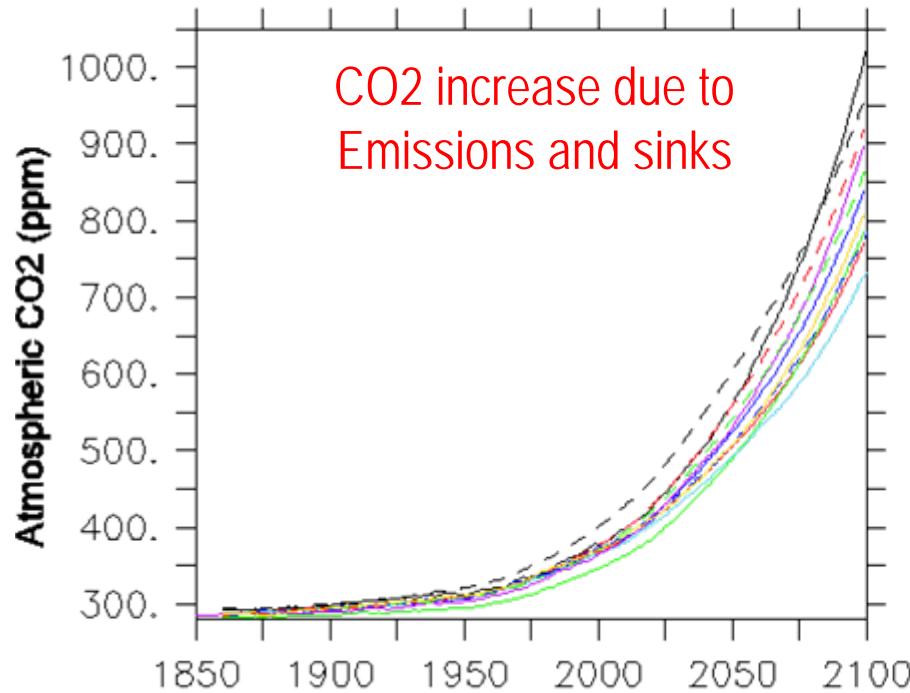
Precursors : Cox et al. 2000 ; Dufresne et al. 2001

C4MIP = 11 models (IPCC AR4) with CO₂, climate

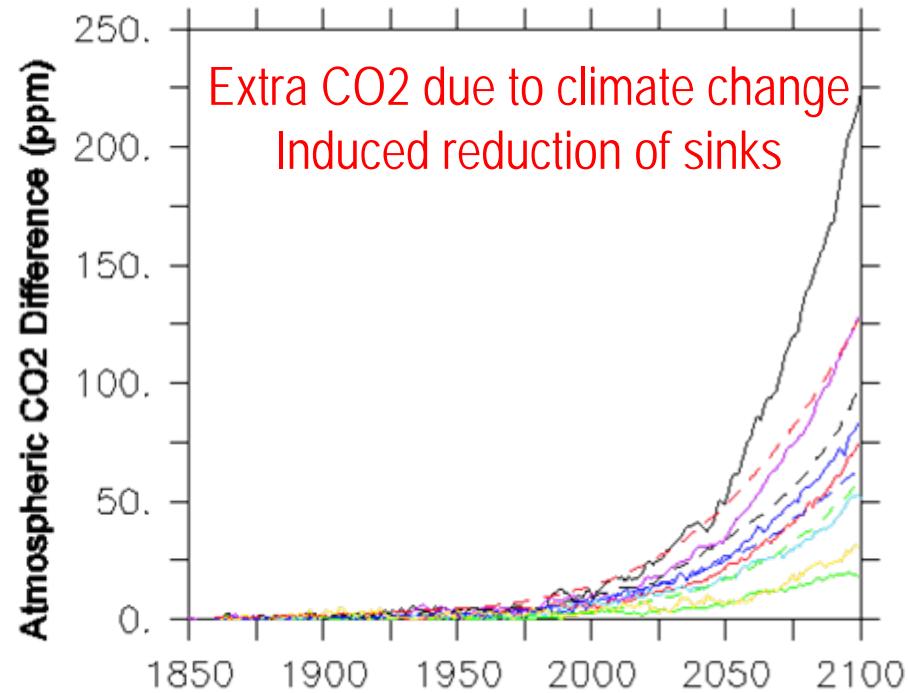
CMIP5 = (IPCC AR5) with CO₂, climate, [nitrogen], land use

Simulated Atmospheric CO₂

(a)



(b)

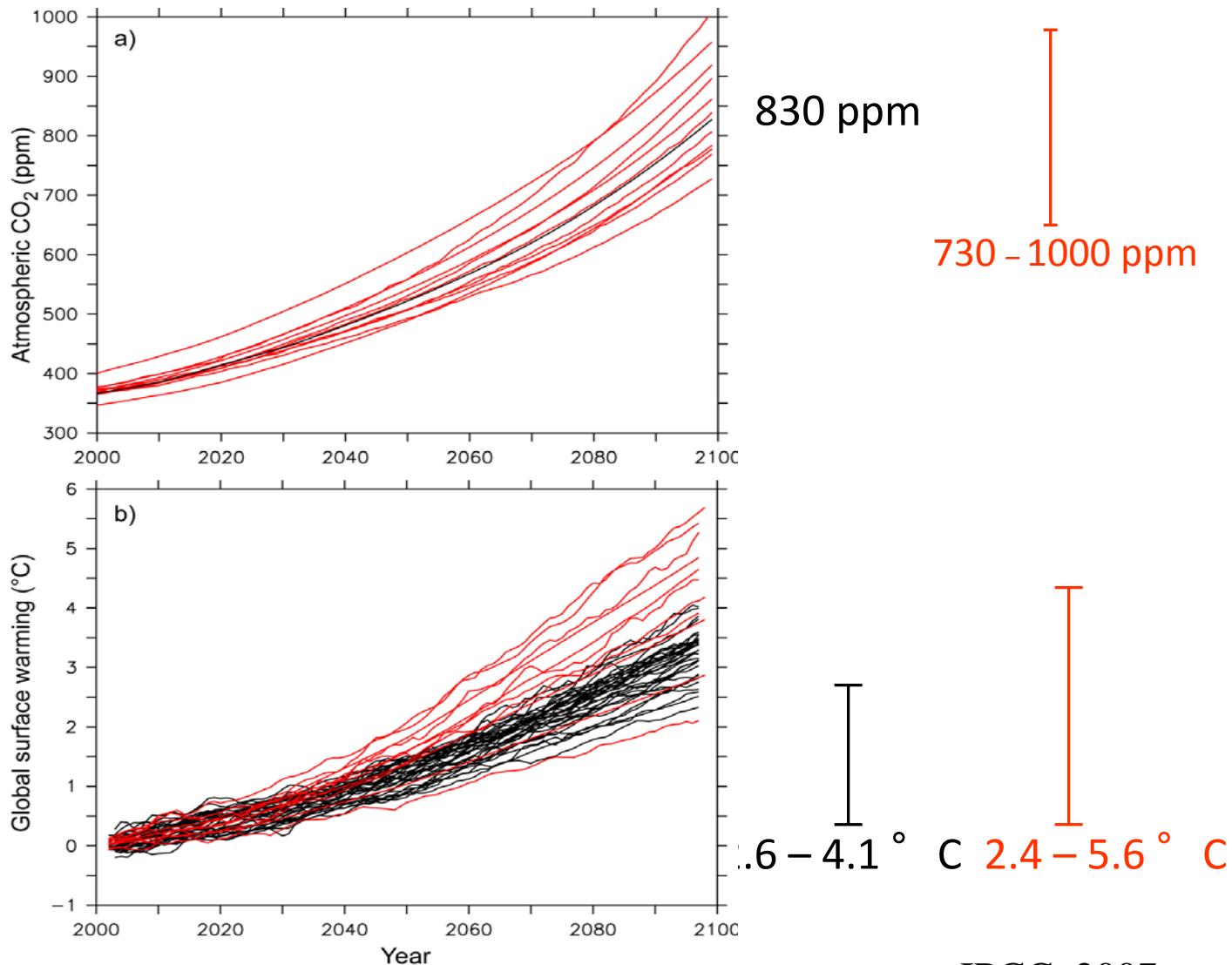


Always Positive Feedback
Large uncertainties

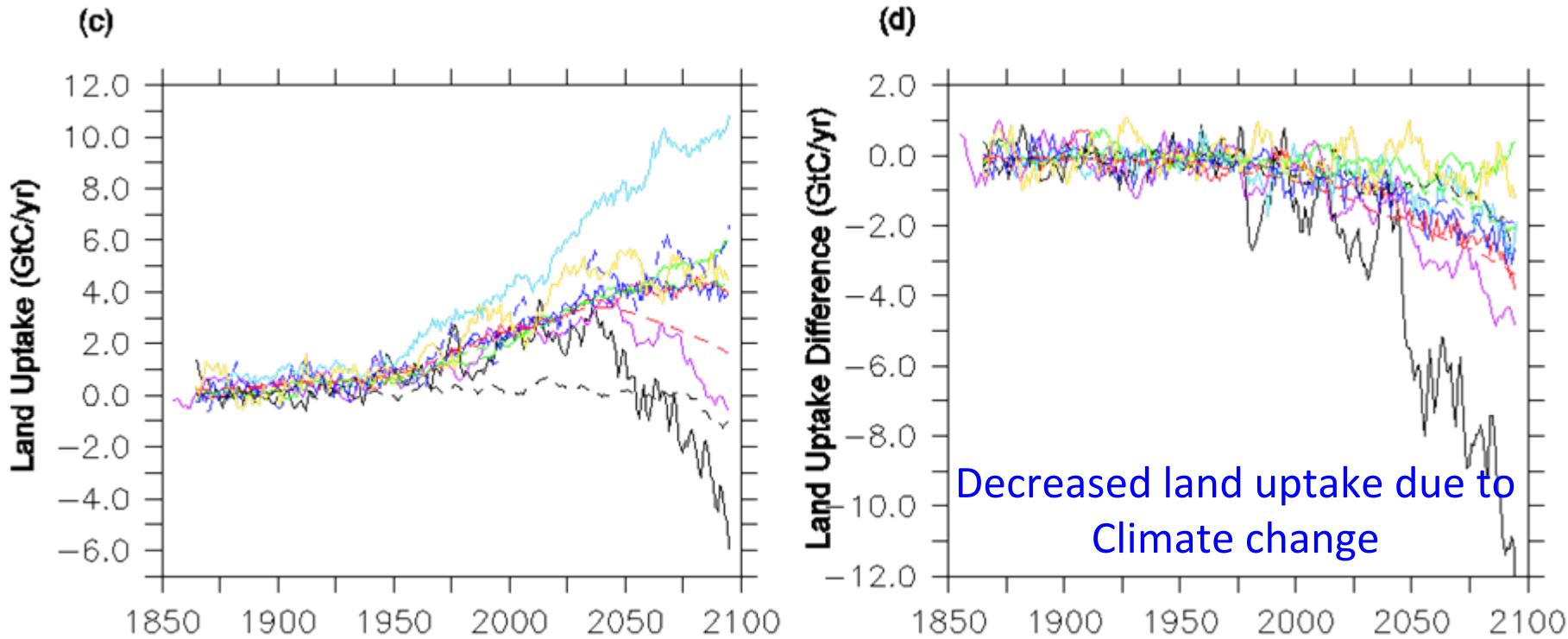


The magnitude of the problem

- Uncertainty due to the carbon cycle uncertainty
- Higher [CO₂] larger climate change

