Alfred Wegener Institute
Helmholtz Centre for
Polar and Marine Research
Bremerhaven, Germany

A model-based interpretation of glacial/interglacial changes in atmospheric CO_2 during the last 740 000 years

Peter Köhler

OLB Foundation Fellowship 2006 for Prof. Dr. Wallace S. Broecker

Hanse Institute for Advanced Study, Delmenhorst — 19 September 2006

In cooperation with:

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Guy Munhoven, Université de Lìege, Belgium

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Outline

The global record of atmospheric CO_2

EPICA — European Project for Ice Coring in Antarctica

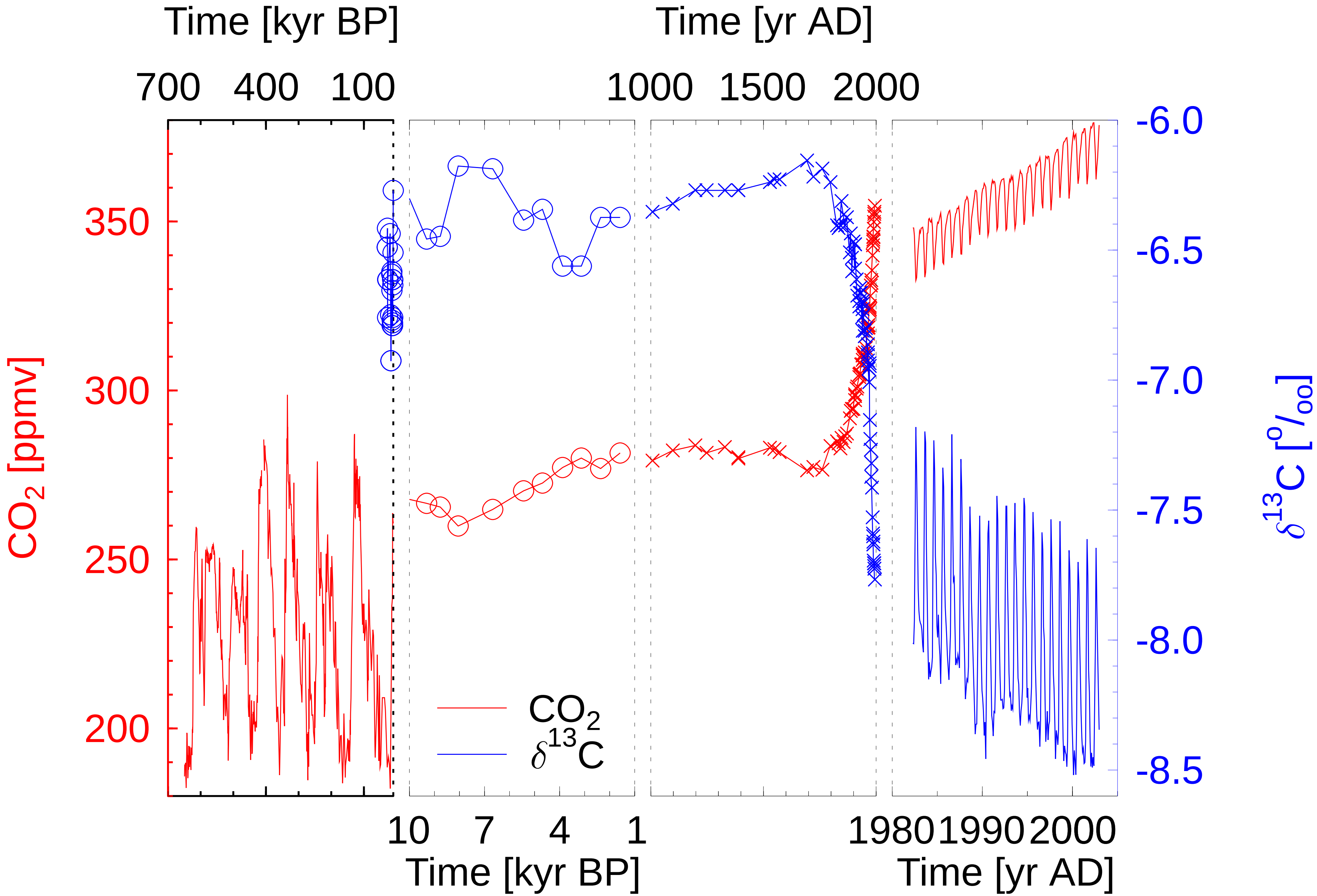
The global carbon cycle and the box model BICYCLE

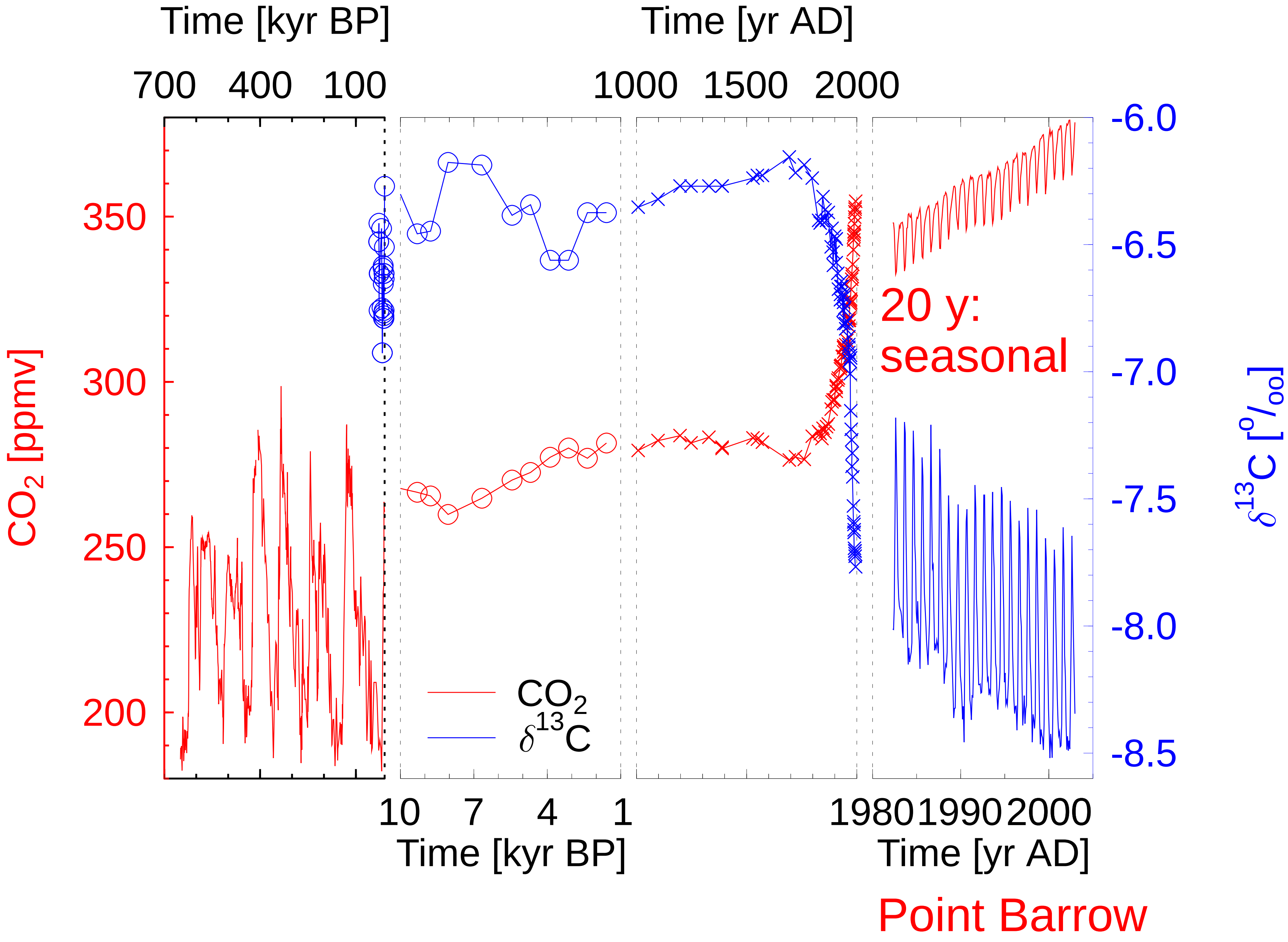
Time-dependent processes: motivations and simulation results

Combined scenarios

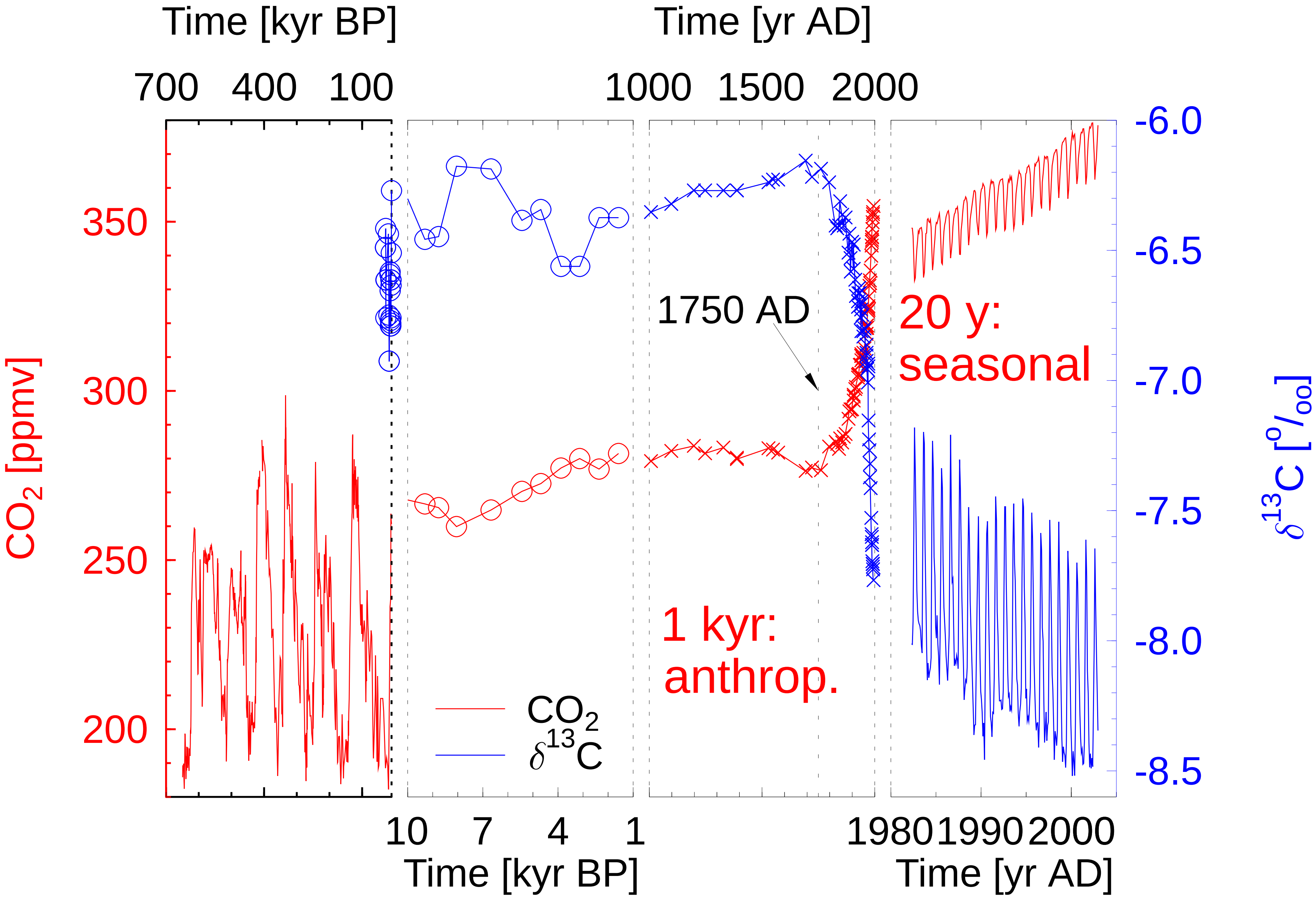
Open questions

Conclusions


Time [kyr BP]
Time [yr AD]
700
400
100
1000
1500
2000
350
300
250
200
CO$_2$ [ppmv]
-6.0
-6.5
-7.0
-7.5
-8.0
-8.5
δ^{13}C [$^o/_{oo}$]
CO$_2$
δ^{13}C
10
7
4
1
1980
1990
2000
Time [kyr BP]
Time [yr AD]

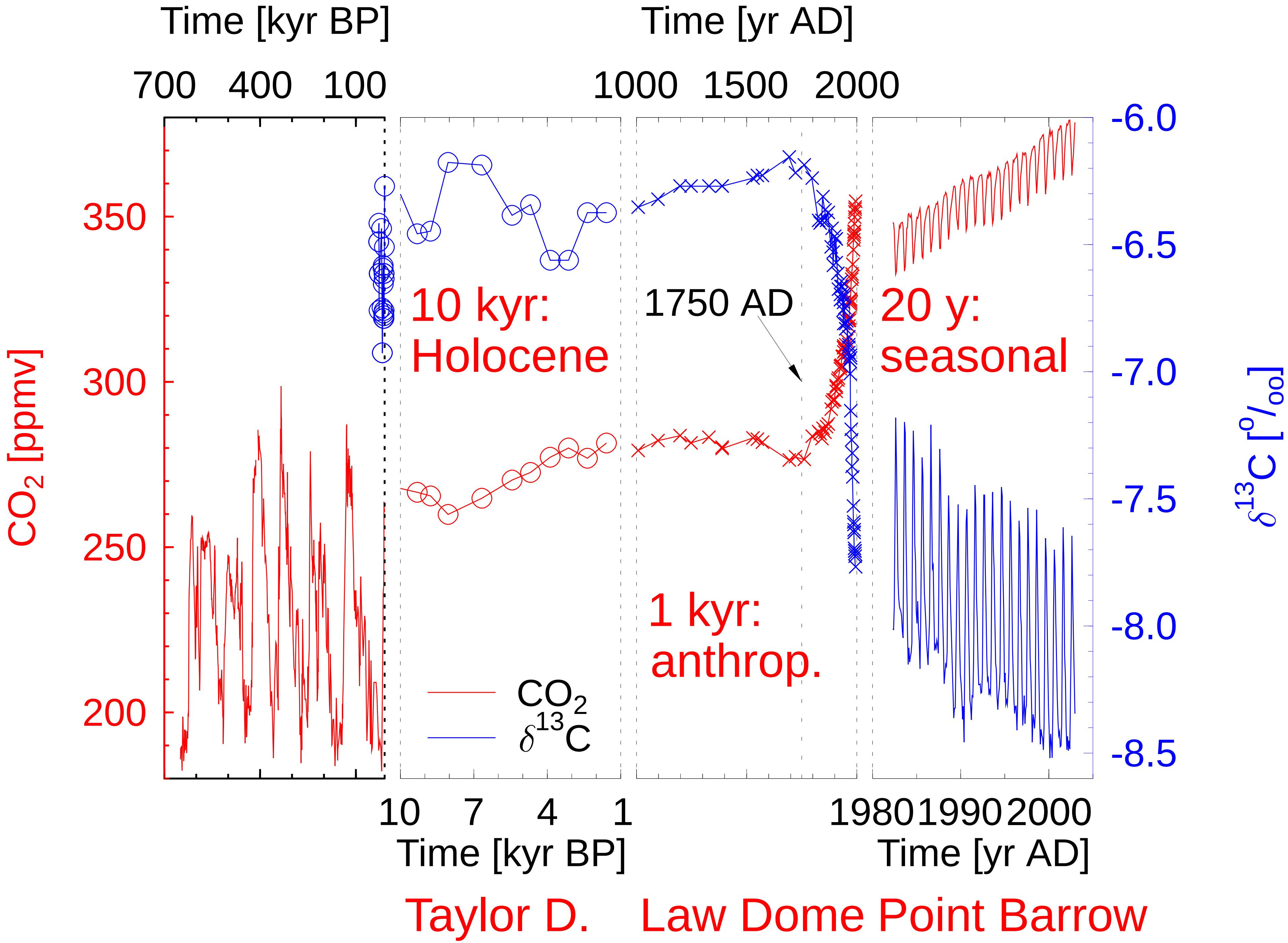


Keeling and Whorf, 2005; Keeling et al., 2005.

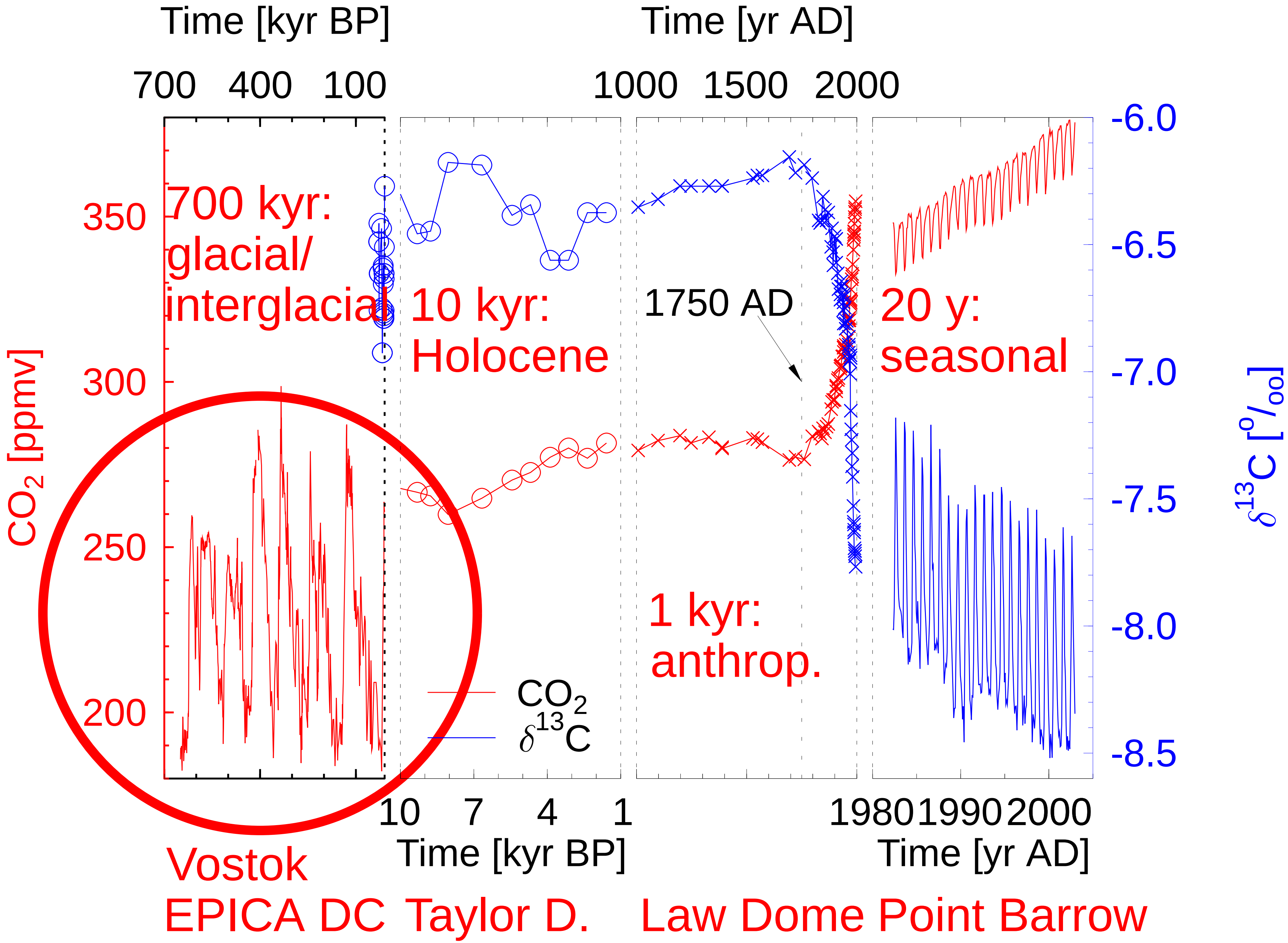


Law Dome Point Barrow

Francey et al., 1998; Trudinger et al., 1999



Smith et al., 1999



Petit et al., 1999; Siegenthaler et al., 2005

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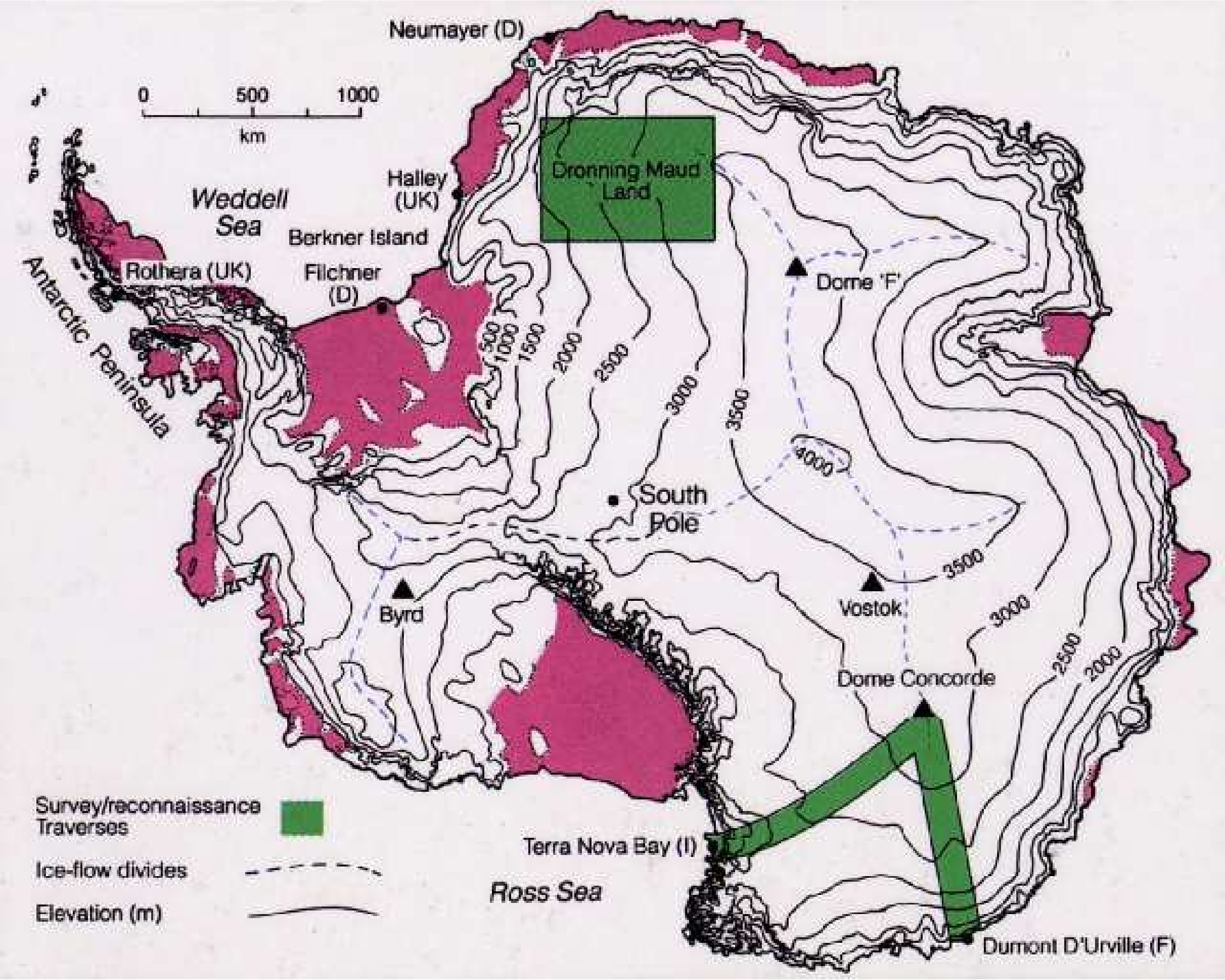
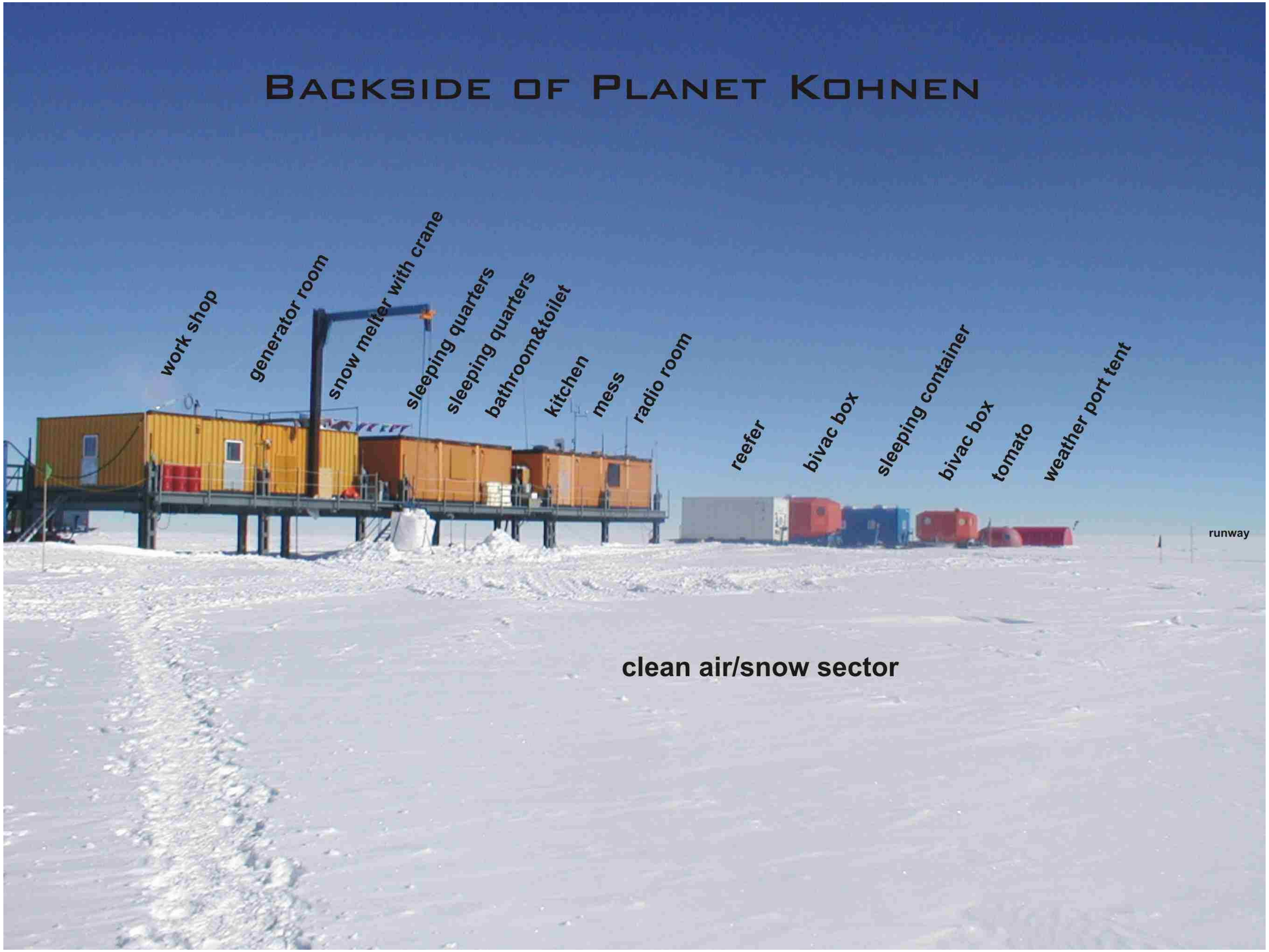


