The Global Carbon Cycle on Glacial/Interglacial Timescales

The Global Carbon Cycle
Bremen Graduate School **Global Change in the Marine Realm (GLOMAR)**
September 26–28 2007

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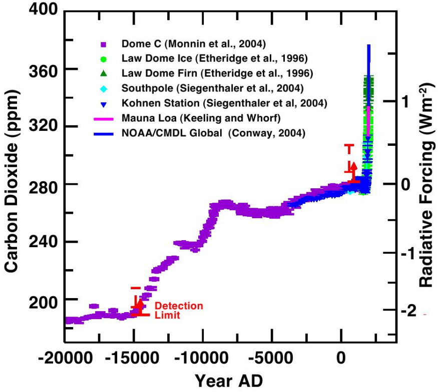
Outline

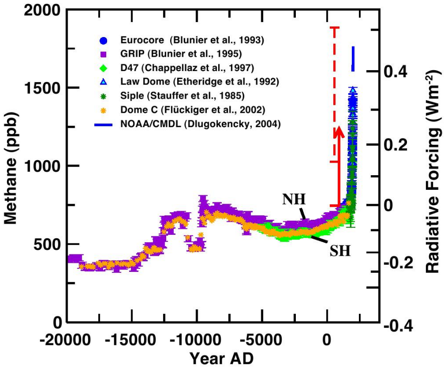
1. Introduction to the GHG problem
2. Radiative Forcing
   - Radiation
   - Greenhouse Effect
3. Ice core records
   - Ice Core Drilling
   - Overview on Ice Core Records
   - Somethings about Orbital Forcing
   - The Holocene — last 10,000 yr BP
   - Glacial/Interglacial Variation — Termination I and the last 650,000 yr

IPCC: CO_2 & CH_4 data 20,000 yr — the cause

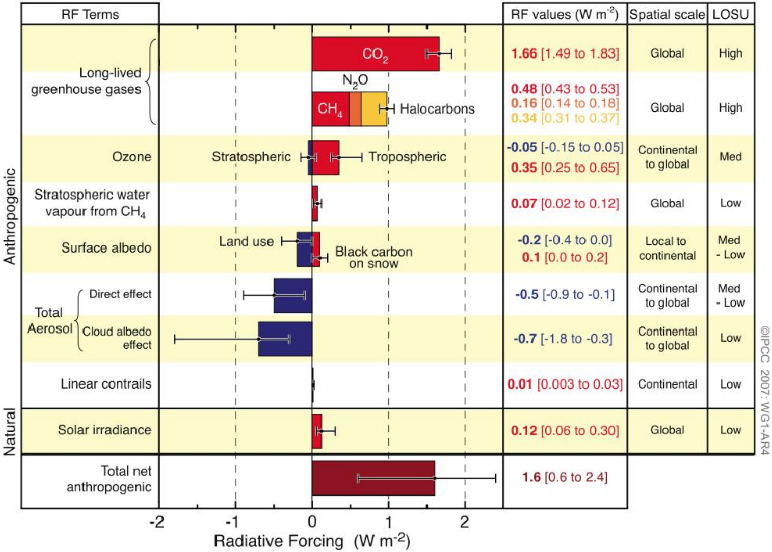
CO_2



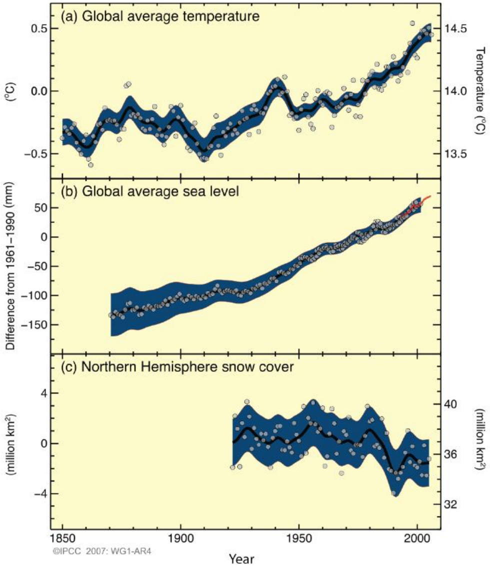
CH_4



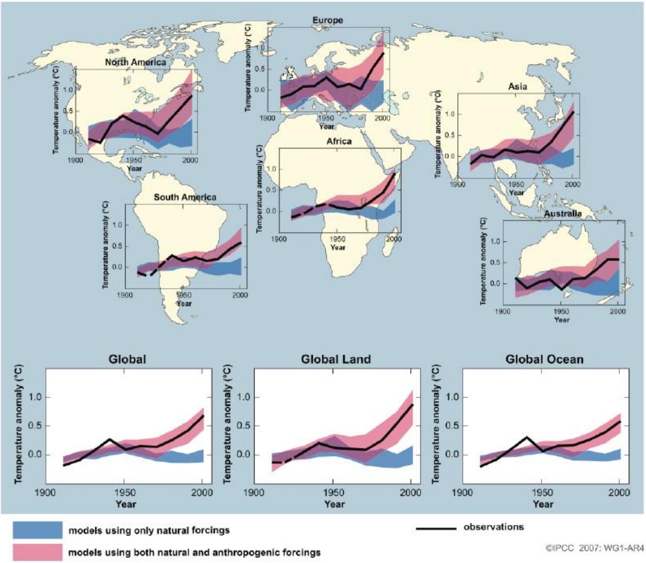
IPCC: Radiative forcing — the process



IPCC: Global responses — the effect

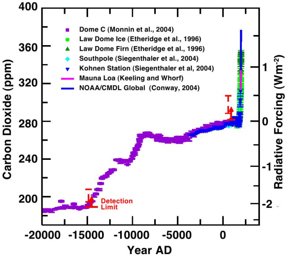


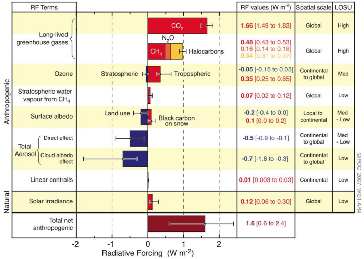
IPCC: Anthropogene versus natural

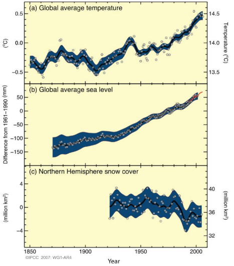


Overview Radiative Forcing

- From cause to effect: Understanding the process.
- From GHG to temperature: Understanding the radiative forcing.







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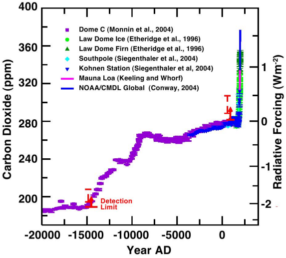
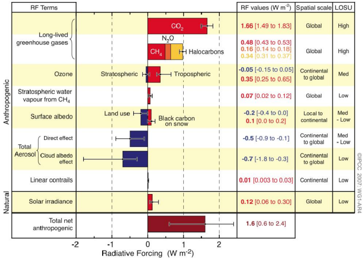
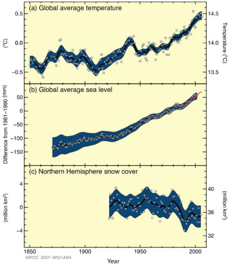
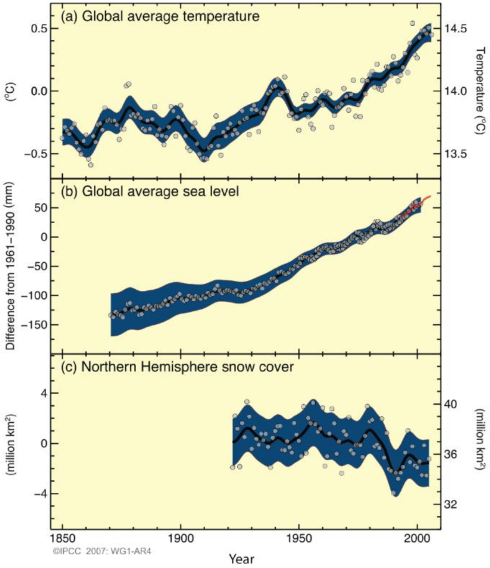


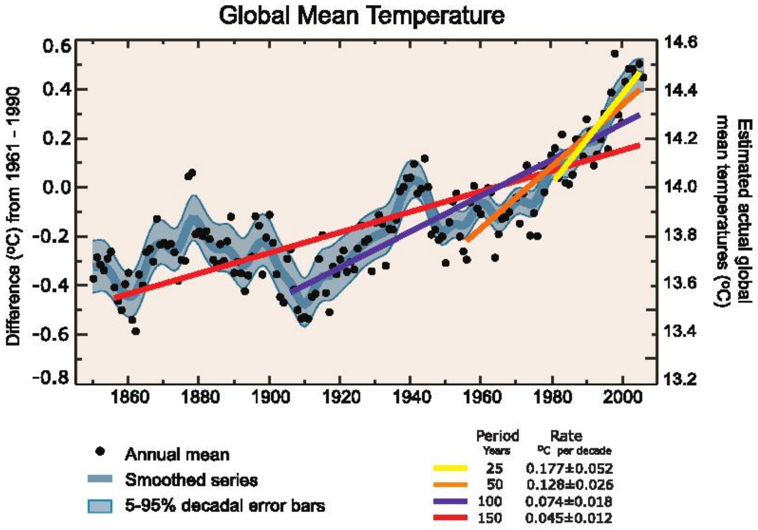




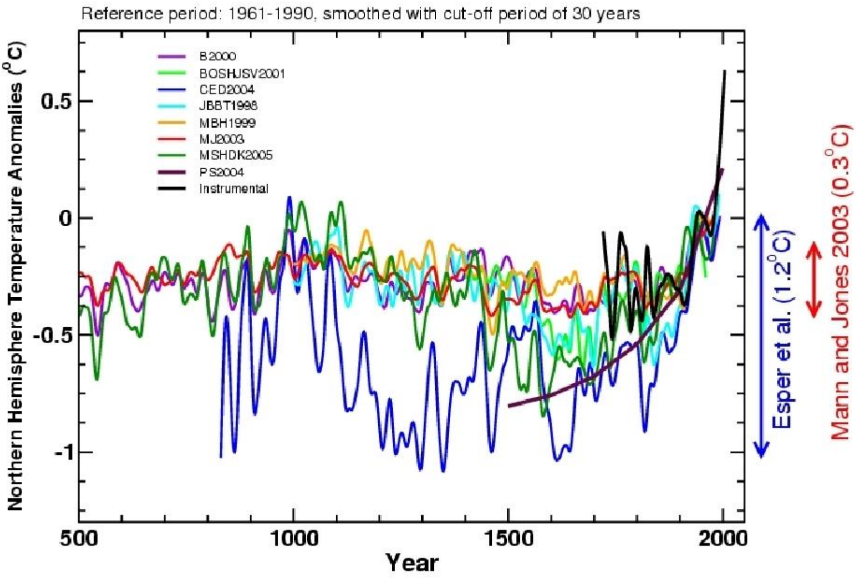
Temperature — Instrumental record



Temperature — Instrumental record II



Temperature — 1500 years — The Hockeystick



Temperature — 1500 years — The Hockeystick

Take-home message:

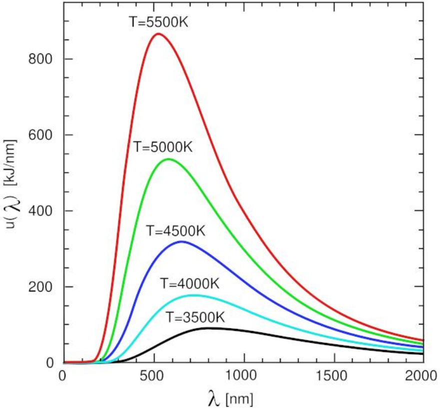
1) The anthropogenic temperature rise is beyond doubt, but details depend on quality and resolution of data sets and model-based reconstructions.

2) It is caused by changing the radiative budget of the Earth's atmosphere.

Outline

Planck's Law

Planck's Law: $$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}.$$



Black Body Radiation

Stefan-Bolzmann-Law: $R = \sigma T^4$
Stefan-Bolzmann-Constant: $\sigma = 5.6710^{-8} W/(m^2 \cdot K^4)$
Solarconstant: $S = 1367 W/m^2$.
Albedo: $\alpha = 0.3$

Steady state (without atmosphere):

$$\text{Incoming} = \text{Outgoing}$$
$$S(1-\alpha)\pi r^2 = R 4\pi r^2$$

$$T_{e,0} = \left(\frac{S(1-\alpha)}{4\sigma}\right)^{(1/4)}$$

$$T_{e,0} = 255K(-18^\circ C)$$

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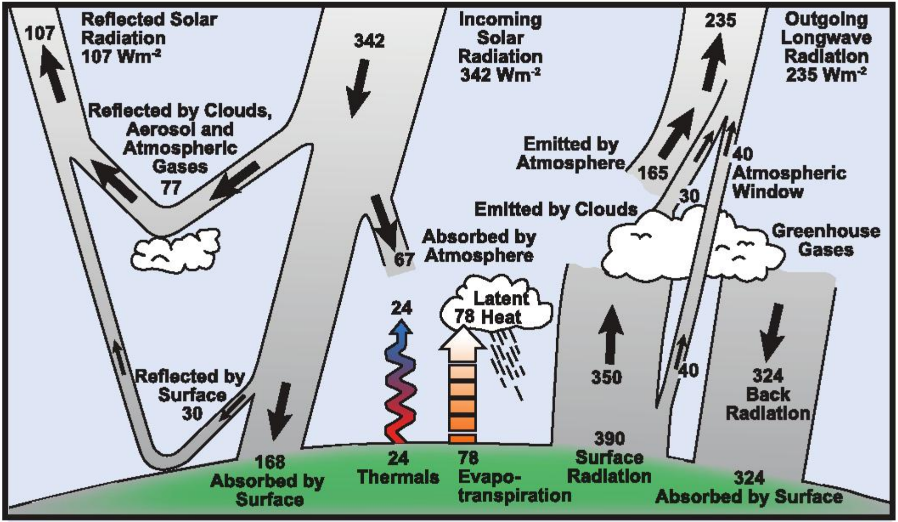
Energy Budget of Atmosphere



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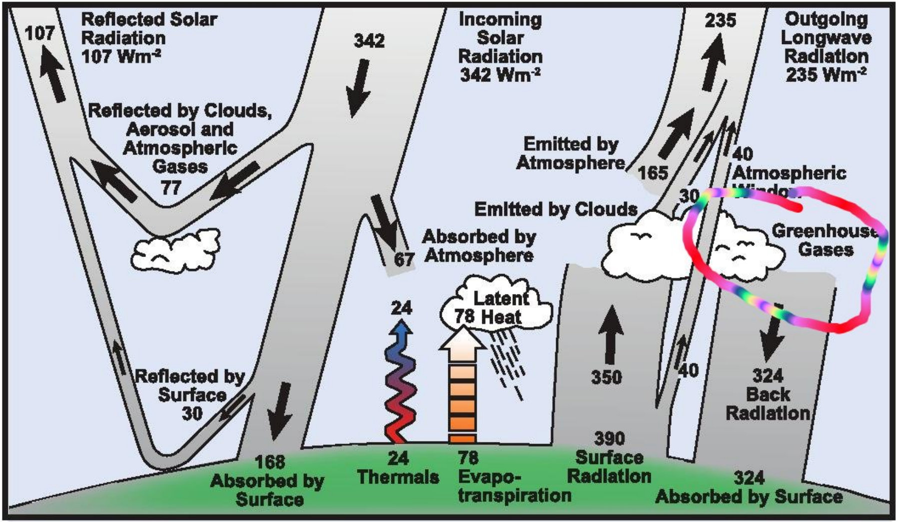
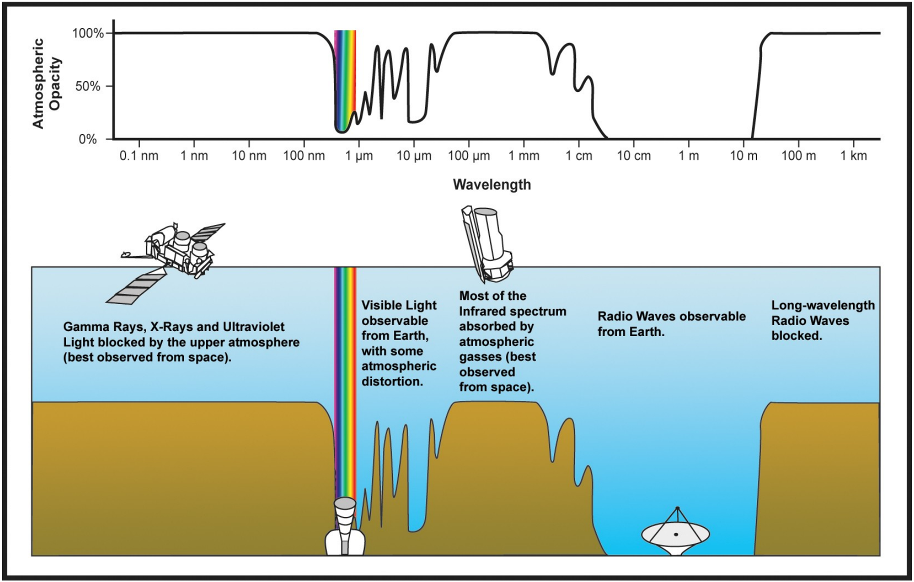
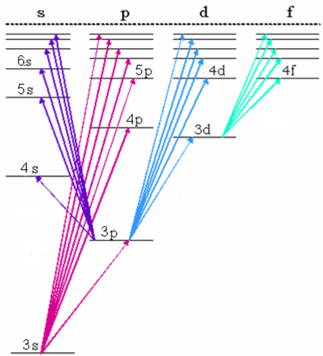


Outline

Atmospheric Spectral Transmission



Some Bacis about Spectroscopy



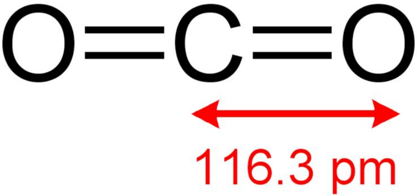
Transition corresponds to a specific energy E and frequency after

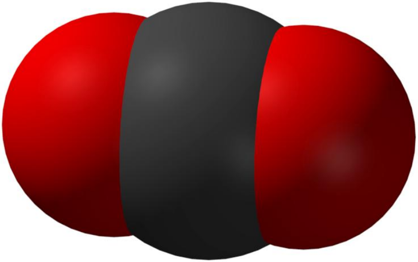
$$E = h \cdot \nu$$

h: Planck's constant; $h \sim 6.6 \times 10^{-34}$Js

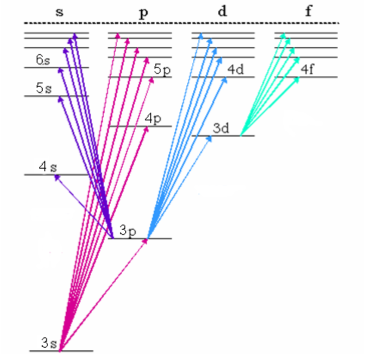
ν: frequency [Hz]

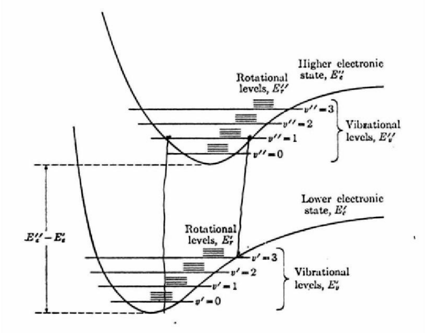
CO_2 — A Molecule





Molecules





Additional transitions through the possibility of rotation and vibration.