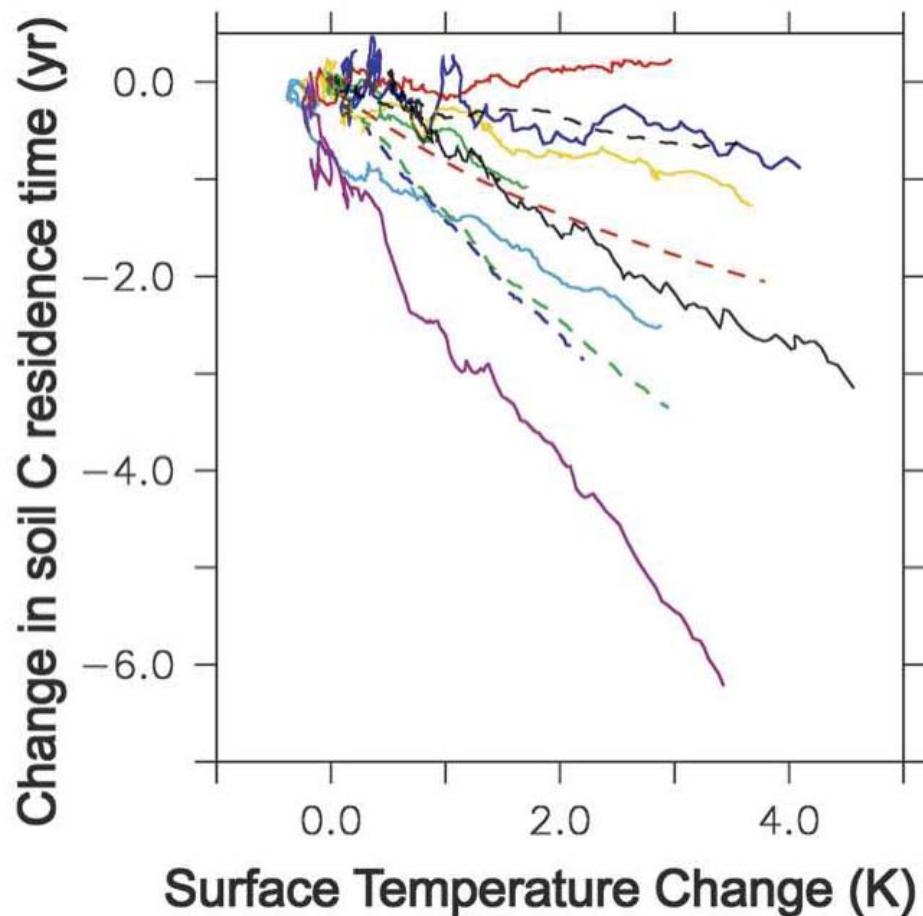
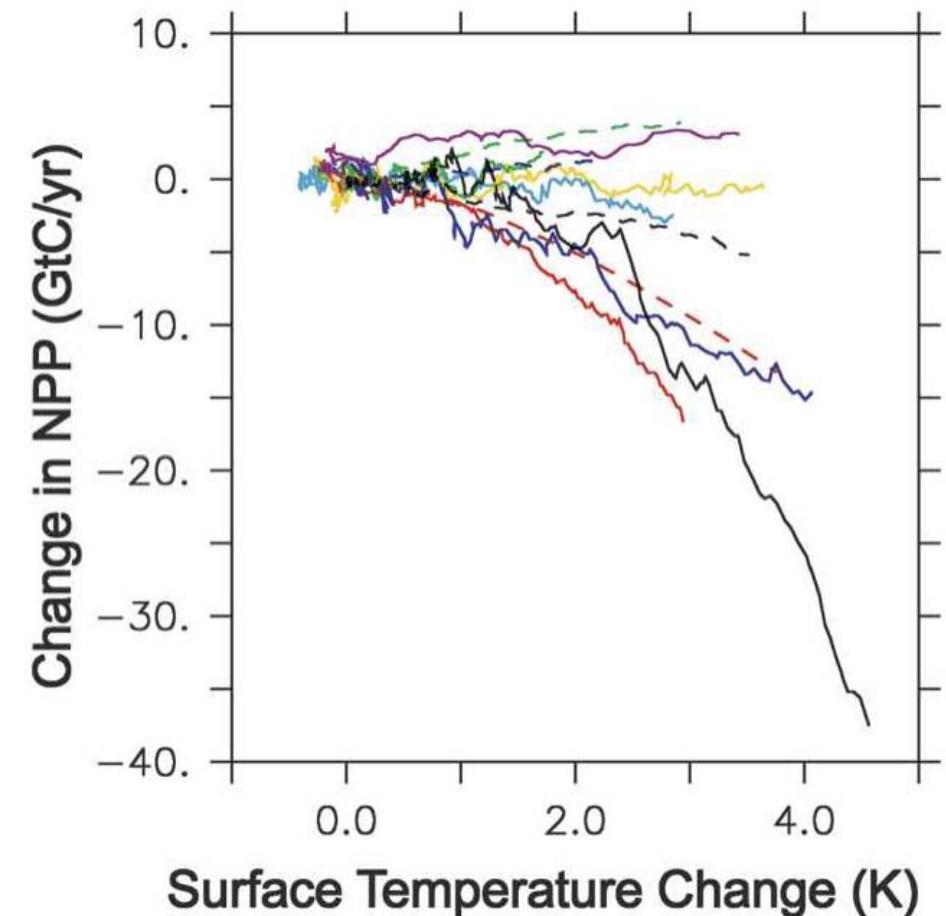


Simulated Land fluxes



Globally a Negative response

Changes in NPP and residence time (stock/NPP)

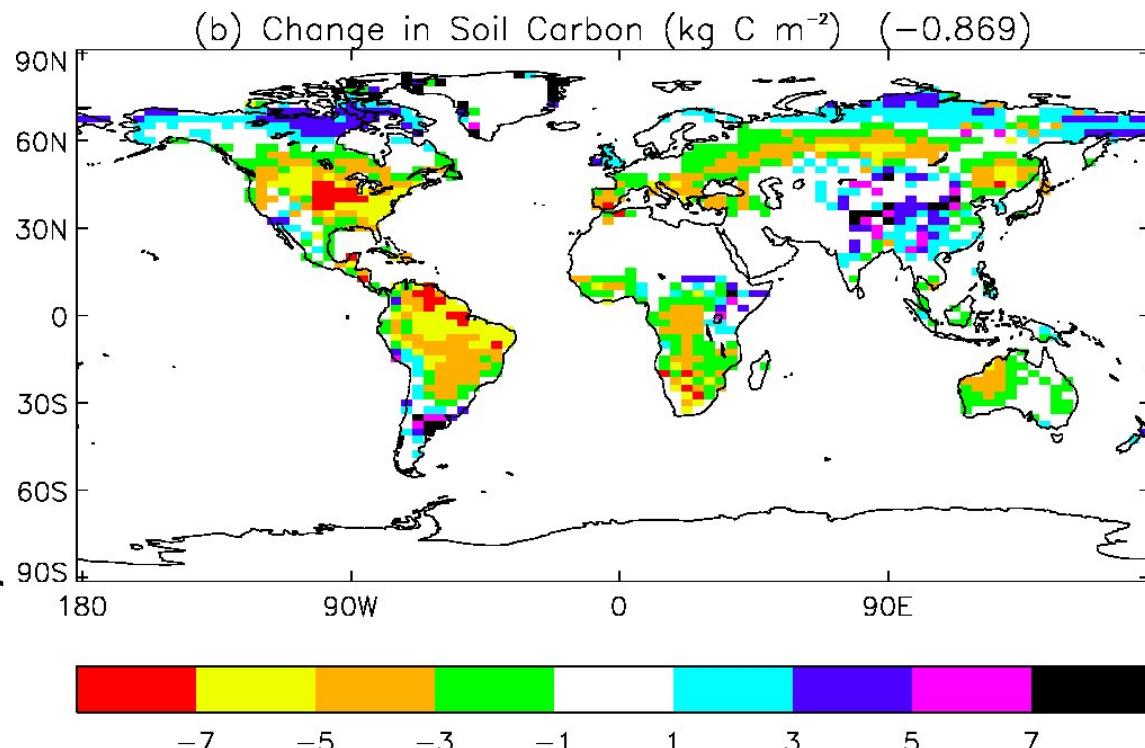
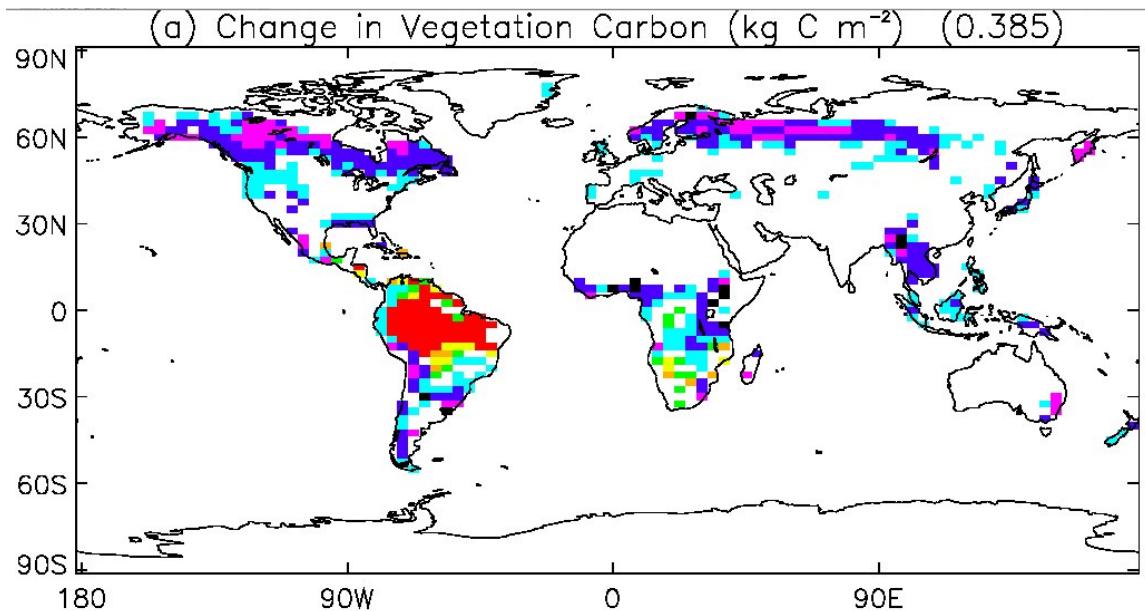


Simulated Changes in Terrestrial Carbon Pools 1860-2100 in Hadley Model

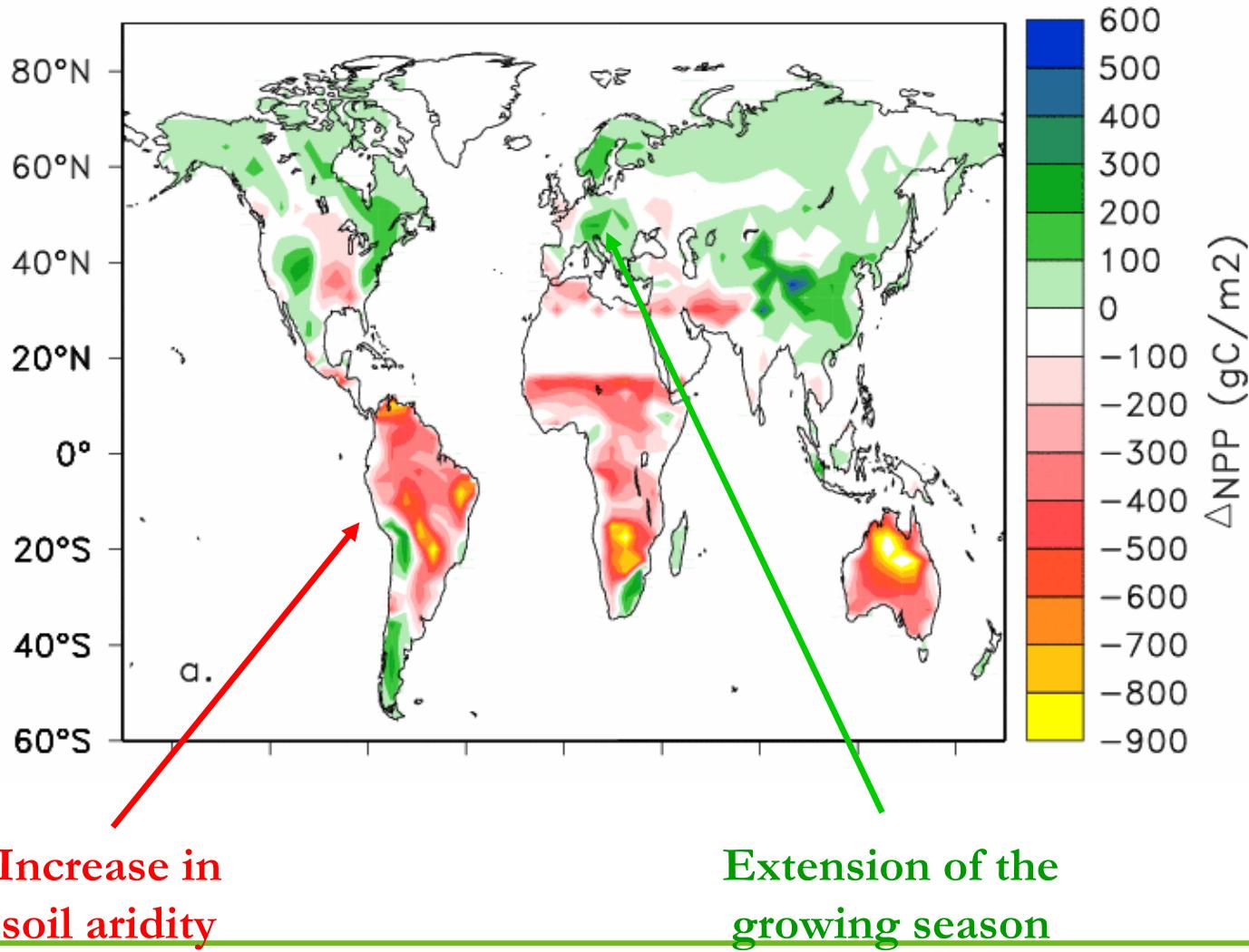
In the future, soil C reduction dominate over biomass changes

Totally different from present perturbation
(biomass dominates over

Gove et al. 2001

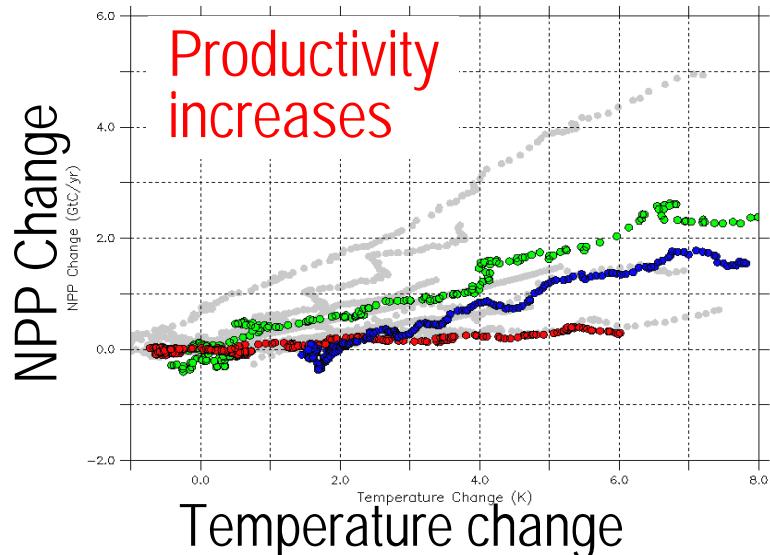


The response of NPP to climate

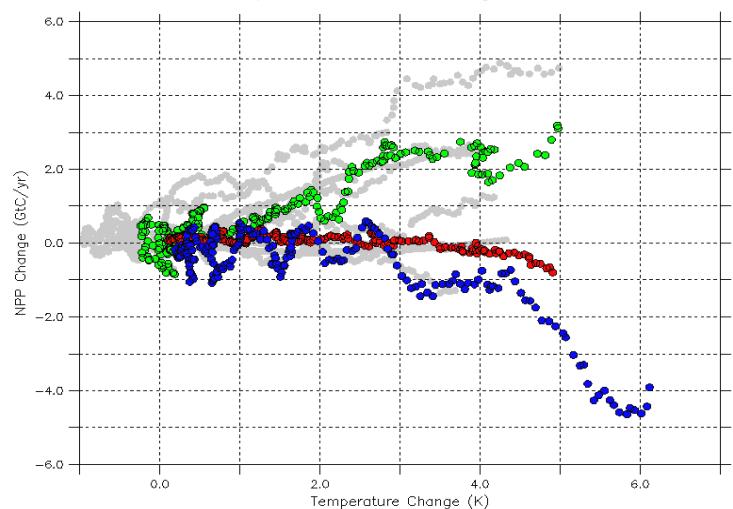


Where are the changes in NPP ?