EPICA drilling sites:

Dome C (EDC): low accumulation rate; long time series ($\sim$8 glacial cycles)

Dronning Maud Land (EDML): high accumulation rate, high resolution

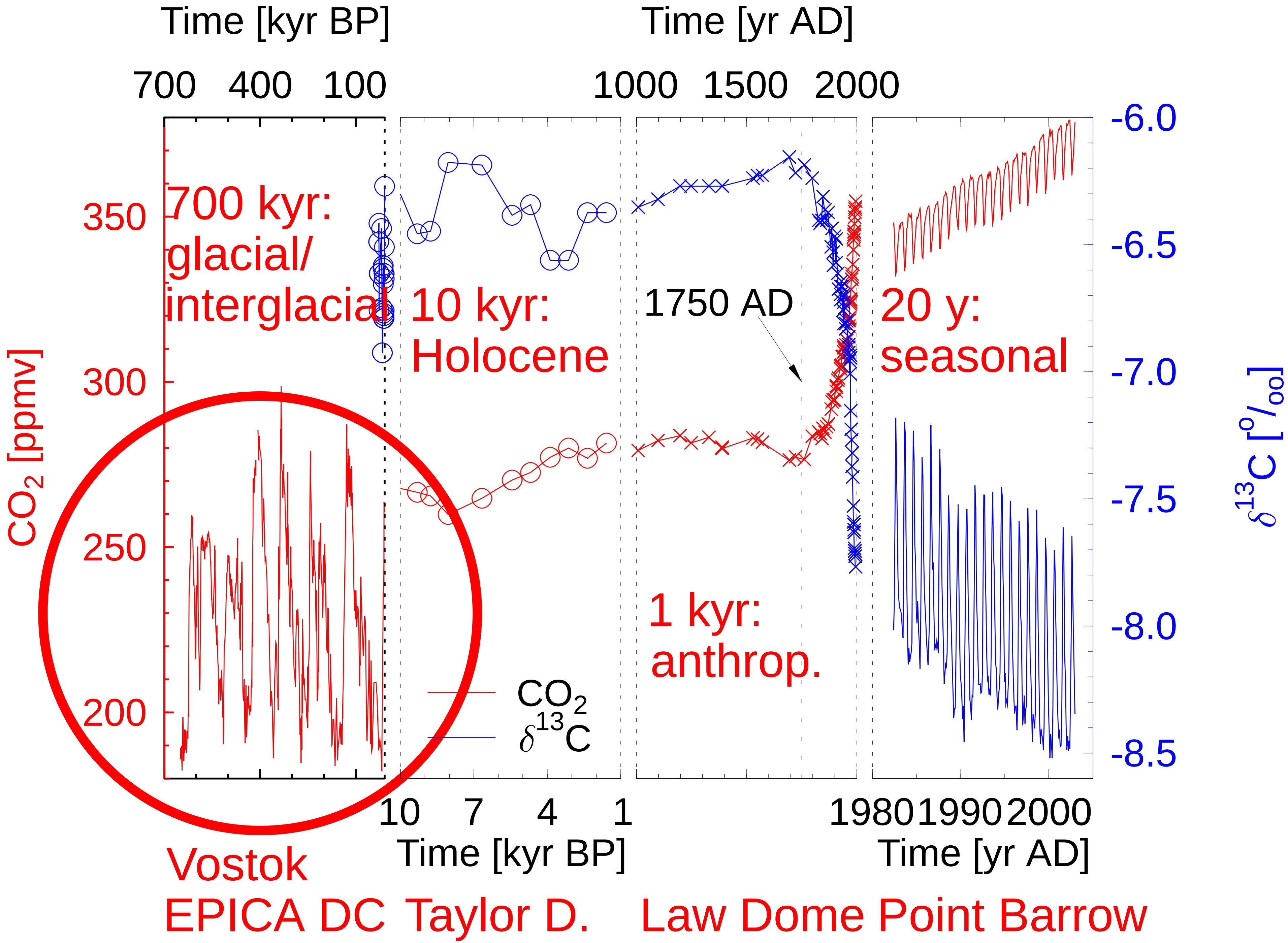


BACKSIDE OF PLANET KOHNEN

Kohnen station in Dronning Maud Land

Drilling team 2005/06 with last section of EDML (from 2774 m depth)

Scientific lab in Kohnen station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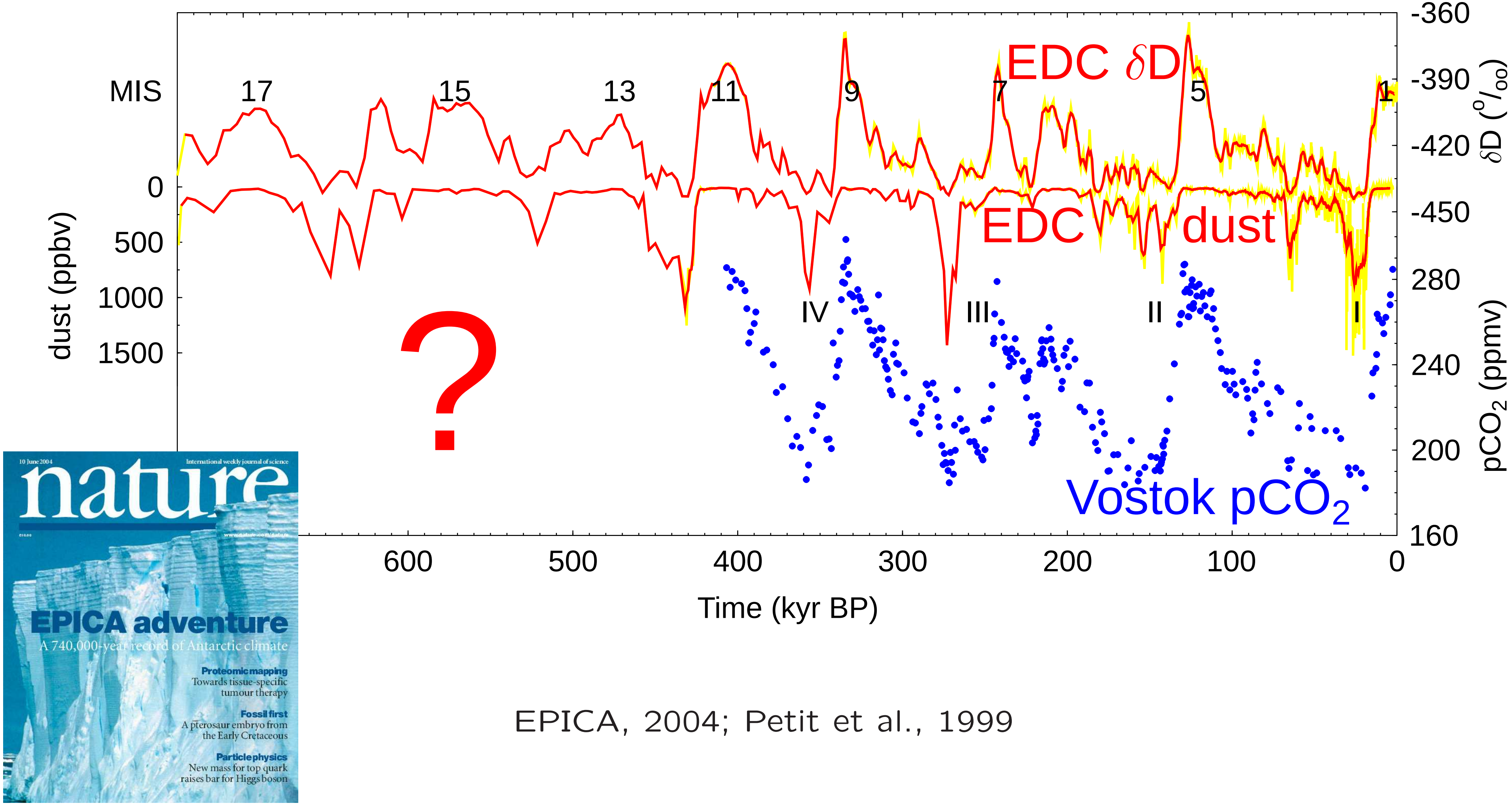
700
400
100
1000
1500
2000
-6.0
-6.5
-7.0
-7.5
-8.0
-8.5
350
300
250
200
CO$_2$ [ppmv]
δ^{13}C [$^{o}/_{oo}$]
700 kyr: glacial/ interglacial
10 kyr: Holocene
1750 AD
1 kyr: anthrop.
20 y: seasonal
CO$_2$
δ^{13}C
10
7
4
1
Time [kyr BP]
1980
1990
2000
Time [yr AD]
Vostok
EPICA DC
Taylor D.
Law Dome
Point Barrow

The EPICA challenge

Predicting $p\mathrm{CO}_2$ prior to Vostok (Wolff et al., 2004, 2005, EOS)
8 contributions: from regression analysis to full carbon cycle model



EPICA, 2004; Petit et al., 1999

The EPICA challenge

Predicting $p\mathrm{CO}_2$ prior to Vostok (Wolff et al., 2004, 2005, EOS)
8 contributions: from regression analysis to full carbon cycle model

Science

25 November 2005

125

AAAS

10 June 2004

International weekly journal of science

nature

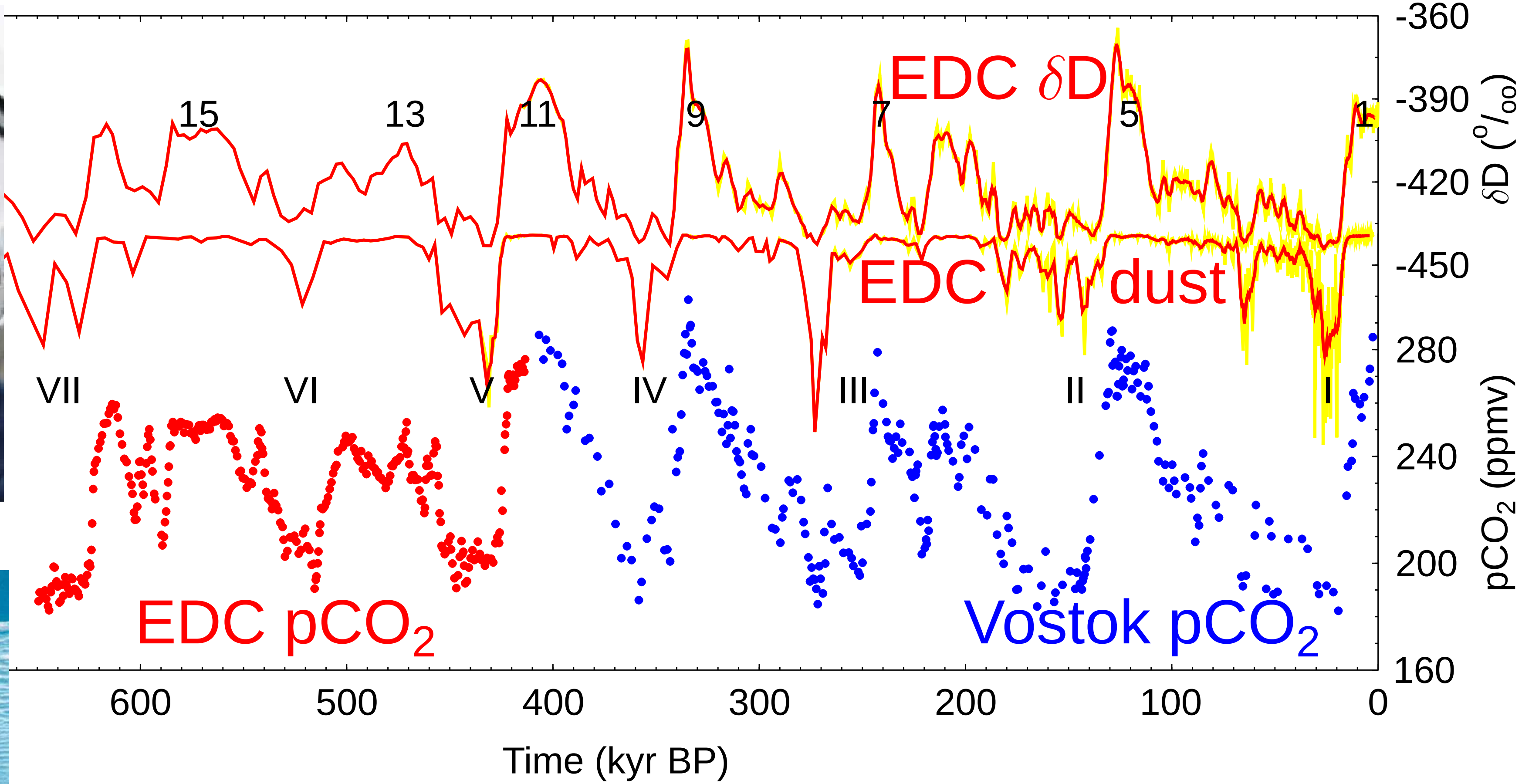
EPICA adventure

A 740,000-year record of Antarctic climate

Proteomic mapping
Towards tissue-specific tumour therapy

Fossil first
A pterosaur embryo from the Early Cretaceous

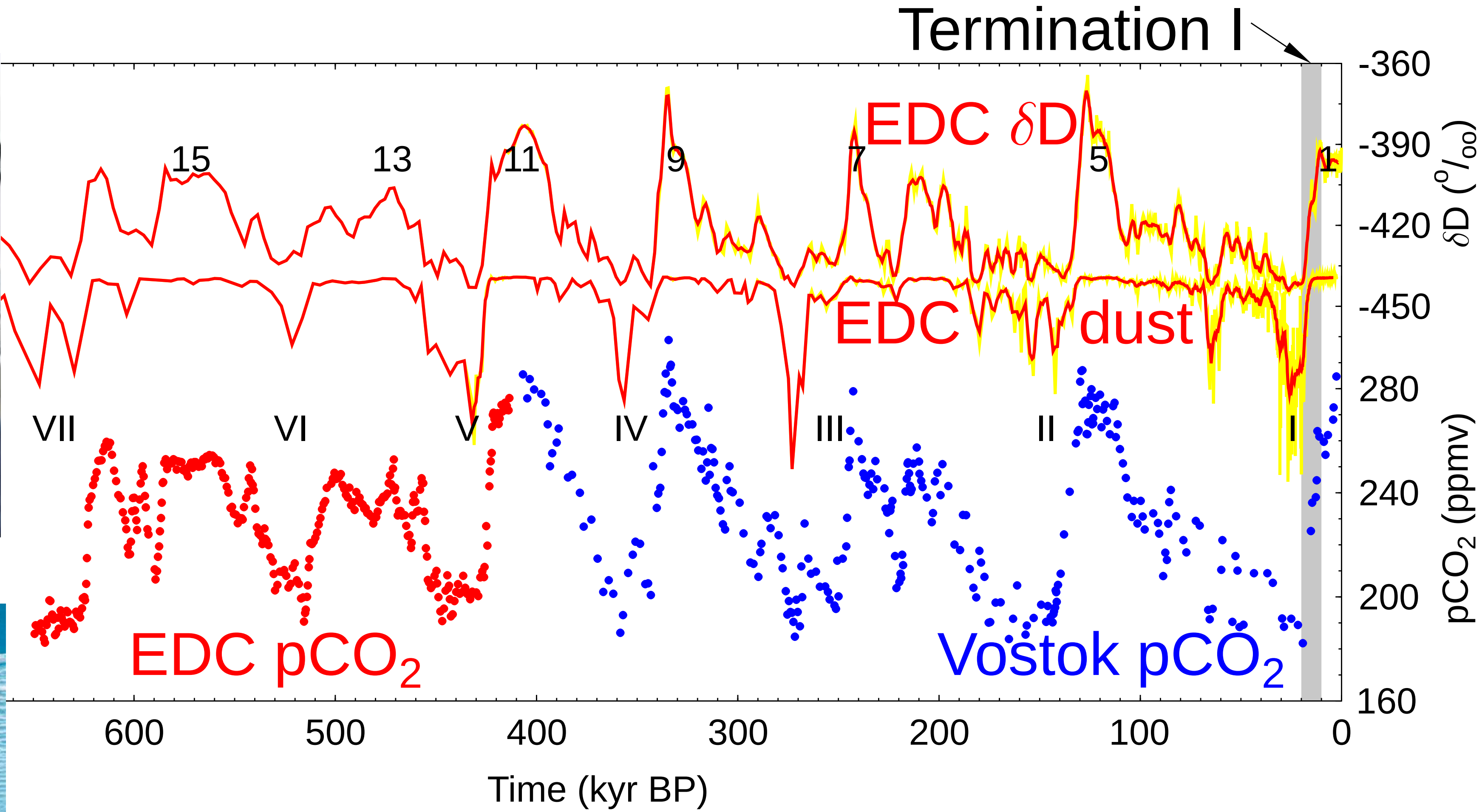
Particle physics
New mass for top quark raises bar for Higgs boson



EPICA, 2004; Petit et al., 1999
Siegenthaler et al., 2005

The EPICA challenge

Our contribution to the EPICA challenge:
Carbon cycle model simulations based on results for Termination I

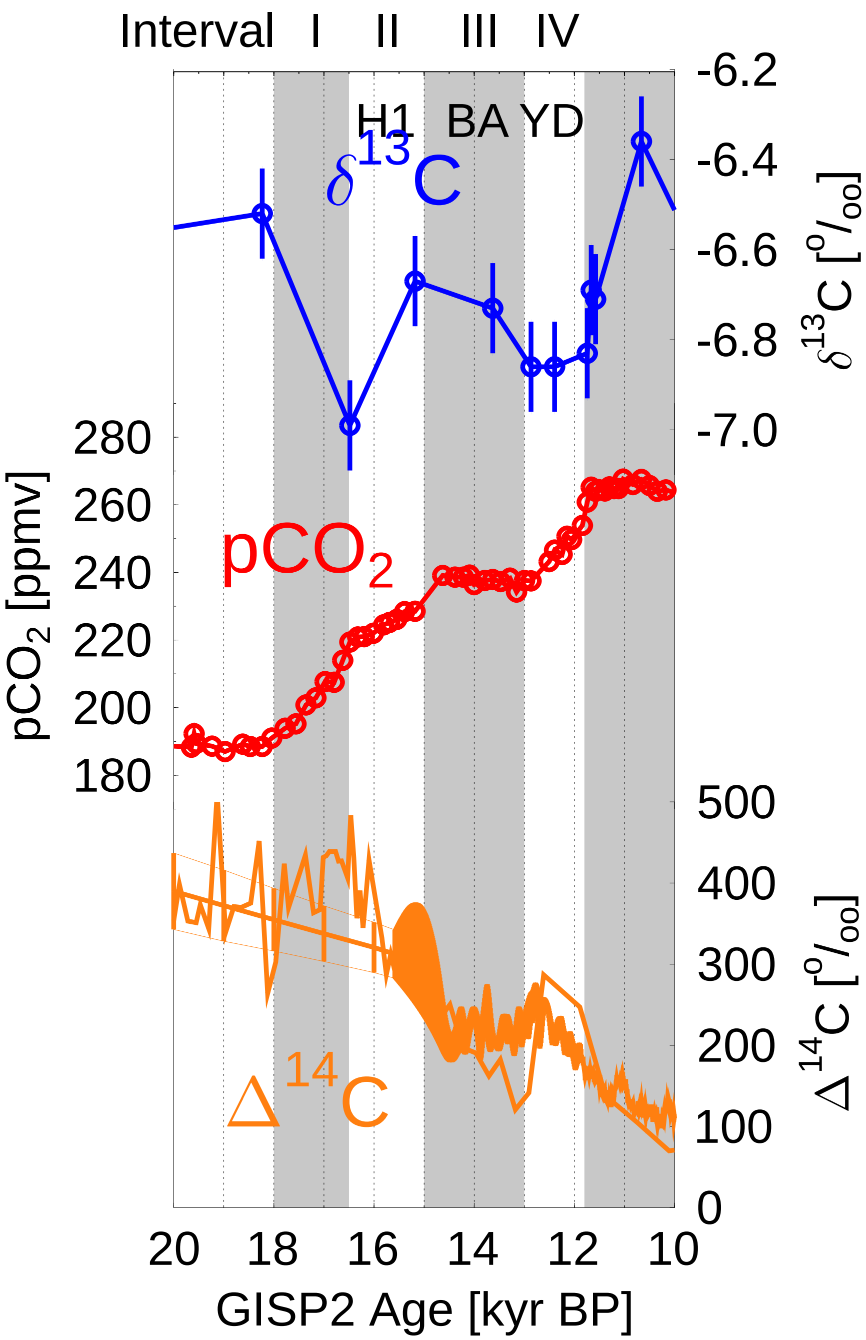


EPICA, 2004; Petit et al., 1999
Siegenthaler et al., 2005

Atmospheric carbon during Termination I

Interprete the temporal evolution of atmospheric CO_2, $\delta^{13}C$, ^{14}C records by carbon cycle simulations.