Possibilities for Gases to Absorb Energy

Process	Energy	Bandwidth
Atoms and Molecules		
Excitation of electrons	eV	VIS to UV
Finestructure	10^{-5} eV	far IR to sub cm
Hyperfinestructure	10^{-6} eV	cm
Molecules only		
Vibration	10^{-1} eV	IR
Rotation	10^{-3} eV	mircowave to IR

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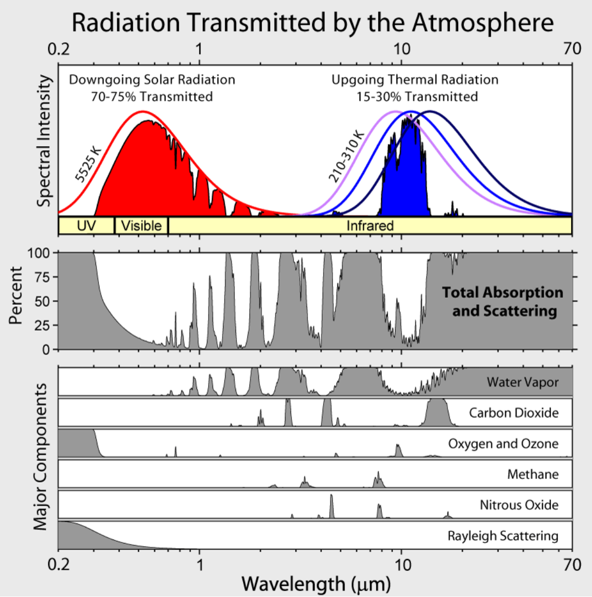

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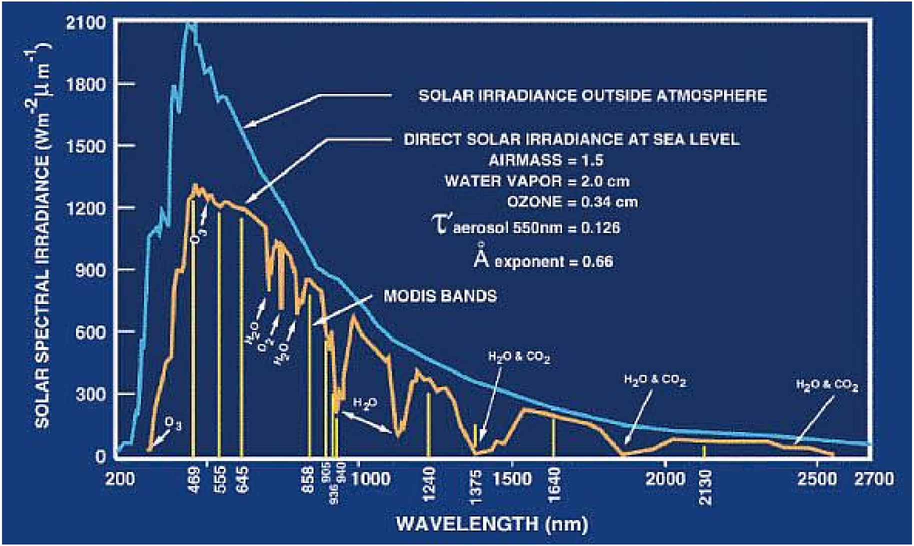


Radiative Forcing — GHG I

Radiative Forcing (RF) is calculated with Radiative Transfer Models and comes up with different equations for every agent.

agent	equation	C_o
CO_2	RF = 5.35 W m^{-2} $\ln(CO_2/CO_{2,o})$	278 ppm
CH_4	RF = 0.036 W m^{-2} $\left(\sqrt{CH_4} - \sqrt{CH_{4,0}}\right) - \left(f[CH_{4,}, N_2O_0] - f[CH_{4,0,}, N_2O_0]\right)$	742 ppb
N_2O	RF = 0.12 W m^{-2} $\left(\sqrt{N_2O} - \sqrt{N_2O_0}\right) - \left(f[CH_{4,o,}, N_2O] - f[CH_{4,0,}, N_2O_0]\right)$	272 ppb
CFC-11	RF = 0.25 W m^{-2} $(CFC\text{-}11 - CFC\text{-}11_0)$	0 ppt
CFC-12	RF = 0.32 W m^{-2} $(CFC\text{-}12 - CFC\text{-}12_0)$	0 ppt

Radiative Forcing — More on CO_2

Radiative forcing (RF): $RF(CO_2) = 5.35 \text{ W m}^{-2} \cdot ln\frac{CO_2}{CO_{2,0}}$

$CO_{2,0} = 278$ ppmv

Three examples:

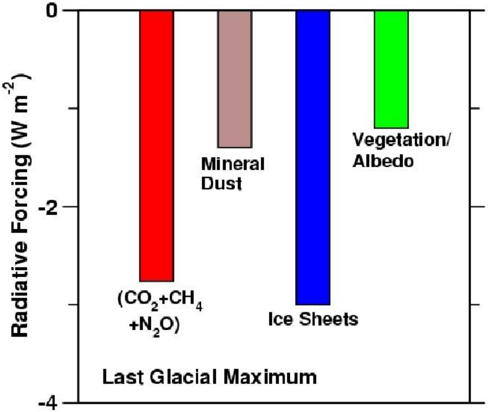
When	CO_2 ppmv	ΔCO_2 ppmv	RF W m^{-2}	All GHG W m^{-2}
Today	383	+105	+1.7	2.7
2× CO_2	556	+278	+3.7	???
LGM	180	–98	– 2.3	–2.8

Radiative forcing of fossil fuel C emission is on the order of the effect from between LGM and preindustrial.

Radiative Forcing — GHG II

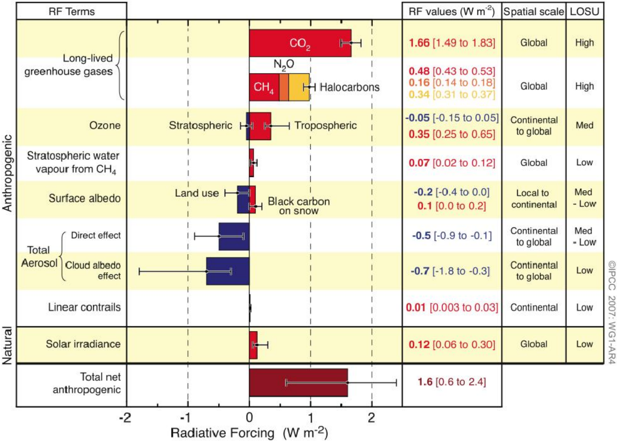
Gas	Current Amount	Increase	Radiative forcing (W m^{-2}) < 1750	1750-2007
H_2O			94	-
CO_2	383 ppm	105 ppm (38%)	50	1.71
CH_4	1745 ppb	1045 ppb(150%)	1.1	0.48
N_2O	314 ppb	44 ppb (16%)	1.25	0.16
CFC-11	268 ppt			0.07
CFC-12	533 ppt			0.17
CFC-113	84 ppt			0.03
Other CFCs	102 ppt			0.01
HCFC-22	69 ppt			0.03
Preindustrial Greenhouse Forcing			146	
Anthropogenic Greenhouse Forcing				2.66

Radiative Forcing — LGM



Radiatiove Forcing (LGM) is one of serveral others and of the order of that from ice sheets.

Radiative Forcing — today



Biggest uncertainty for the anthropogenic RF is the effects from aerosols.

From CO_2 to W m^{-2} to ΔTemperature, I

Climate Sensitivity

Radiative forcing (RF) after reaching a new steady state:

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Stefan-Bolzmann-Constant: $\sigma = 5.6710^{-8} W/(m^2 \cdot K^4)$

$T_{e,0} = 255K(-18^\circ C)$

$$\Delta R = \frac{\delta R}{\delta T}|_{T=T_{e,0}} \cdot \Delta T^*_{S,\infty} = RF$$

with $\frac{\delta R}{\delta T} = 4\sigma T^3$

Climate sensitivity without feedbacks λ^*

$$\lambda^* = \frac{\Delta T^*_{S,\infty}}{RF} = \frac{1}{4\sigma T^3_{e,0}}$$

$$\lambda^* = 0.26K/(W/m^2)$$

From CO_2 to W m^{-2} to ΔTemperature, I

Example: CO_2 double

Climate sensitivity without feedbacks $\lambda^* = 0.26K/(W/m^2)$

Radiative forcing (RF)

$$RF(CO_2) = 5.35 \cdot ln\frac{CO_2}{CO_{2,0}} Wm^{-2} = 5.35 \cdot ln(2) Wm^{-2} = 3.7 Wm^{-2}$$

ΔTemperature

$$\Delta T^*_{S,\infty} = \lambda^* \cdot RF = 0.26K/(W/m^2) \times 3.7Wm^{-2} \sim 1K$$

$\Delta T^*_{S,\infty}$ for $CO_2(t) = 2 \times CO_2(t_0)$ also called $\Delta T_{2\times CO_2}$

With feedbacks (albedo, water vapour content)

$\Delta T_{2\times CO_2} = [1.5 - 4.5]K$

(measurements, models, global system analysis)

$\lambda = [0.4 - 1.2]K/(W/m^2)$ Climate sensitivity

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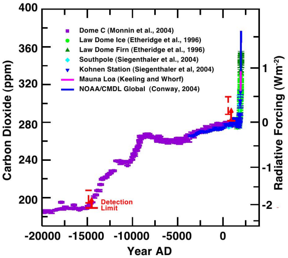
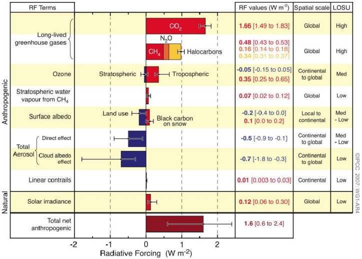
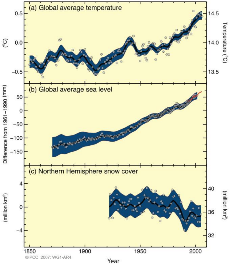
Radiative Forcing

- From cause to effect: Understanding the process.
- From GHG to temperature: Understanding the radiative forcing.







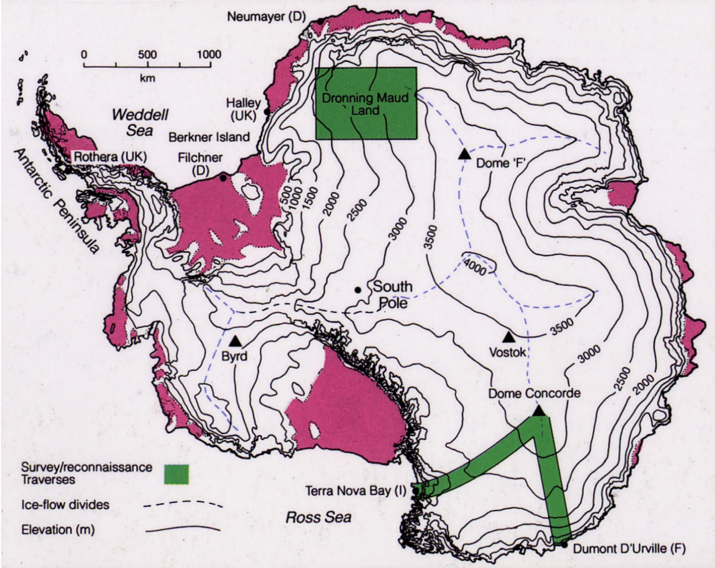
Take-home messages:

3) The amplitude in the rise in GHG from LGM to preindustrial is of similar size than from preindustrial to present.

4) The full range of observed temperature rise can not be explained solely with the rise in GHG, feedbacks in the climate system contribute a significant amount to it.

Outline

European Project for Ice Coring in Antarctica



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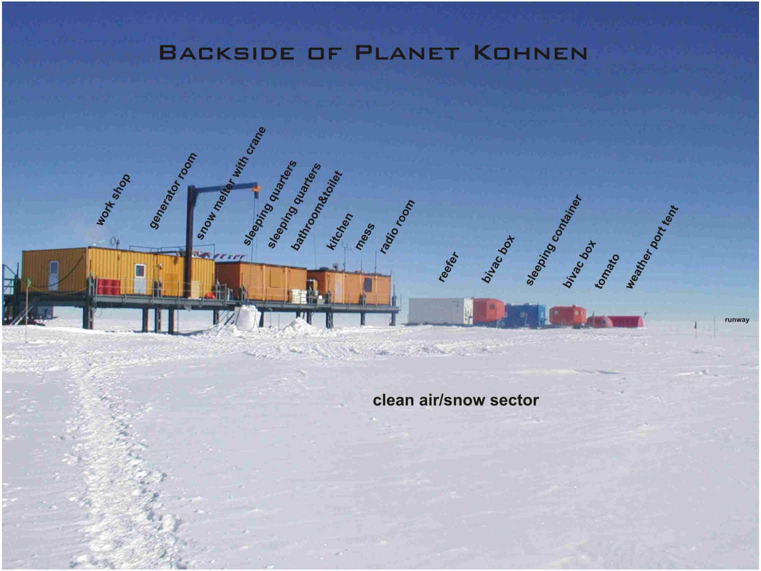

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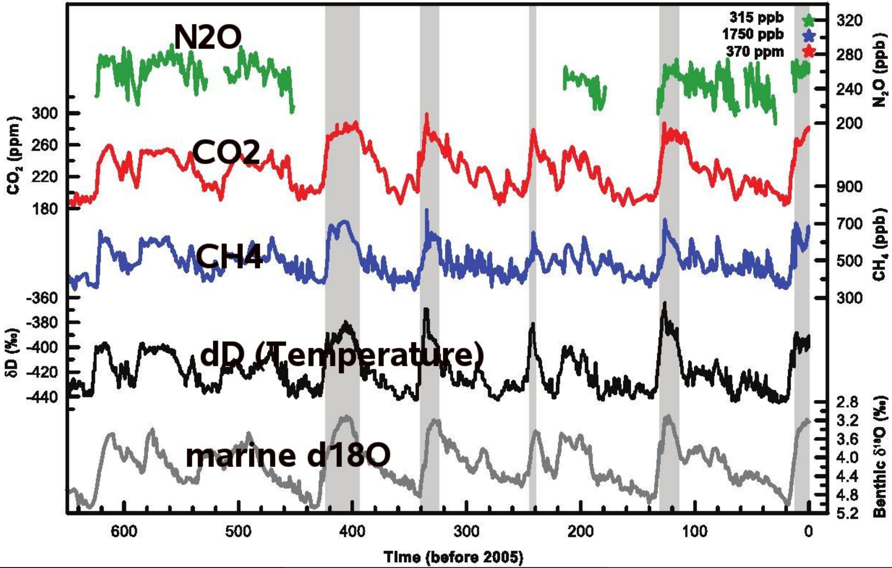
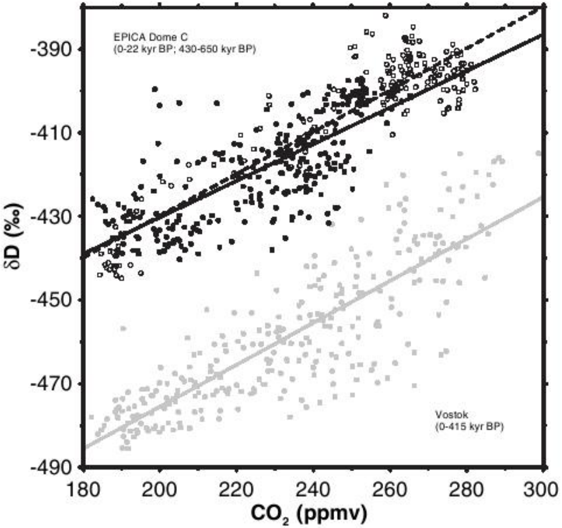
Outline

Ice cores, last 650,000 yr

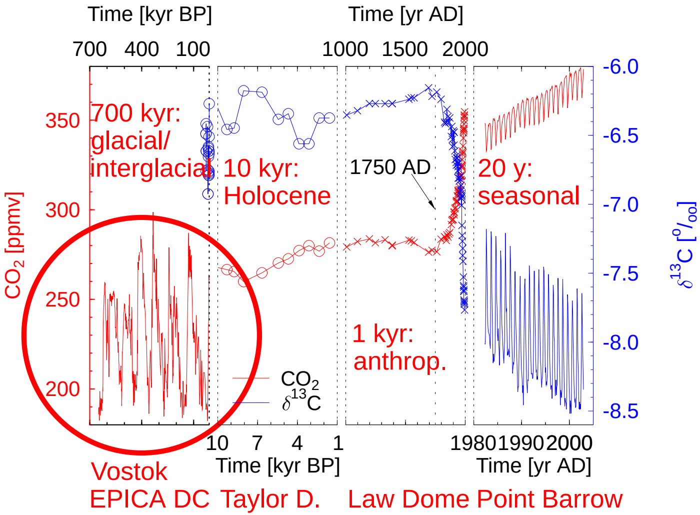
Glacial minima (180 ppmv), interglacial maxima (280 ppmv)



CO_2 and Antarctic Temperature



CO_2 on different Time Scales



Outline

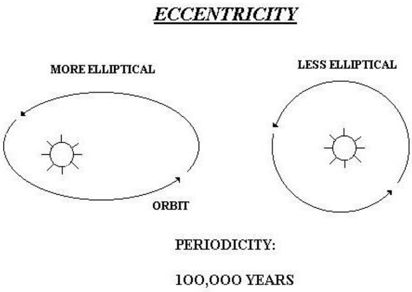
Milutin Milankovitch

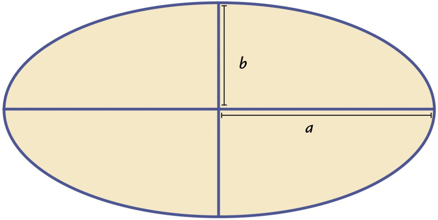
Milutin Milankovitch (1941) *Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem*