Boreal regions

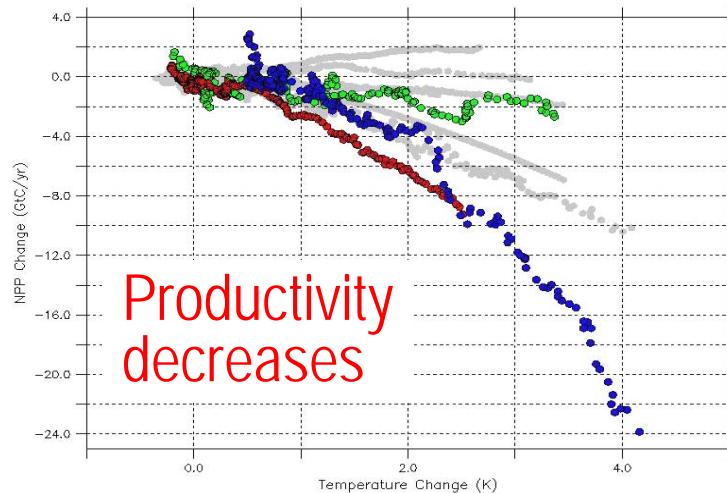


Temperate regions



Temperature change

Tropical regions



HadCM3LC, UK

IPSL_CM4_LOOP, FR

IPSL-CM2_C, FR

Take home

First order linear dynamics of coupled carbon-climate system are expected to change in the future

Major non linearities in current models C4MIP

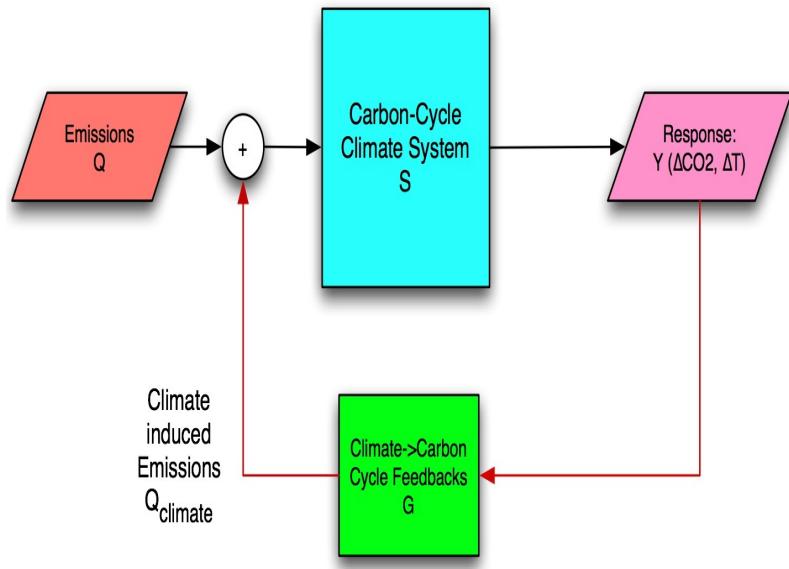
- Ocean chemistry
- Terrestrial responses of GPP, Respiration (to CO₂ and climate)

All models suggest that climate feedbacks will reduce sinks in the future

- Ocean stratification
- Tropical drying reducing GPP
- Longer northern growing seasons increase GPP
- Soil changes dominate over biomass changes



Climate-Carbon Cycle Feedback



$$\Delta CO_2 = EMI - \Delta F_O - \Delta F_L \quad (1)$$

$$\Delta T^c = \alpha \Delta CO_2^{unc} + \Delta T_{ind} \quad (2)$$

$$\Delta F_O = \beta_O \Delta CO_2 - \gamma_O \Delta T \quad (3)$$

$$\Delta F_L = \beta_L \Delta CO_2 - \gamma_L \Delta T \quad (4)$$

(3) and (4) in (1), then (1) in (2) gives:

$$\Delta T = 1/(1-g) \Delta T_{unc}$$

g , the gain of the feedback, defined by:

$$g = \alpha (\gamma_O + \gamma_L) / (1 + \beta_O + \beta_L)$$

Positive feedback of carbon on climate change if $g < 1$

f is the feedback factor

$$f = 1/(1-g)$$

Terminology

$$g = \alpha (\gamma_o + \gamma_L) / (1 + \beta_o + \beta_L)$$

g is the gain of the climate-carbon cycle feedback

$$f = 1/(1-g)$$

f is the feedback factor

α is the warming per unit of CO₂ (similar to the climate sensitivity) ($\Delta T / \Delta C_A$)

$\beta_{L/O}$ is the land/ocean cumulated carbon flux per unit of CO₂ ($\Delta F_{L/O} / \Delta C_A$)

$\gamma_{L/O}$ is the land/ocean cumulated carbon flux per unit of warming ($\Delta F_{L/O} / \Delta T$)

Gain for C4MIP models

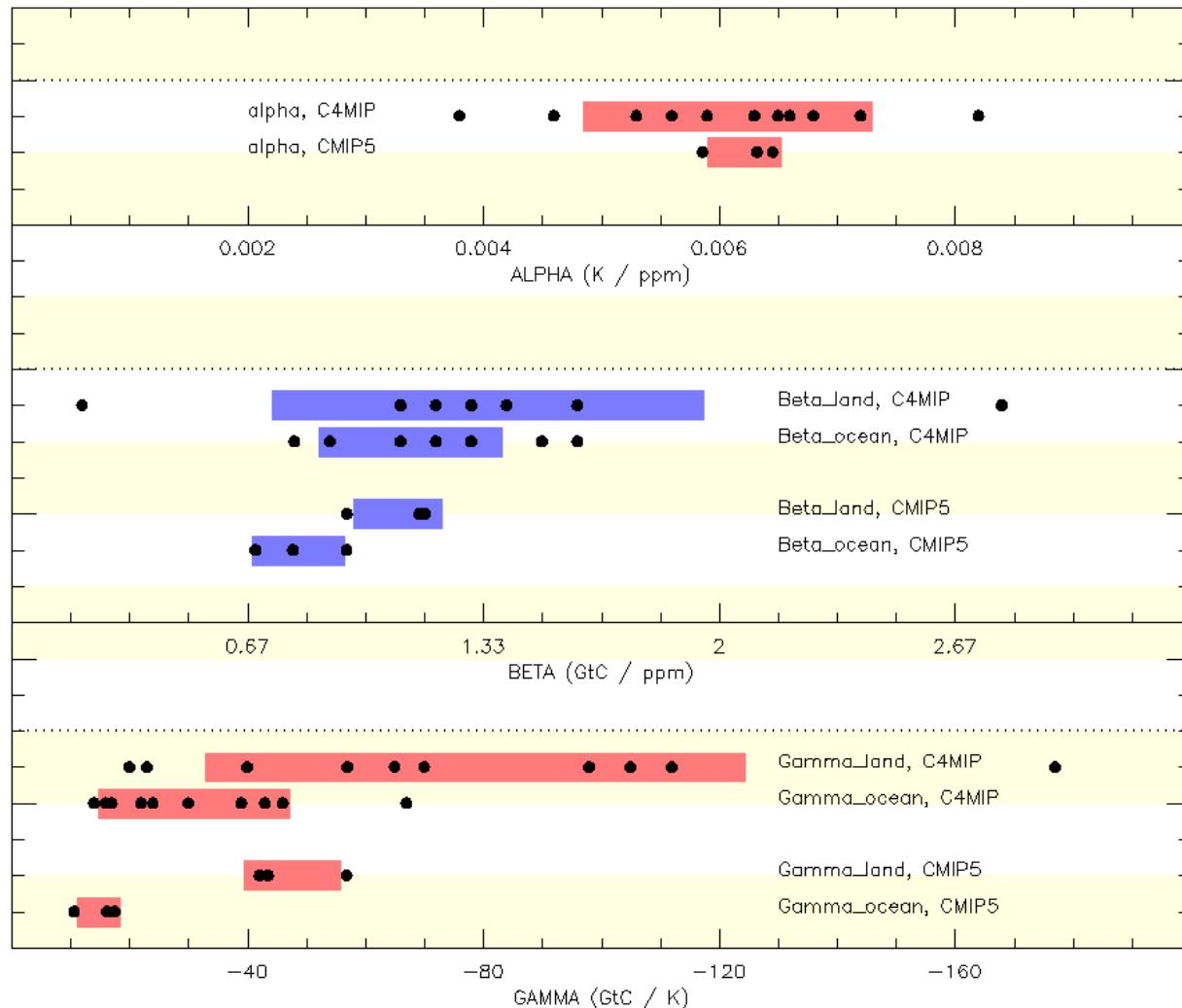
TABLE 3. Carbon cycle gain, g , along with component sensitivities of climate to CO₂ (α), land and ocean carbon storage to CO₂ (β_L , β_O), and land and ocean carbon storage to climate (γ_L , γ_O). Calculations are done for year 2100.

Models	α (K ppm ⁻¹)	β_L (GtC ppm ⁻¹)	β_O (GtC ppm ⁻¹)	γ_L (GtC K ⁻¹)	γ_O (GtC K ⁻¹)	Gain
HadCM3LC	0.0066	1.3	0.8	-177	-24	0.31
IPSL-CM2C	0.0065	1.6	1.6	-98	-30	0.15
IPSL-CM4-LOOP	0.0072	1.3	1.1	-20	-16	0.06
CSM-1	0.0038	1.1	0.9	-23	-17	0.04
MPI	0.0082	1.4	1.1	-65	-22	0.20
LLNL	0.0068	2.8	0.9	-70	-14	0.10
FRCGC	0.0059	1.2	1.2	-112	-46	0.21
UMD	0.0056	0.2	1.5	-40	-67	0.14
UVic-2.7	0.0063	1.2	1.1	-98	-43	0.20
CLIMBER	0.0053	1.1	0.9	-57	-22	0.10
BERN-CC	0.0046	1.6	1.3	-105	-39	0.13
Models avg	0.0061	1.35	1.13	-79	-30	0.15

Large differences
Need to evaluate models results

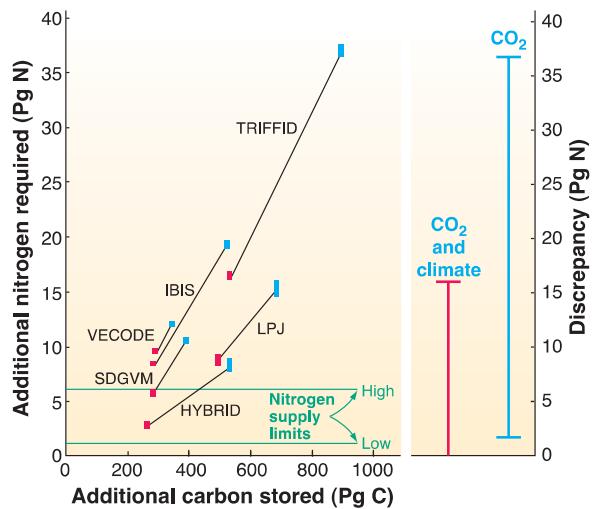


Alpha, beta and gamma for C4MIP and CMIP5

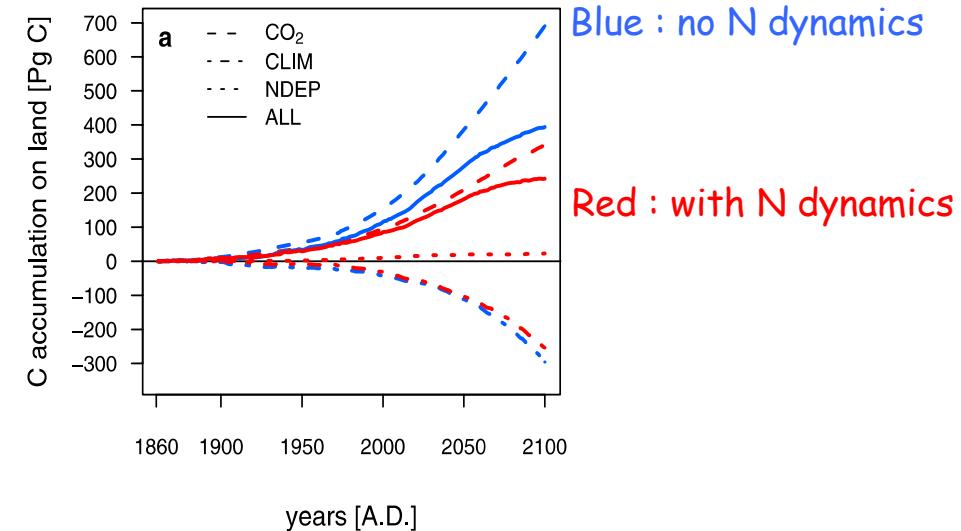


Nitrogen dynamics

Reduces beta, Increases gamma



Supply and demand. (Left) Nitrogen required to support terrestrial carbon uptake (1), compared to likely limits of nitrogen supply (green). For each model (2), values are shown for CO₂-only (blue) and CO₂-climate (red) projections. The upper nitrogen requirement assumes a fixed tree C:N of 200; the lower value assumes that all new tree carbon is allocated to wood. (Right) Discrepancy between nitrogen required for projected carbon uptake and likely nitrogen availability for CO₂-only (blue) and CO₂-and-climate-change (red) scenarios. Upper value: maximum calculated nitrogen required minus low nitrogen supply limit. Lower value: minimum nitrogen required minus high nitrogen supply limit.