Smith et al., 1999; Monnin et al., 2001;
Stuiver et al., 1998; Hughen et al., 2004



The global record of atmospheric CO_2

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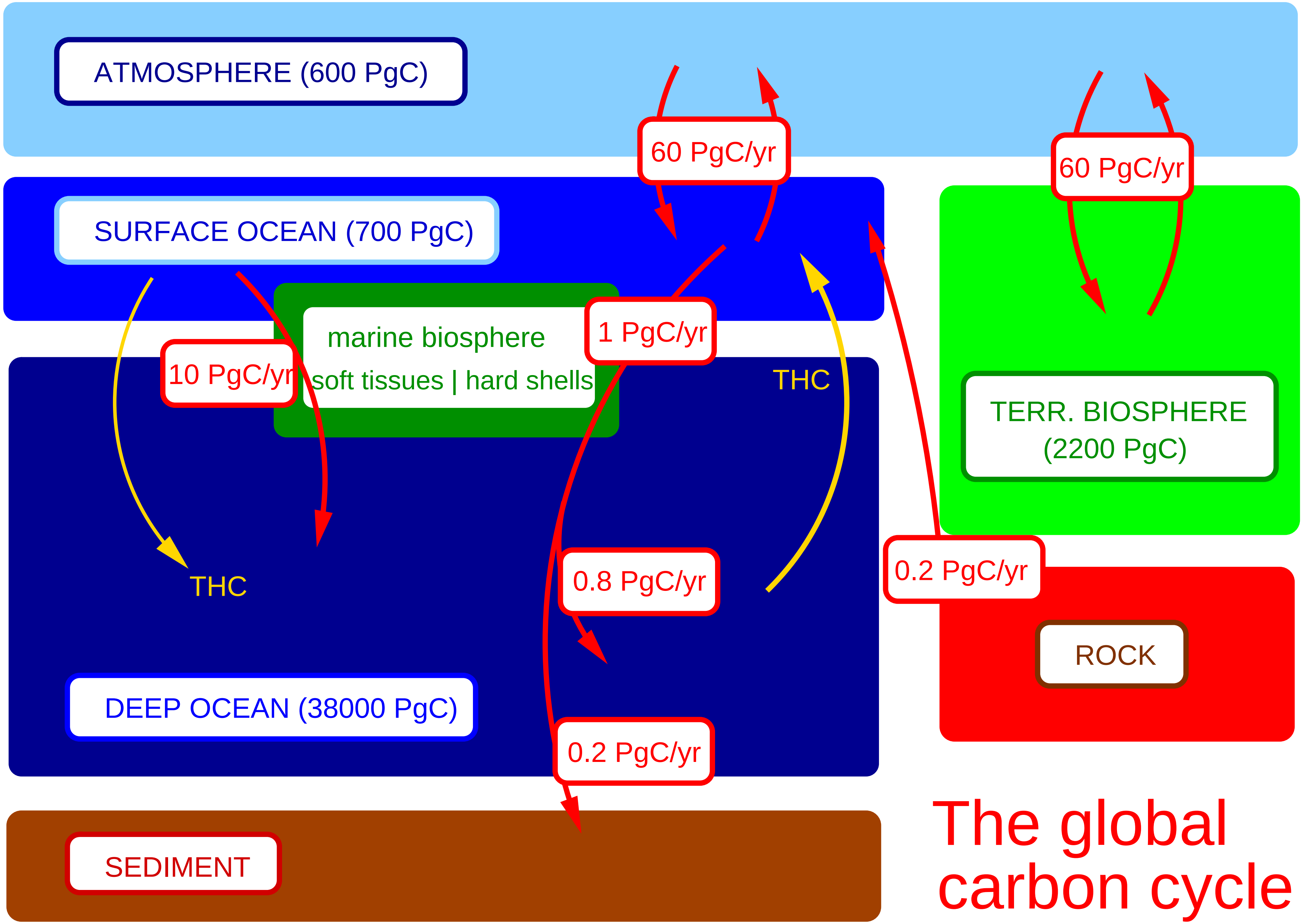
The global carbon cycle



ATMOSPHERE (600 PgC)

60 PgC/yr

60 PgC/yr

SURFACE OCEAN (700 PgC)

marine biosphere

soft tissues | hard shells

10 PgC/yr

1 PgC/yr

THC

THC

TERR. BIOSPHERE (2200 PgC)

0.8 PgC/yr

0.2 PgC/yr

ROCK

DEEP OCEAN (38000 PgC)

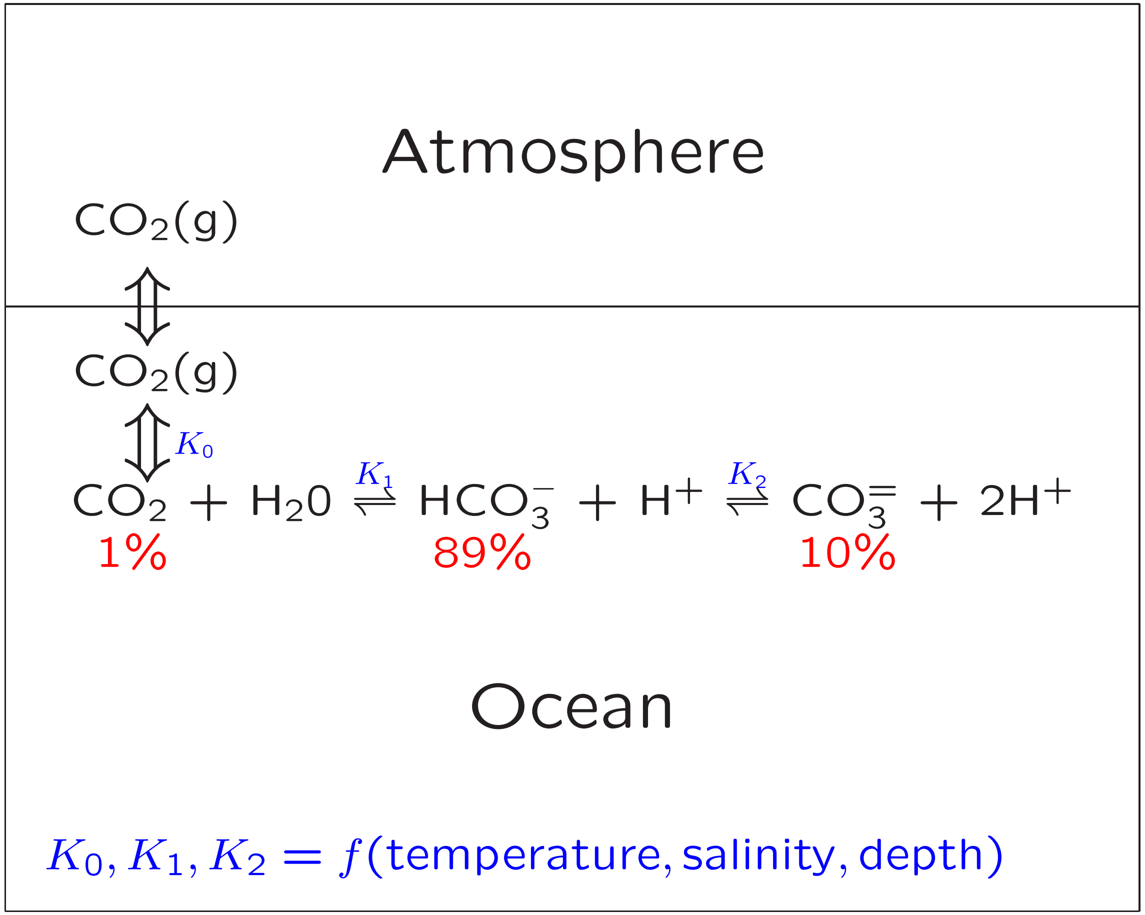
0.2 PgC/yr

SEDIMENT

preindustrial reservoir sizes and annual fluxes

Carbonate System in the Ocean

Dissolved Inorganic Carbon (DIC) $= CO_2 + HCO_3^- + CO_3^=$



Atmosphere

$CO_2(g)$

$\Updownarrow$

$CO_2(g)$

$\Updownarrow K_0$

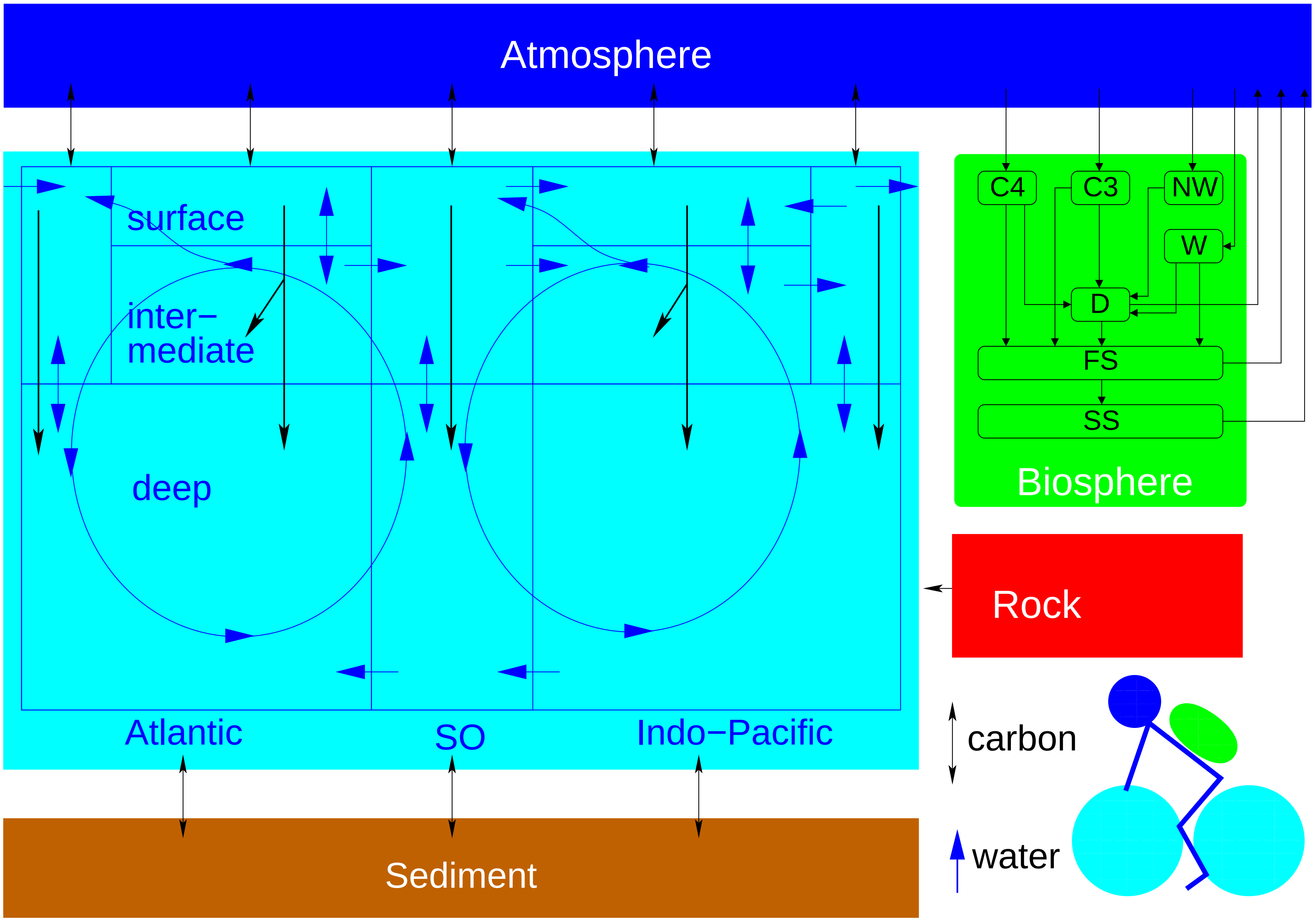
$$CO_2 + H_20 \overset{K_1}{\rightleftharpoons} HCO_3^- + H^+ \overset{K_2}{\rightleftharpoons} CO_3^= + 2H^+$$

1% 89% 10%

Ocean

$K_0, K_1, K_2 = f(\text{temperature, salinity, depth})$

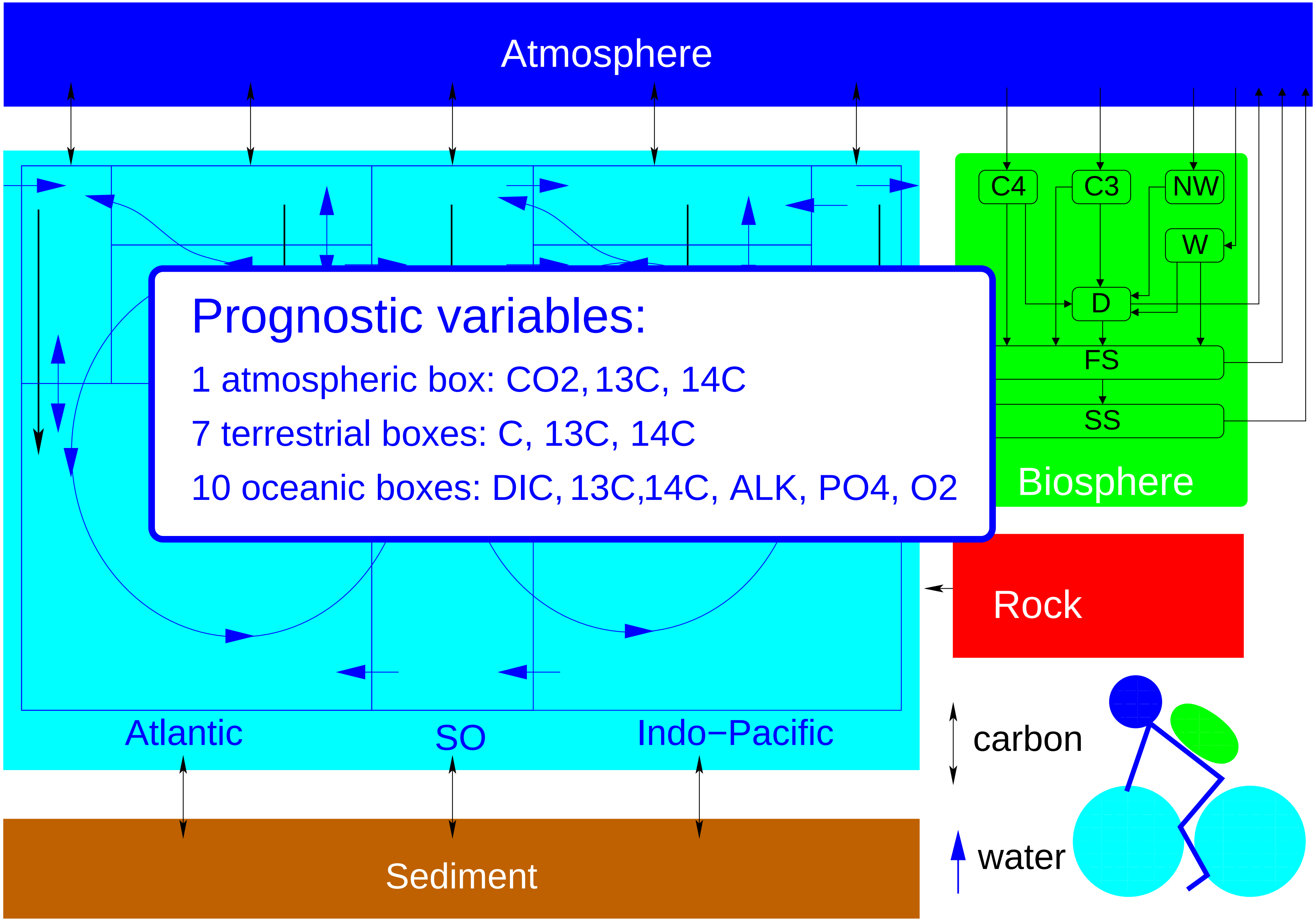
after Zeebe and Wolf-Gladrow, 2001



Box model of the Isotopic Carbon cYCLE

BICYCLE

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



Prognostic variables:

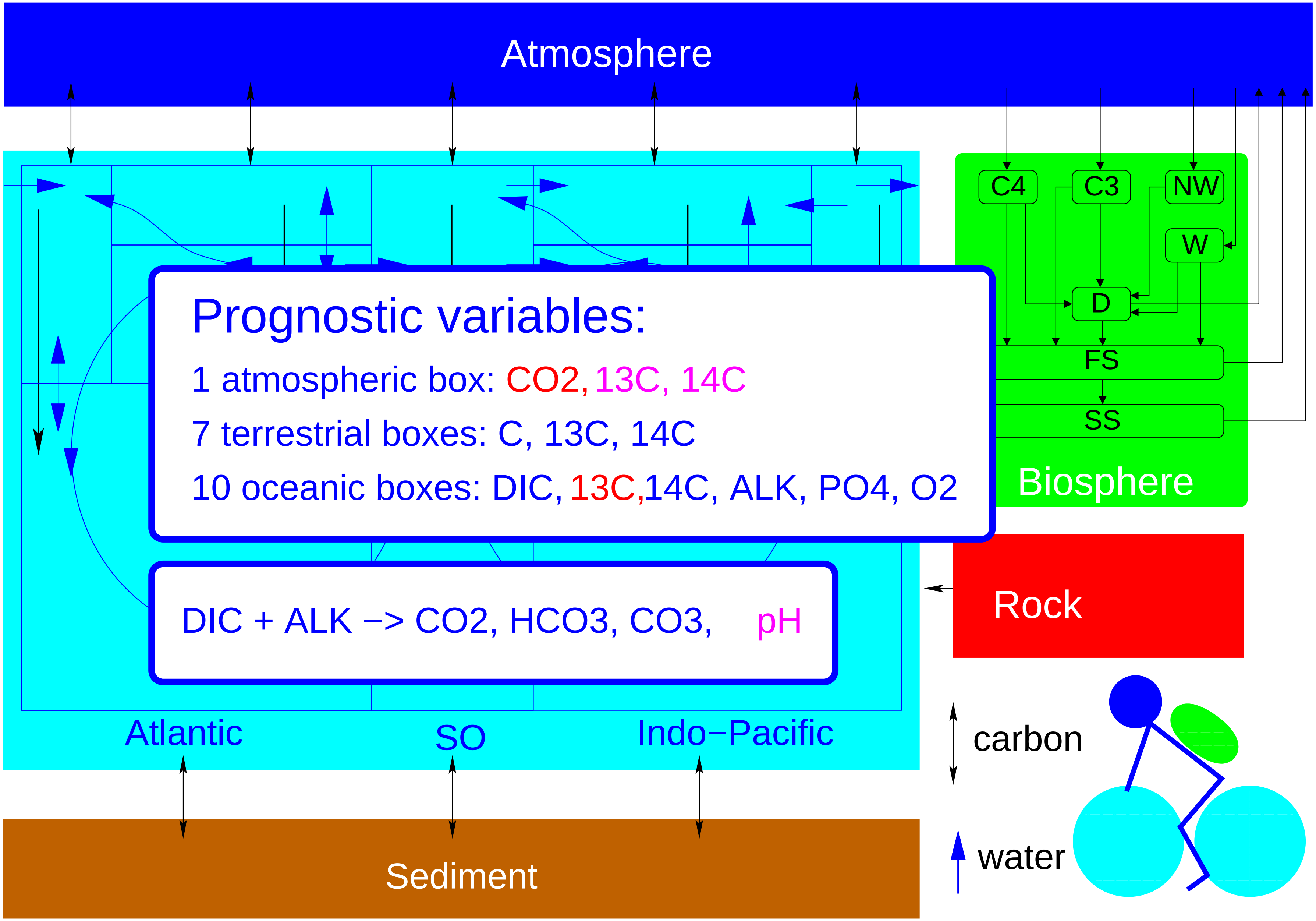
1 atmospheric box: CO2, 13C, 14C

7 terrestrial boxes: C, 13C, 14C

10 oceanic boxes: DIC, 13C,14C, ALK, PO4, O2

Box model of the Isotopic Carbon cYCLE BICYCLE

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



Prognostic variables:

1 atmospheric box: CO2, 13C, 14C

7 terrestrial boxes: C, 13C, 14C

10 oceanic boxes: DIC, 13C,14C, ALK, PO4, O2

DIC + ALK −> CO2, HCO3, CO3, pH

Box model of the Isotopic Carbon cYCLE BICYCLE

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Overall objective and procedure for time-dependent simulations

Novelty:

- BICYCLE runs forward in time (no inverse studies)
- Transient simulations based on and forced with available paleo records

Three steps:

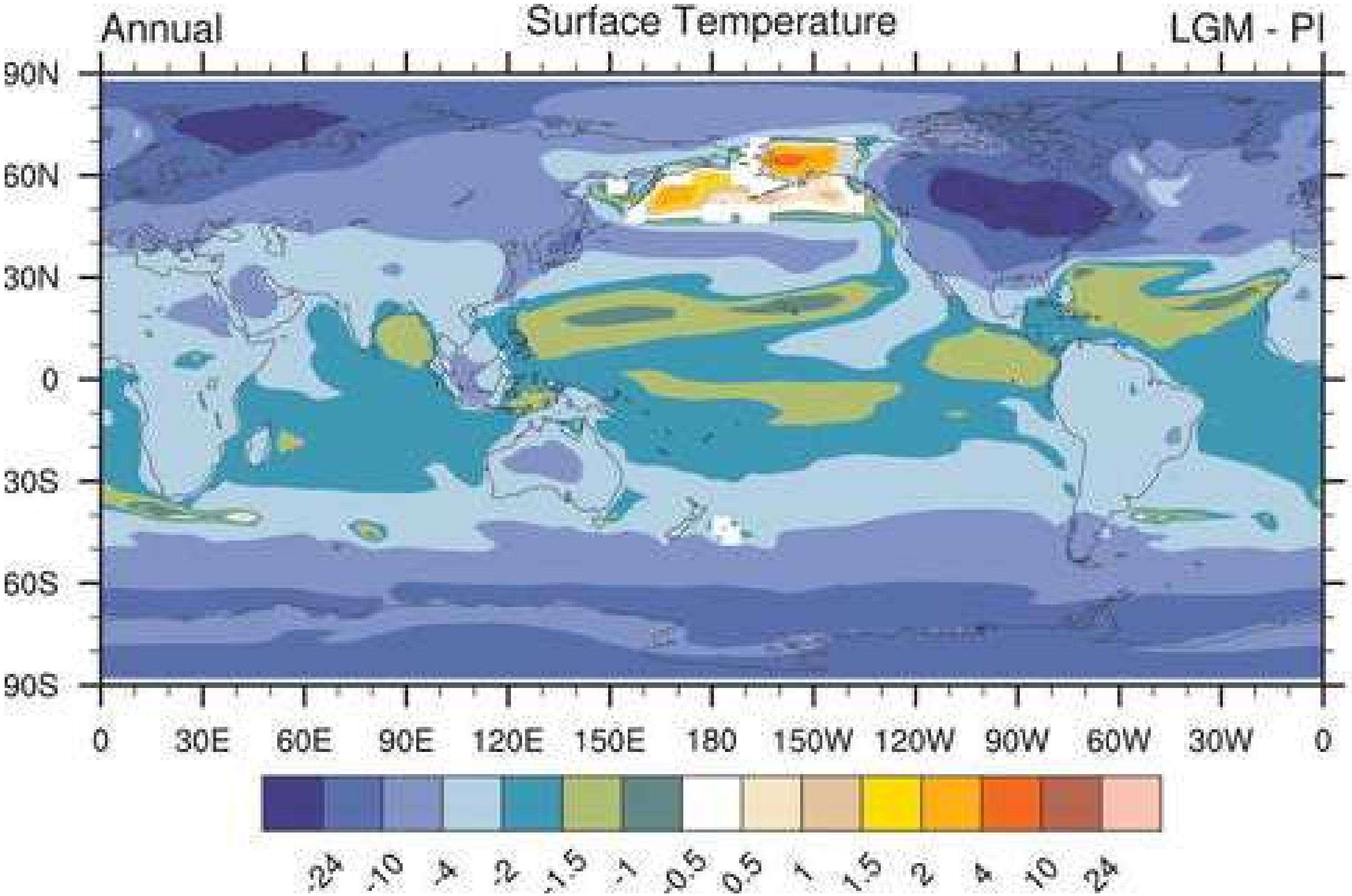
1. **Which** time-dependent processes were changing the carbon cycle on glacial/interglacial timescales?
2. **How** can we prescribe / force these processes in BICYCLE?
3. **What** are the impacts on CO_2?