Variability of the Earth and its Position relative to the Sun

- Eccentricity
- Axial Tilt / Obliquity
- Precession

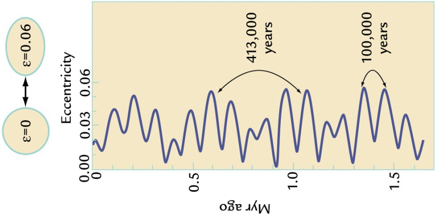
Eccentricity — $\sim$ 100,000 and 400,000 yr cycles





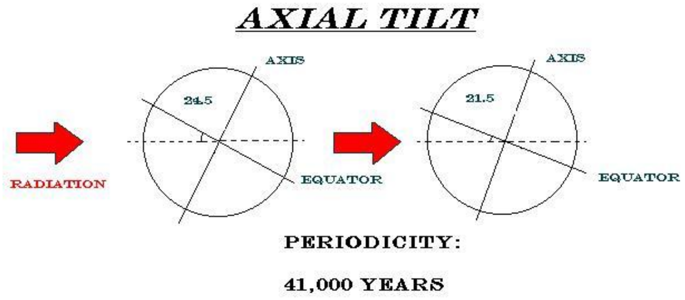
Eccentricity $\varepsilon = \frac{(a^2 - b^2)^{1/2}}{a}$

Little effect (some %) on total amount of insolation $\varepsilon \in [0.005, 0.607]$

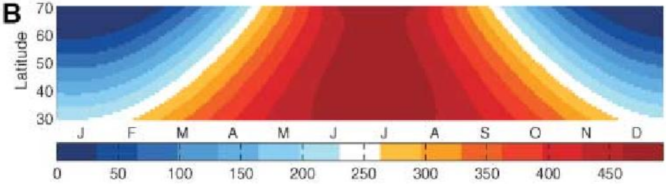


Obliquity — $\sim$ 40,000 yr cycles

Caused by Gravity of larger planets (Jupiter)

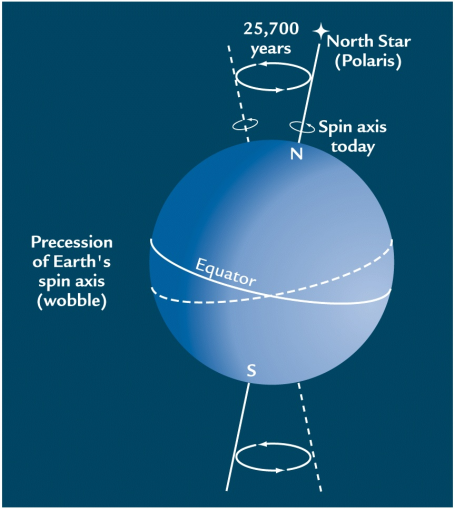


Changes the difference between seasons, especially in high latitude

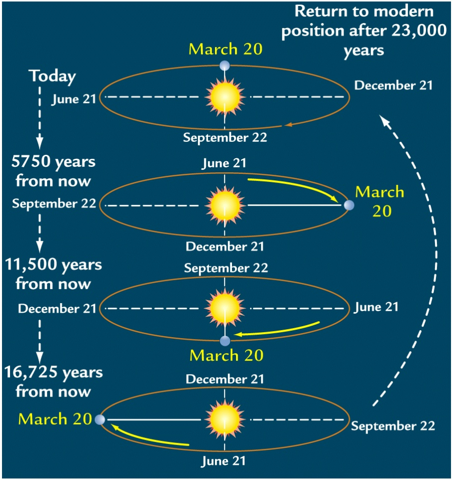


Precession — ∼ 20,000 yr cycles

Precession of the Earth's Axis



Precession of the Equinoxes



Changes the difference between seasons, especially in high latitude

Orbital Insolation at 65° N

From 40-kyr to 100-kyr world

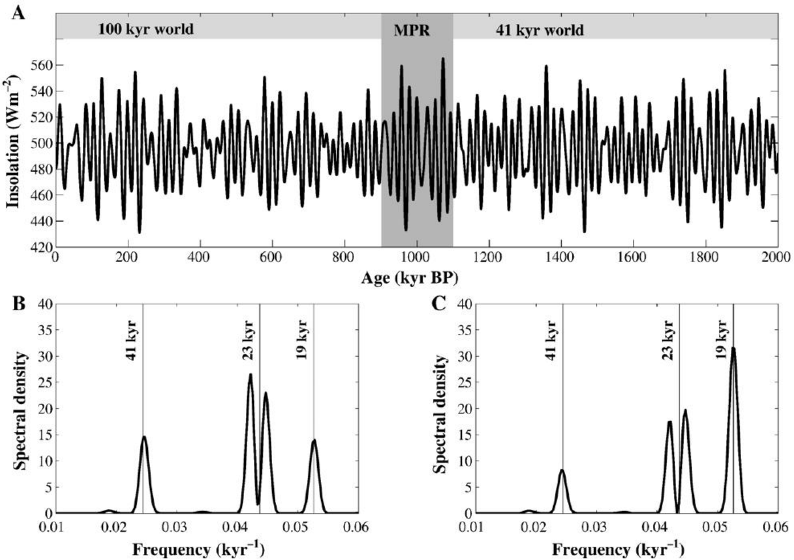
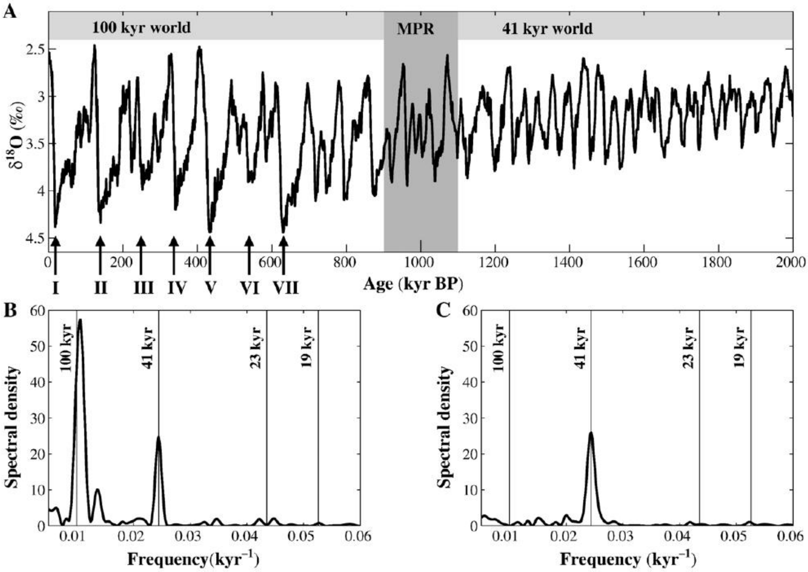


Fig. 5. Comparison of variability in insolation between the Late and Early Pleistocene. (A) Midsummer insolation at 65 °N of the last 2 Myr. (B)

Climate Sigale in benthic δ^{18}O stack LR04

From 40-kyr to 100-kyr world

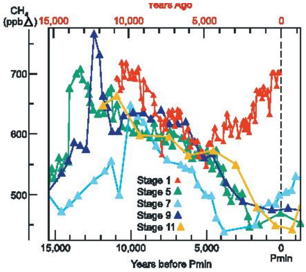


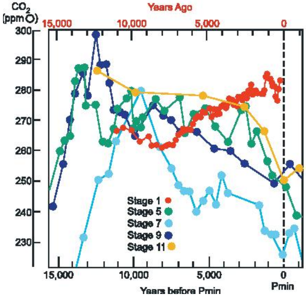
Orbital Forcing Against Paleo Records

Power in the 100 kyr band in Insolation is too weak to explain records (100k Problem). Feedbacks (e.g. land ice sheets) are important.

Outline

Ruddiman's Hypothesis on Early Anthropocene



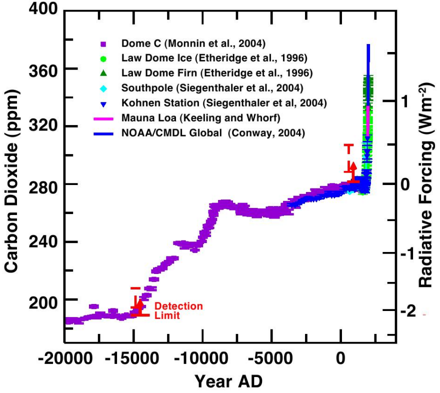


- Earlier Interglacials had drop in CO_2 and CH_4 while Holocene has a rise
- Might be caused by Early (8000 yr BP) deforestation
- Direct effect can at maximum explain 25% of the observed offset in CO_2
- Feedbacks need to account for rest 75%.
- Problem: Depends on the way Interglacials are compared, typically alined along insolation minima or maxima
- The jury is still out

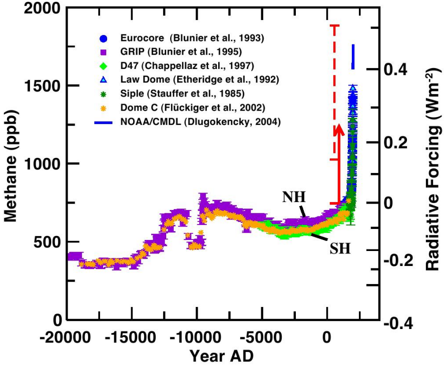
Outline

Ice cores, last 20,000 yr

CO_2



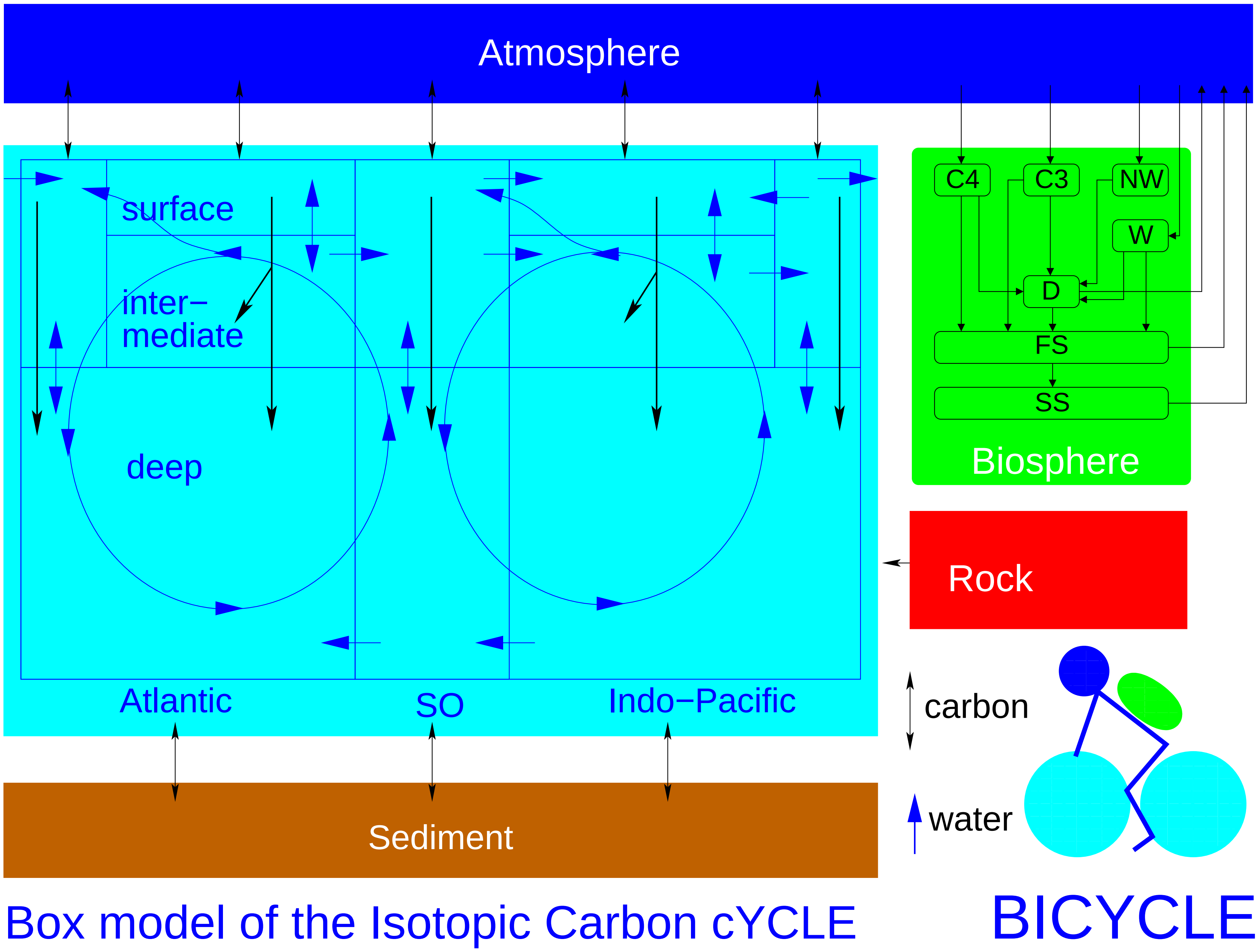
CH_4



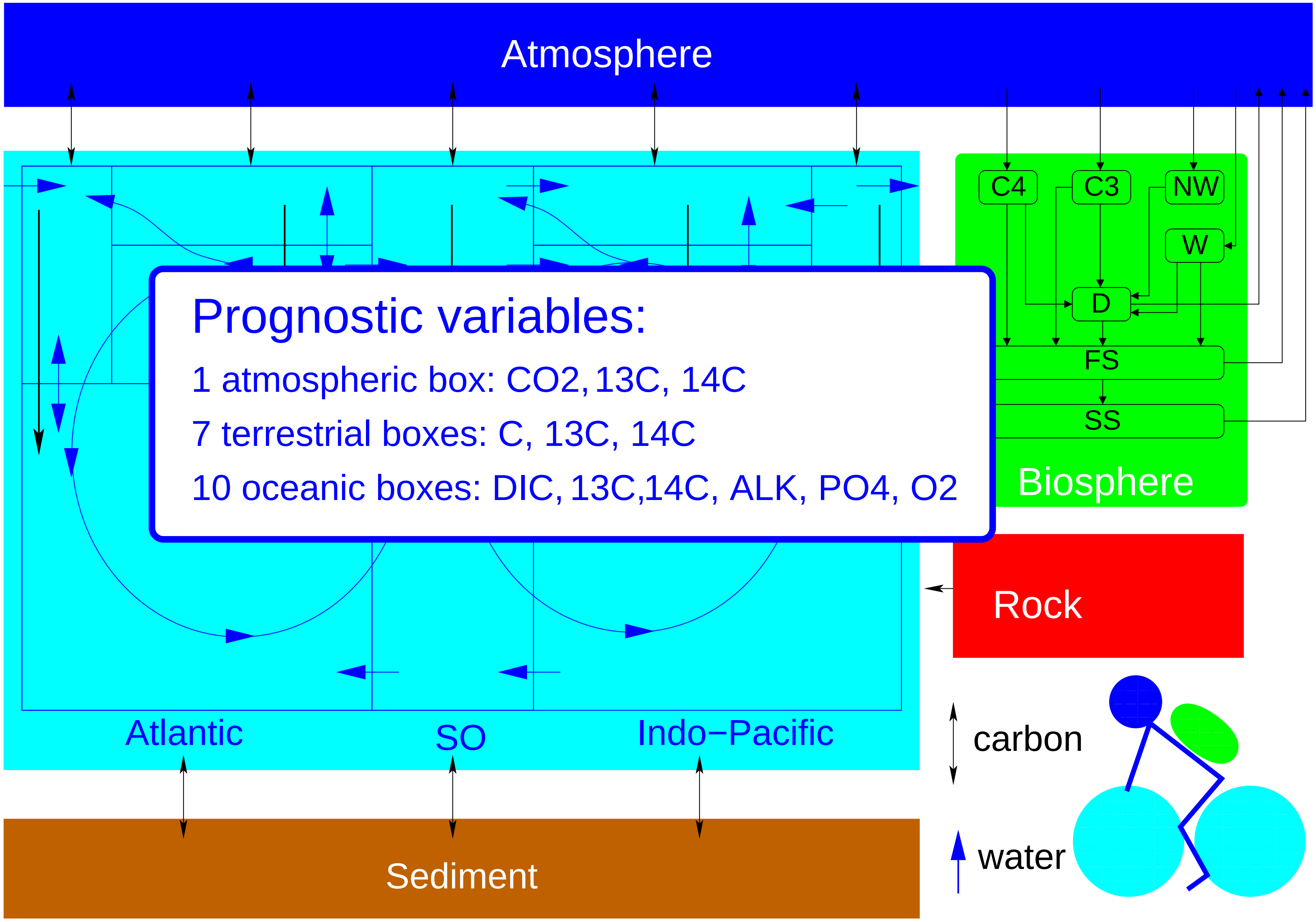
	Today	1750 AD	LGM	Δ(G/IG)	Δ(Ant)
CO_2 (ppmv)	380	280	180	100 (35%)	100 (35%)
CH_4 (ppbv)	1750	700	360	340 (49%)	1050 (150%)

Understanding the CO_2 rise

Experiments with the Carbon Cycle Box Model BICYCLE



Köhler, et al., 2005, Global Biogeochemical Cycles.