Blue : no N dynamics

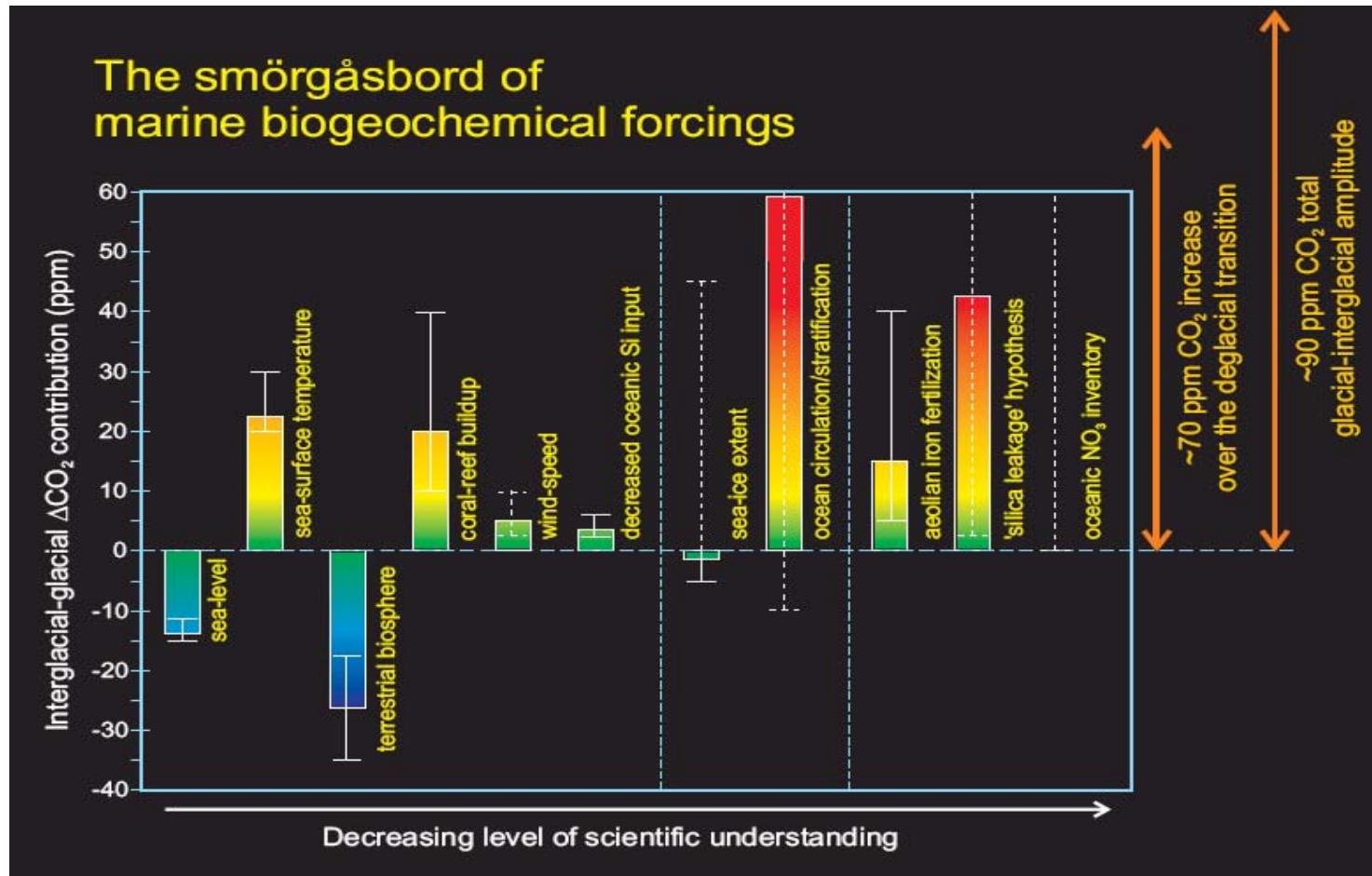
Red : with N dynamics

Difference with
minus without N
dynamics

Zaehle et al. 2010

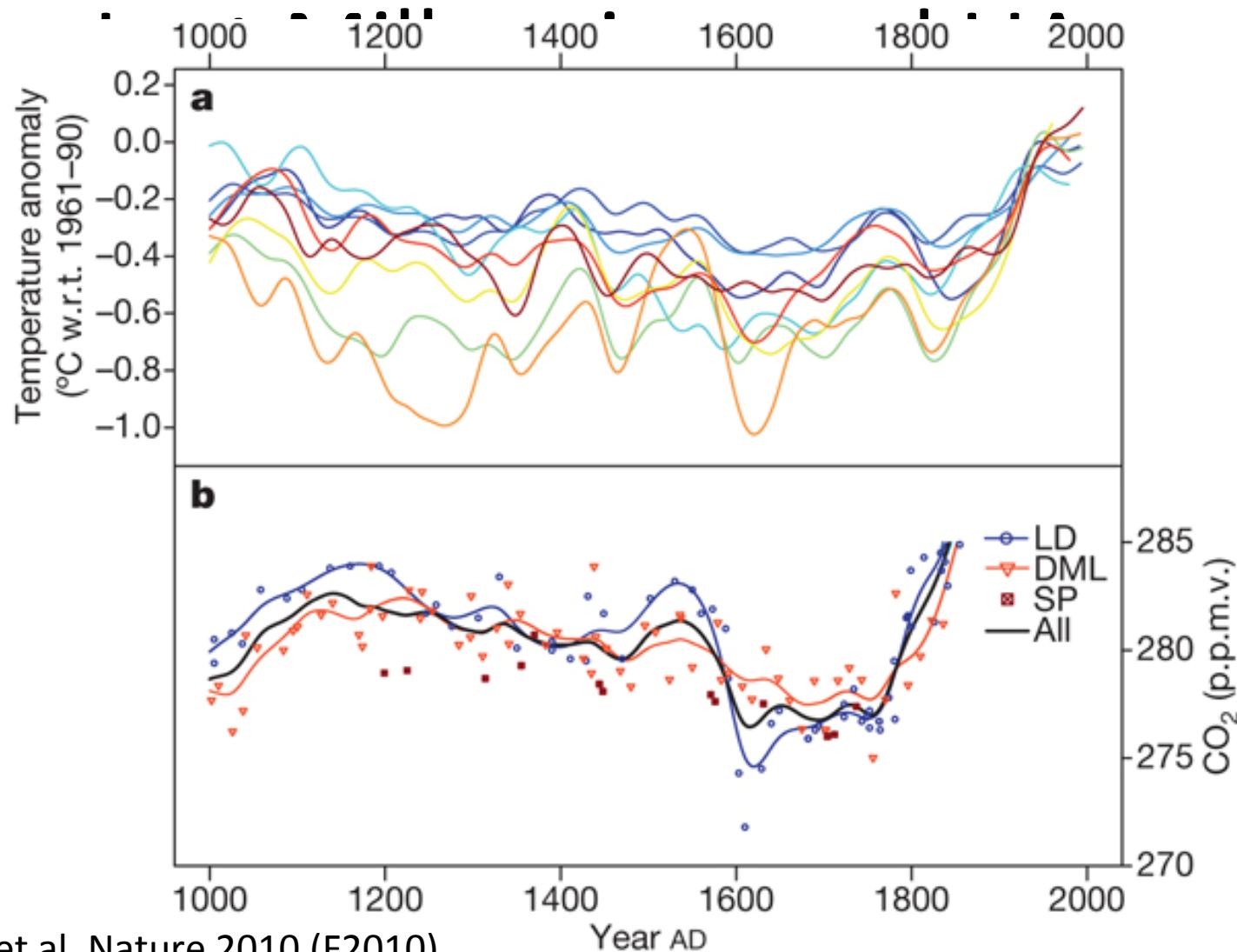


Looking at glacial-interglacial changes in CO₂ and climate :Does this help future projections?



Not really because the state of the carbon-climate system is very different

Looking at the Little Ice Age



Frank et al. Nature 2010 (F2010)

Last Millennium and LIA

Vol 463 | 28 January 2010 | doi:10.1038/nature08769

nature

LETTERS

Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate

David C. Frank^{1,2}, Jan Esper³, Christoph C. Raible^{2,4}, Ulf Büntgen¹, Valerie Trouet¹, Benjamin Stocker^{2,4} & Fortunat Joos^{2,4}

$$\gamma = 7.7 [1.7 - 21.4] \text{ ppm/K}$$

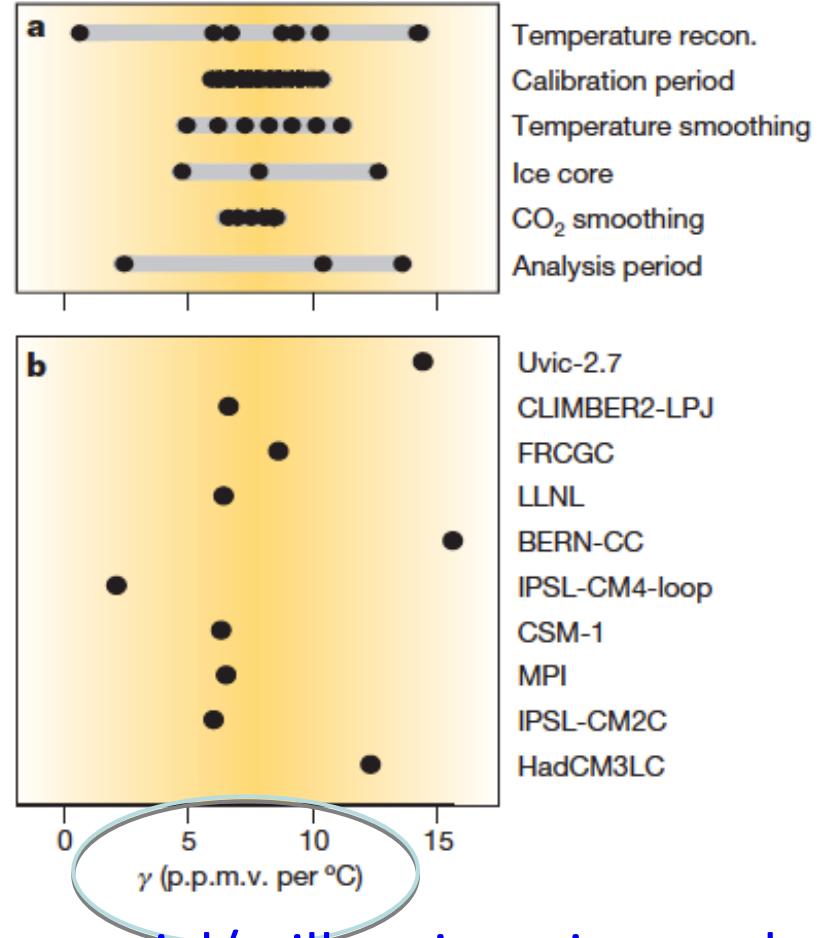
Confusion in terminology:

γ_{F2010} is not γ_{C4MIP}

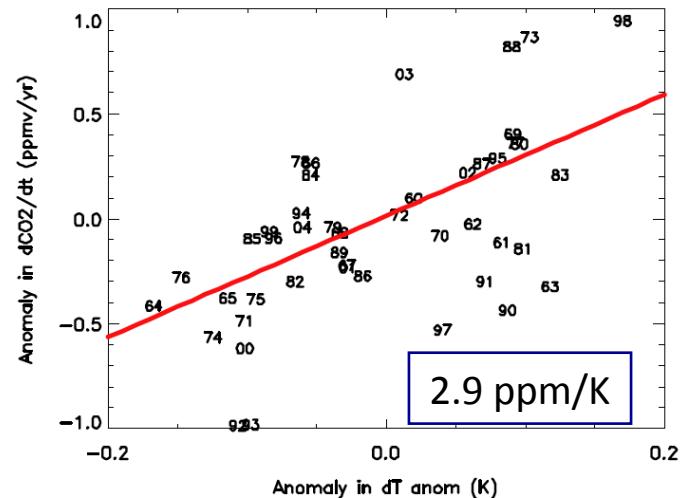
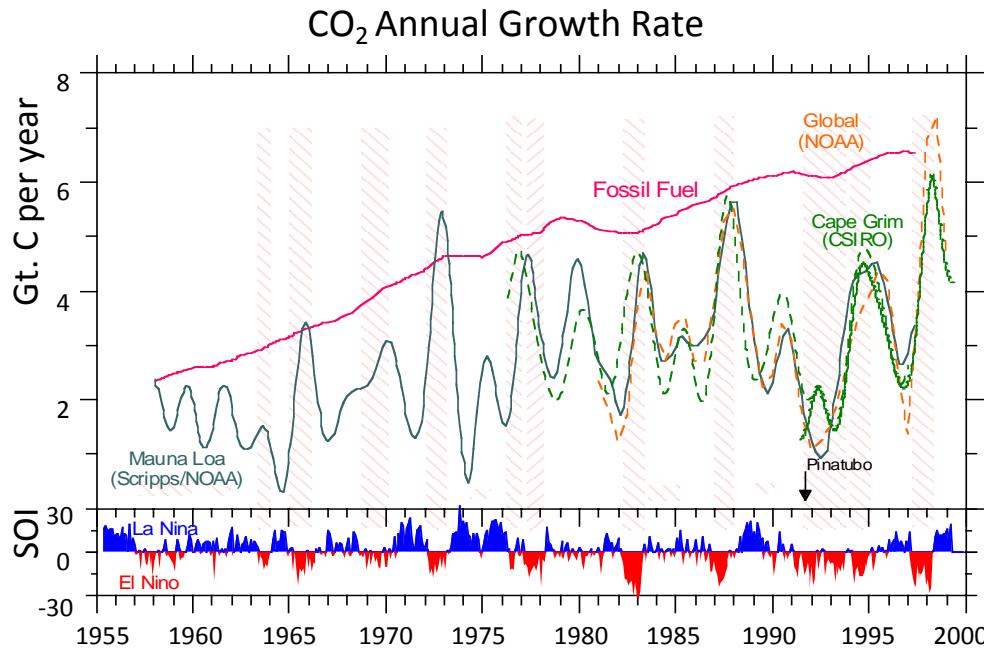
$\gamma_{F2010} = d\text{CO}_2/dT$

$$\gamma_{F2010} = \frac{\gamma_{C4MIP}}{1 + \beta}$$

One could derive γ_{C4MIP} knowing β on centennial/millennium time scales .