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** (⊤ 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			
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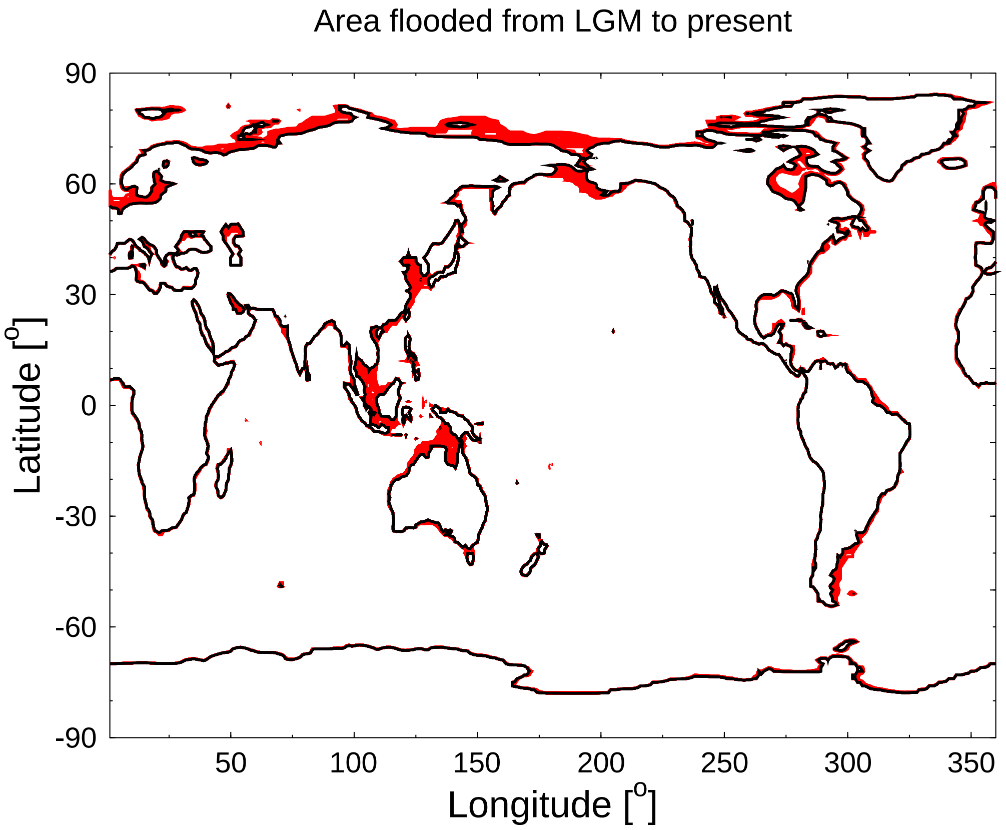
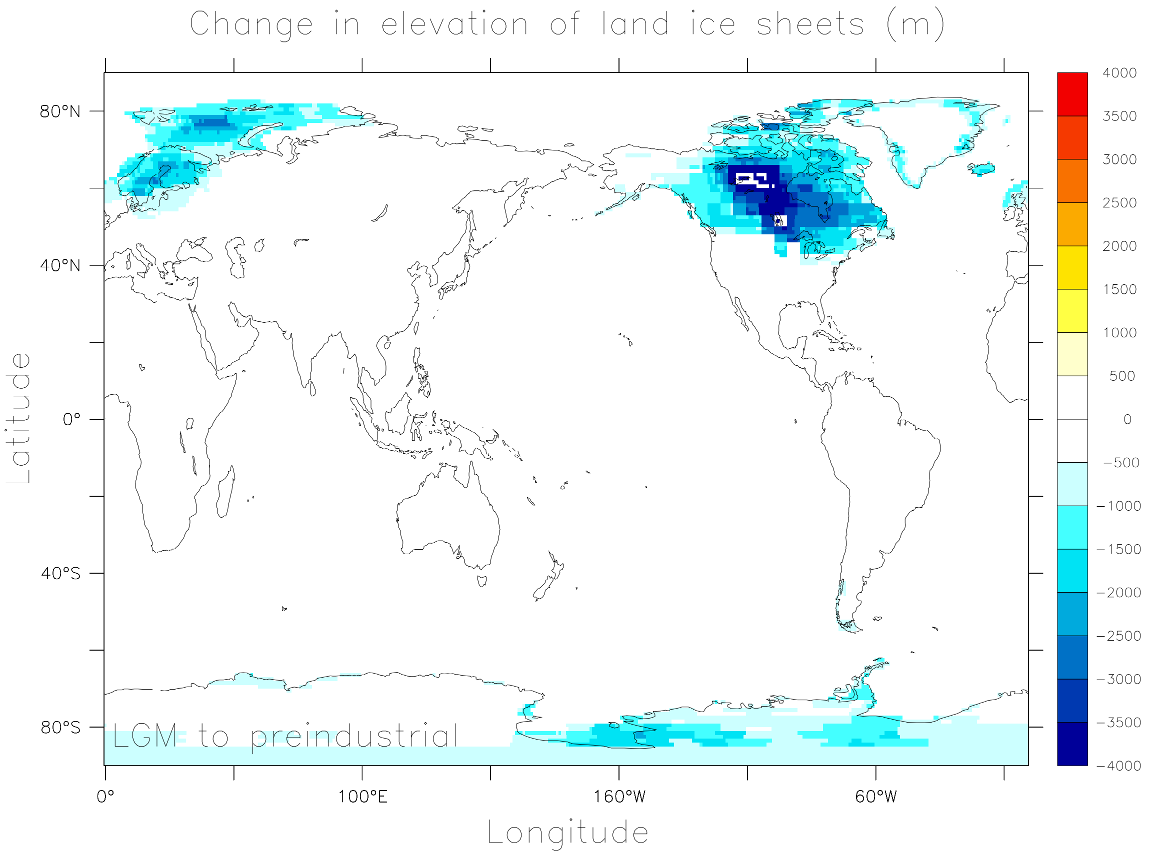
2 Sea Level / Salinity

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:

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5	Southern Ocean ventilation			
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6	Marine biota / iron fertilisation			
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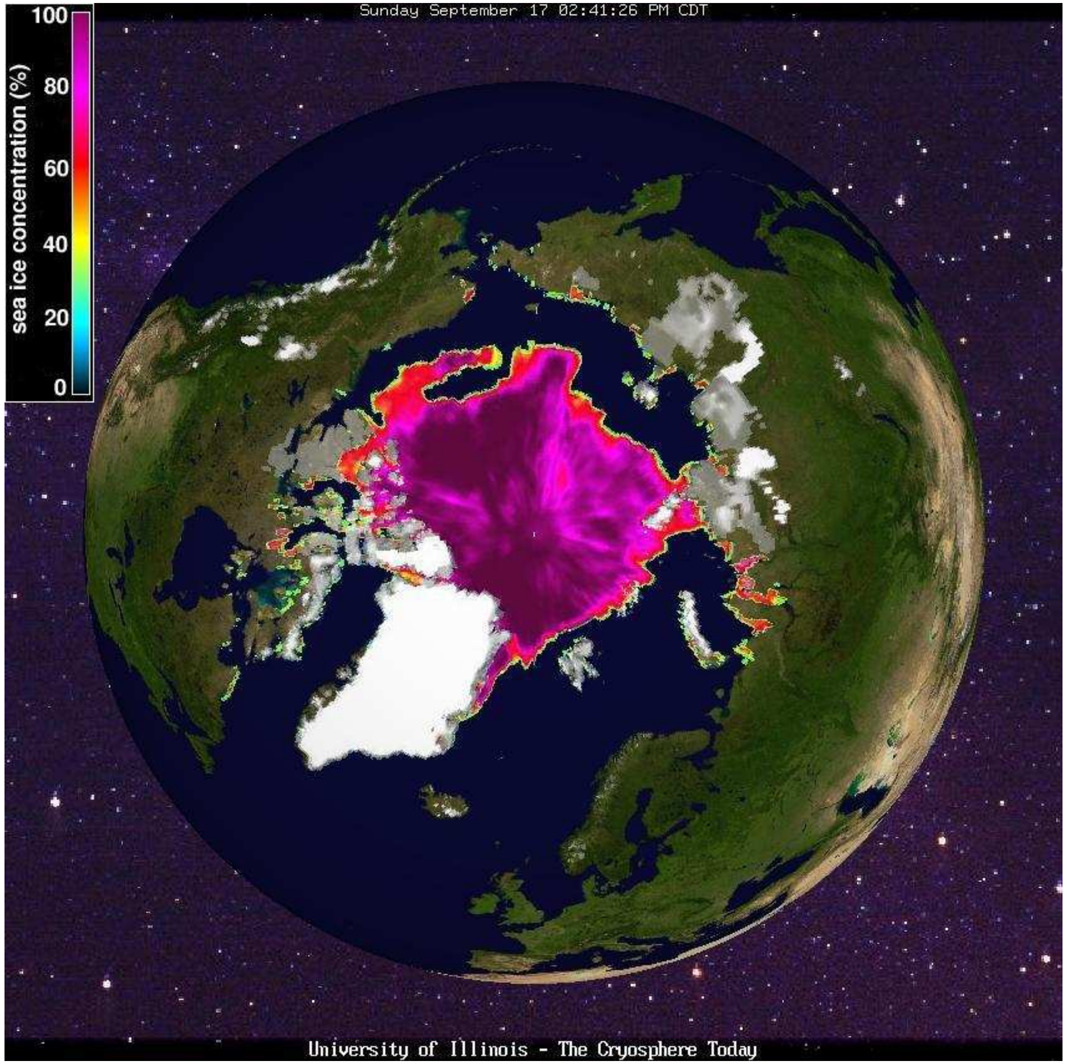
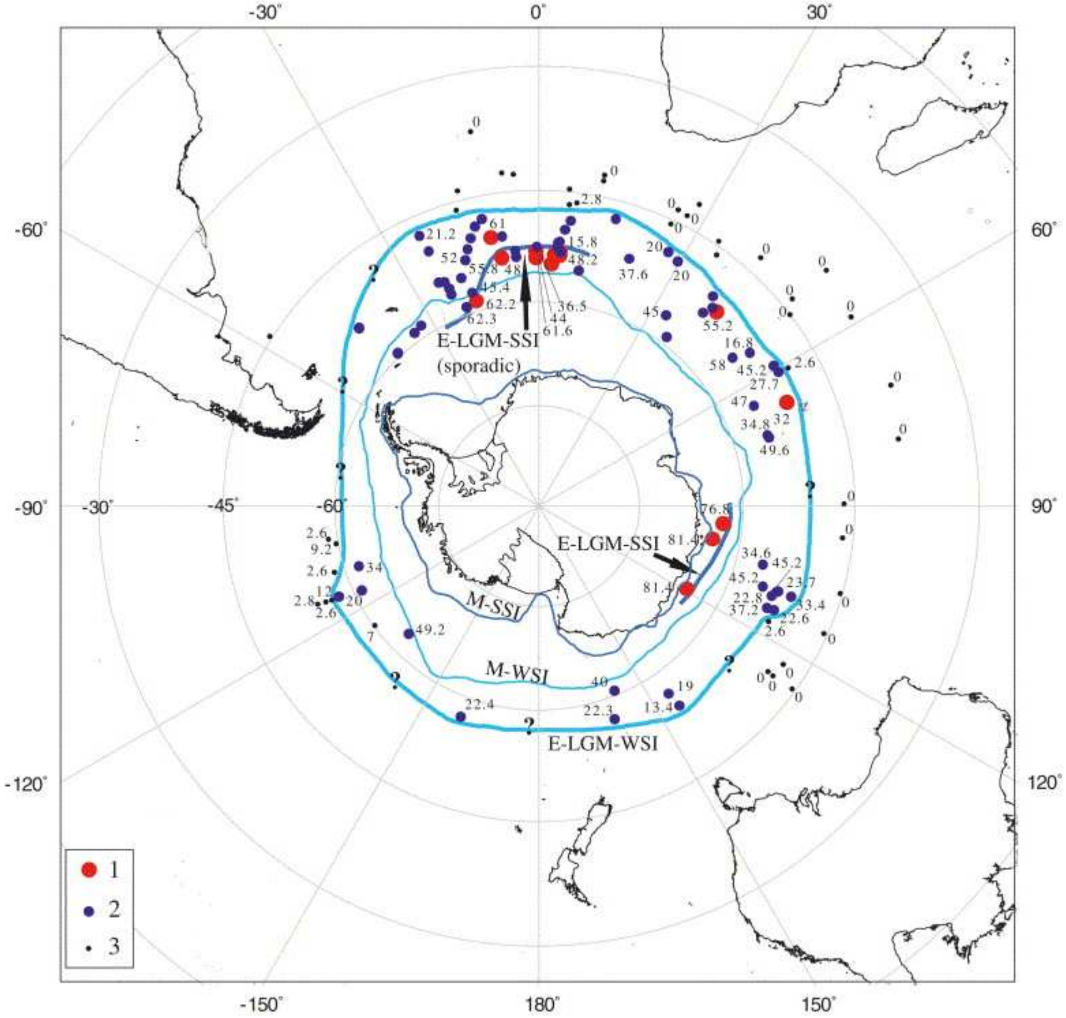
3 Gas Exchange / Sea Ice

Annual mean sea ice area shrunk by ∼50% (Termination I)
Dynamics coupled to temperature in the high latitude surface boxes

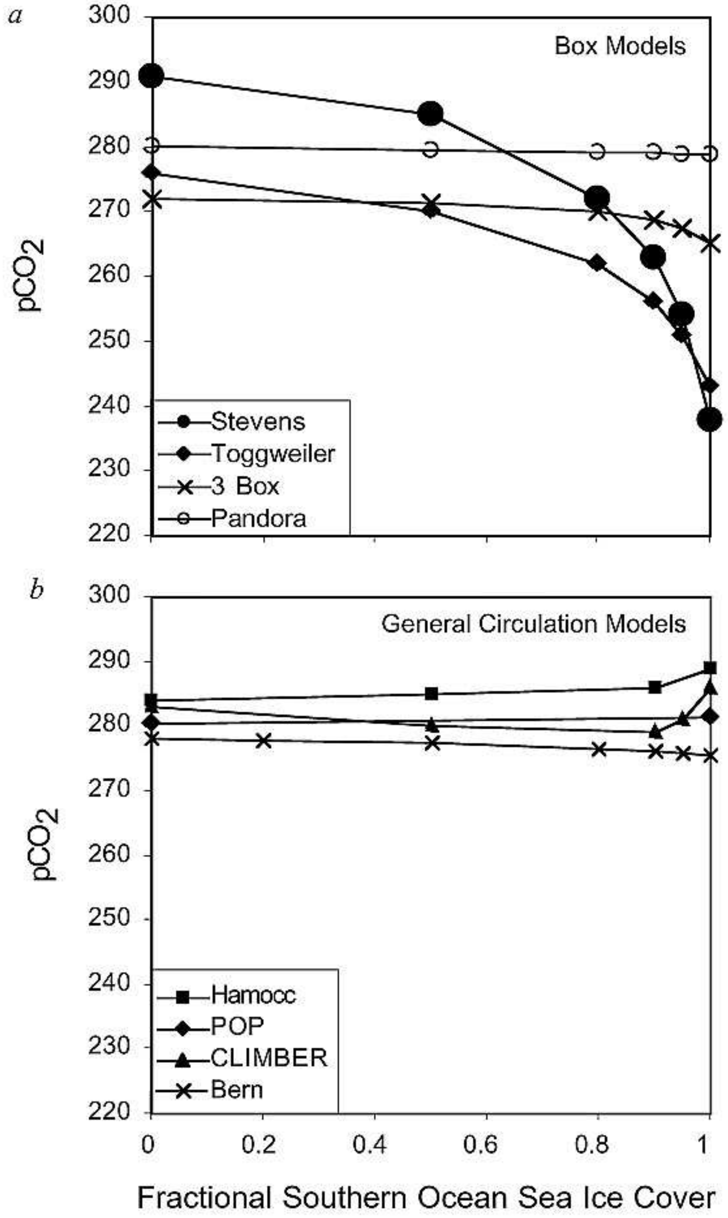




Arctic (present): The Cryosphere Today (www)

Antarctic (LGM) Gersonde et al., 2005

3 Gas Exchange / Sea Ice



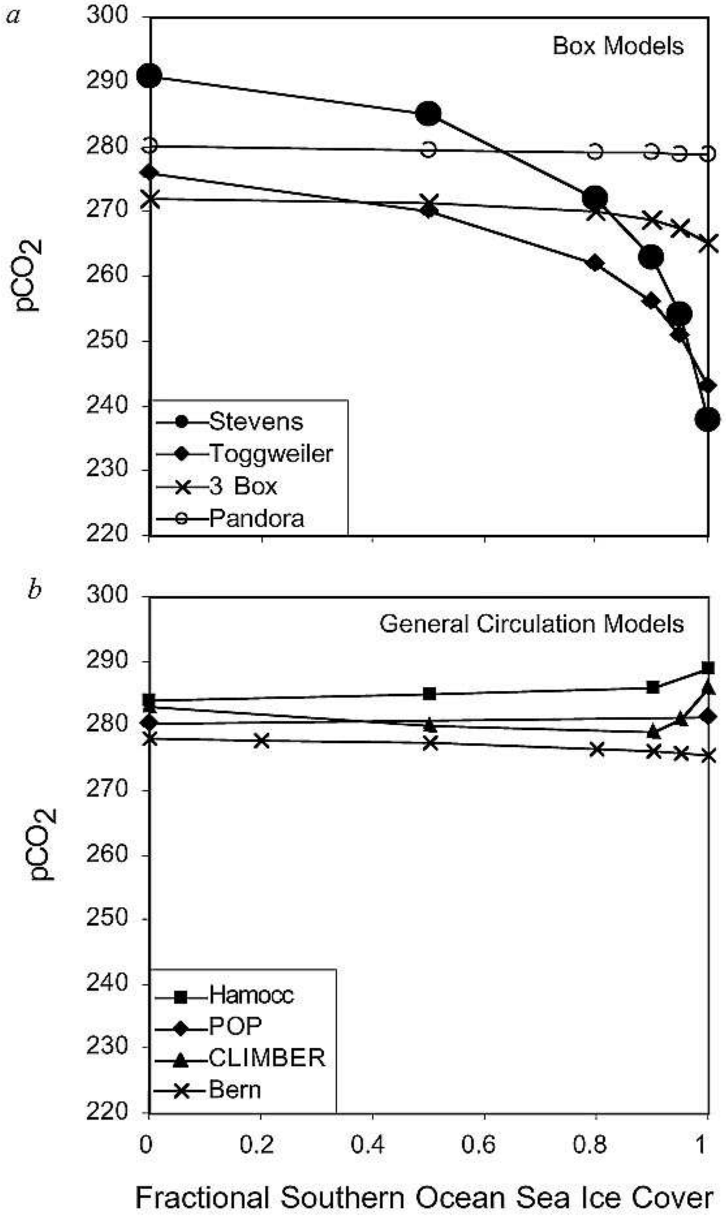
Model comparions came to ambiguous results

Box models: full sea ice cover in SO reduces CO_2

GCMs: only small changes

Archer et al., 2003

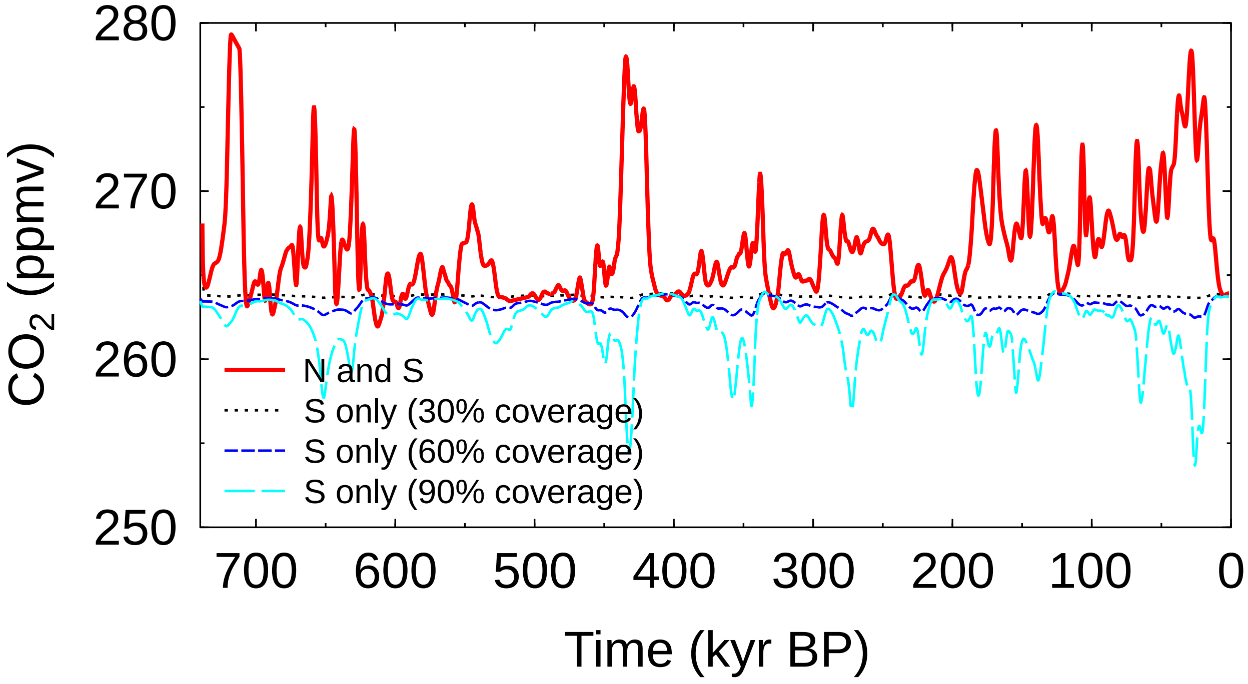
3 Gas Exchange / Sea Ice



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:

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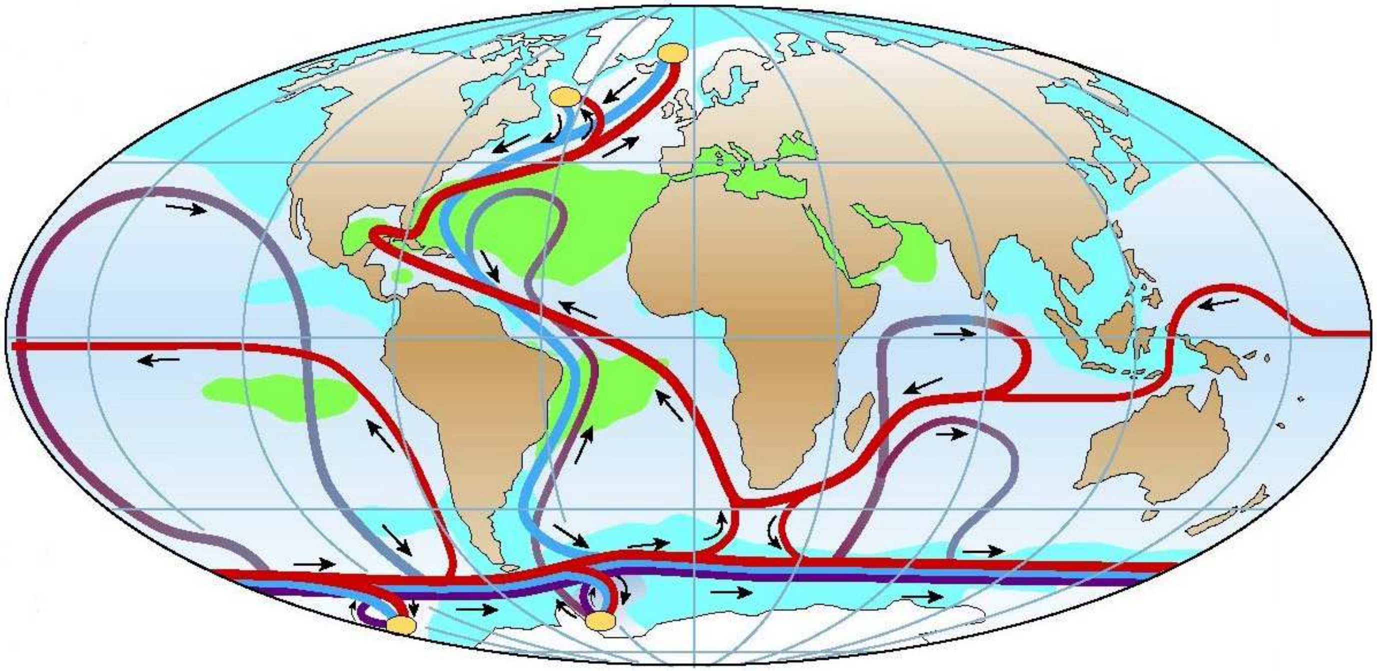
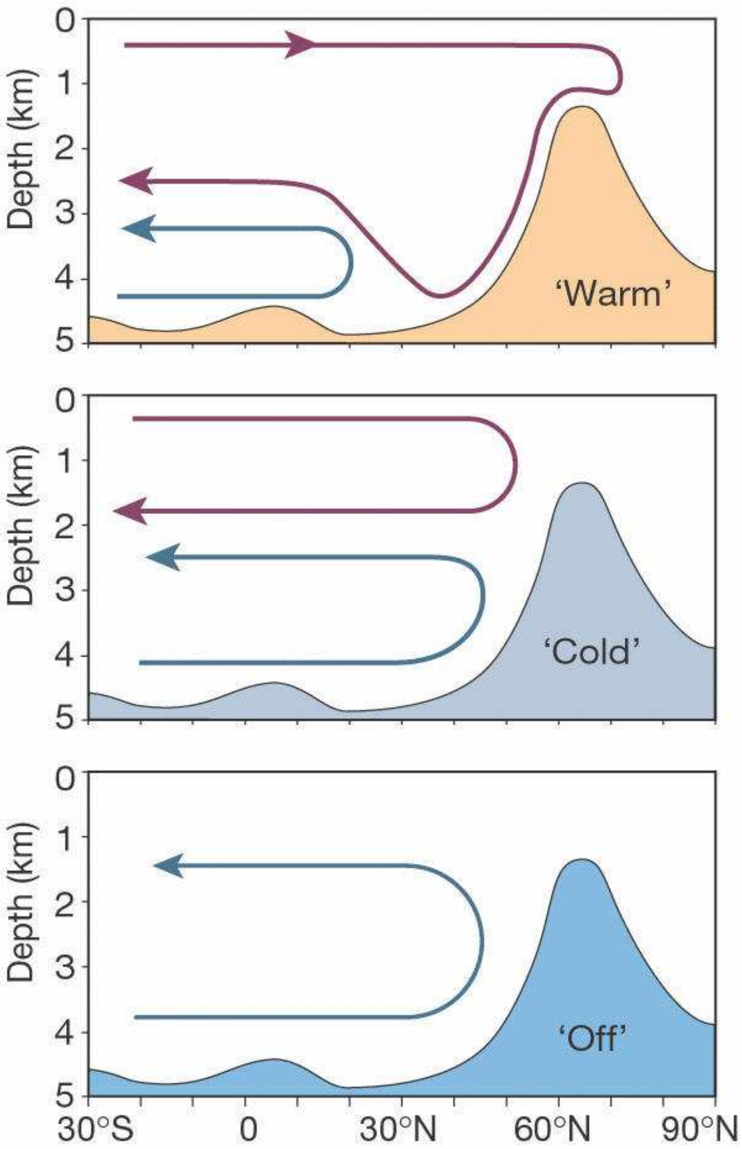
4 NADW Formation

Conveyor belt



Changes in Atlantic THC

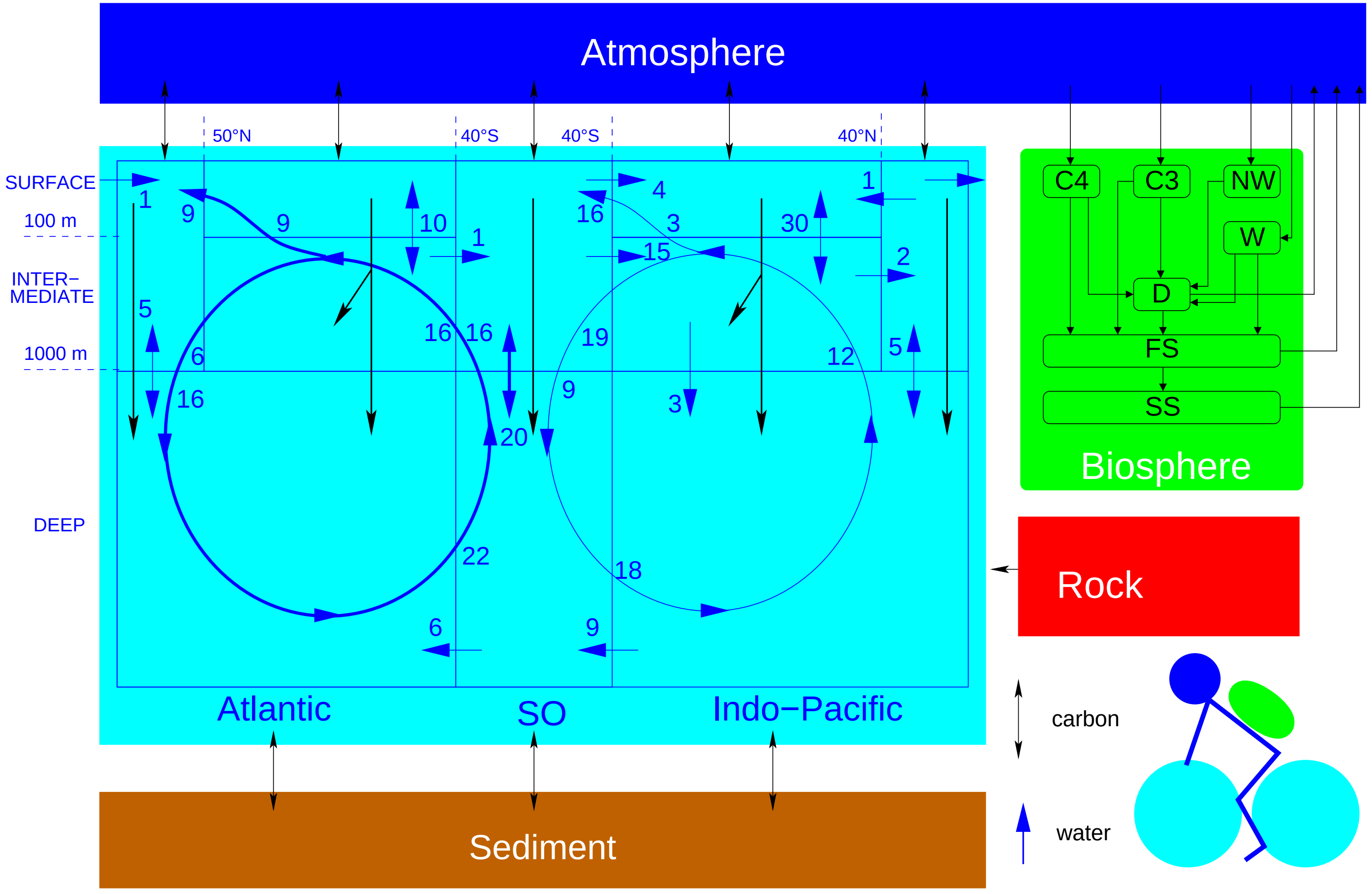


Rahmstorf, 2002

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

BICYCLE

Circulation after Ganachaud & Wunsch, 2000

Time-dependent processes:

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	Ocean circulation			
4	NADW formation	+6 Sv	+15	!
5	Southern Ocean ventilation			
	Biogeochemistry			
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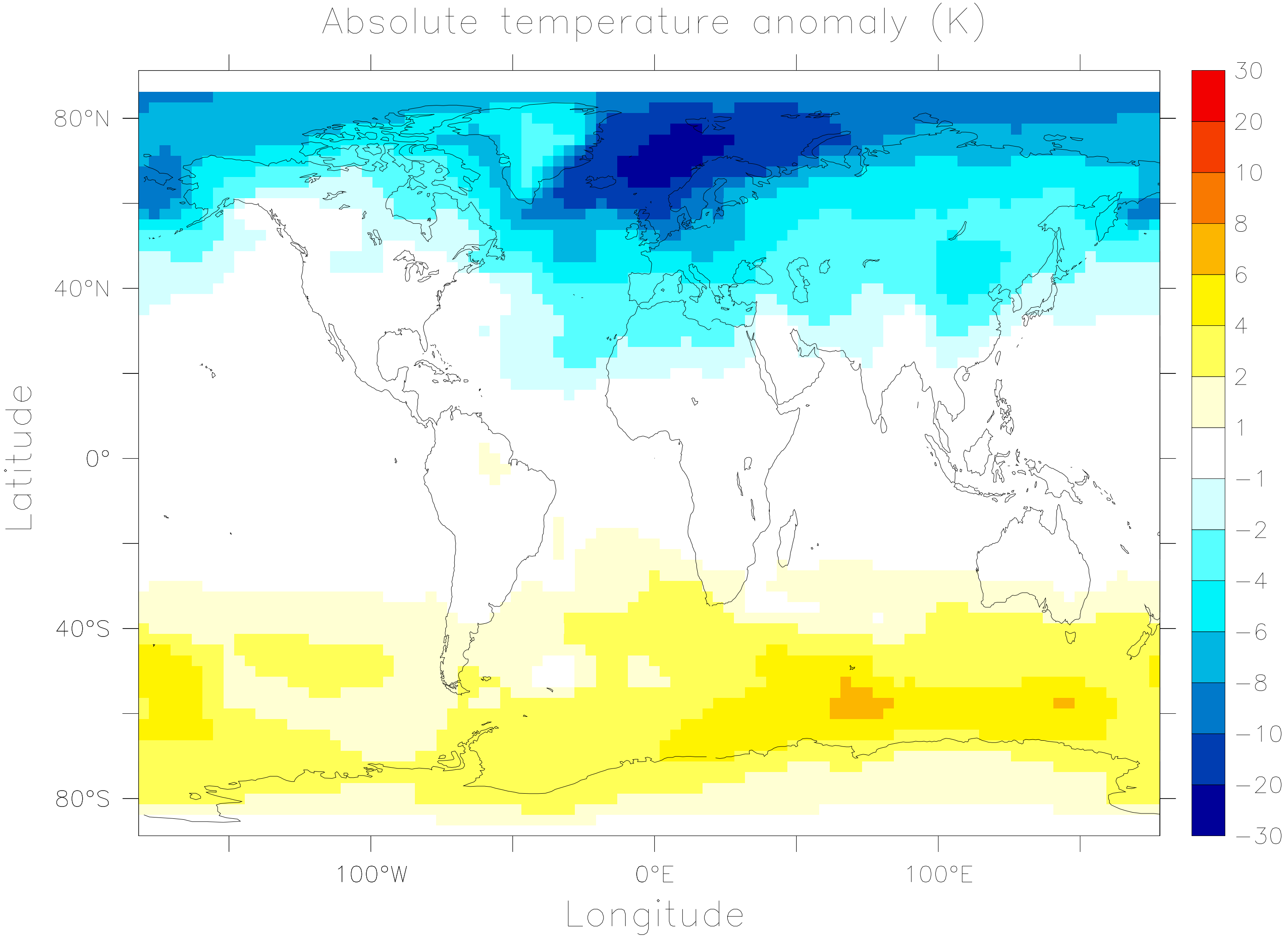
4 Indirect effects of shutdown of NADW (not in BICYCLE)

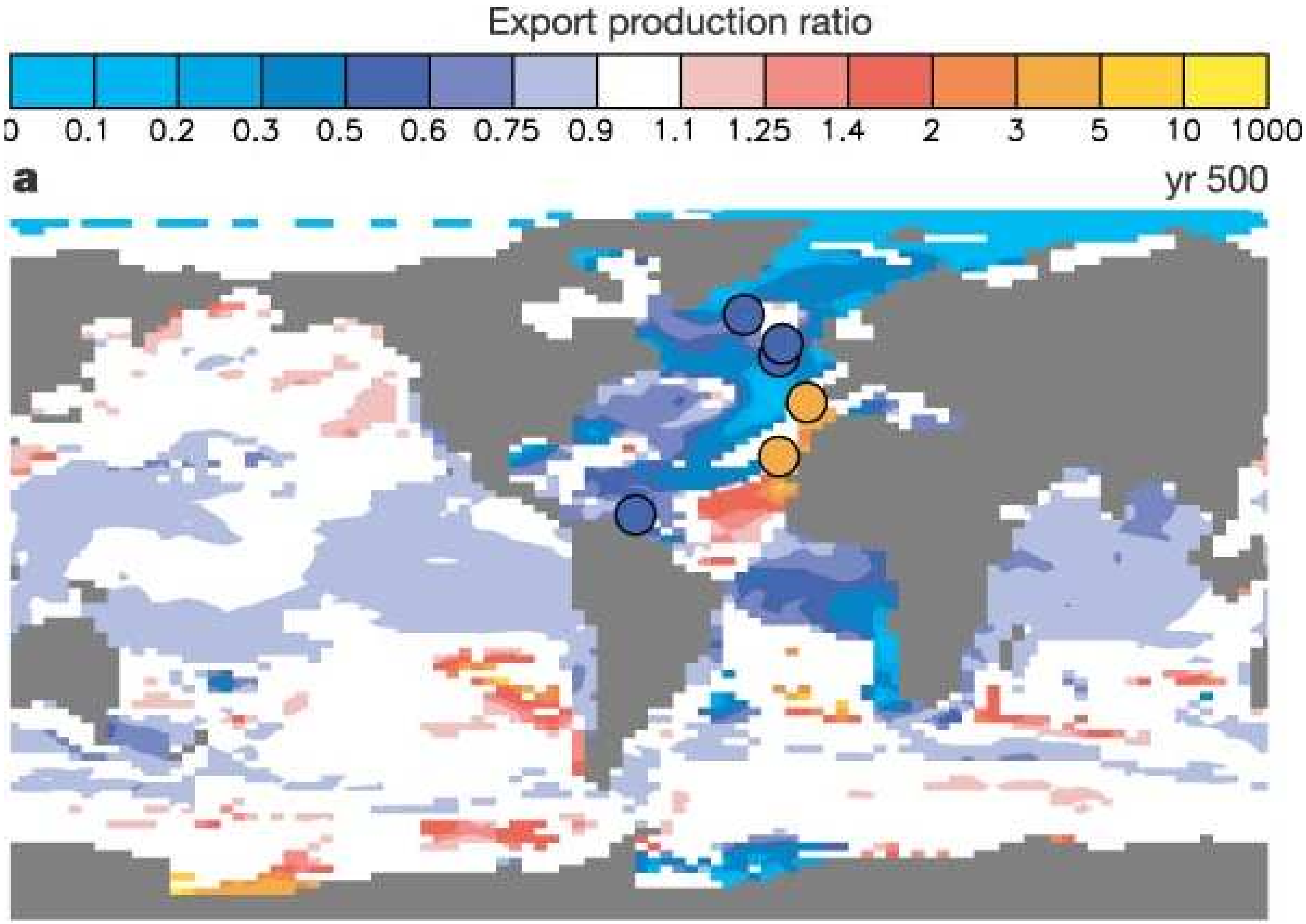
Additionally, a NADW shutdown would lead to cooling in Eurasia
Temperature anomalies simulated with ECBILT-CLIO



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%

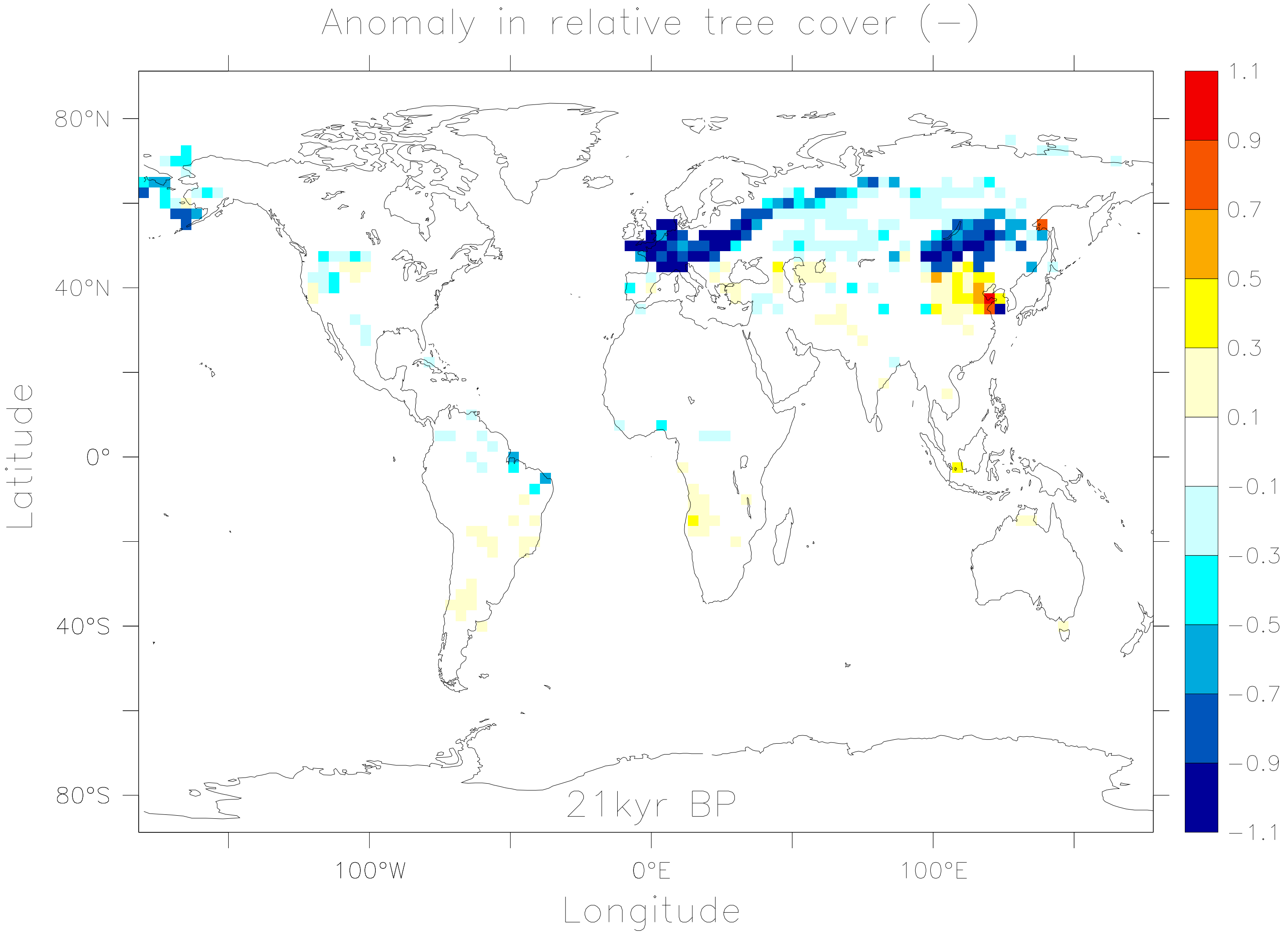


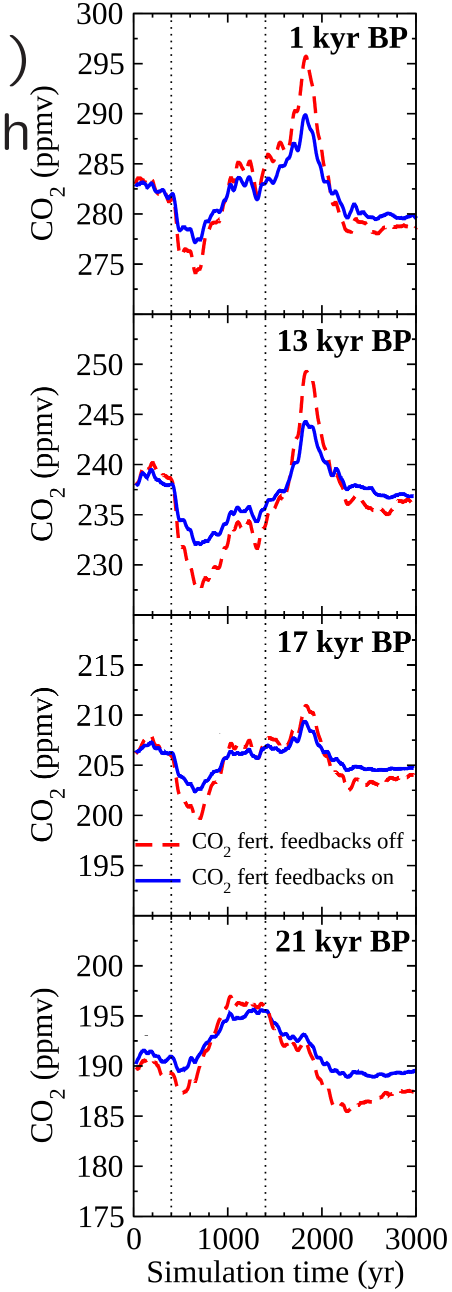
Schmittner ,2005

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

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	Ocean circulation			
4	NADW formation	+6 Sv	+15	!/? (off)
5	Southern Ocean ventilation			
	Biogeochemistry			
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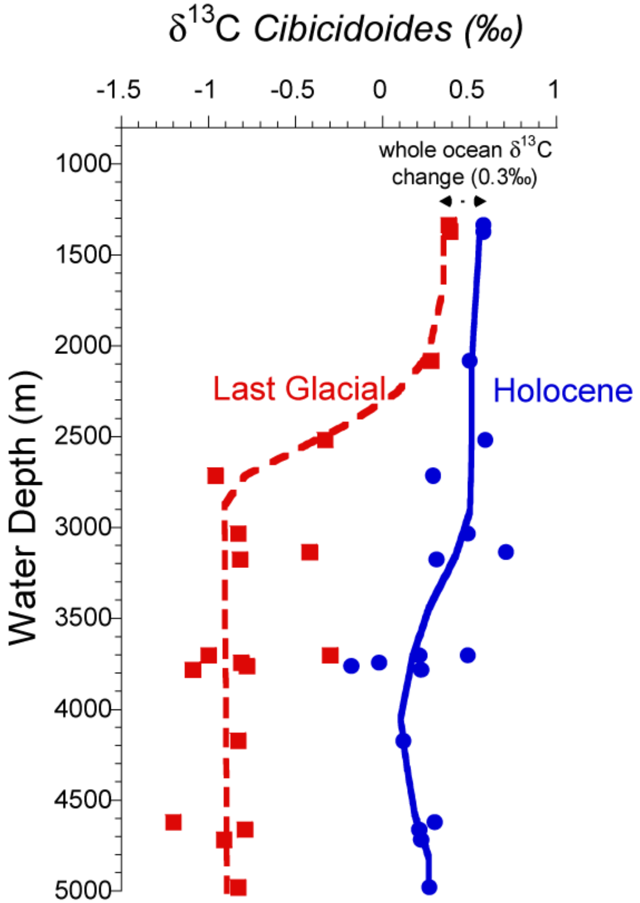
5 Southern Ocean Ventilation

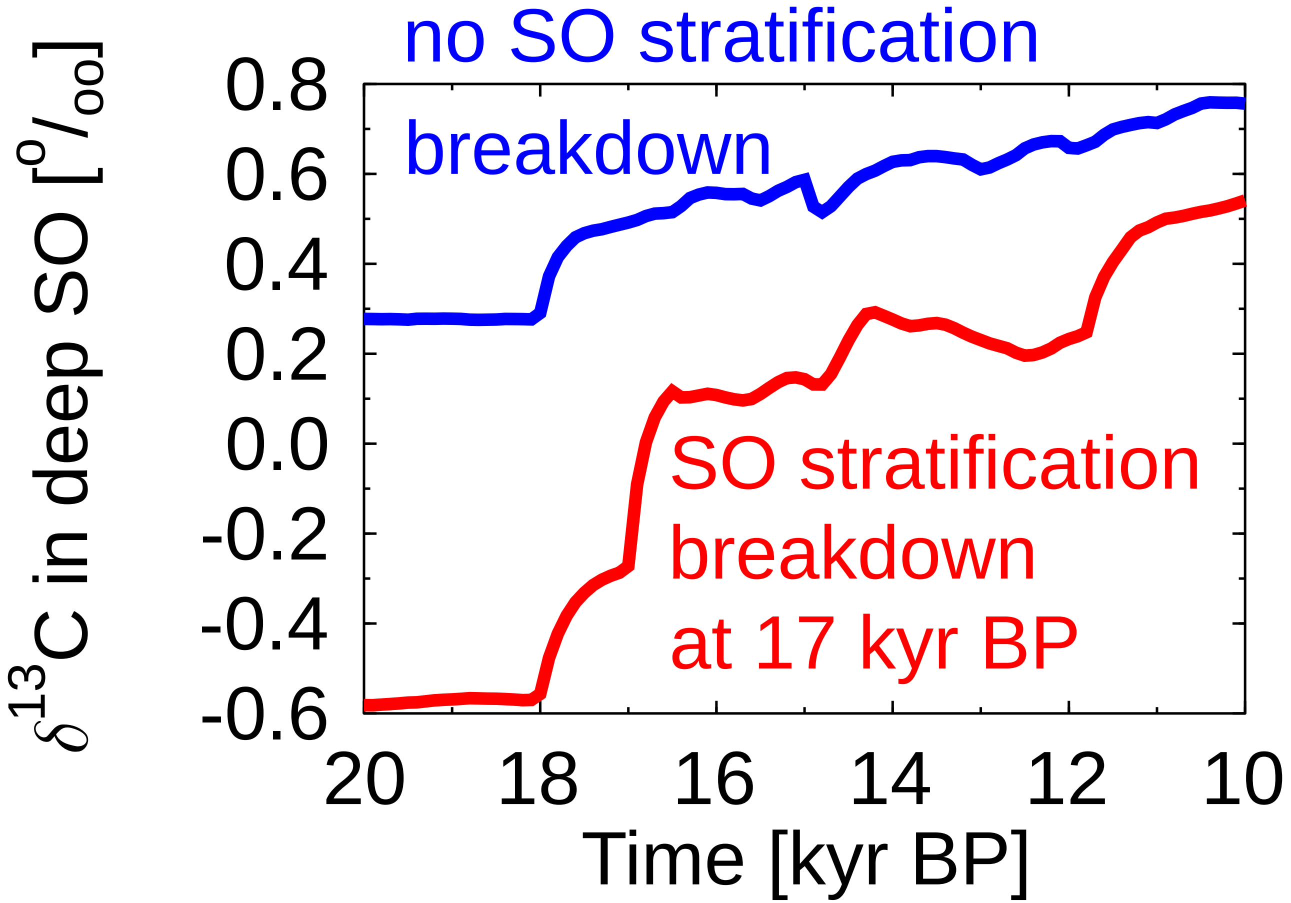
How to explain $\Delta\delta^{13}$C(PRE-LGM)=+1.2‰ in deep Southern Ocean?