Box model of the Isotopic Carbon cYCLE

BICYCLE

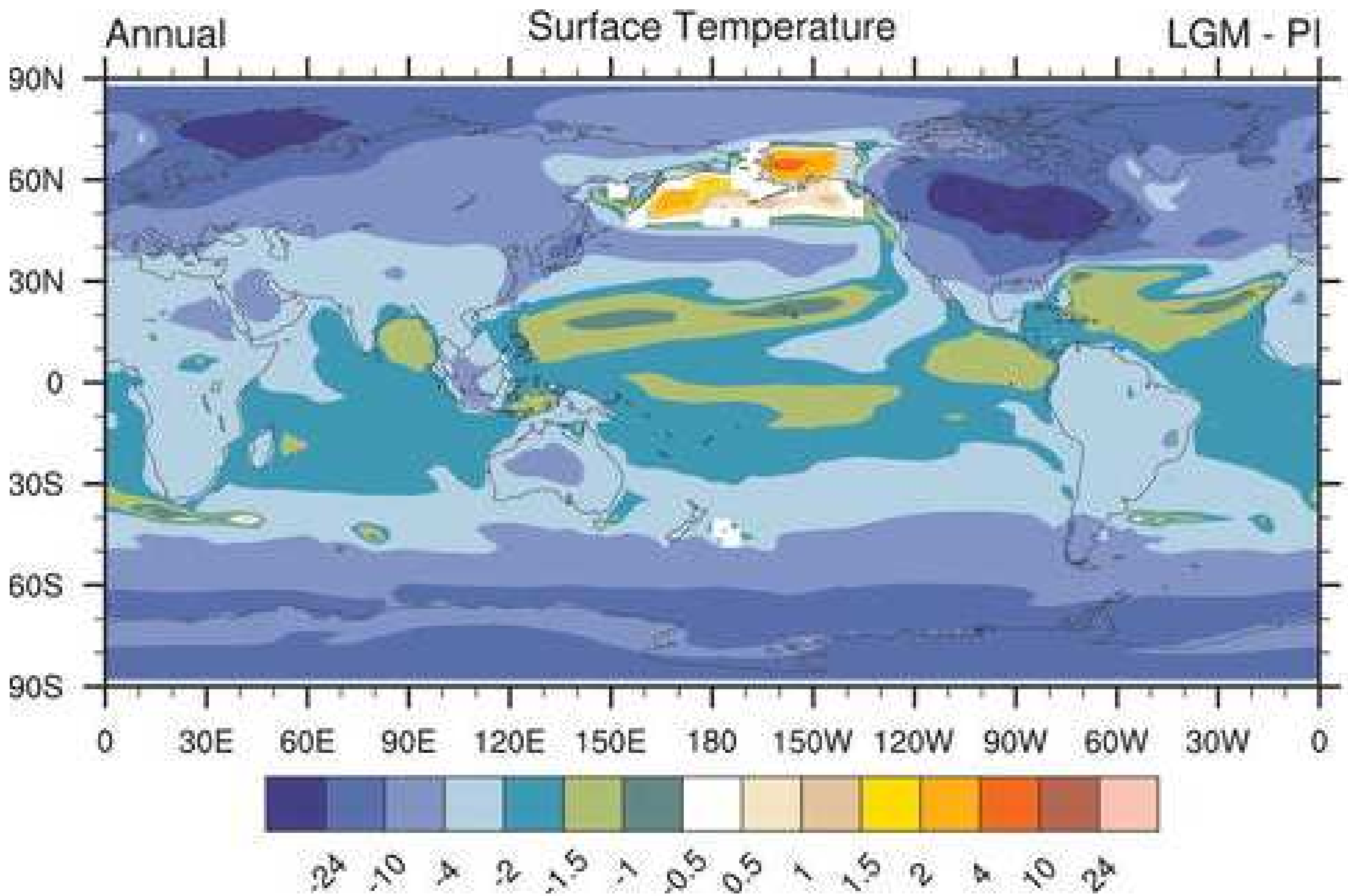
Köhler, et al., 2005, Global Biogeochemical Cycles.

Time-dependent processes:

Which	**How**	**What**	**?**
Physics (without ocean circulation)			
1 Temperature			
2 Sea level / salinity			
3 Gas exchange / sea ice			
Ocean circulation			
4 NADW formation			
5 Southern Ocean ventilation			
Biogeochemistry			
6 Marine biota / iron fertilisation			
7 Terrestrial carbon storage			
8 $CaCO_3$ chemistry			

1 Temperature

Simulation with the climate model CCSM3
LGM–Preindustrial: light blue: −(2-4)K



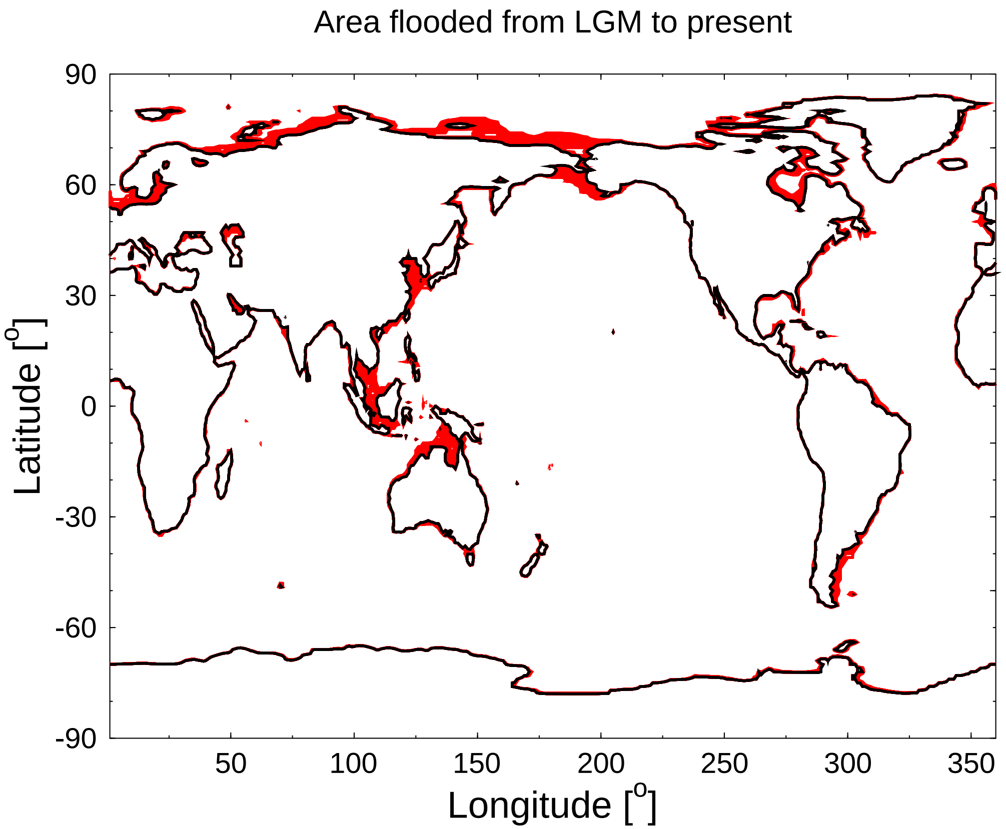
Otto-Bliesner et al., 2006

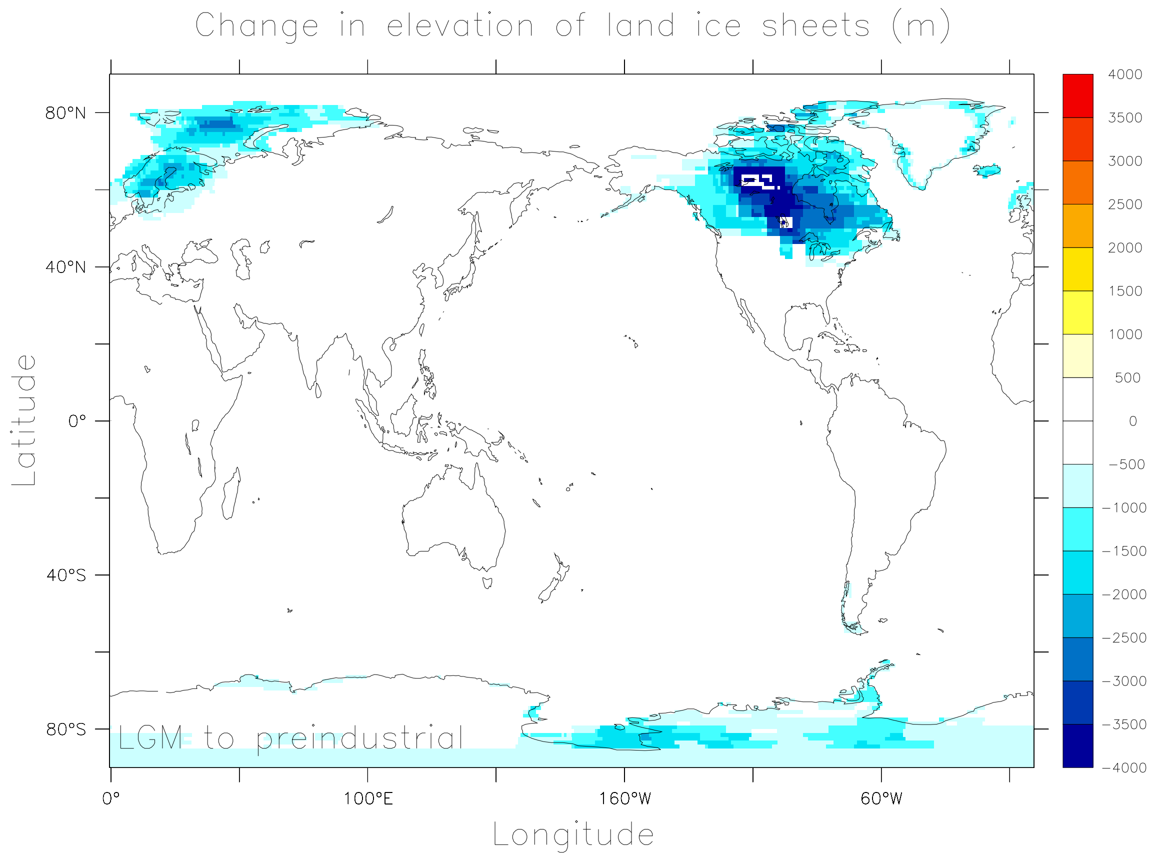
Time-dependent processes:

	Which	How (T I)	What (ppmv)	?
	Physics (without ocean circulation)			
1	Temperature	+(3–5) K	+30	!
2	Sea level / salinity			
3	Gas exchange / sea ice			
	Ocean circulation			
4	NADW formation			
5	Southern Ocean ventilation			
	Biogeochemistry			
6	Marine biota / iron fertilisation			
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

2 Sea Level / Salinity

Sea level rose during Termination I by 125 m; salinity dropped by 3%





Bathymetry from Scripps Institiute of Oceanography

from ICE-5G, Peltier, 2004

Time-dependent processes:

	Which	How (T I)	What (ppmv)	?
	Physics (without ocean circulation)			
1	Temperature	+(3–5) K	+30	!
2	Sea level / salinity	+125 m	−15	!
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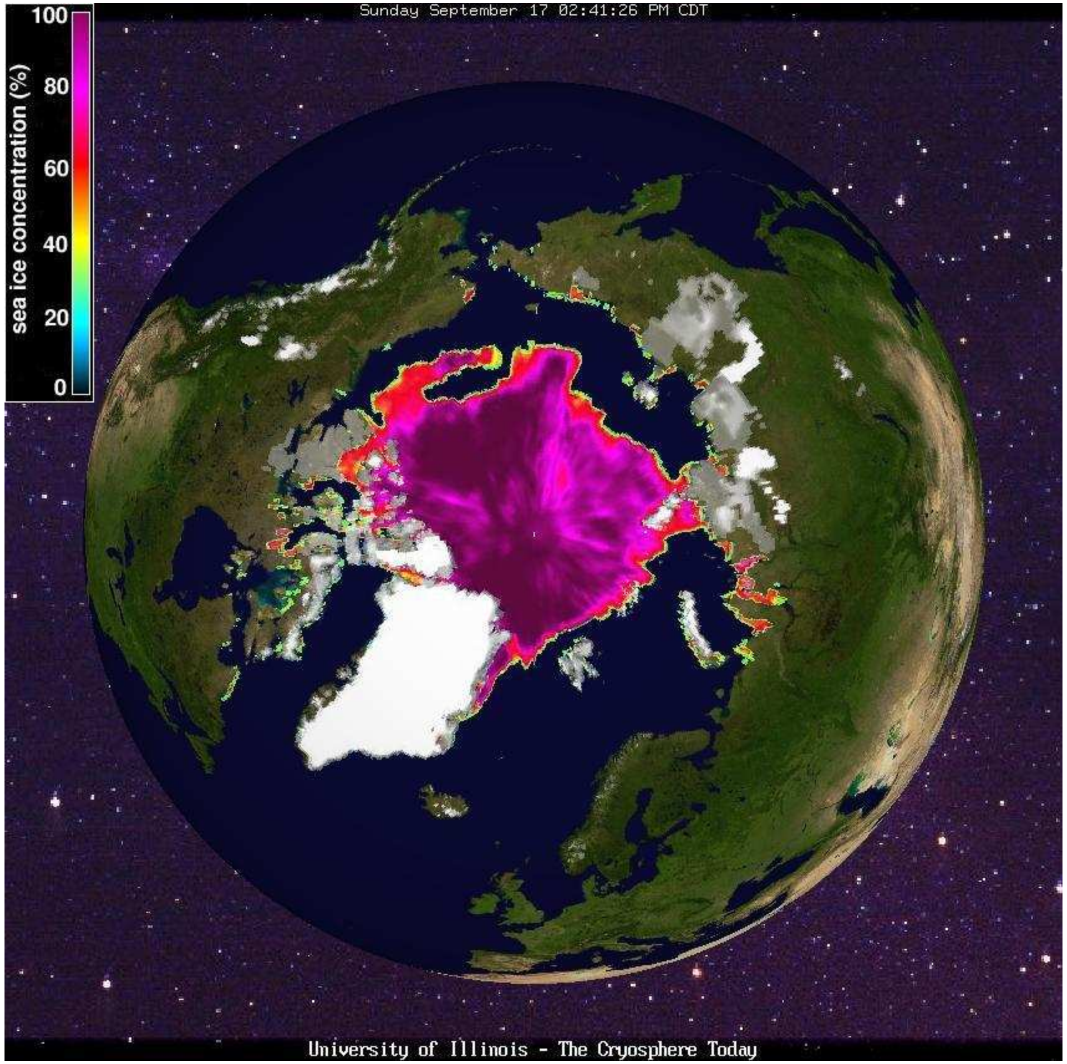
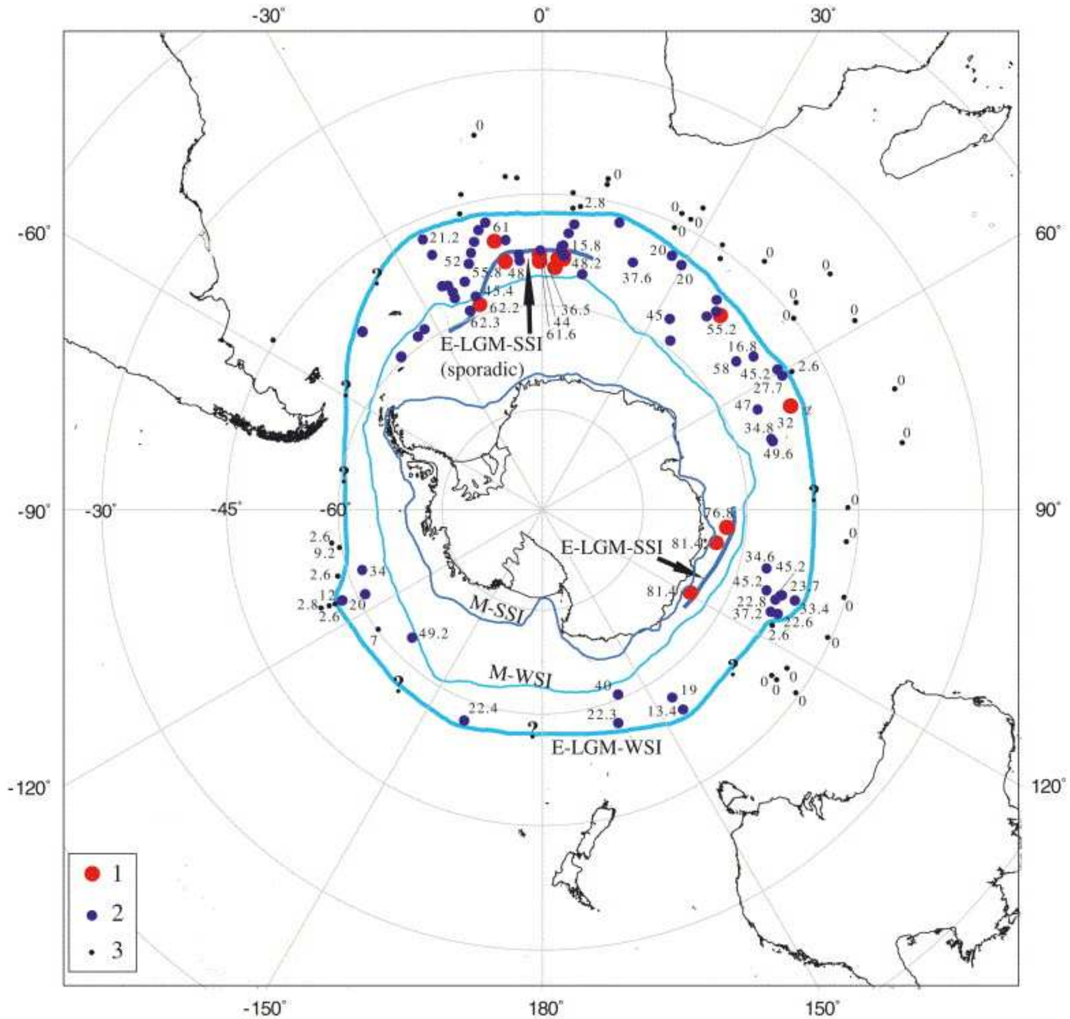
4	NADW formation			
5	Southern Ocean ventilation			
	Biogeochemistry			
6	Marine biota / iron fertilisation			
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

3 Gas Exchange / Sea Ice

Annual mean sea ice area shrunk by ~50% (Termination I)

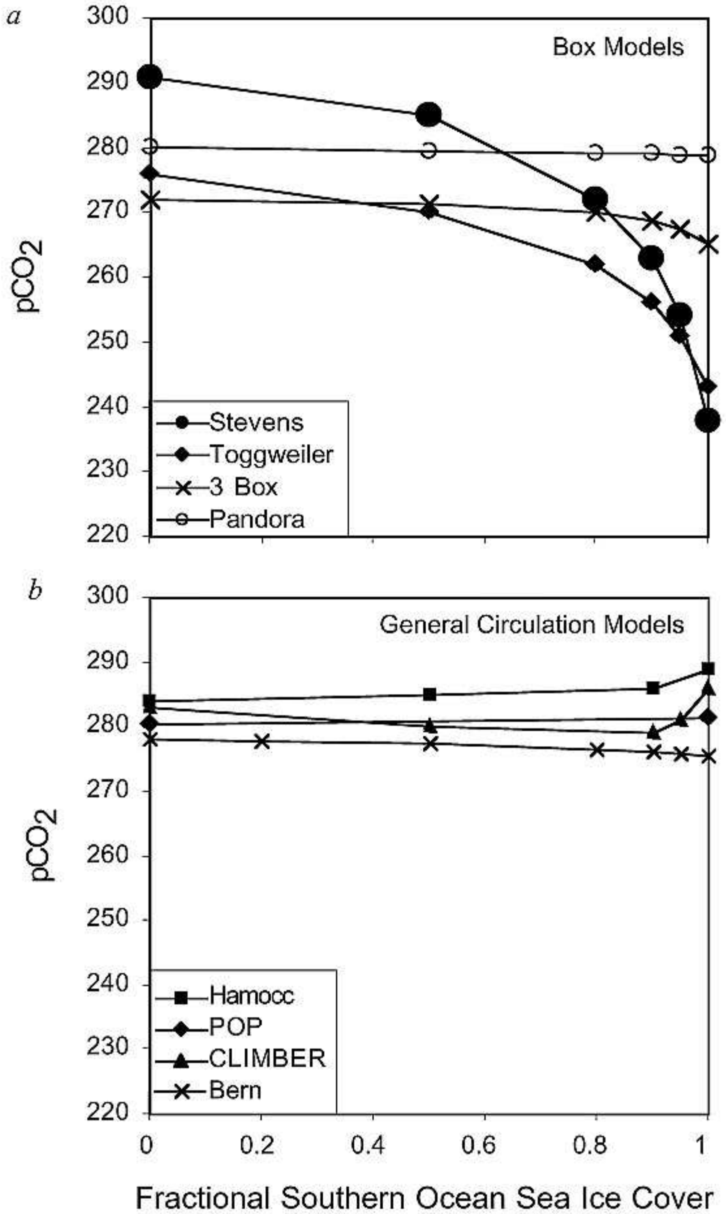
Dynamics coupled to temperature in the high latitude surface boxes