Interannual variability of CO₂



One could derive γ_{C4MIP}
knowing β on IAV time scales
(assumed $\beta \approx 0$)

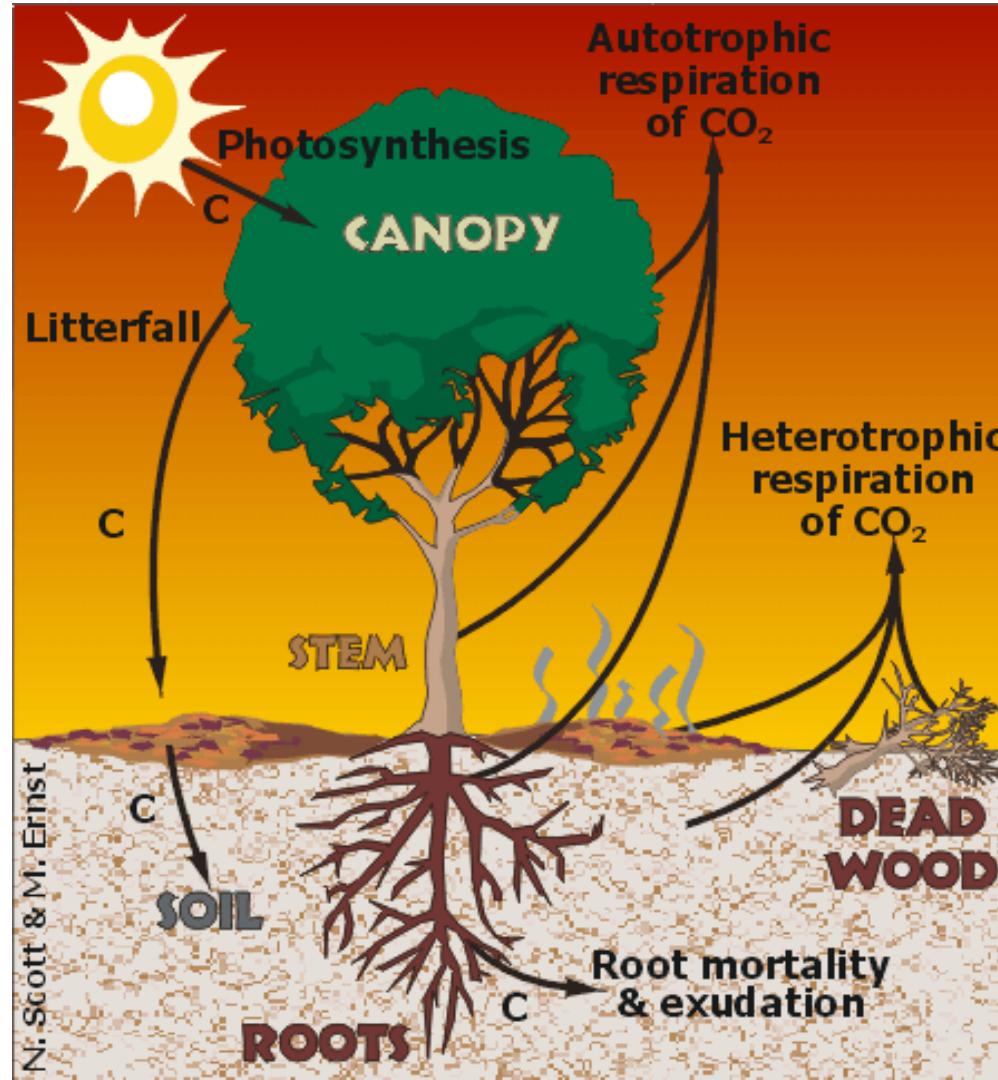
As before this gives a
 $d\text{CO}_2/dT$ interannual,
not directly a γ_{C4MIP}

Terrestrial β and γ zoo

$$\beta_{GPP}$$

$$\beta_{NPP}$$

$$\beta_{NEP} = \beta_{store}$$



$$\gamma_{GPP}$$

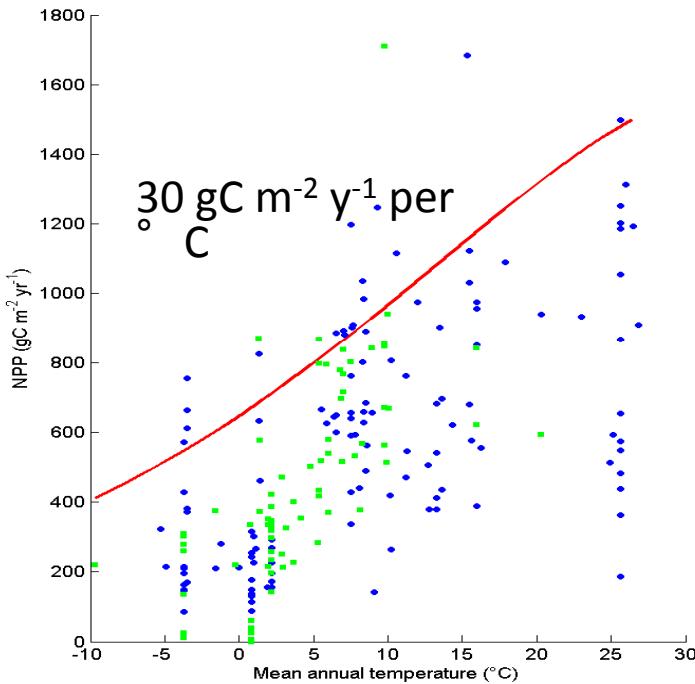
$$\gamma_{NPP}$$

$$\gamma_{Resp}$$

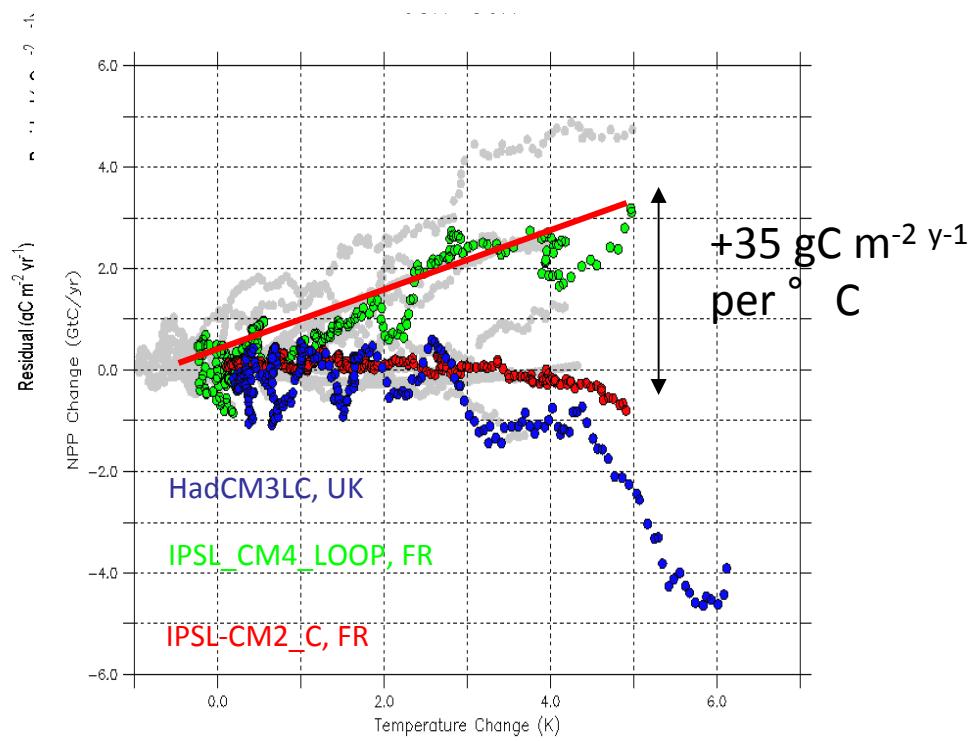
$$\gamma_{NEP} = \gamma_{store}$$

Can γ_{NPP} be measured ?

Ecological data
Spatial NPP-T regression
Lluyssaert et al. database



Model future predictions
Temperate regions



Missing processes in coupled models

Lorraine, France, August 2003

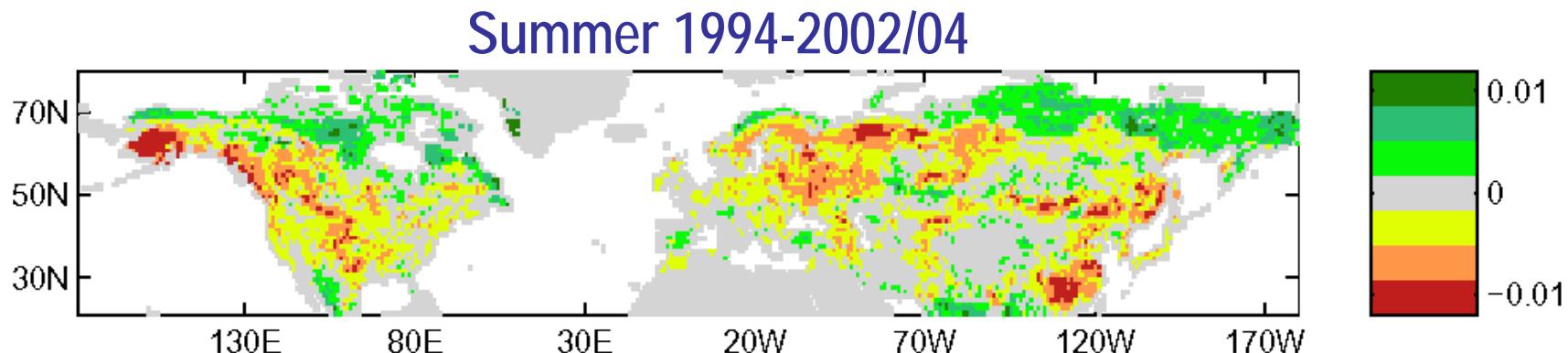
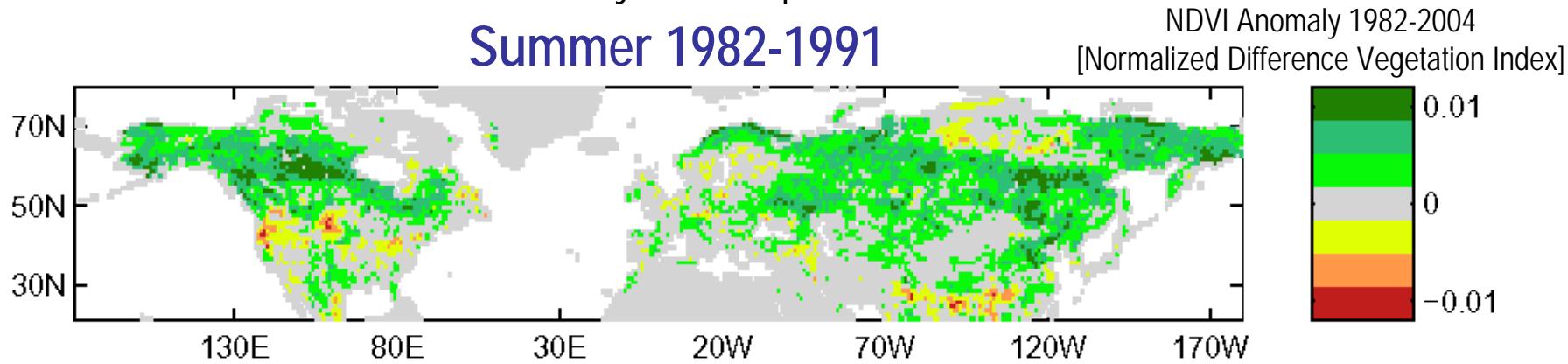


Extreme events

NPP responds to seasonal water availability

A number of major droughts in mid-latitudes have contributed to the weakening of the growth rate of terrestrial carbon sinks in these regions.

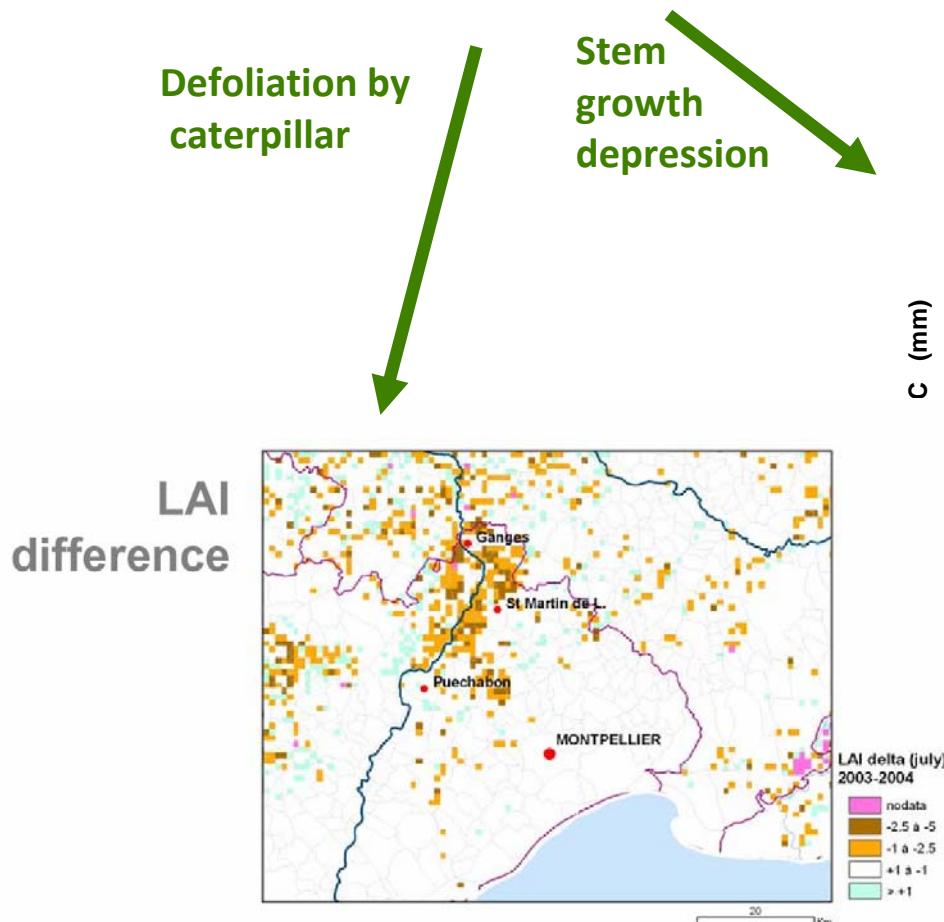
GPP decreases more than ecosystem respiration in the short term