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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5	Southern Ocean ventilation	+20 Sv	+35	o
	Biogeochemistry			
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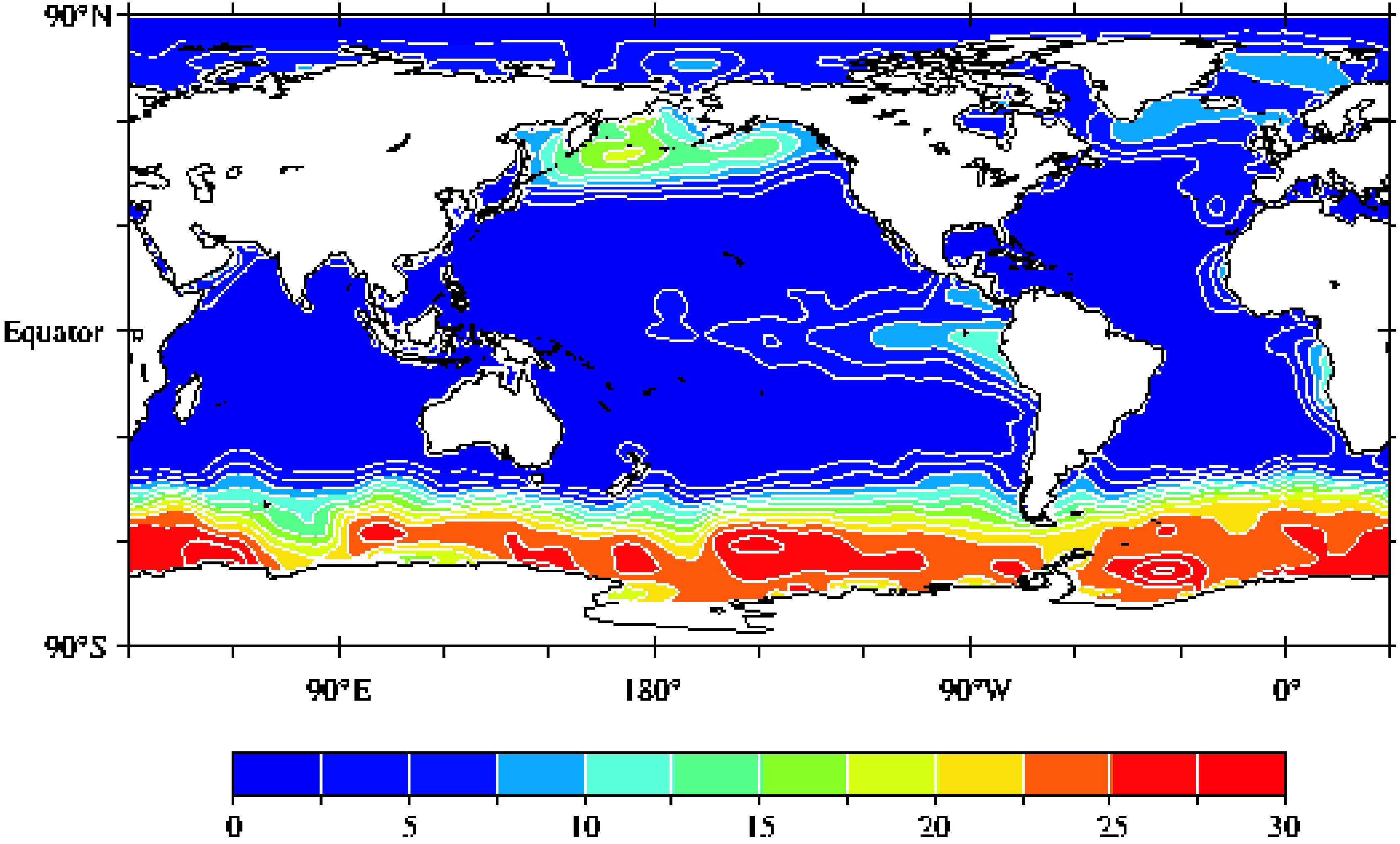
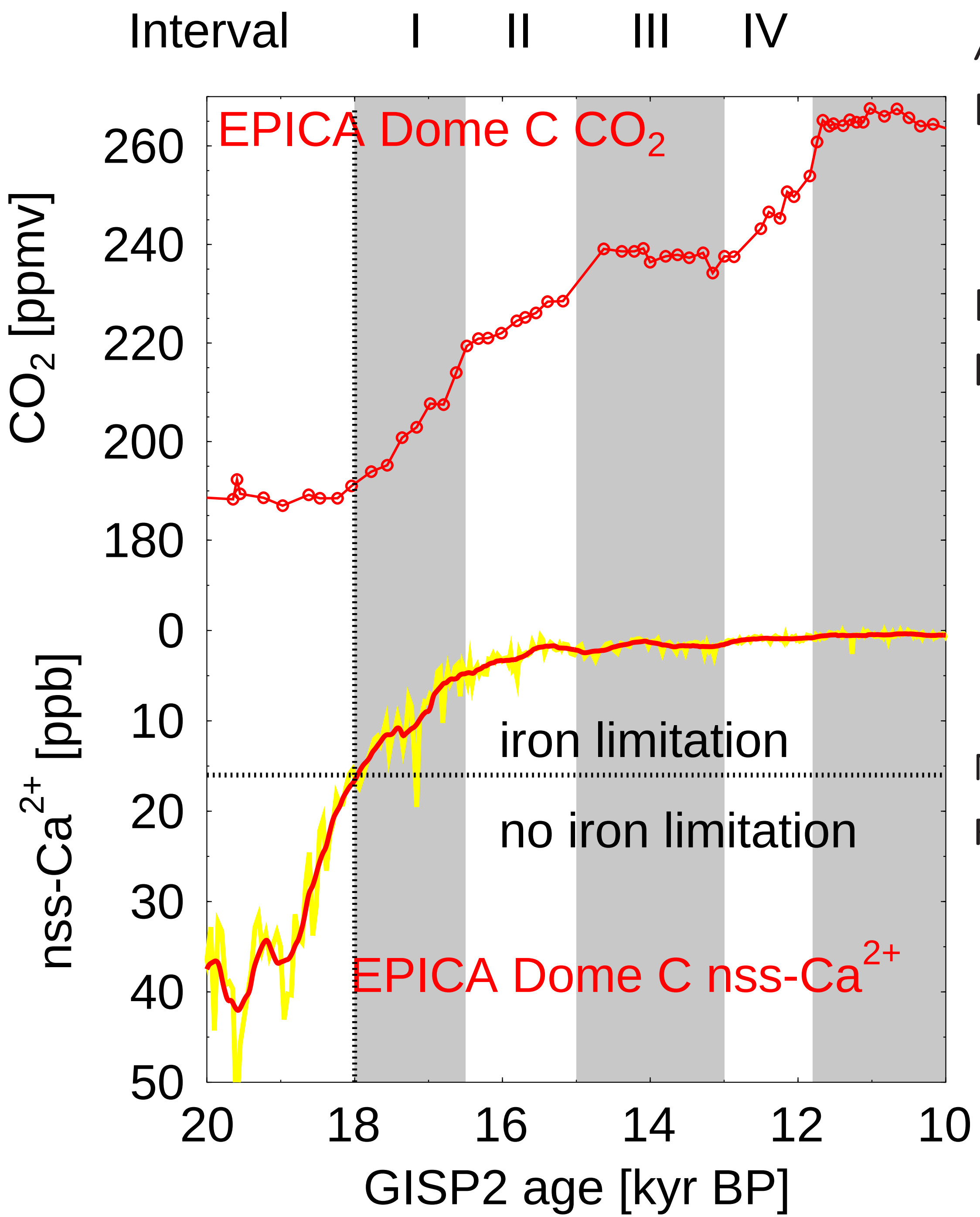
6 Marine Biota / Iron fertilisation

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:

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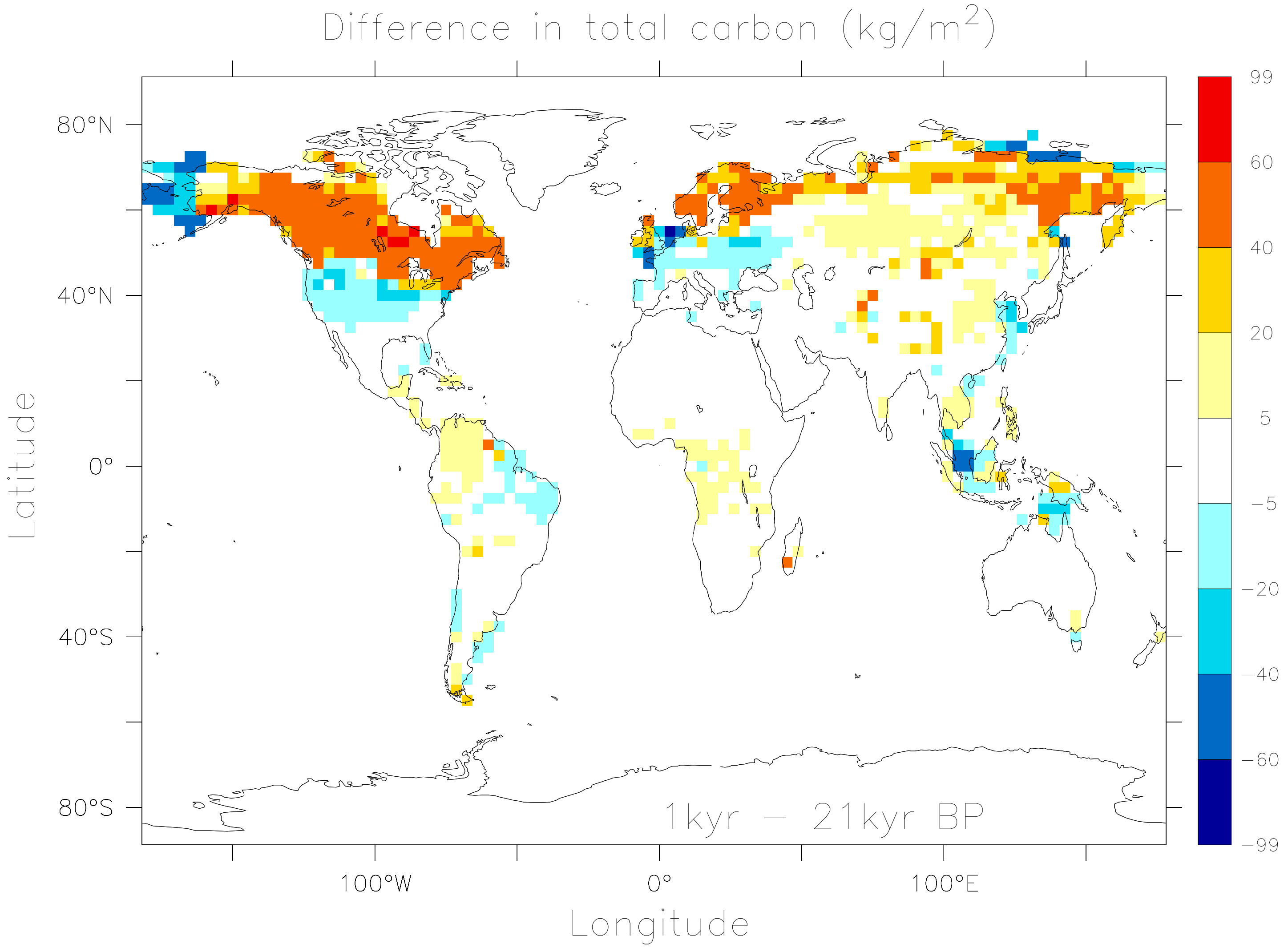
	Ocean circulation			
4	NADW formation	+6 Sv	+15	!/? (off)
5	Southern Ocean ventilation	+20 Sv	+35	o
	Biogeochemistry			
6	Marine biota / iron fertilisation	–2 PgC yr^{-1}	+20	?
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

7 Terrestrial carbon storage

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



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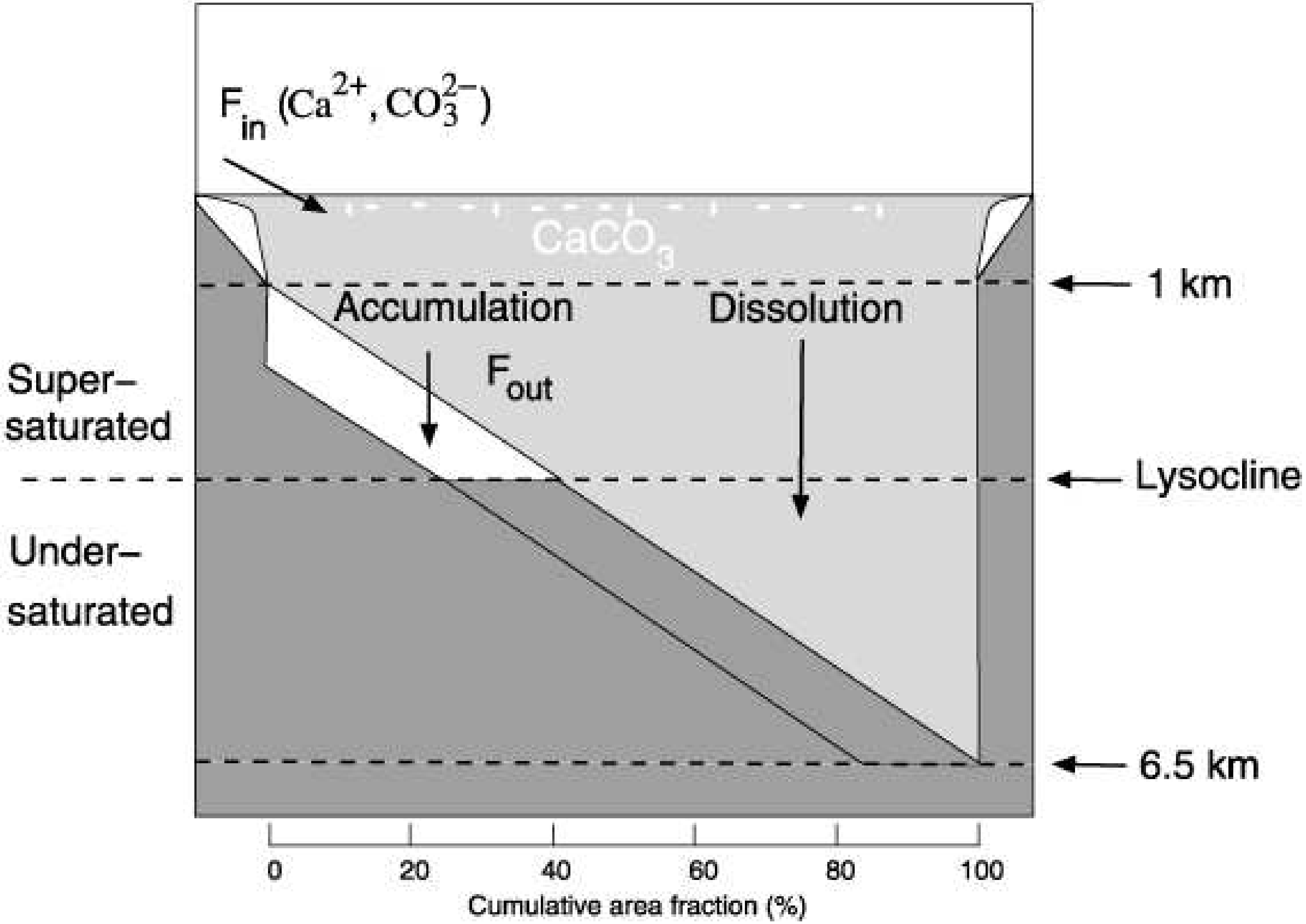
	Ocean circulation			
4	NADW formation	+6 Sv	+15	!/? (off)
5	Southern Ocean ventilation	+20 Sv	+35	o
	Biogeochemistry			
6	Marine biota / iron fertilisation	−2 PgC yr^{-1}	+20	?
7	Terrestrial carbon storage	+500 PgC	−15	!
8	CaCO$_3$ chemistry			

8 Carbonate compensation

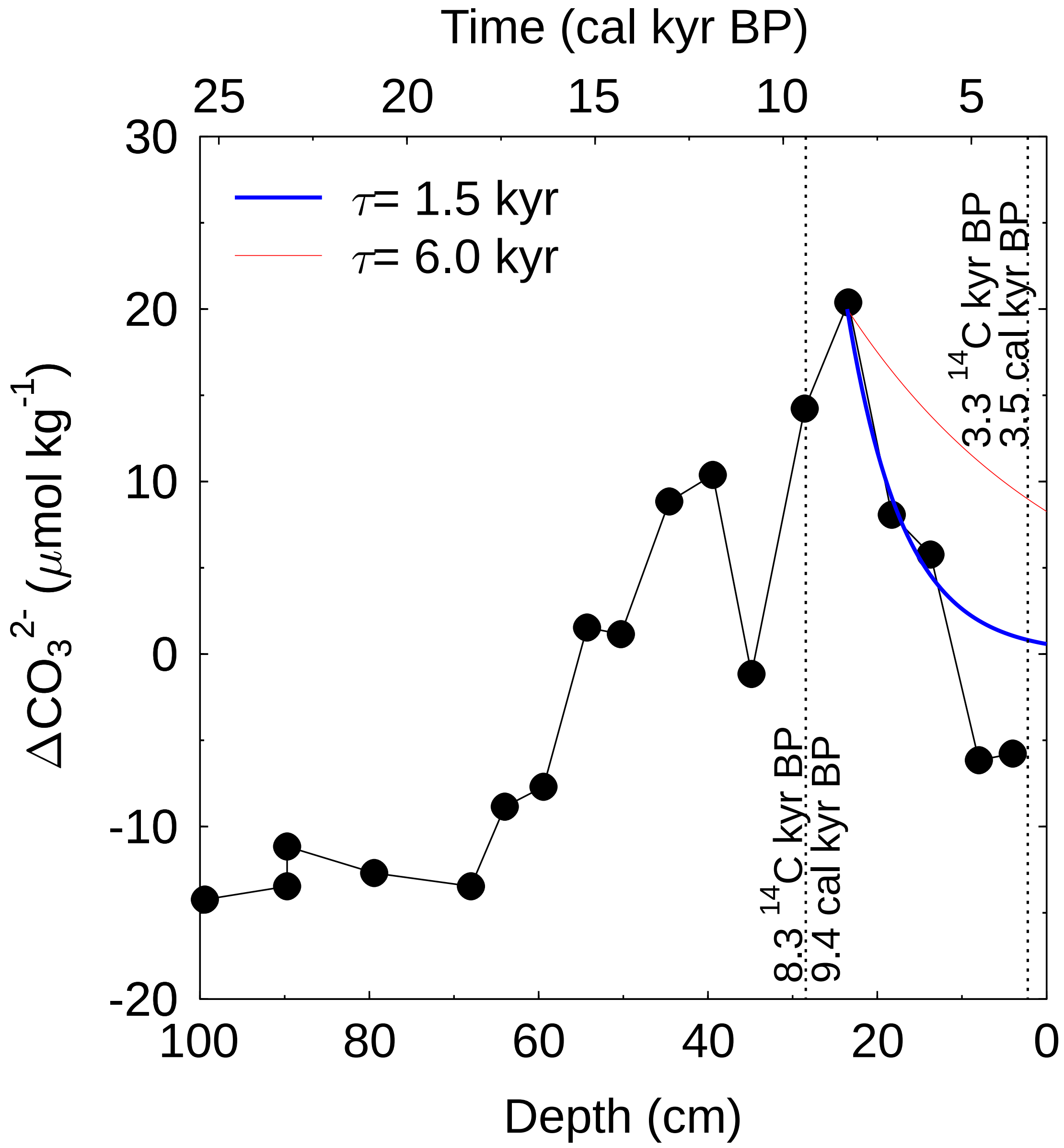
Dissolution / accumulation of $CaCO_3$ depends on deep ocean $[CO_3^{2-}]$



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



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

$\tau = 1.5$ 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	!
3	Gas exchange / sea ice	–50%	–15	?
	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	+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	!
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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	$\mathrm{CaCO_3}$ chemistry	τ=1.5 kyr	+20	?
	Sum		+75	
	Sum (without sea ice)		+90	
	Vostok (incl. Holocene rise)		+103	

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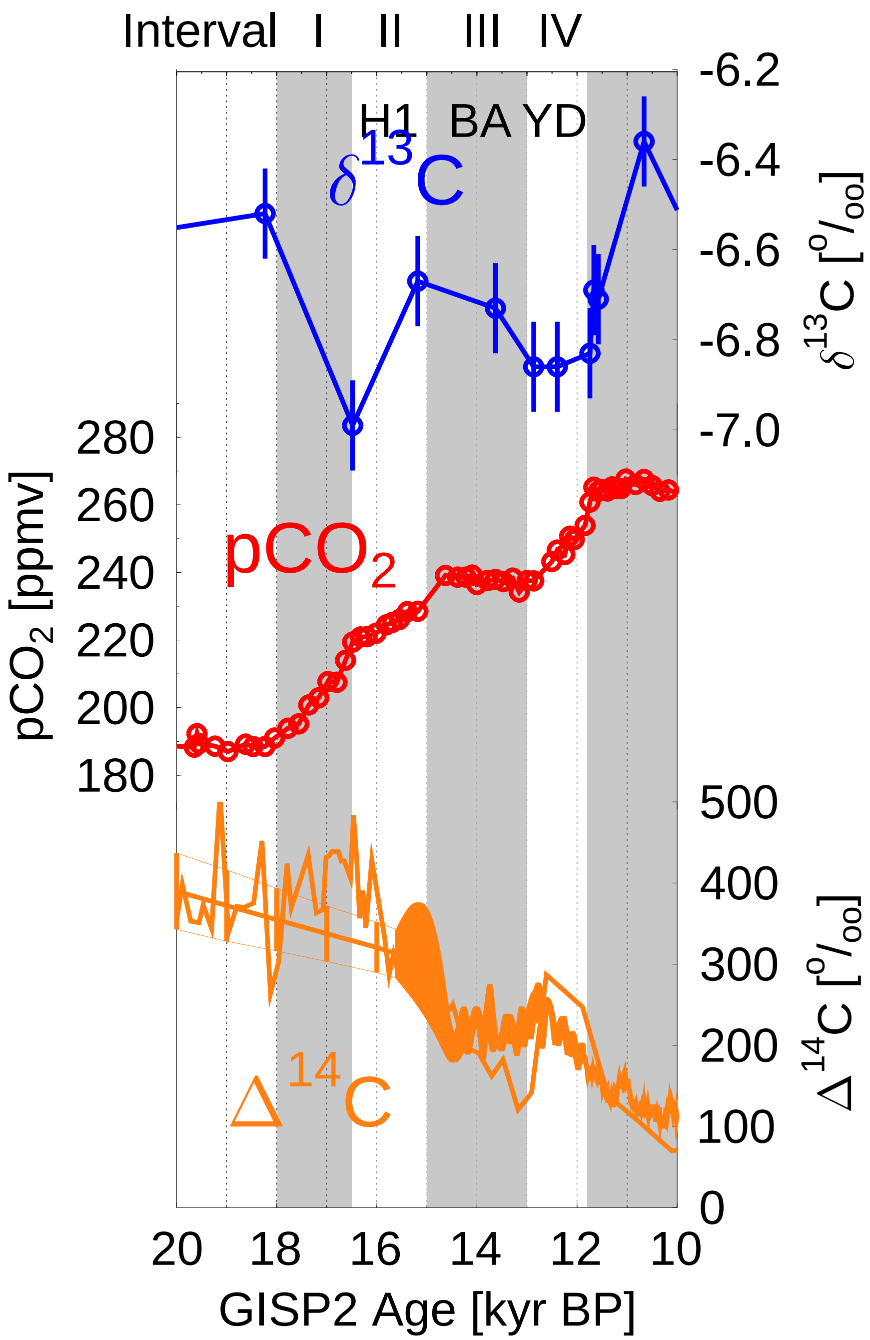
Atmospheric carbon during Termination I

Interprete the temporal evolution of atmospheric CO_2, $\delta^{13}C$, ^{14}C records by carbon cycle simulations.