Arctic (present): The Cryosphere Today (www) Antarctic (LGM) Gersonde et al., 2005

3 Gas Exchange / Sea Ice



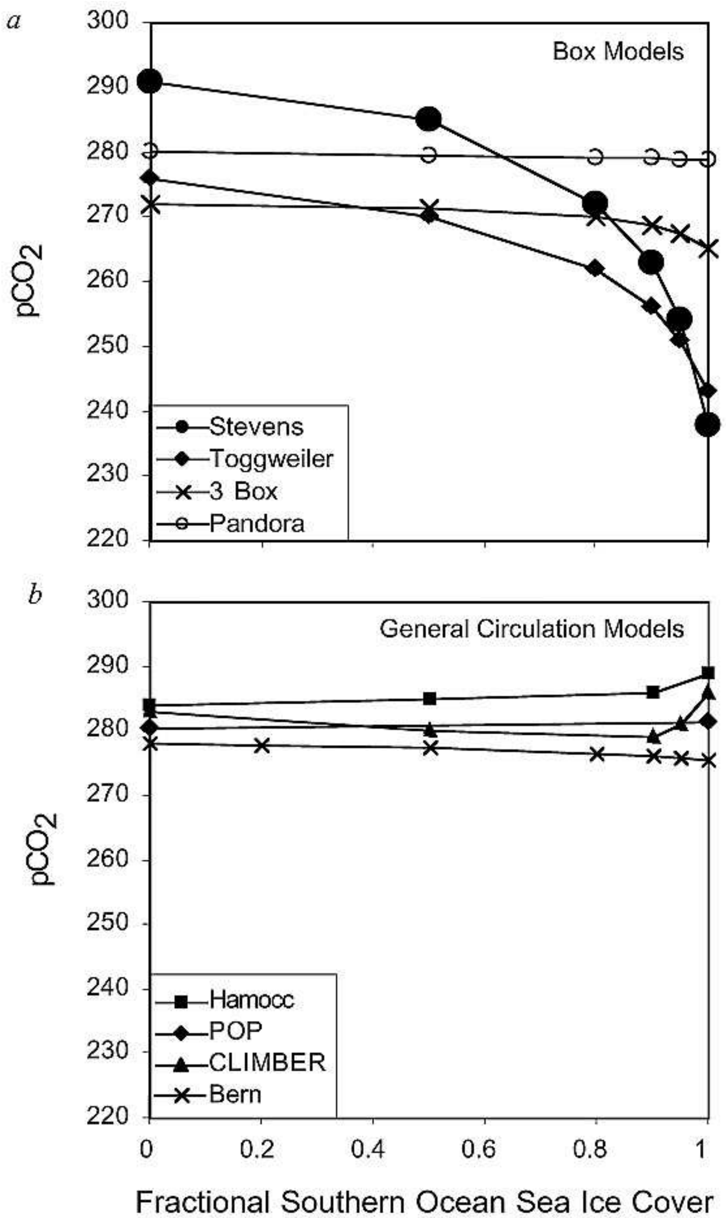
Model comparions came to ambiguous results

Box models: full sea ice cover in SO reduces CO_2

GCMs: only small changes

Archer et al., 2003

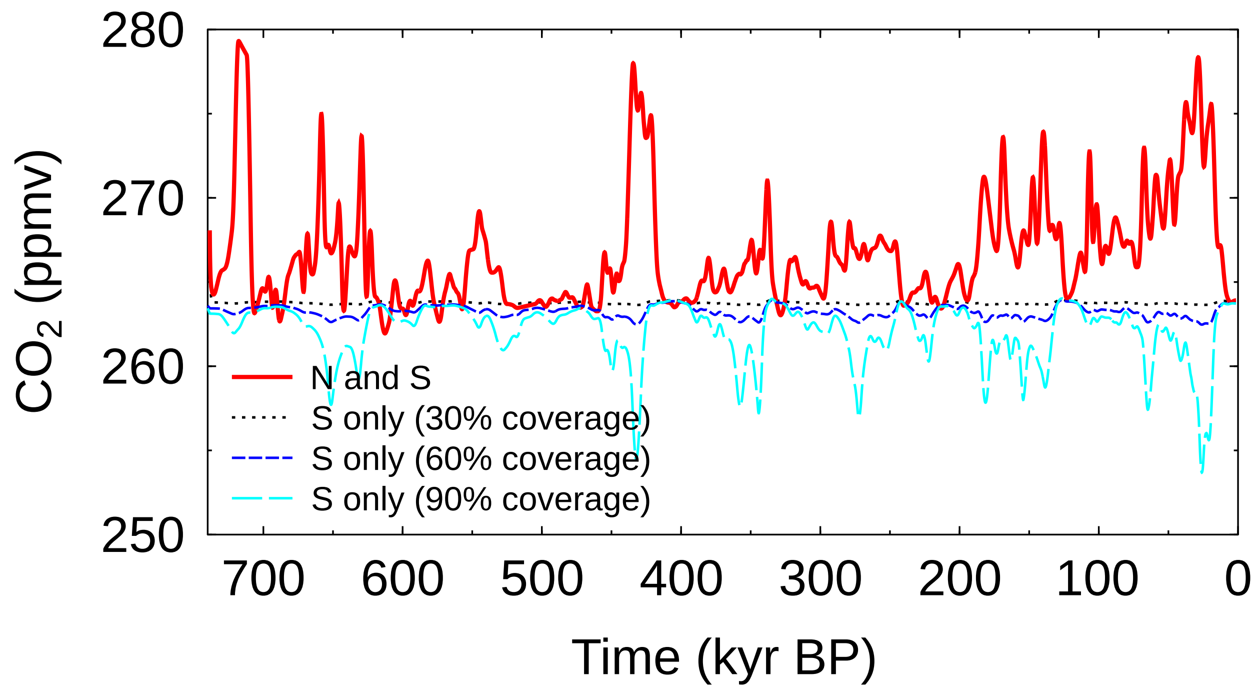
3 Gas Exchange / Sea Ice



BICYCLE: Sea ice change in N and S

N is sink for CO_2; S is source for CO_2

S as in box models, but N dominates over S



Archer et al., 2003

BICYCLE

Time-dependent processes:

	Which	**How** (T I)	**What** (ppmv)	**?**
	Physics (without ocean circulation)			
1	Temperature	+(3–5) K	+30	!
2	Sea level / salinity	+125 m	–15	!
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	Ocean circulation			
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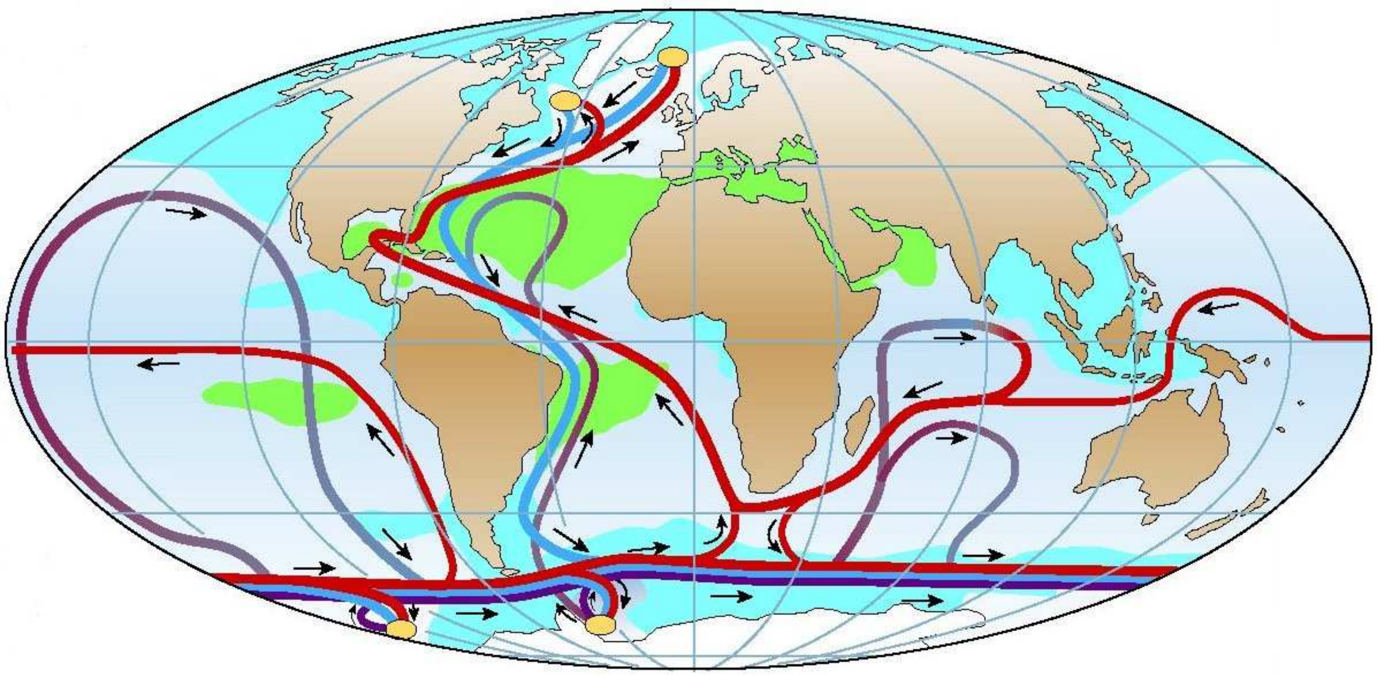
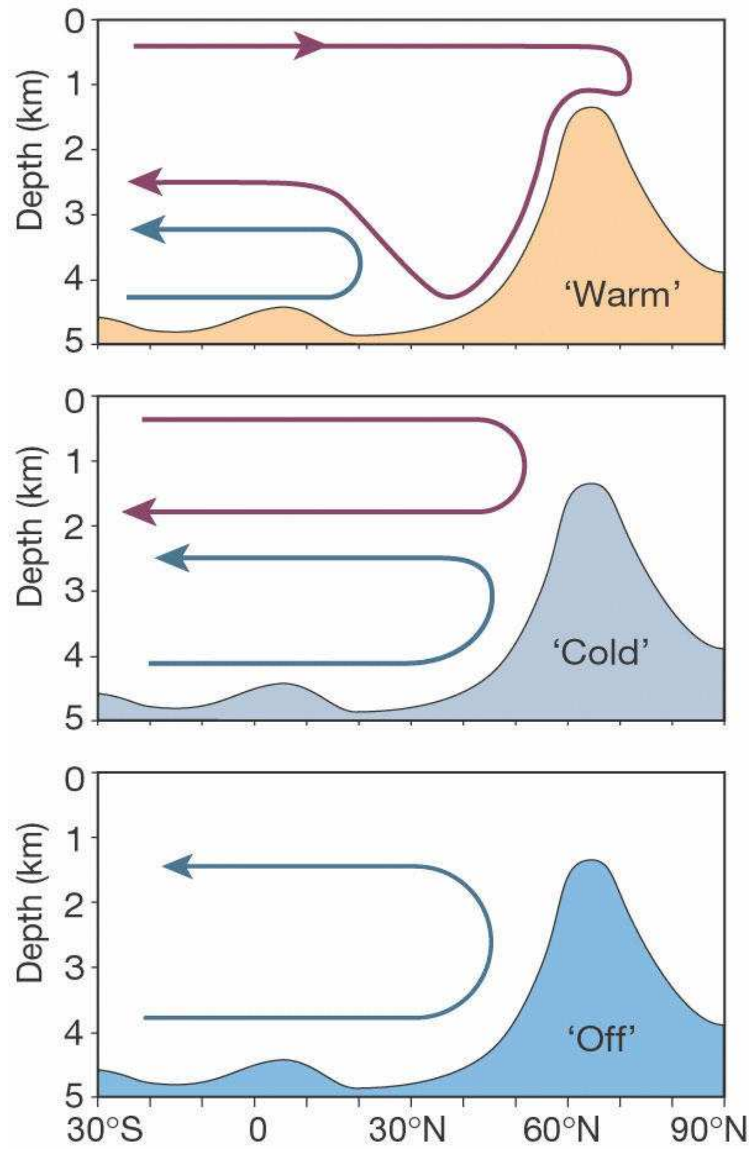
5	Southern Ocean ventilation			
	Biogeochemistry			
6	Marine biota / iron fertilisation			
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

4 NADW Formation

Conveyor belt



Changes in Atlantic THC

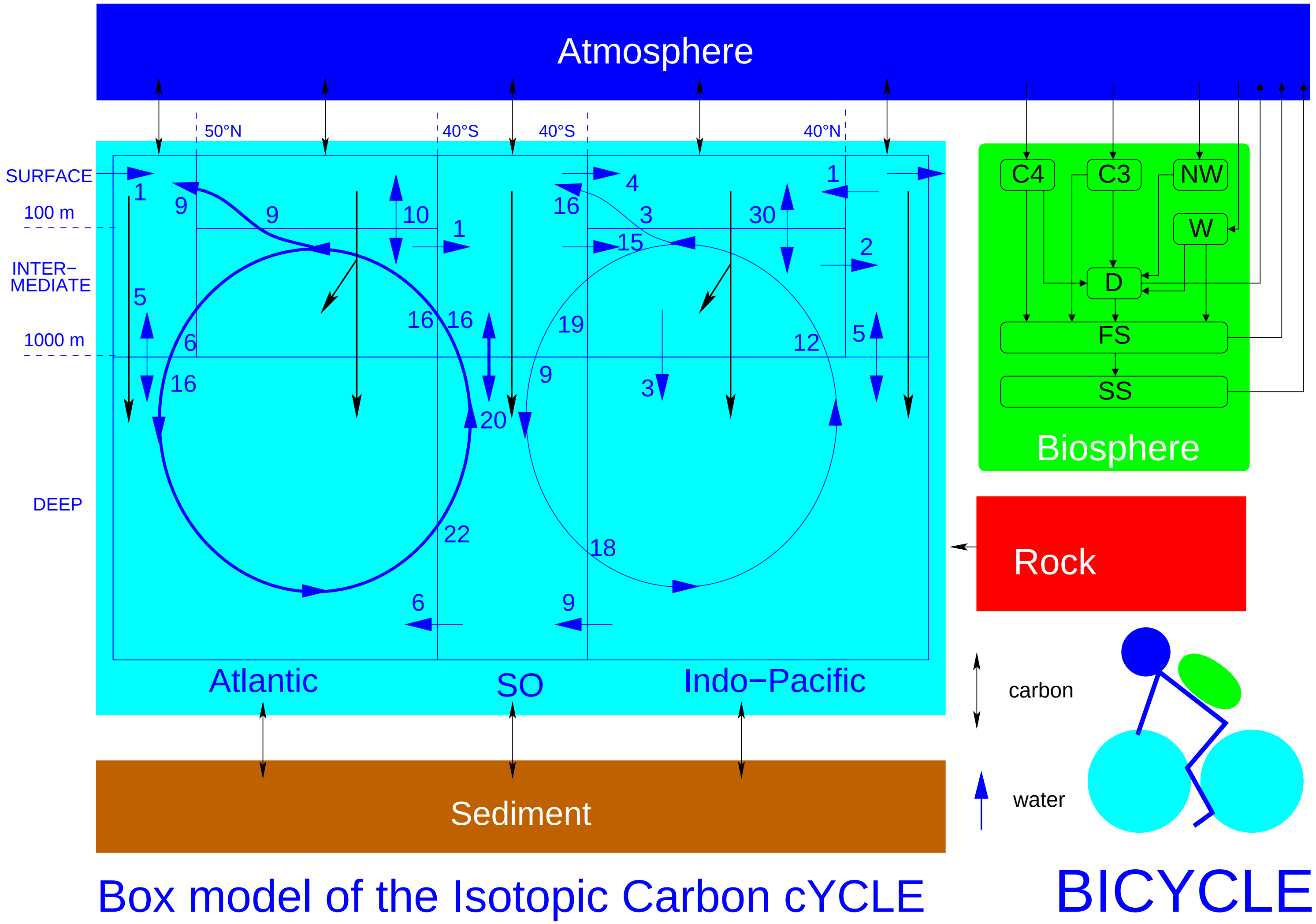


Rahmstorf, 2002

4 NADW Formation

Preindustrial circulation: WOCE data

Temporal changes: NADW reduce from 16 Sv to 10 Sv (0 Sv)



Box model of the Isotopic Carbon cYCLE

Circulation after Ganachaud & Wunsch, 2000

Time-dependent processes:

	Which	**How** (T I)	**What** (ppmv)	**?**
	Physics (without ocean circulation)			
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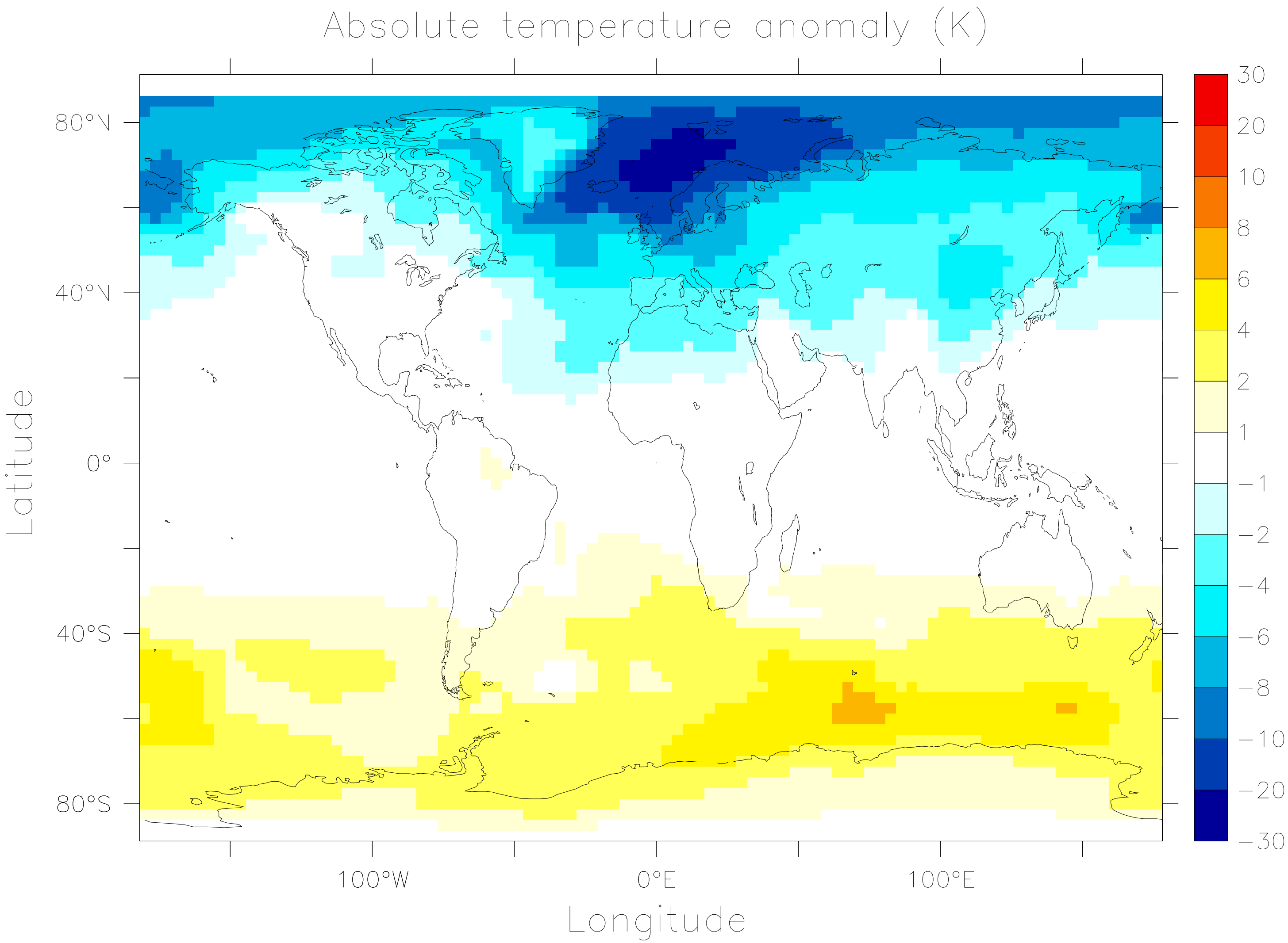
	Biogeochemistry			
6	Marine biota / iron fertilisation			
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

4 Indirect effects of shutdown of NADW (not in BICYCLE)

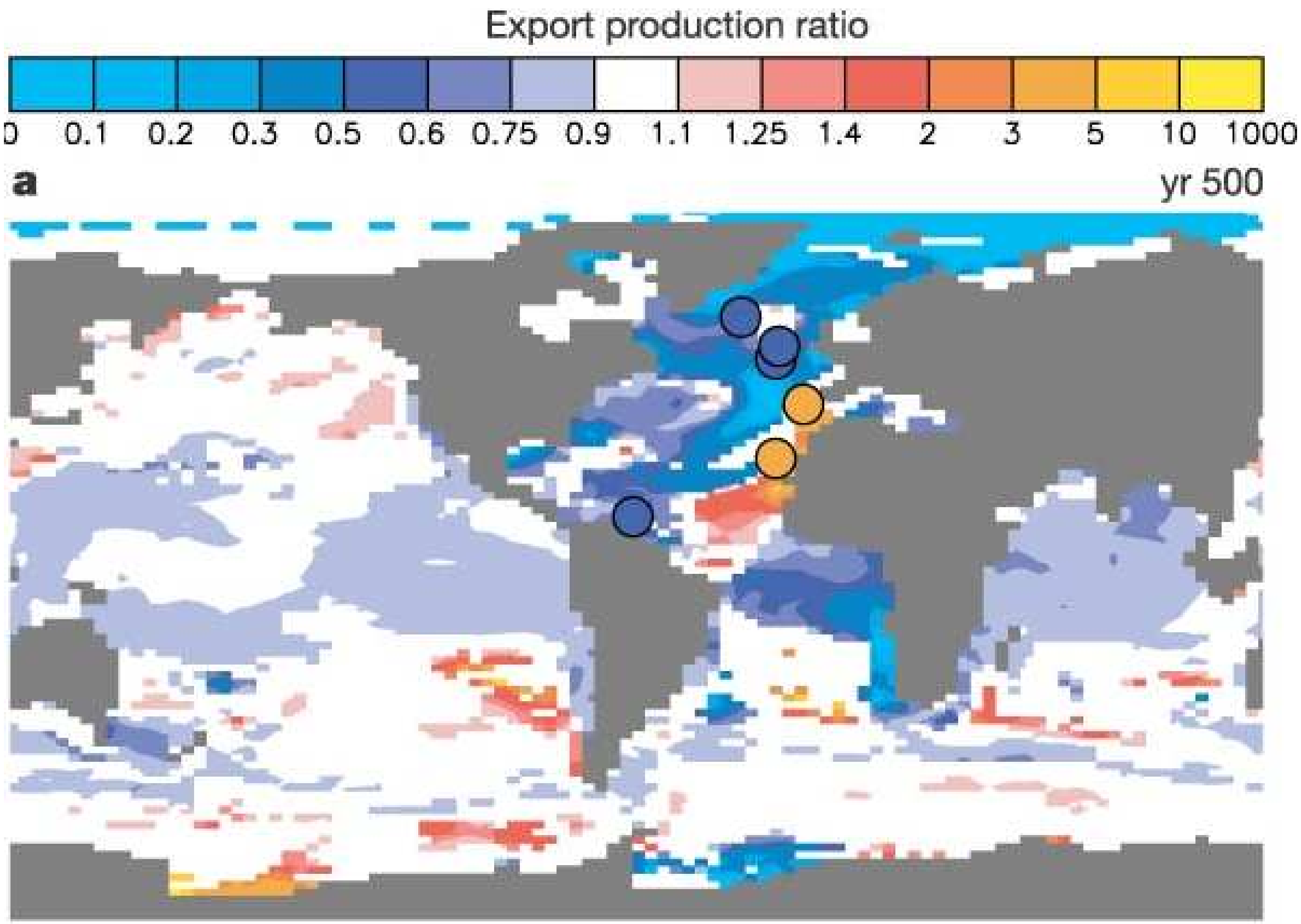
Additionally, a NADW shutdown would lead to cooling in Eurasia
Temperature anomalies simulated with ECBILT-CLIO



Köhler et al., 2005, Climate Dynamics (after Knutti et al., 2004)

4 Indirect effects of shutdown of NADW (not in BICYCLE)

Reduction of marine export production (blue) in North Atlantic by 50%

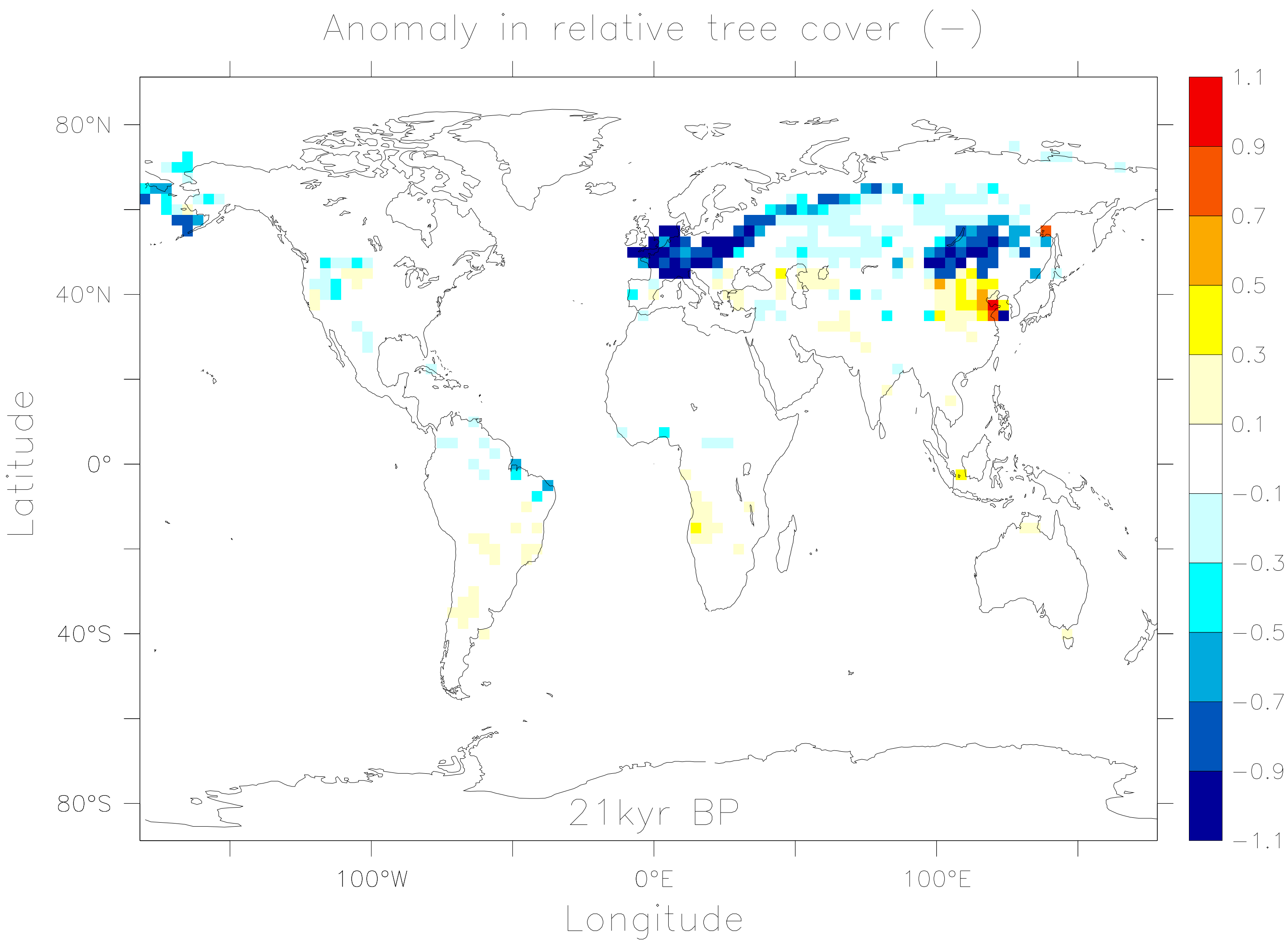


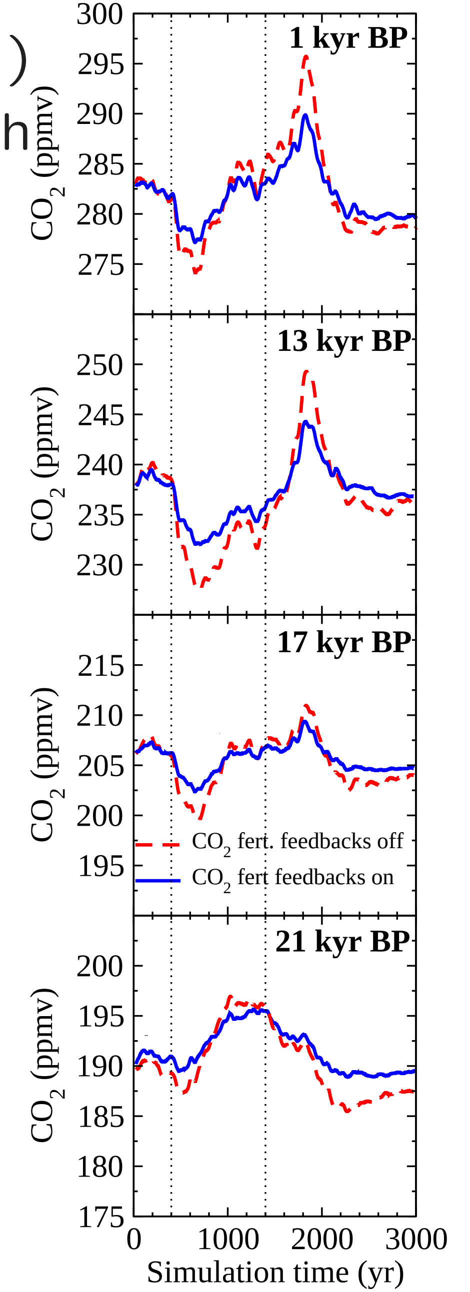
Schmittner ,2005

4 Indirect effects of shutdown of NADW (not in BICYCLE)

Cooling leads to southwards shift of treeline (LPJ-DGVM)

Competing effect of soil respiration and vegetation growth





Köhler et al., 2005, Climate Dynamics

Time-dependent processes:

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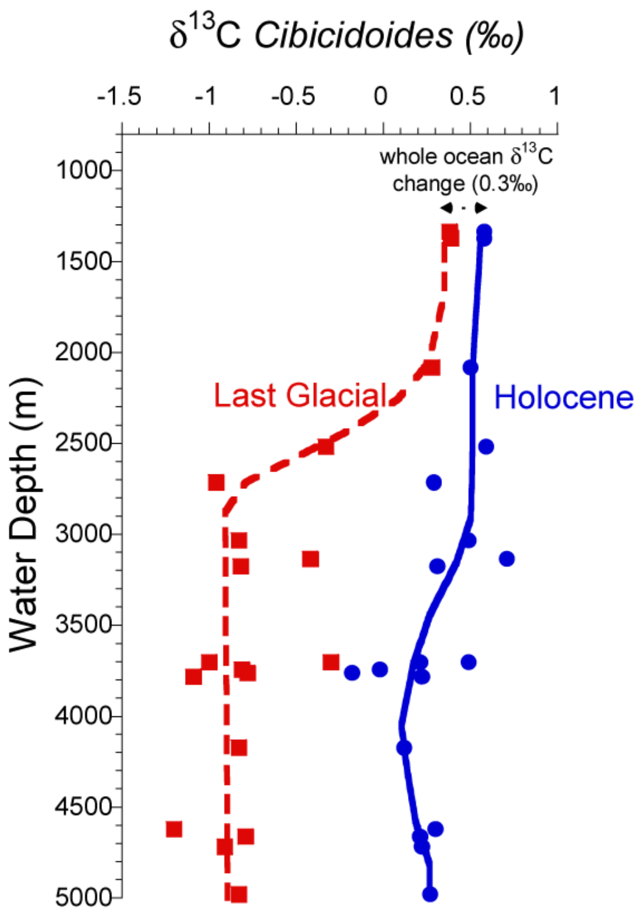
3	Gas exchange / sea ice	–50%	–15	?
	Ocean circulation			
4	NADW formation	+6 Sv	+15	!/? (off)
5	Southern Ocean ventilation			
	Biogeochemistry			
6	Marine biota / iron fertilisation			
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

5 Southern Ocean Ventilation

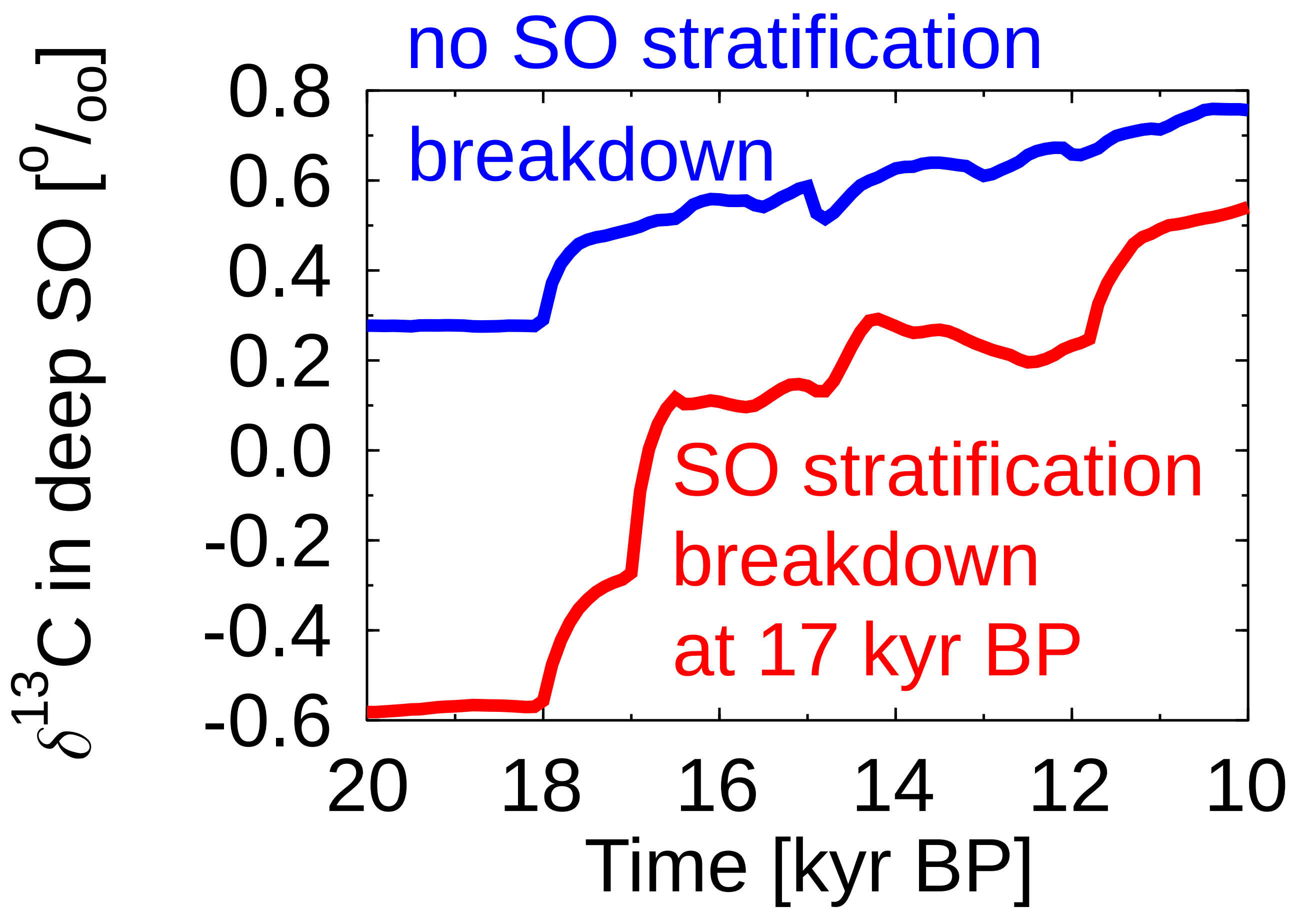
How to explain $\Delta\delta^{13}C(\text{PRE-LGM})=+1.2‰$ in deep Southern Ocean?