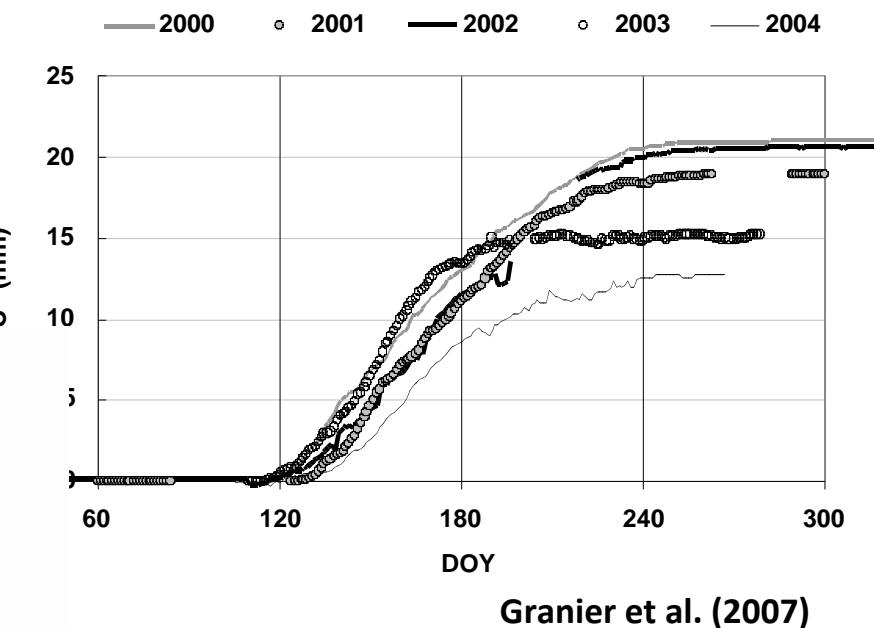
Angert et al. 2005, PNAS; Buermann et al. 2007, PNAS; Ciais et al. 2005, Nature

Missing representations of biosphere in global models: extreme events and lag-effects

Lag effects of heatwave 2003 ?



Decreased growth
One year later in 2004 ...

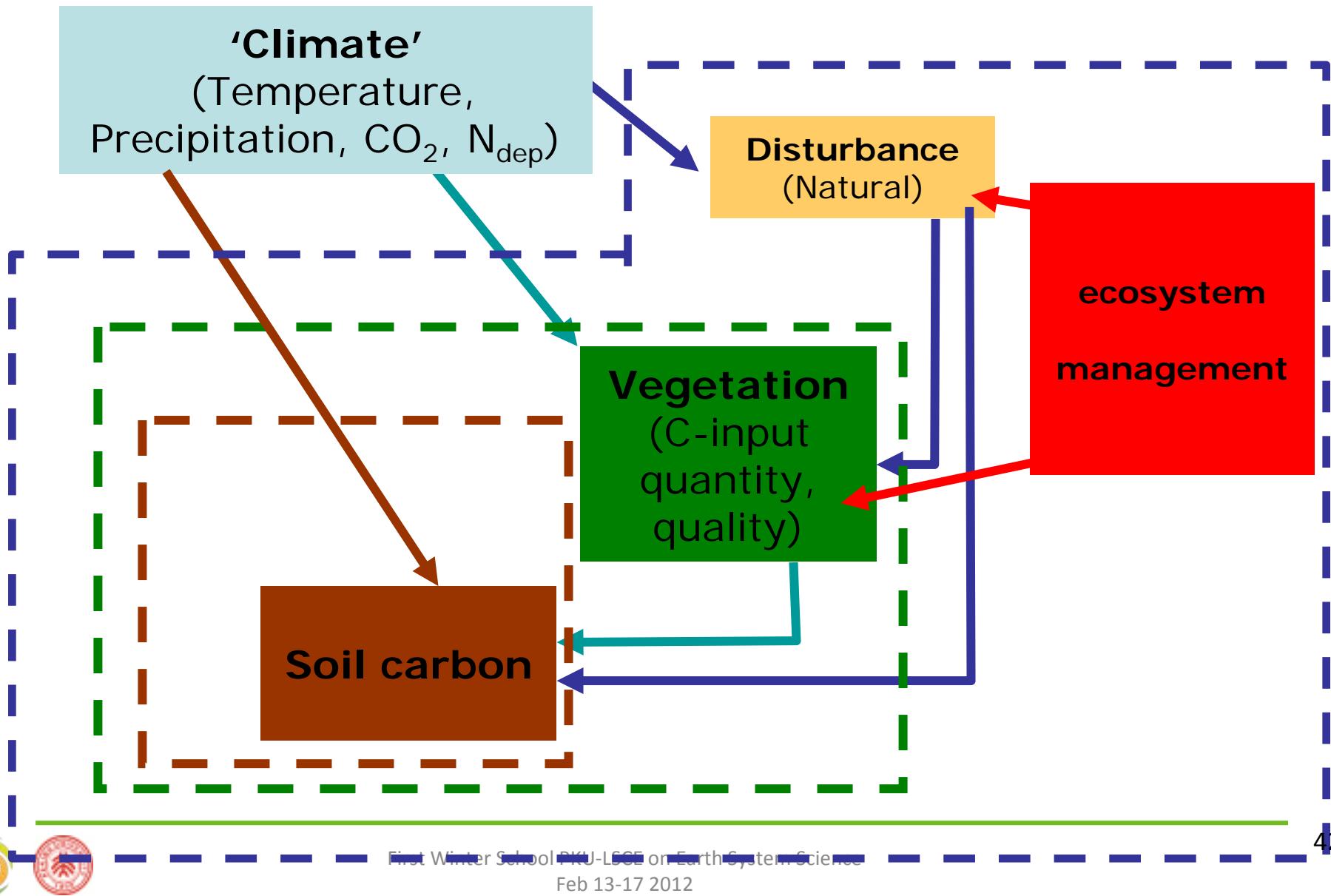


Ourcival et al. (2008)

Missing (or poor) representations of biosphere in global models: fire



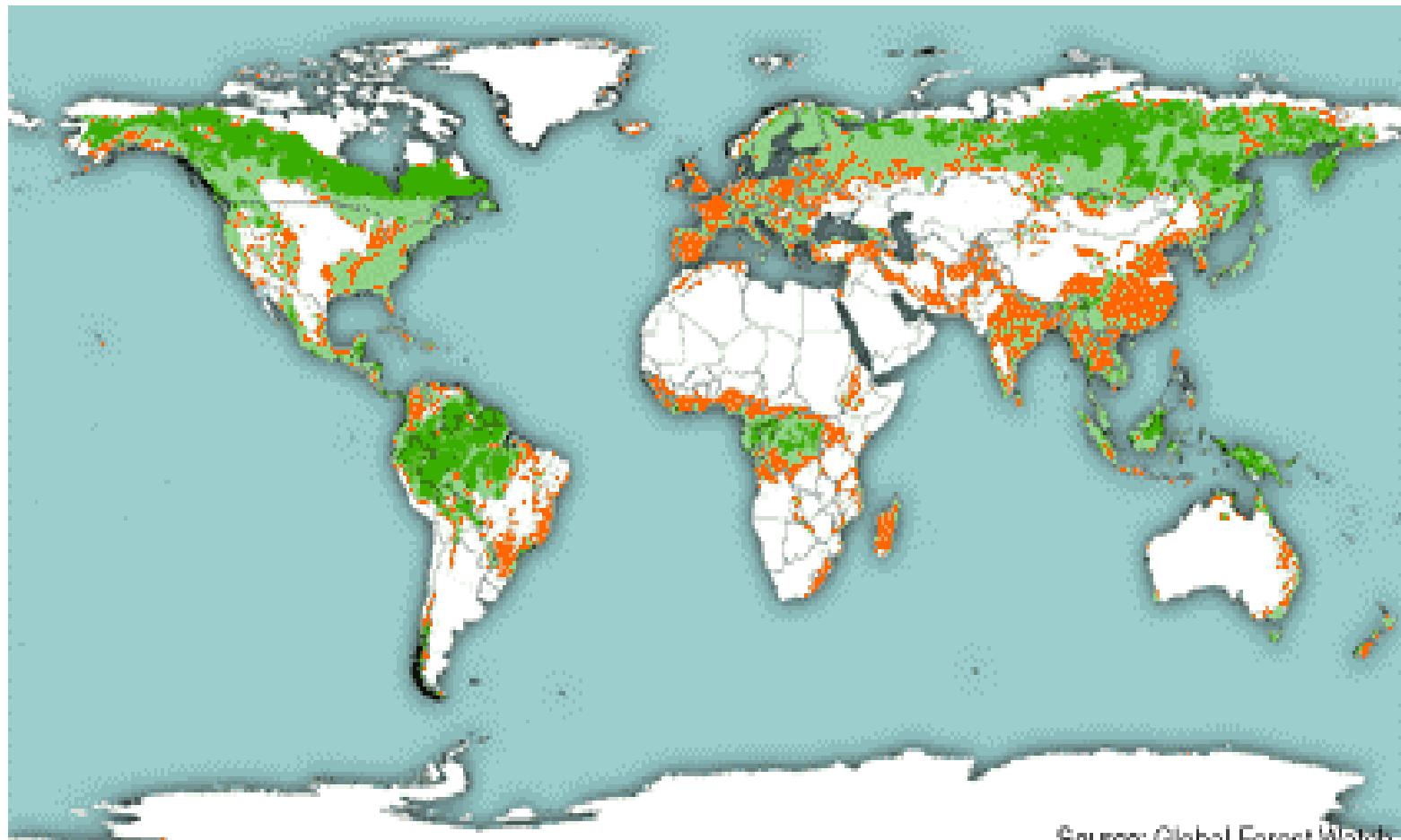
Interactions between management and climate



Dark green : primary forest

Light green : secondary forest

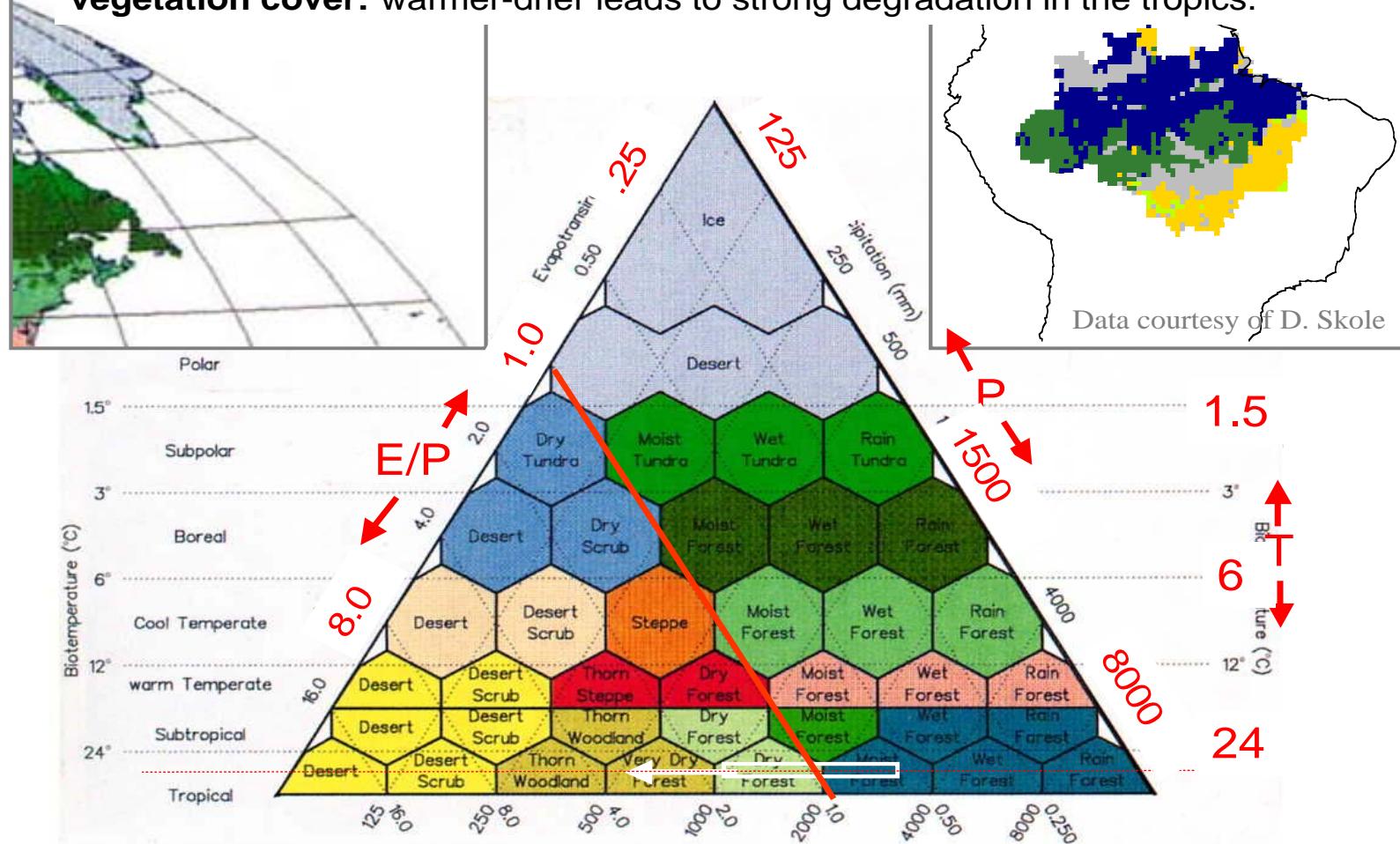
Orange : forest converted to agriculture