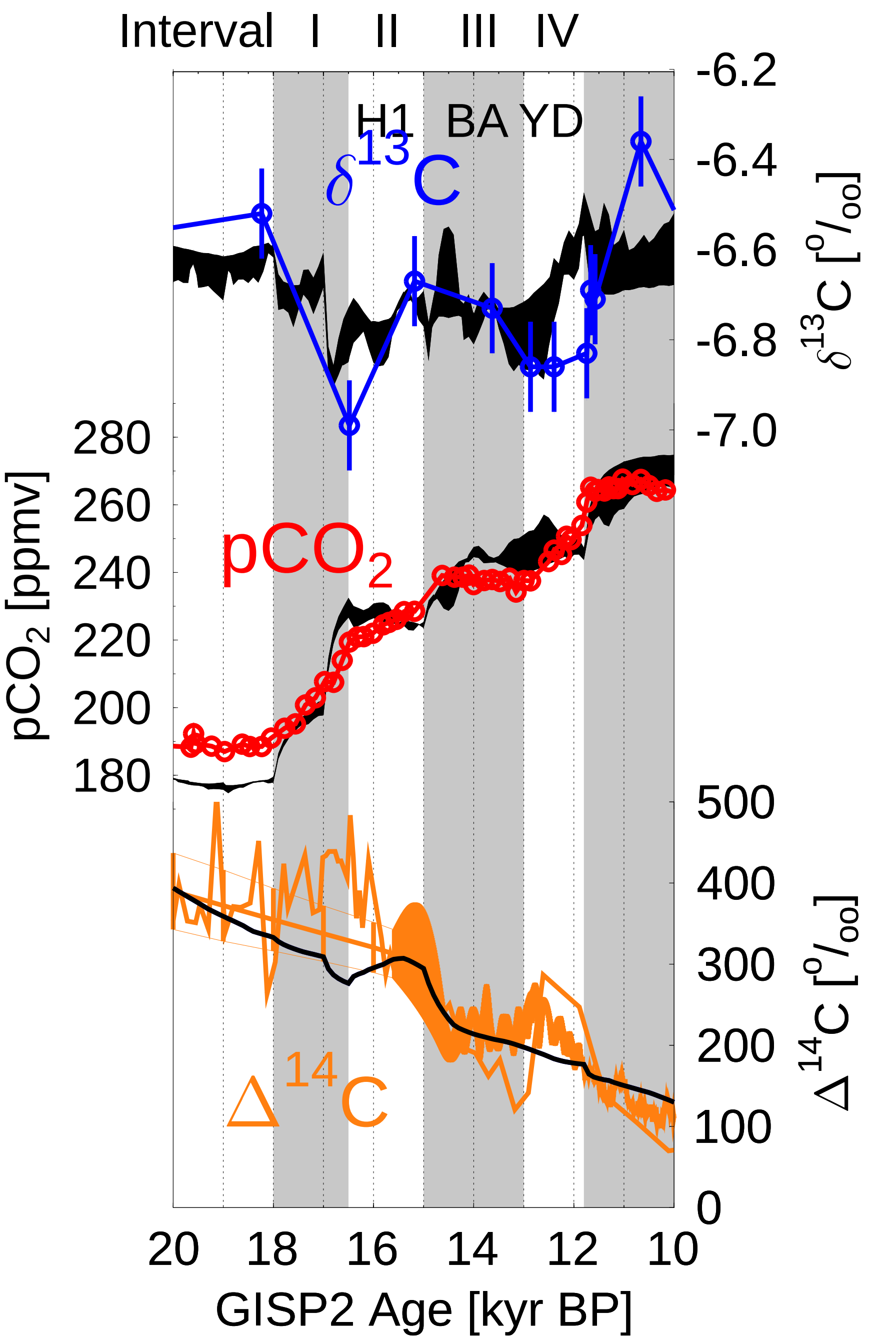
Smith et al., 1999; Monnin et al., 2001;
Stuiver et al., 1998; Hughen et al., 2004



Atmospheric carbon during Termination I

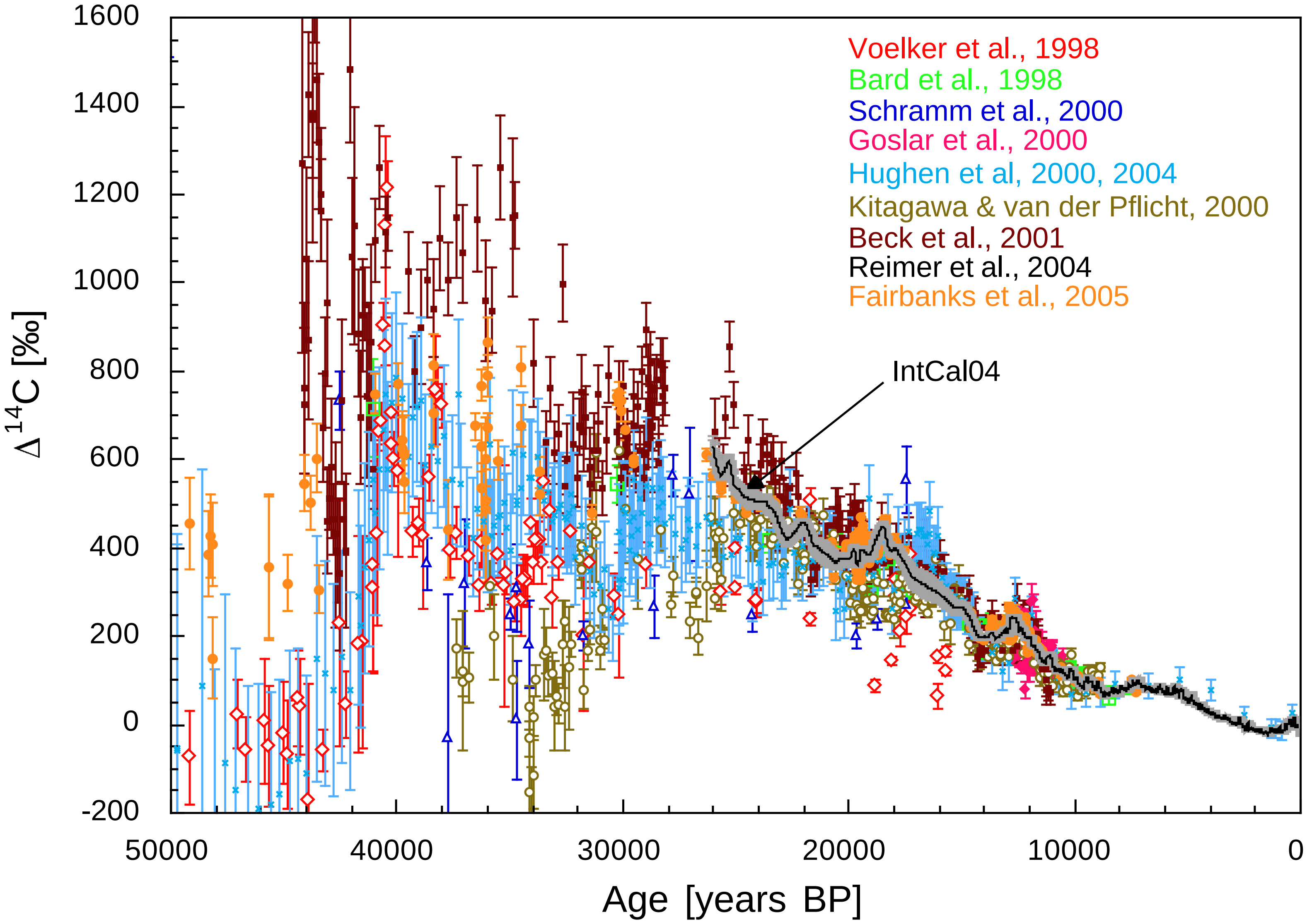
Not only the amplitudes but also the timing of the changes in CO_2, $\delta^{13}C$, ^{14}C seems to be appropriate.

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



^{14}C cycle

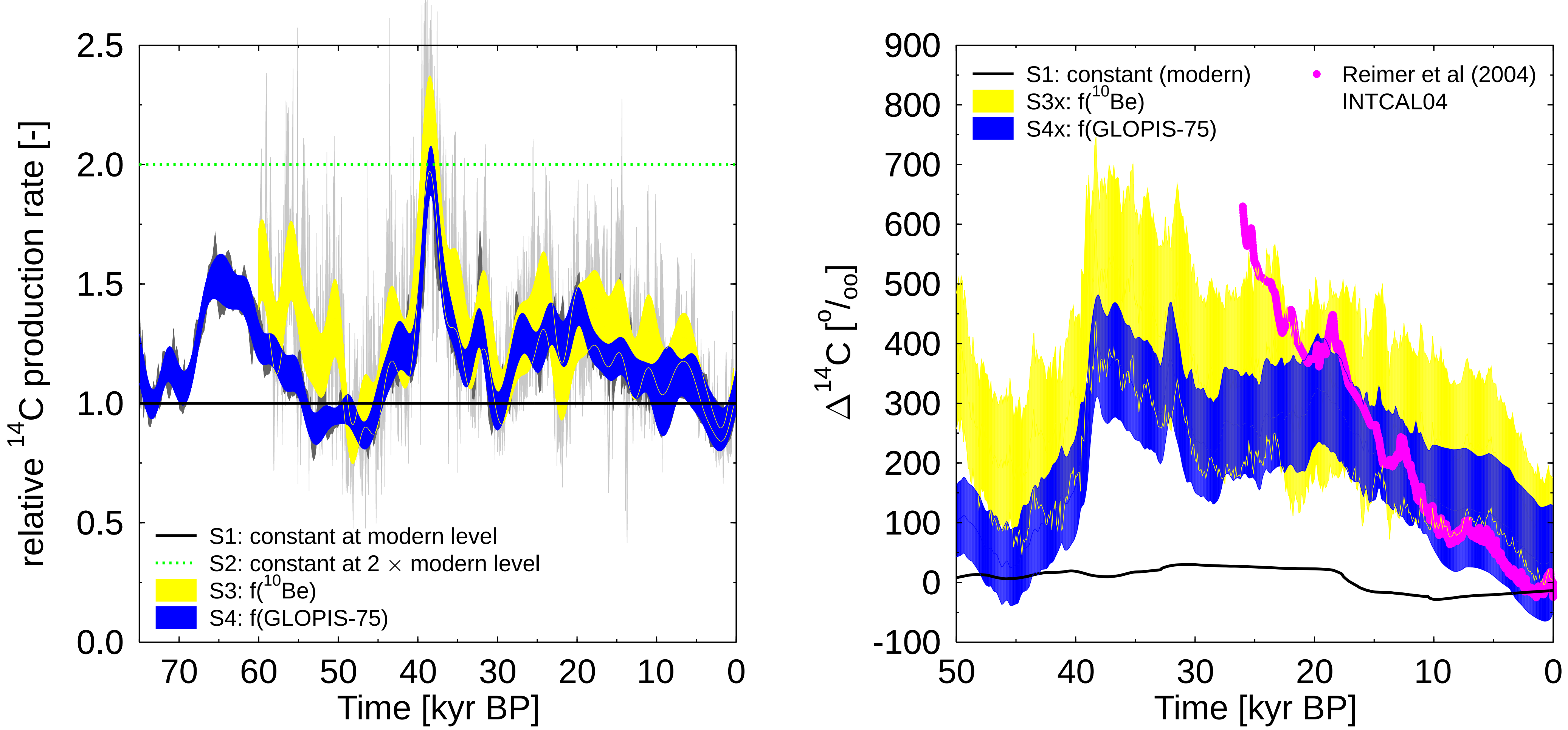
Atmospheric Δ^{14}C reconstructions are highly scattered especially before 25 kyr BP



Köhler, Muscheler, Fischer, G-Cubed, in press

^{14}C cycle

Δ^{14}C highly depends on the chosen ^{14}C production rate
GBC paper used coarsly resolved paleo magnetic stack SINT-200
below new paleo magnetic GLOPIS-75 or ^{10}Be are used



Köhler, Muscheler, Fischer, G-Cubed, in press

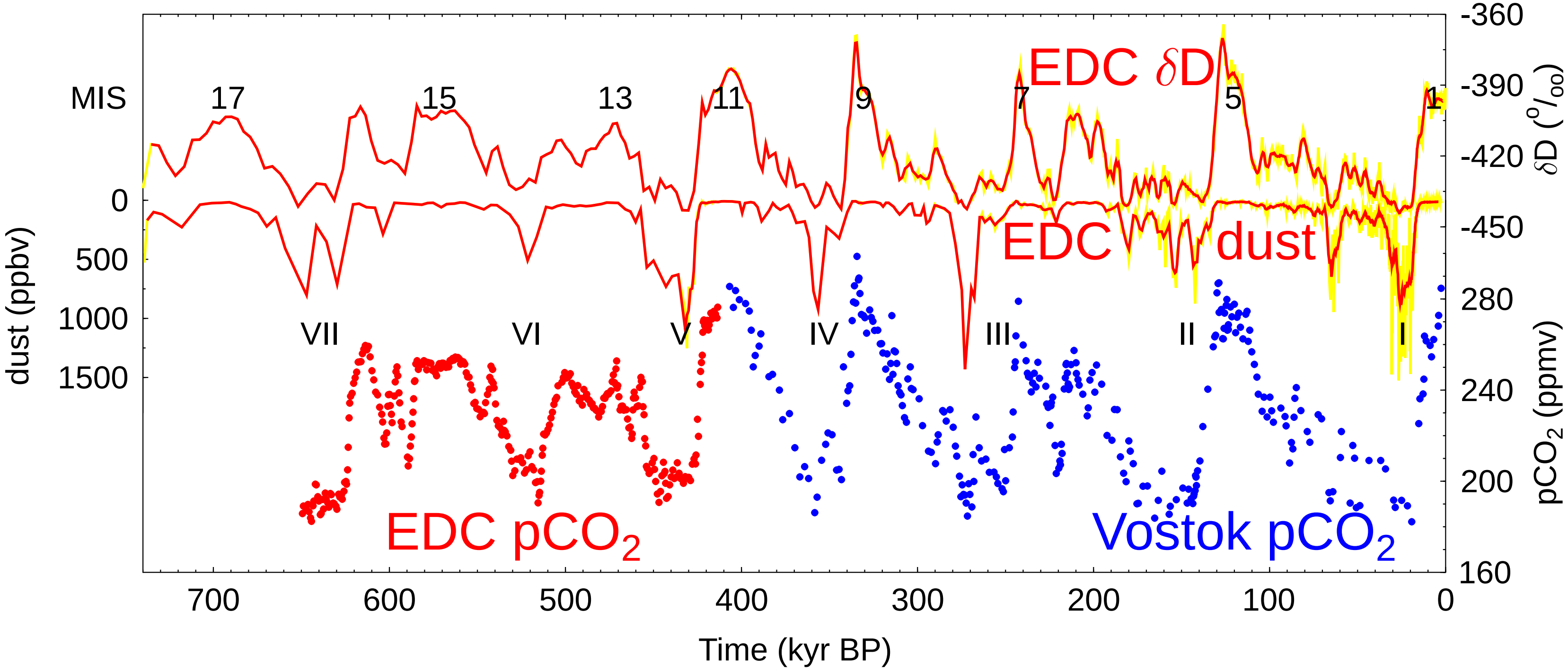
The EPICA challenge

Working hypothesis:

Our findings for Termination I are of general nature.

Approach:

Use same assumptions and extend forcing data set back in time.



a: Heinrich

b: N-SST

c: NADW

d: EQ-SST

e: NH ΔT

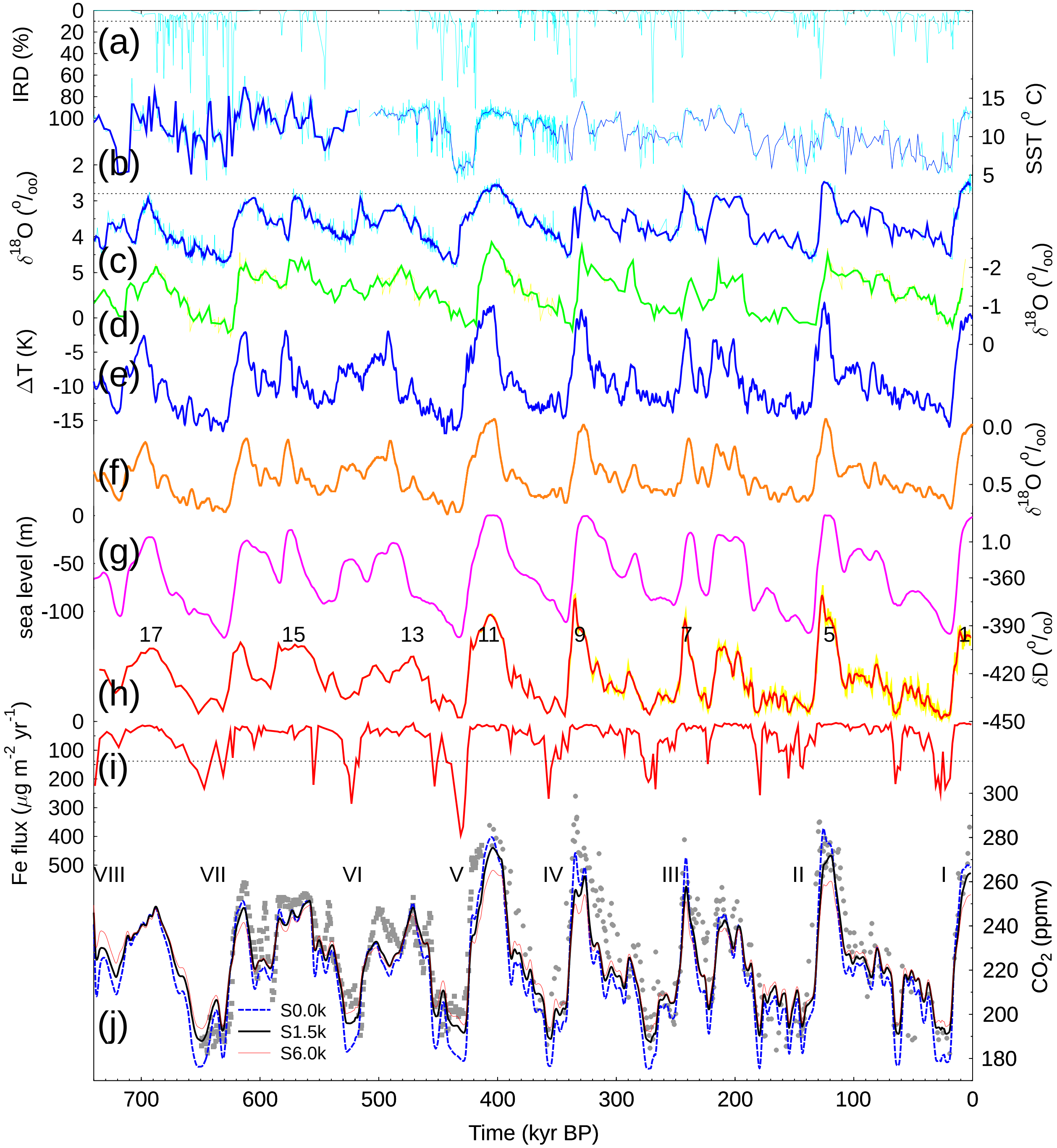
f: deep sea ΔT

g: sea level

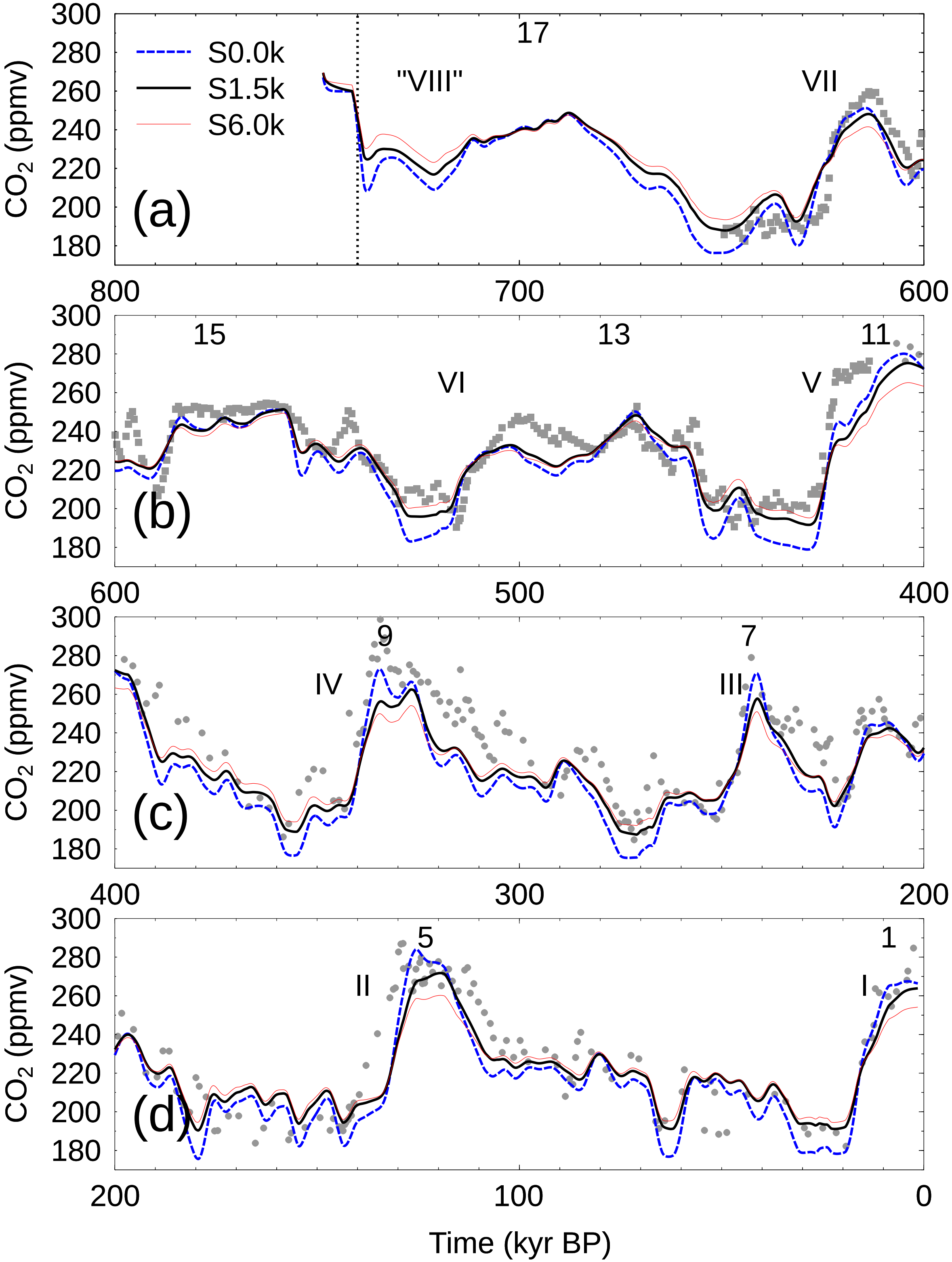
h: SO SST

i: Fe fert.