SO mixing reduced by 2/3 coupled to SO SST = f(EDC δD)

Different hypotheses on the physical cause behind this process



Hodell et al, 2003



Köhler, et al., 2005, Global Biogeochemical Cycles

Time-dependent processes:

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	Biogeochemistry			
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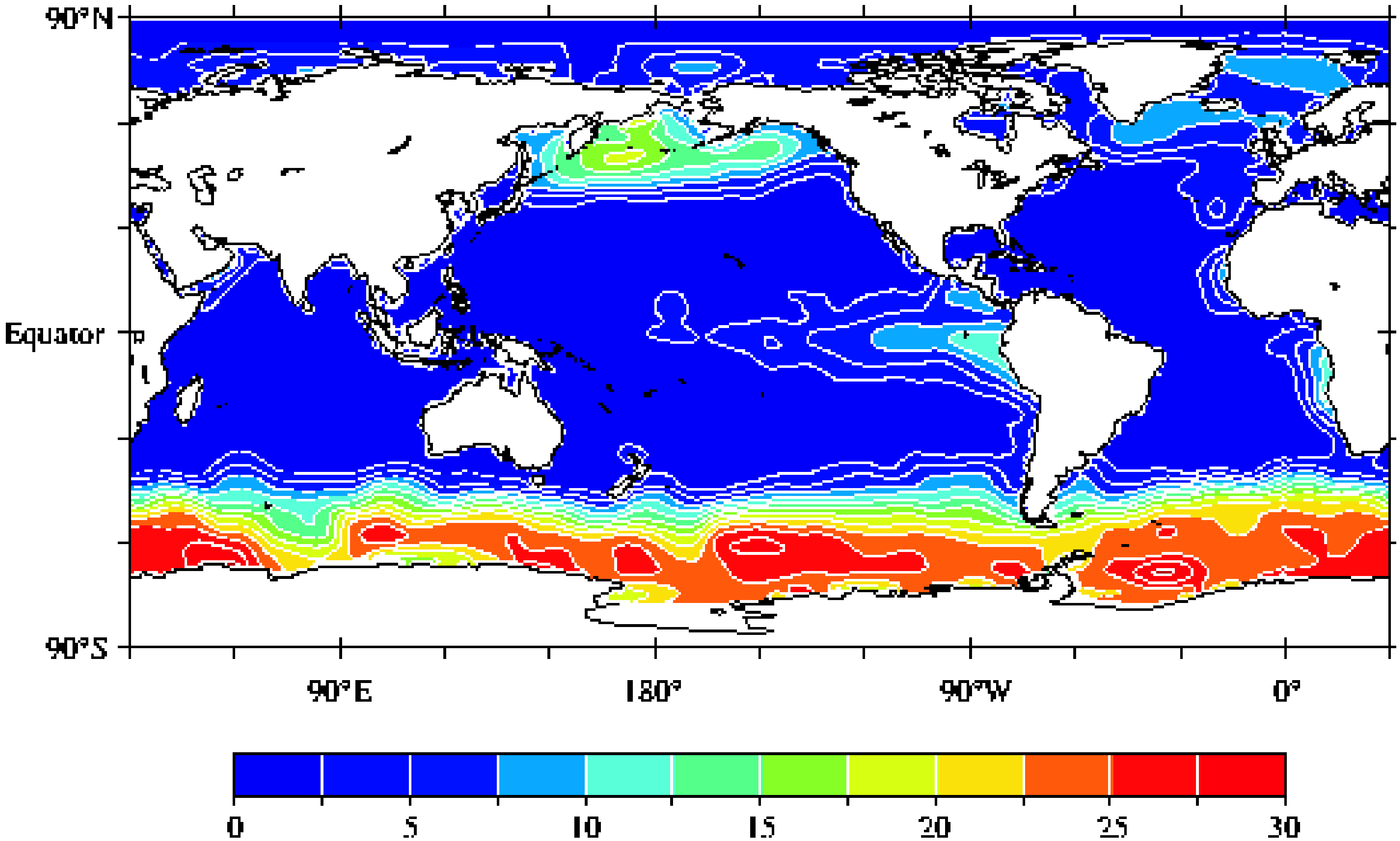
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

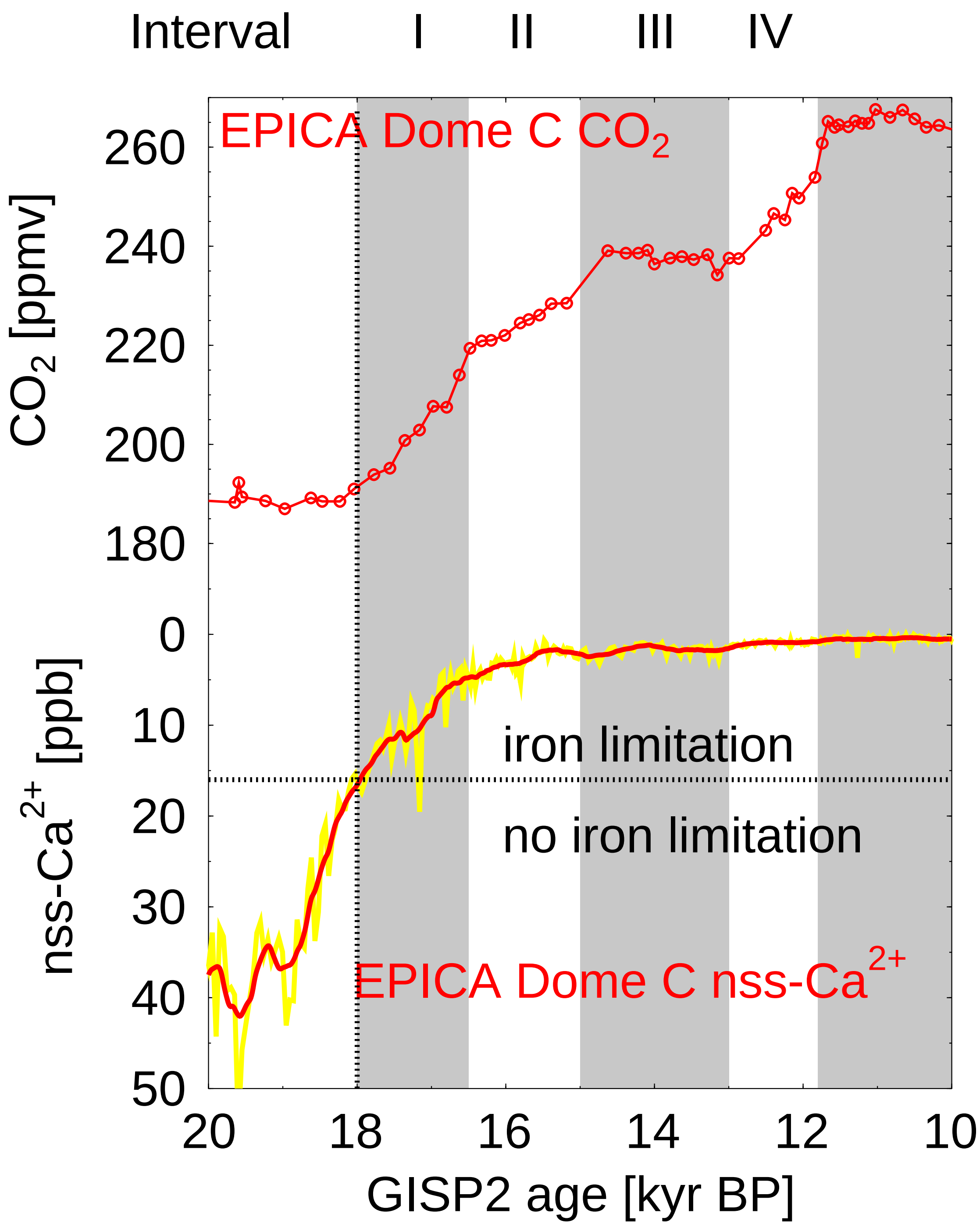
6 Marine Biota / Iron fertilisation

Marine biological productivity might be Fe limited
in high nitrate low chlorophyll (HNLC) areas (Martin, 1990)



Ridgwell, 2002

6 Marine Biota / Iron fertilisation



Aeolian dust input to Antarctica

LGM export production: + 20% (12 PgC yr^{-1})

Dust/iron input is reduced before rise in CO_2 starts

Monnin et al., 2001;

Röthlisberger et al., 2002

Time-dependent processes:

	Which	**How** (T I)	**What** (ppmv)	**?**
	Physics (without ocean circulation)			
1	Temperature	+(3–5) K	+30	!
2	Sea level / salinity	+125 m	−15	!
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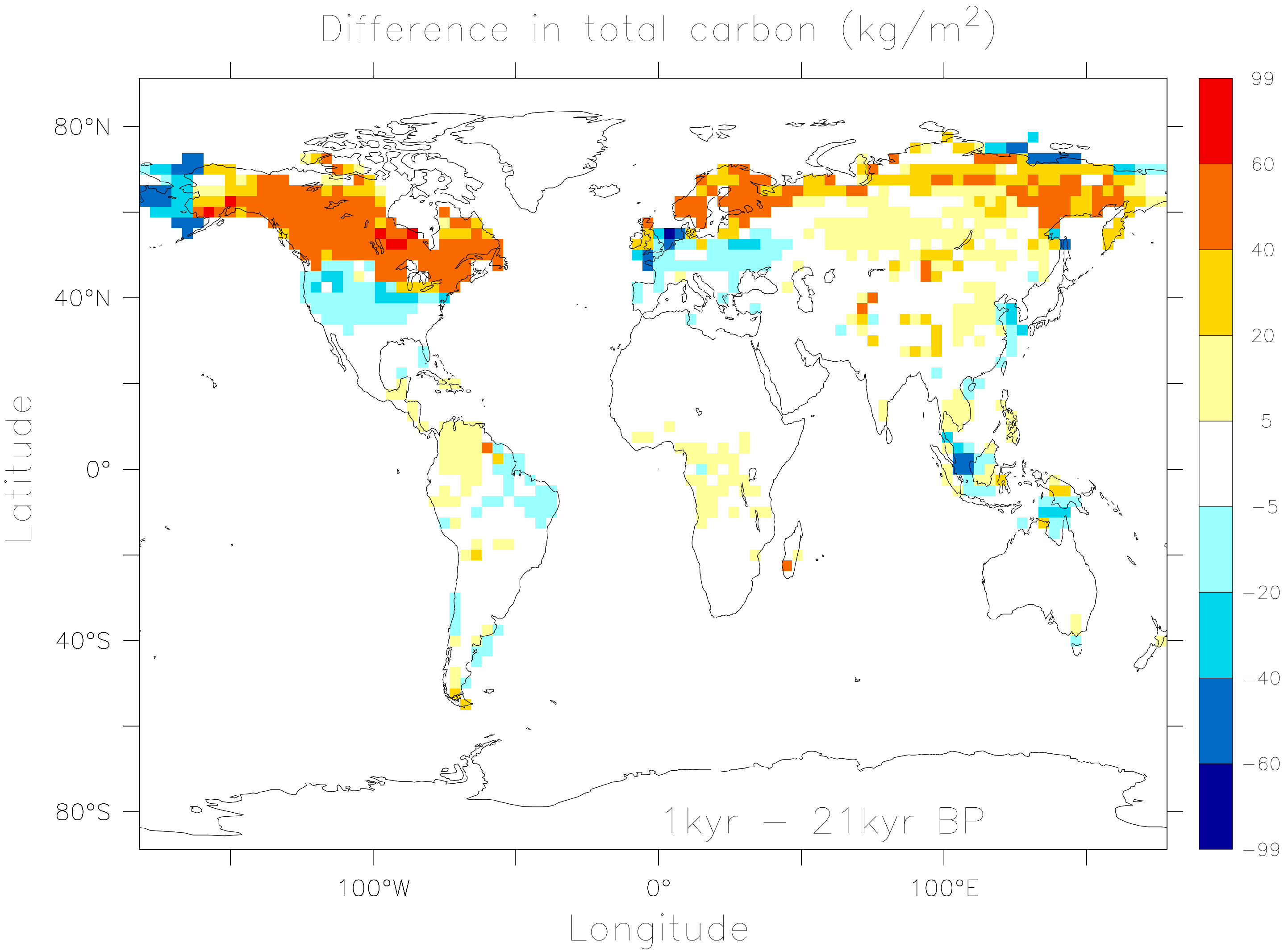
	Ocean circulation			
4	NADW formation	+6 Sv	+15	!/? (off)
5	Southern Ocean ventilation	+20 Sv	+35	o
	Biogeochemistry			
6	Marine biota / iron fertilisation	−2 PgC yr^{-1}	+20	?
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

7 Terrestrial carbon storage

Model and data-based estimates range from 300 to 800 PgC
Example from LPJ-DGVM (Preindustrial–LGM)



Köhler et al., 2005, Climate Dynamics

Time-dependent processes:

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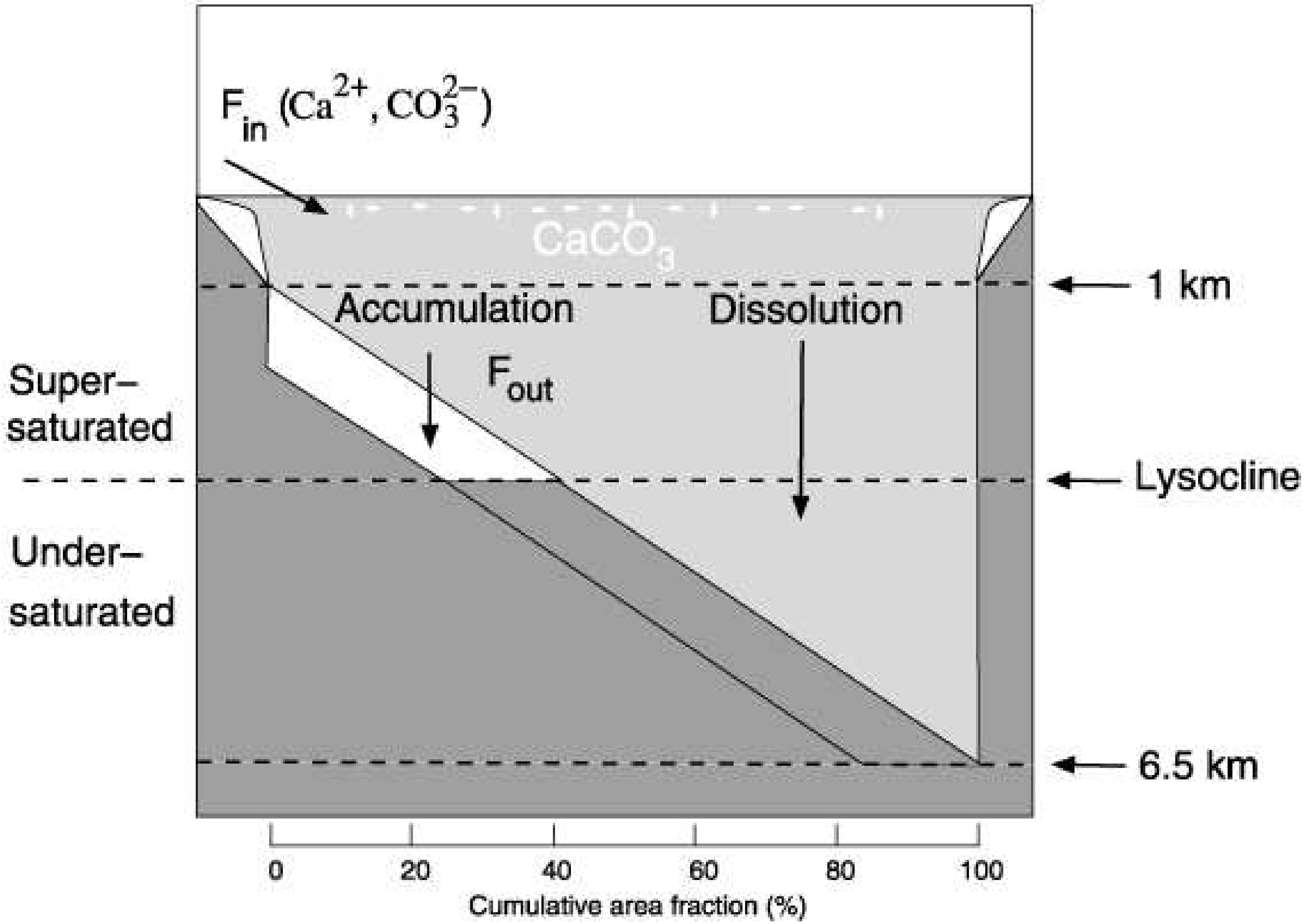
	Biogeochemistry			
6	Marine biota / iron fertilisation	−2 PgC yr^{-1}	+20	?
7	Terrestrial carbon storage	+500 PgC	−15	!
8	$CaCO_3$ chemistry			

8 Carbonate compensation

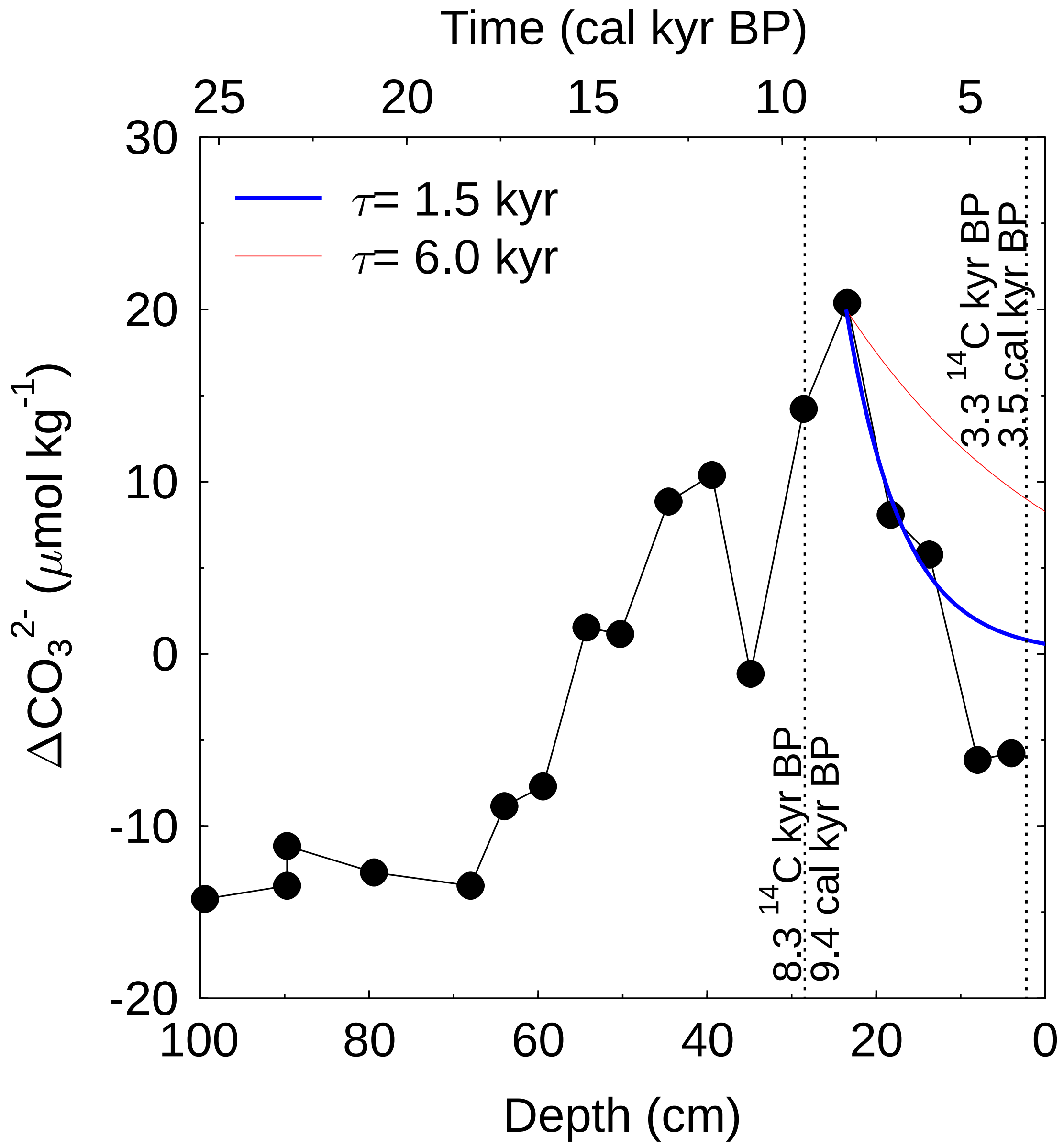
Dissolution / accumulation of $CaCO_3$ depends on deep ocean $[CO_3^{2-}]$



Zeebe and Westbroeck, 2003

8 Carbonate compensation

Anomalies in deep ocean [CO_3^{2-}] caused by carbon cycle variations relax to initial state with an e-folding time τ of 1.5 to 6 kyr



τ = 6.0 kyr:
process-based sediment model
(Archer et al., 1997)

τ = 1.5 kyr:
reconstruction of deep ocean [CO_3^{2-}]
(Marchitto et al., 2005)

after Marchitto et al., 2005

Time-dependent processes:

	Which	How (T I)	What (ppmv)	?
	Physics (without ocean circulation)			
1	Temperature	+(3–5) K	+30	!
2	Sea level / salinity	+125 m	–15	!
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	Biogeochemistry			
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7	Terrestrial carbon storage	+500 PgC	–15	!
8	$CaCO_3$ chemistry	τ=1.5 kyr	+20	?