Source: Global Forest Watch

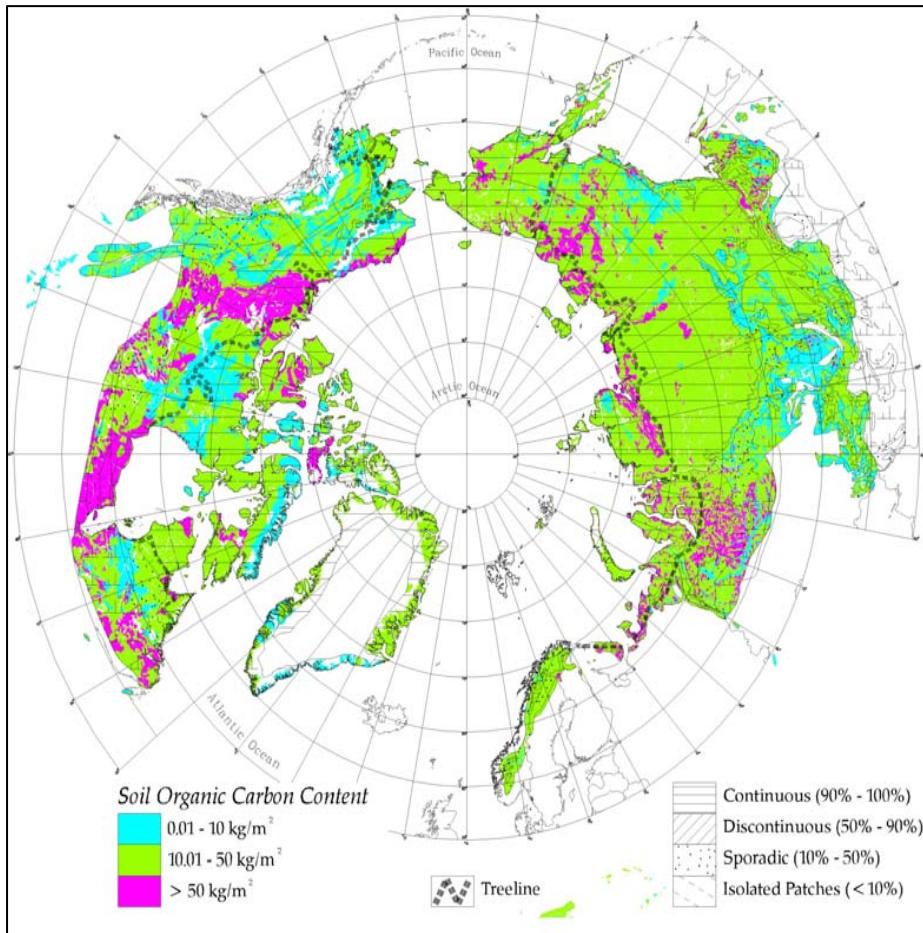
Representations of biosphere in global models: tropical forest dyeback

Holdridge Life Zones & potential vegetation: **Mean T, Precip, and E/P control vegetation cover:** warmer-drier leads to strong degradation in the tropics.



Holdridge life zones (Holdridge 1967)

Missing representations of biosphere in global models: frozen carbon



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

Take Home

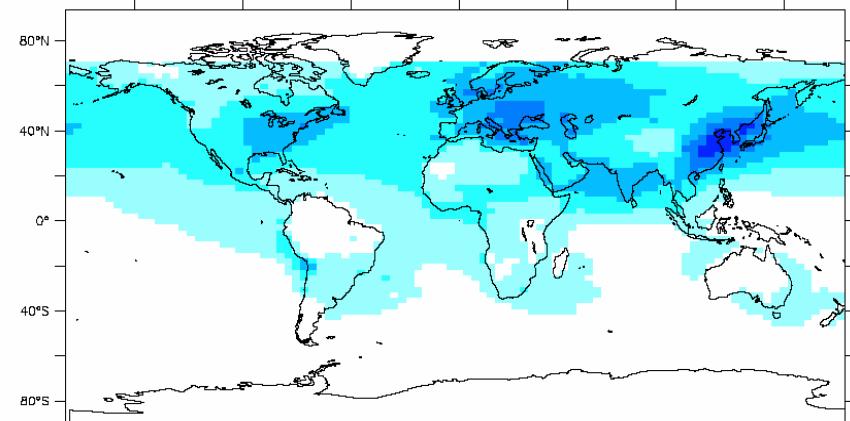
missing processes in models

- Land use forcing effects not considered not in CMIP4, partially in CMIP5
- Not in current models
 - Nitrogen (Phosphorus) limitations on sinks
 - Disturbance regimes
 - Permafrost, peat decomposition
 - Species composition and traits

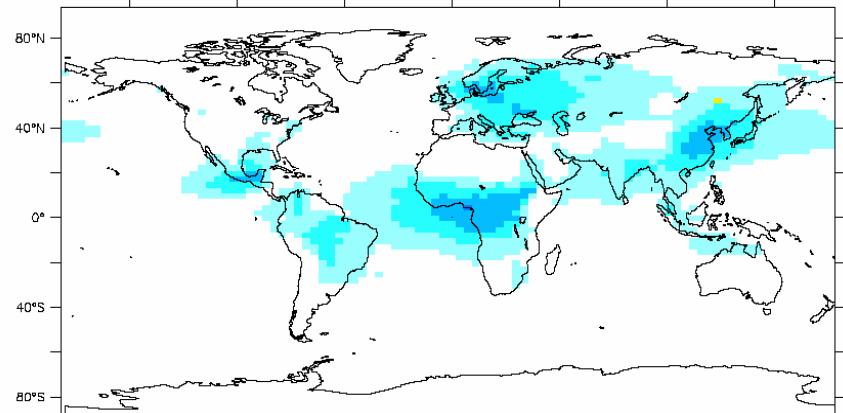
Aerosols – carbon interactions

Aerosols have a regional climate effect

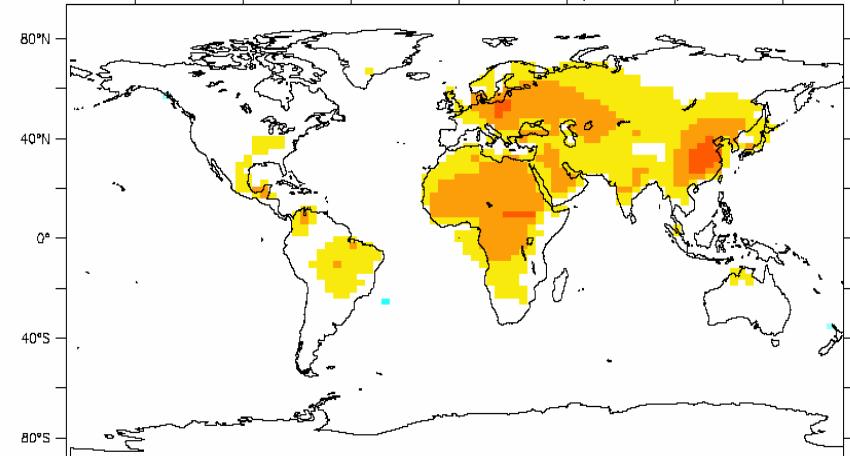
Sulfates W m^{-2}



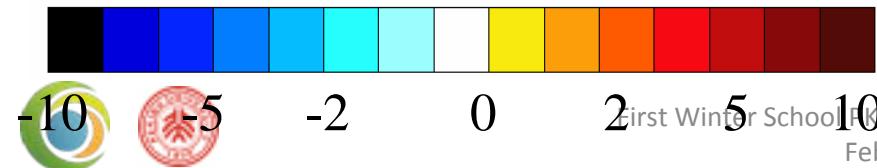
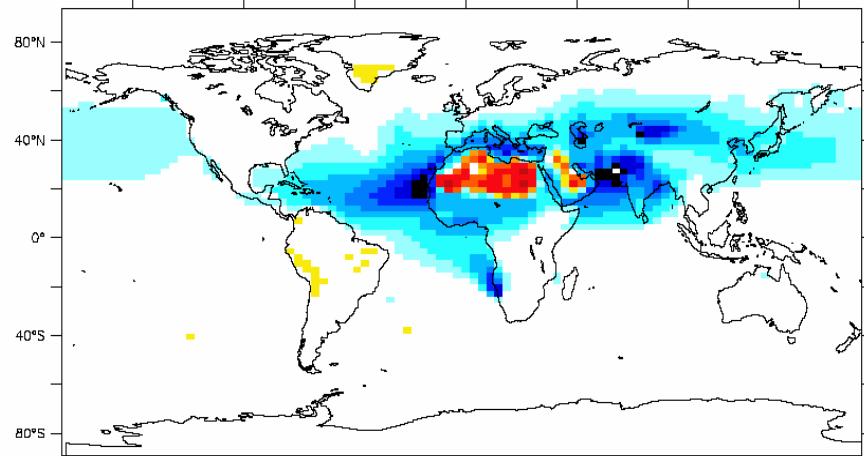
Organic aerosols



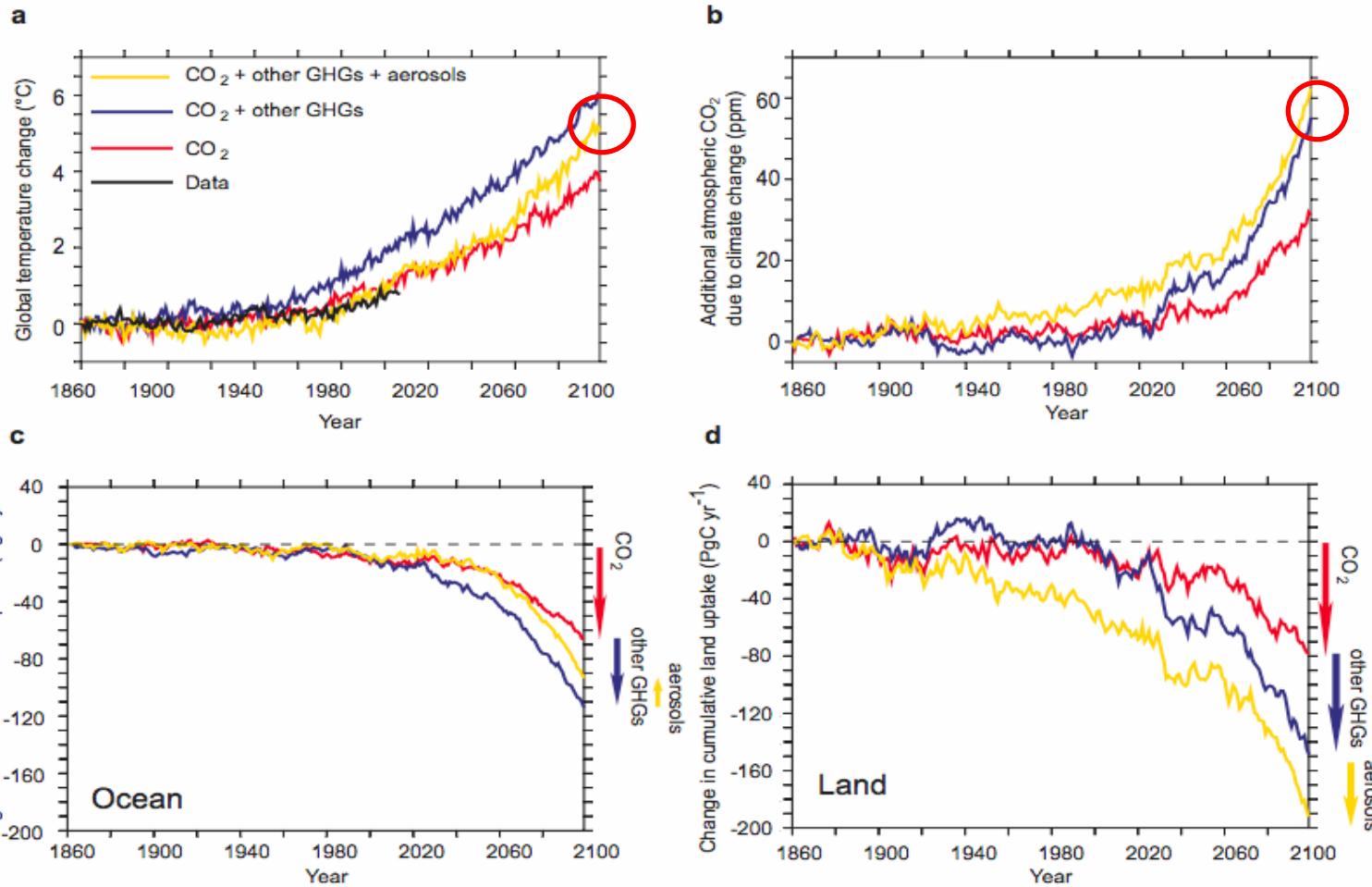
Black carbon (soot)



Dust



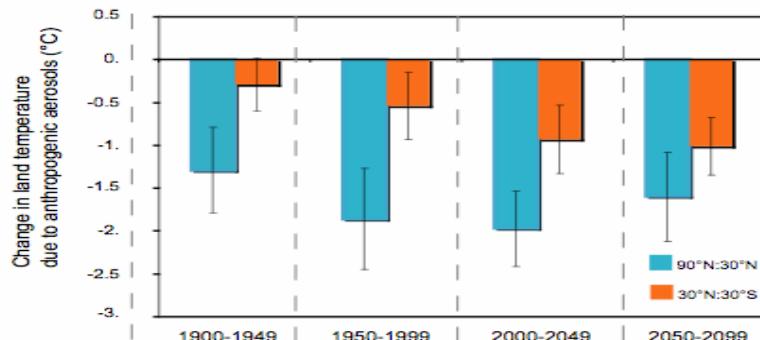
Aerosols change the carbon-climate feedbacks



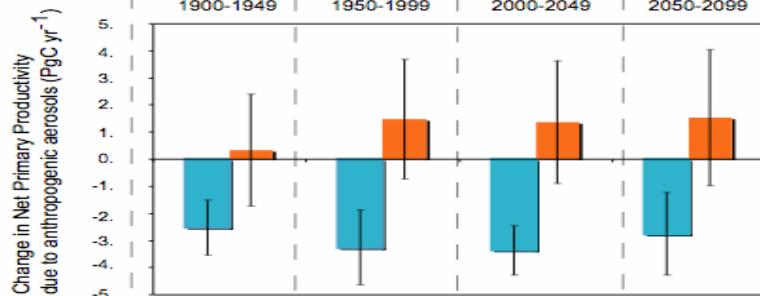
Unexpectedly, including sulfate aerosols further increases CO_2 by 2100, although it cools the climate by 0.51° C !!!!!