Time-dependent processes:

	Which	**How** (T I)	**What** (ppmv)	**?**
1	Temperature	+(3–5) K	+30	!
2	Sea level / salinity	+125 m	−15	!
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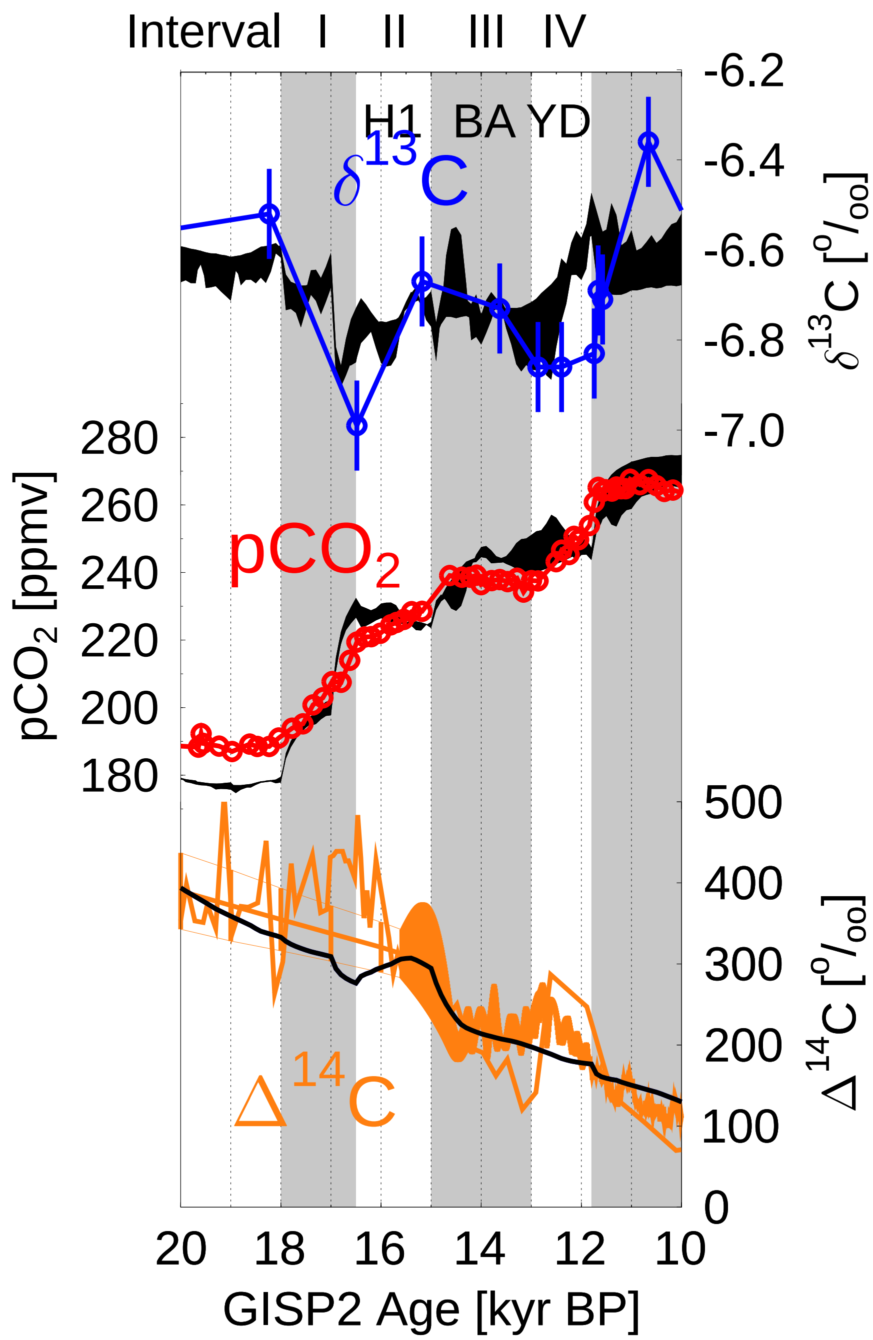
4	NADW formation	+6 Sv	+15	!/? (off)
5	Southern Ocean ventilation	+20 Sv	+35	o
6	Marine biota / iron fertilisation	−2 PgC yr^{-1}	+20	?
7	Terrestrial carbon storage	+500 PgC	−15	!
8	$CaCO_3$ chemistry	τ=1.5 kyr	+20	?
	Sum		+75	
	Sum (without sea ice)		+90	
	Vostok (incl. Holocene rise)		+103	

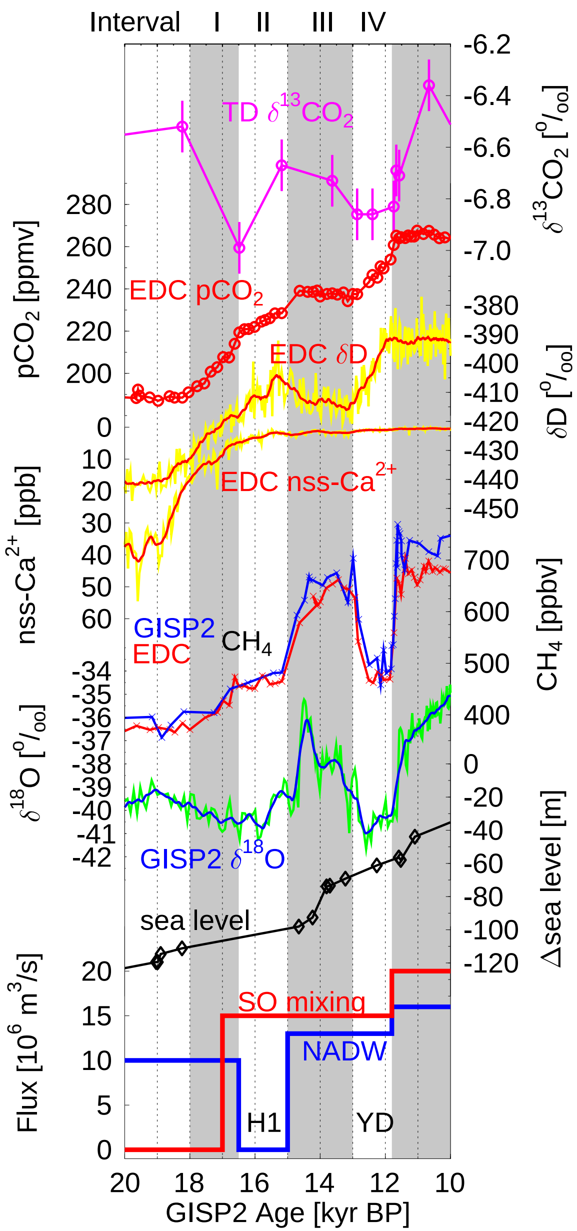
Atmospheric carbon during Termination I

Not only the amplitudes but also the timing of the changes in CO_2, $\delta^{13}C$, ^{14}C seems to be appropriate.

Smith et al., 1999; Monnin et al., 2001;
Stuiver et al., 1998; Hughen et al., 2004
Köhler et al., 2005,
Global Biogeochemical Cycles

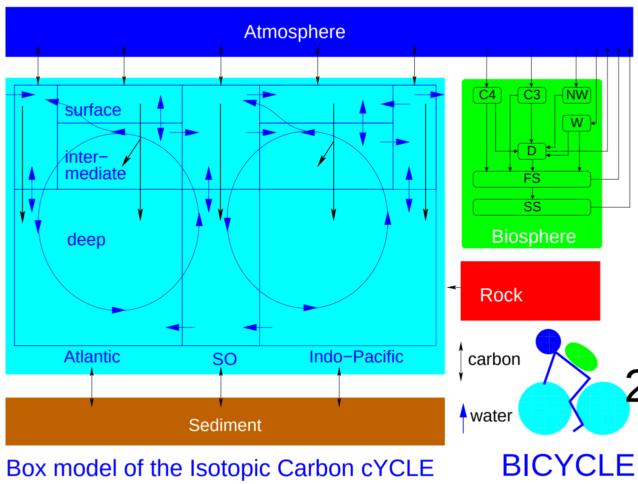


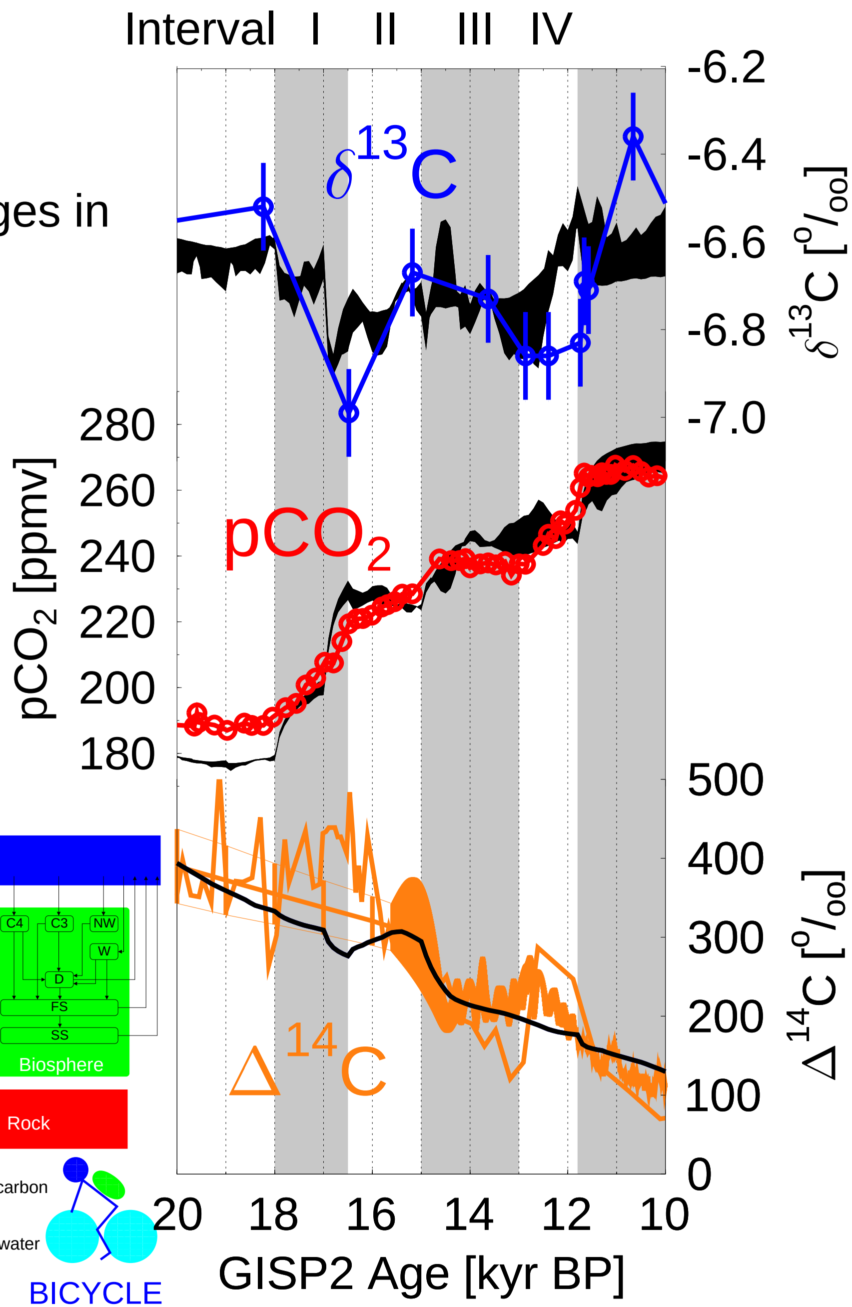
Termination I



Assumptions on changes in

- Fe fertilization in SO
- Ocean circulation (NADW, SO mixing)
- Climate (ΔT, sealevel, sea ice)
- $CaCO_3$ chemistry
- terrestrial biosphere





Forcing ⇒ Model ⇒ Results

Köhler et al., GBC, 2005 doi: 10.1029/2005GB002345

a: Heinrich

b: N-SST

c: NADW

d: EQ-SST

e: NH ΔT

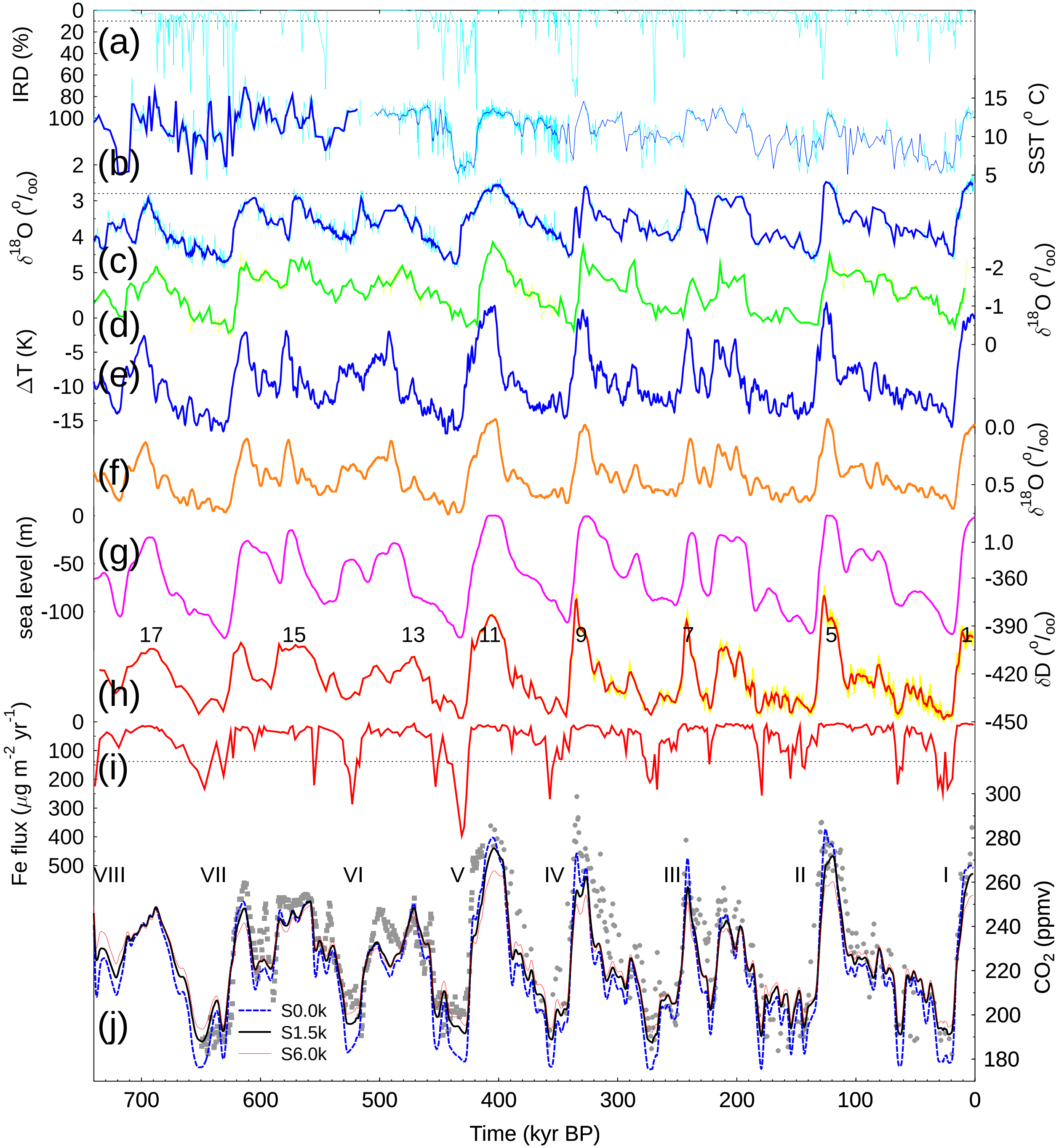
f: deep sea ΔT

g: sea level

h: SO SST

i: Fe fert.

j: CO_2



Köhler and Fischer, 2006, Climate of the Past

Take-Home Messages:

- The anthropogenic temperature rise is beyond doubt, but details depend on quality and resolution of data sets and model-based reconstructions.
- It is caused by changing the radiative budget of the Earth's atmosphere.
- The amplitude in the rise in GHG from LGM to preindustrial is of similar size than from preindustrial to present.
- The full range of observed temperature rise can not be explained solely with the rise in GHG, feedbacks in the climate system contribute a significant amount to it.
- The variability in CO_2 in the Holocene might be partially caused by early anthropogenic activity (Ruddiman's Hypothesis).
- To understand the glacial/interglacial rise in CO_2 at least eight important processes, which were known to have been changed over time, need to be considered (temperature, sea level, sea ice, ocean circulation, marine and terrestrial biota, $CaCO_3$ chemistry).

Further Reading

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