Regionally distinct impact of sulfate aerosols cooling on land sinks

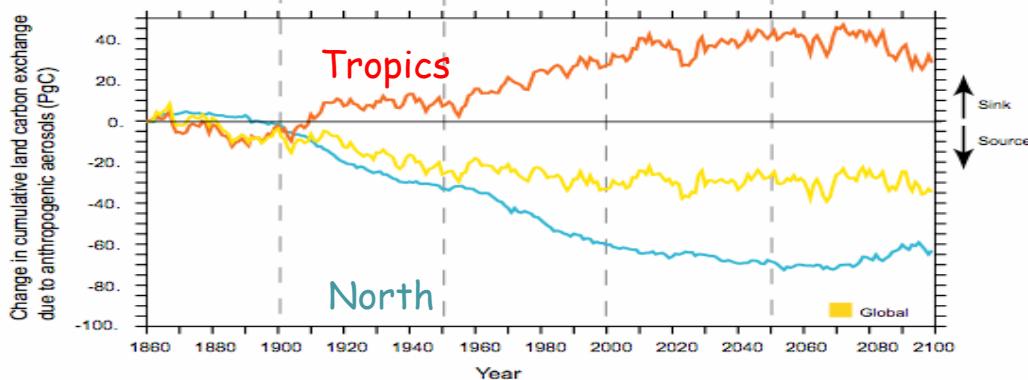
a



b



c



Effect of aerosols:

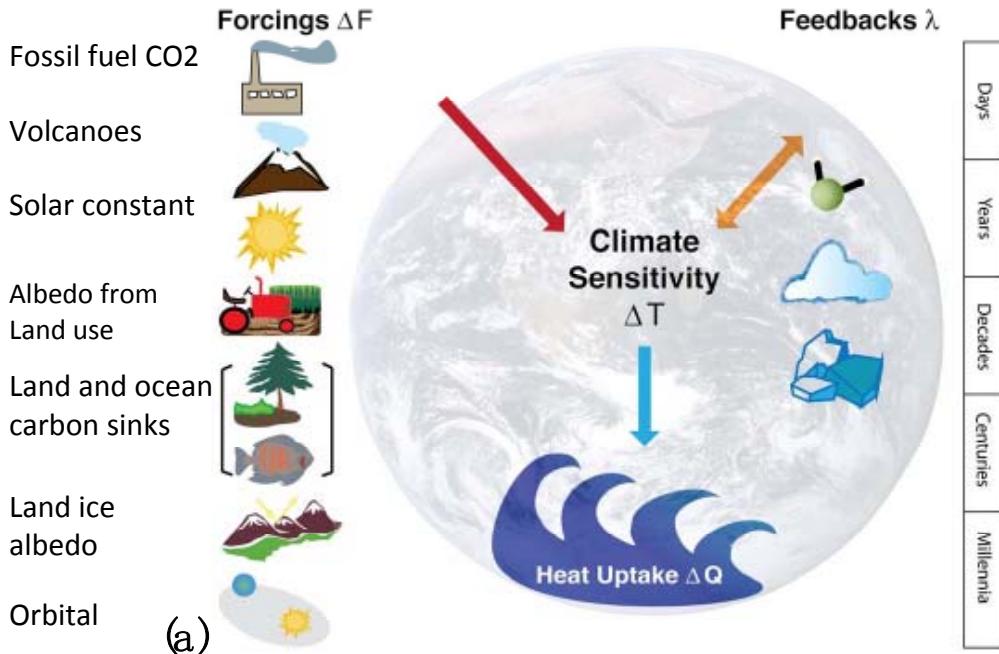
Tropics : sinks increase
NPP increase

North : sinks decrease
NPP decreases

Globe :
net *decrease* in C sink relative
to model without aerosols

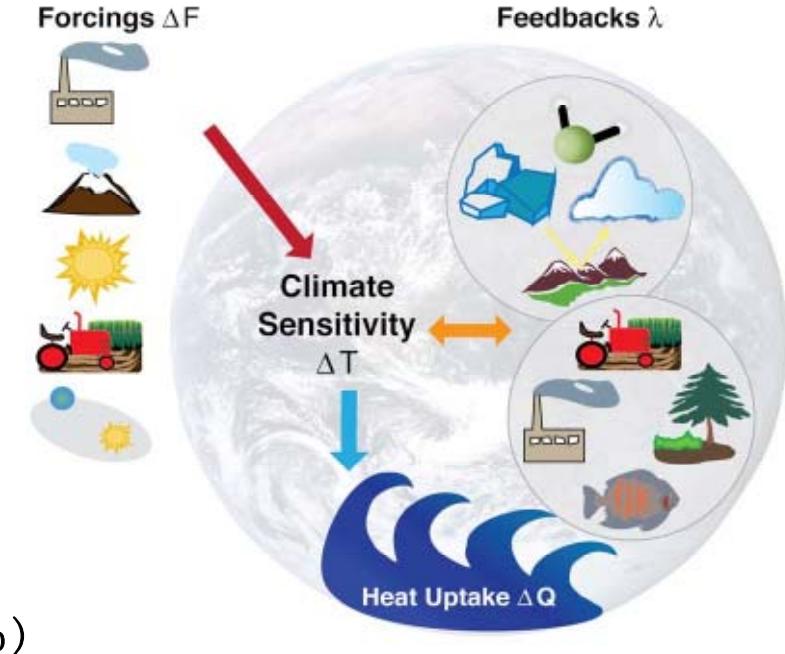
Feedbacks and climate sensitivity definition

In absence of feedback $2\text{CO}_2 \rightarrow 1^\circ \text{ C}$ warming



Charney sensitivity
 $3^\circ \text{ C per } 2\text{x CO}_2$

Only fast feedbacks (water vapour, clouds, sea-ice)



Long term climate sensitivity
 $6^\circ \text{ C per } 2\text{xCO}_2$

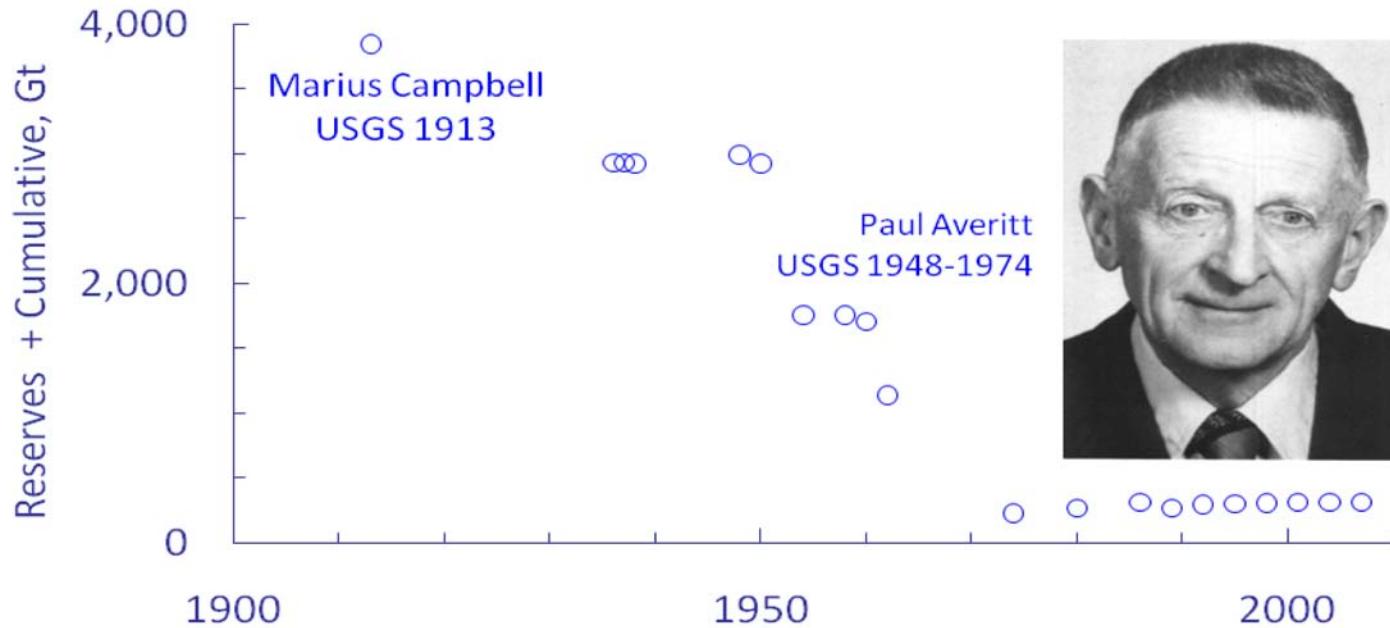
Only fast feedbacks (water vapour, clouds, sea-ice)

Positive and Negative feedbacks

- Positive feedbacks
 - Respiration sensitivity to temperature
 - GPP saturation and nutrient limitations
 - Permafrost C decomposition
 - Increased boreal fires
 - Increased extreme events (drought, storms)
 - Tropical forest dyeback
- Negative feedbacks
 - CO₂ fertilization
 - Trees Northward expansion
 - N-deposition ; Increased N fixation
 - Increased radiation ?
 - Coal and oil resource limitation ; economic crisis



B R)01+2<\$(\$%\$())



- G! \%18)& \$)q 1%5)S5\$%Z)01"5@2(" %\$Z()
- G! *+" 2I ; \$%6)%\$(J 156\$6)&1)@24@(8)P%18)8 559)\$595\$\$%#Z)
49/ &559)%\$(%\$%)@28%4+u)(\$+8 ()+85+(&Kc)5 @\$(()& 7@-) J)&1
Y-LLL)P\$\$&6\$\$J -)= 7&5)[nH)8 75)P%18)+8 \$+("%8 \$5&)f Lk)%\$@; \$%
- G! Y[)48 \$()21= \$%& +5)5)YeY[)

--

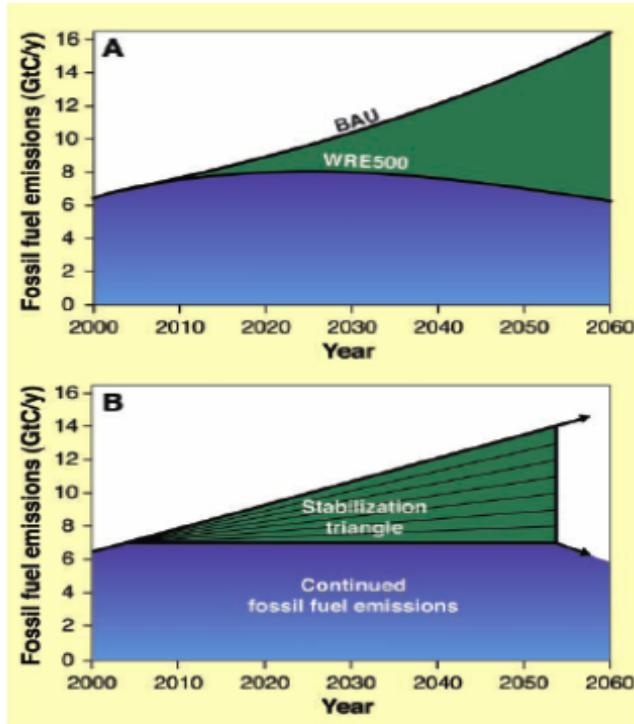
Coal reserves used by successive IPCC reports

q 1%5)S5\$%Z) 01"5@(" %\$Z)	*%1; \$6)%@; \$%#Z) %(\$%\$(-)W&	667415+2%@; \$%#Z) %(\$%\$(-)W&
YeeK)	Y-L[e)	M K)
Yeef)	Y-L[K)	gcL)
Yeec)	ecH)	[-[gc)
KLLY)	ecH)	HLe)
KLLH)	eLe)	HHe)
KLLM)	cHM)	YcL)

- G! . / \$(@5+%1)%\$J 1%R<SR)%\$P\$%\$5@()& \$)Yeef)q S0)(" %\$Z()
- G! : 1= 5= +%)&\$56)5)J %1; \$6)%@; \$%#Z)%(\$%\$(-)= +()51&\$6)#Z)
q \$%\$%W%\$2+56)r1%0)R@ 56Z%1P& \$)W\$%8 +5)S5\$%Z)q +&@)W%1" J)
u)&\$56)&1= +%)%\$J 1%59)%@; \$%#Z)@1+2+56)@1+2+8= 1% 59)8 5\$()
- G! . / \$)E*00)@1(\$)&1)" (\$)| 667415+2%@; \$%#Z)%(\$%\$(-)+56)& \$Z)+41)
@1(\$)Yeec)Q -[gcW&-)%& \$%& +5)Yeef)DgcLW&u))| 667415+2
%\$@; \$%#Z)%(\$%\$(-)+%)51=)KL)48 \$()8 +25%& +5)5)Yeec) H[)



Stabilization wedges: Solving the climate problem for the next 50 years with current technologies - S. Pacala & R. Socolow (Science, 2004)



With a carbon-climate feedback of +200ppm, how many more wedges do you need to stabilize climate ?

Conclusions

- The land carbon-climate feedback magnitude is as large as the (economic) differences among emission scenario : 30 – 200 ppm in C4MIP models
- Larger positive feedback is plausible (permafrost, disturbance)
- More intensive emission scenarios will be creating higher feedbacks, making mitigation even harder
- Another good reason for acting sooner, to pay less tribute to manage the natural carbon cycle in the future
- Need to design adaptative management strategies to make ecosystem C stocks less vulnerable to climate change, in particular the soils