j: CO$_2$



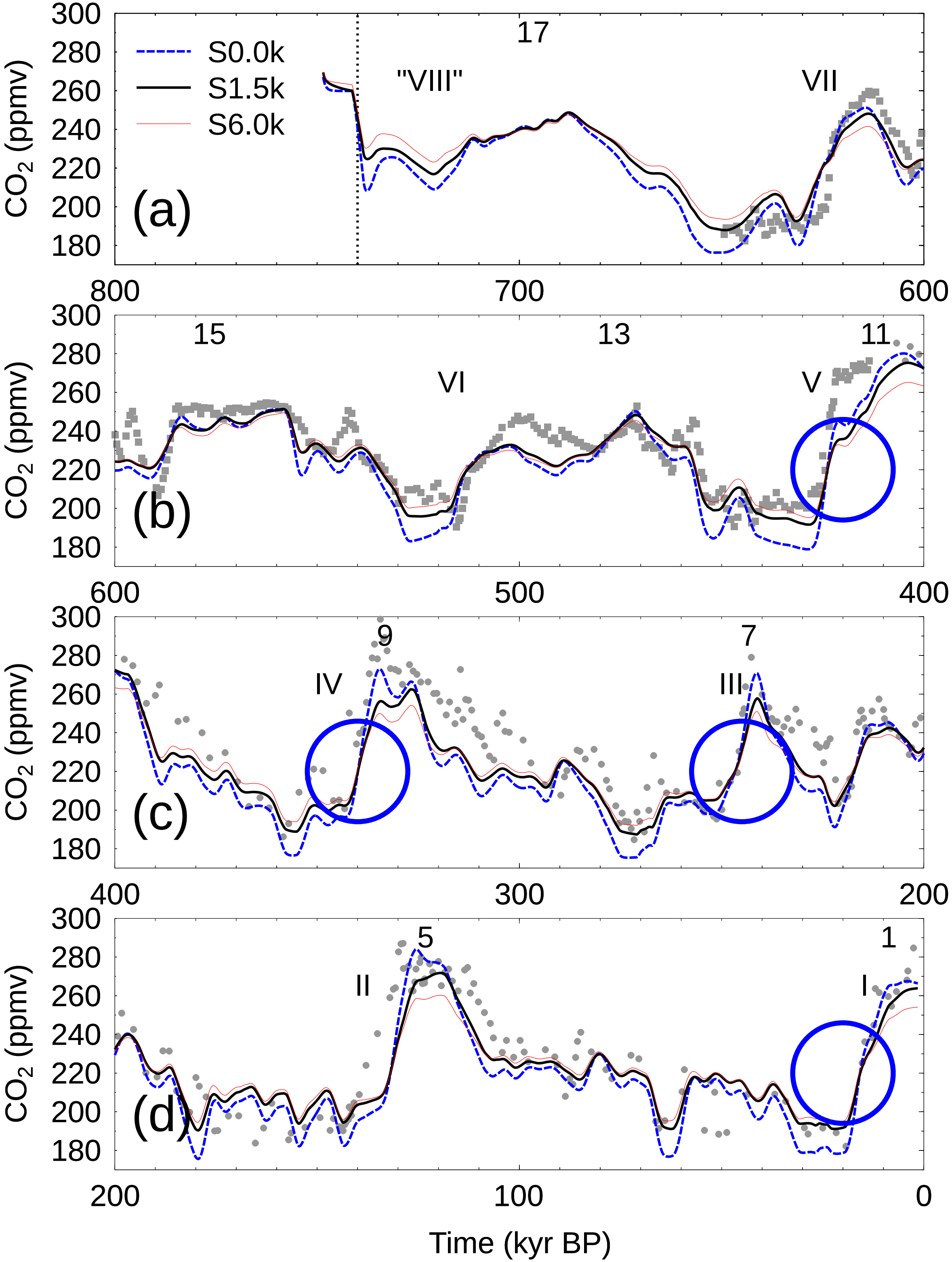
Köhler and Fischer, 2006, Climate of the Past



The EPICA challenge

Köhler and Fischer, 2006,

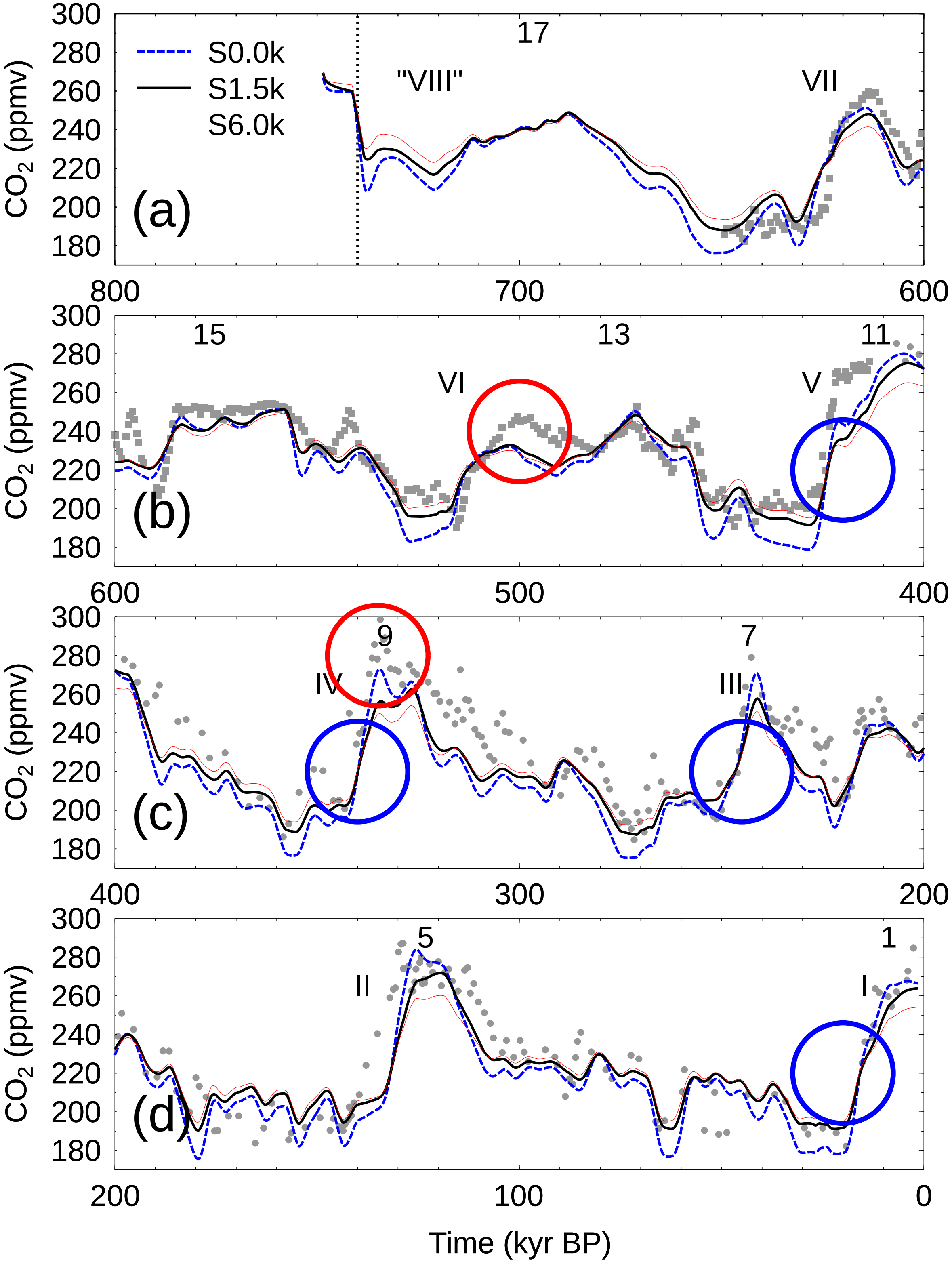
Climate of the Past



The EPICA challenge

1. Terminations I, III, IV, V

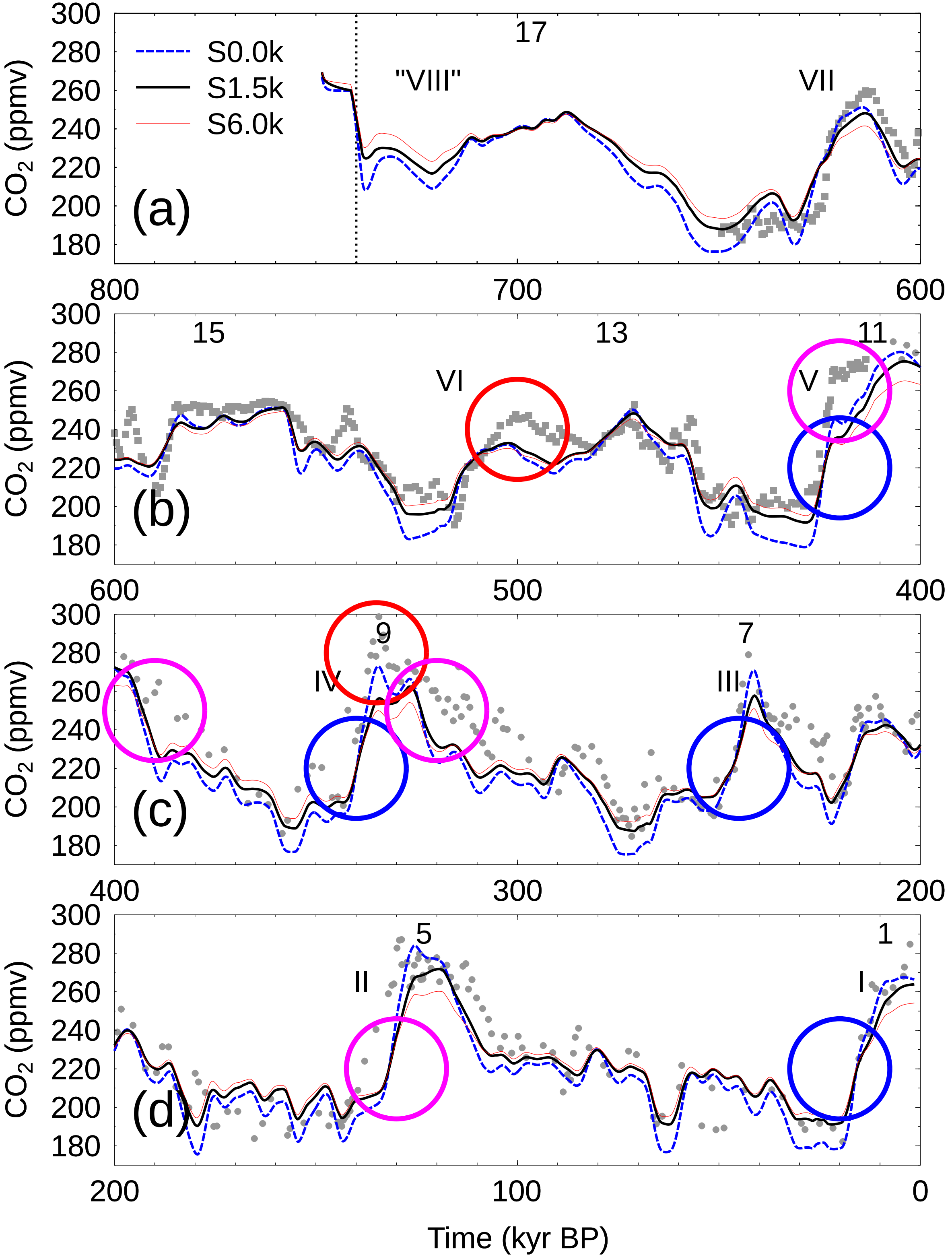
Köhler and Fischer, 2006,
Climate of the Past



The EPICA challenge

1. Terminations I, III, IV, V
2. Maximum peaks

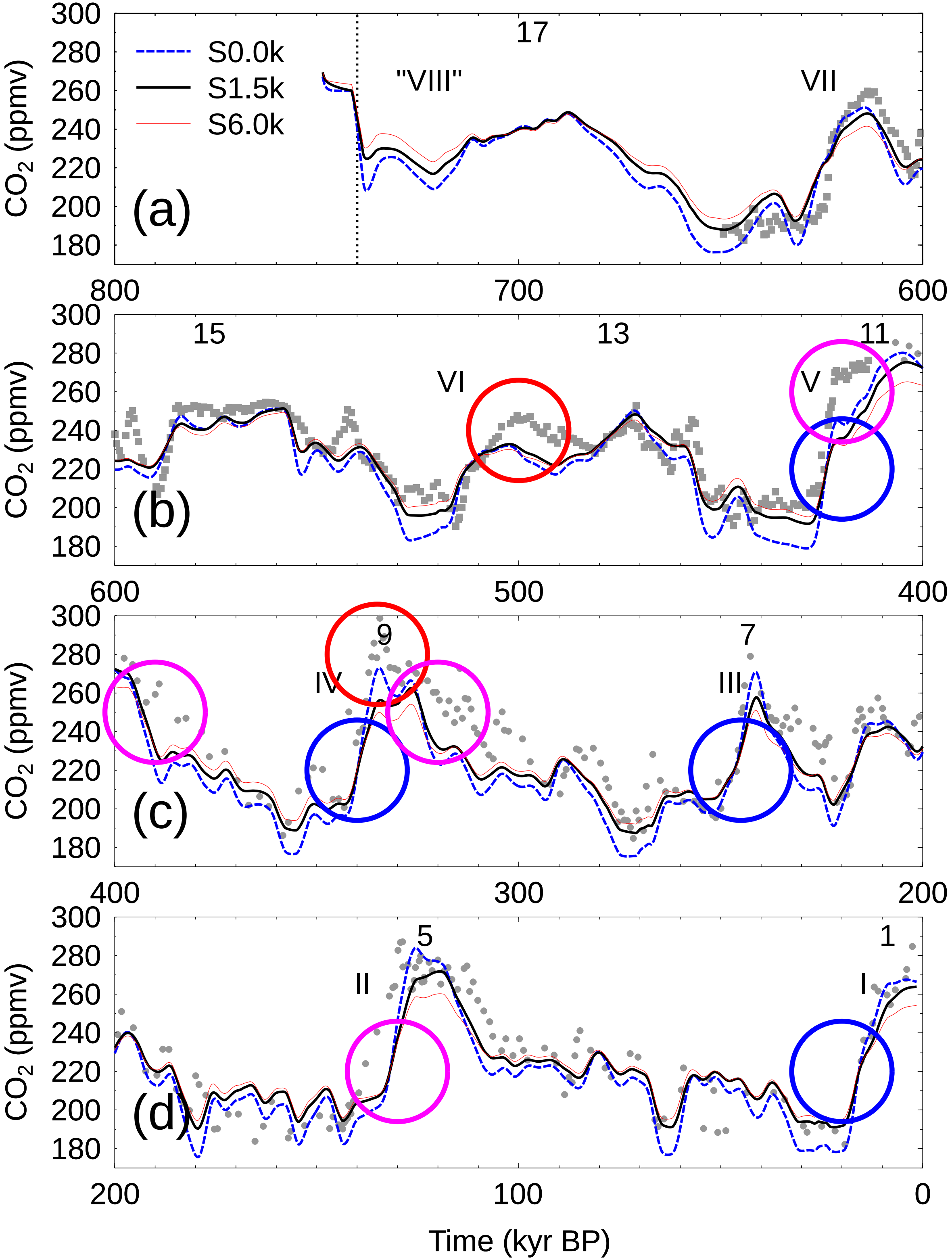
Köhler and Fischer, 2006,
Climate of the Past



The EPICA challenge

1. Terminations I, III, IV, V
2. Maximum peaks
3. Timing inconsistencies

Köhler and Fischer, 2006,
Climate of the Past



The EPICA challenge

1. Terminations I, III, IV, V
2. Maximum peaks
3. Timing inconsistencies

Solutions:

A: Synchronisation errors?

B: Missing processes?

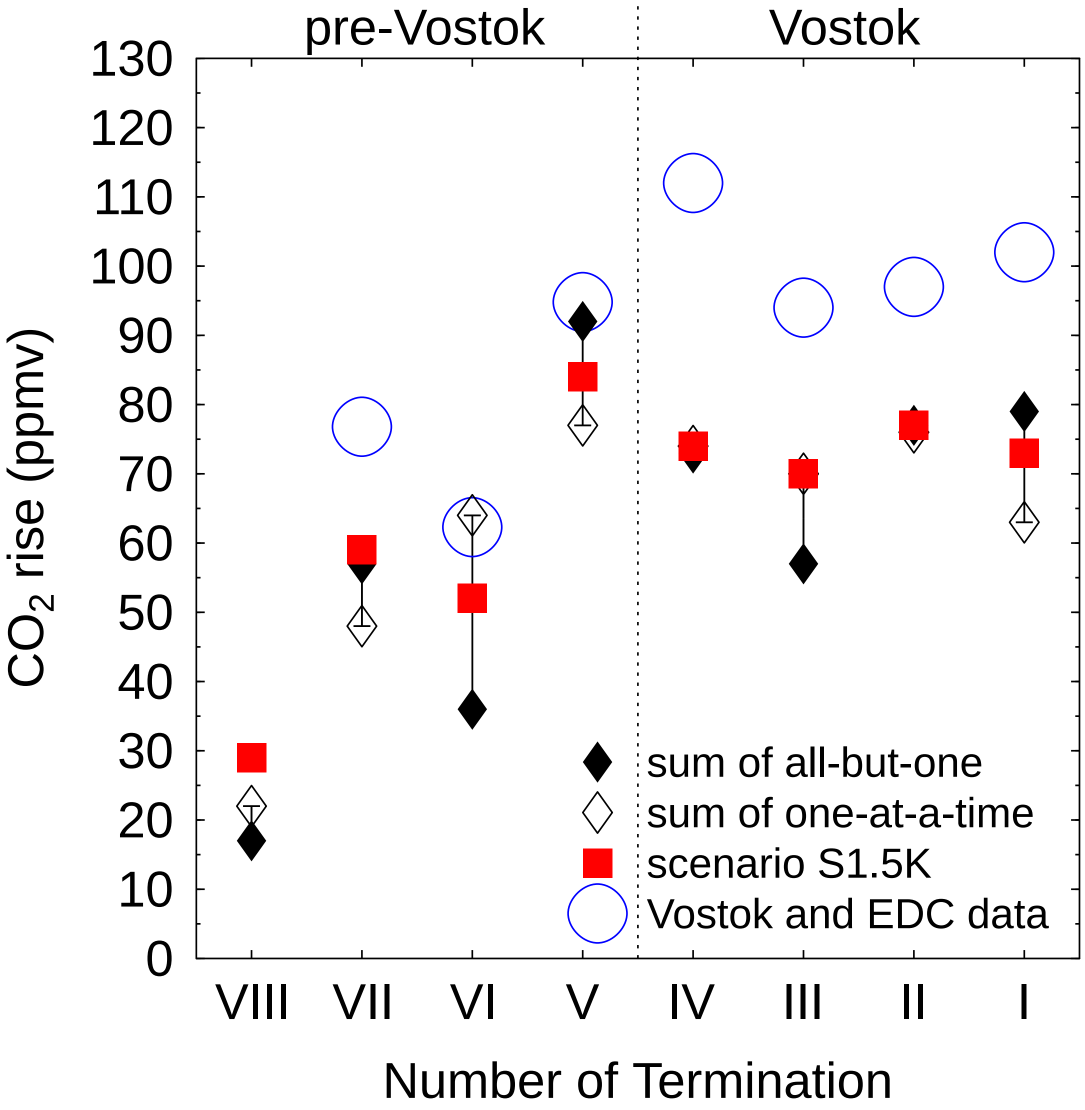
C: Are our findings for Termination I of general nature?

Köhler and Fischer, 2006, Climate of the Past

Terminations I–VIII

combined simulation vs. ice core data

∼20 ppmv per Termination are missing

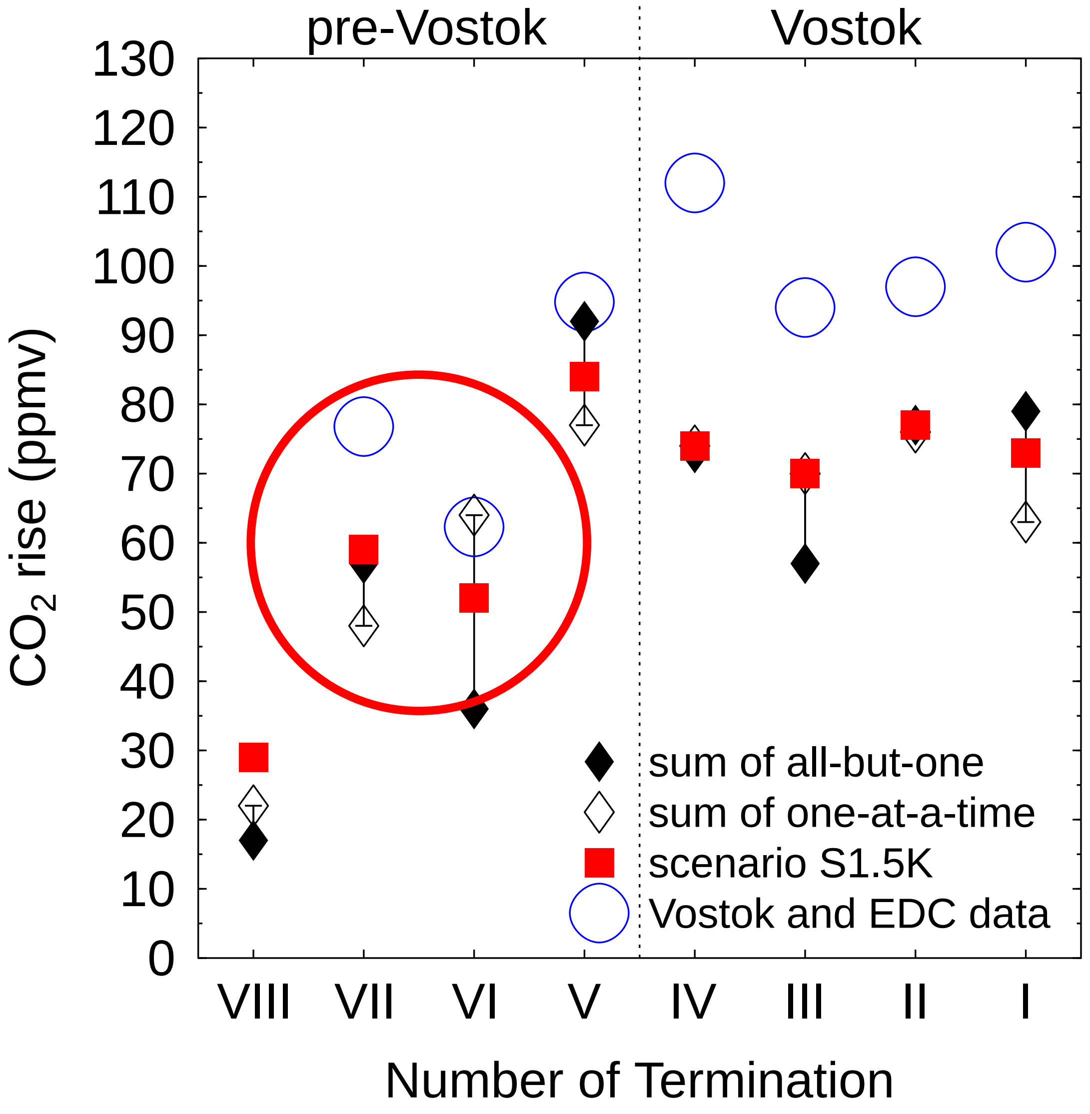


Köhler and Fischer, 2006, Climate of the Past

Terminations I-VIII

combined simulation vs. ice core data

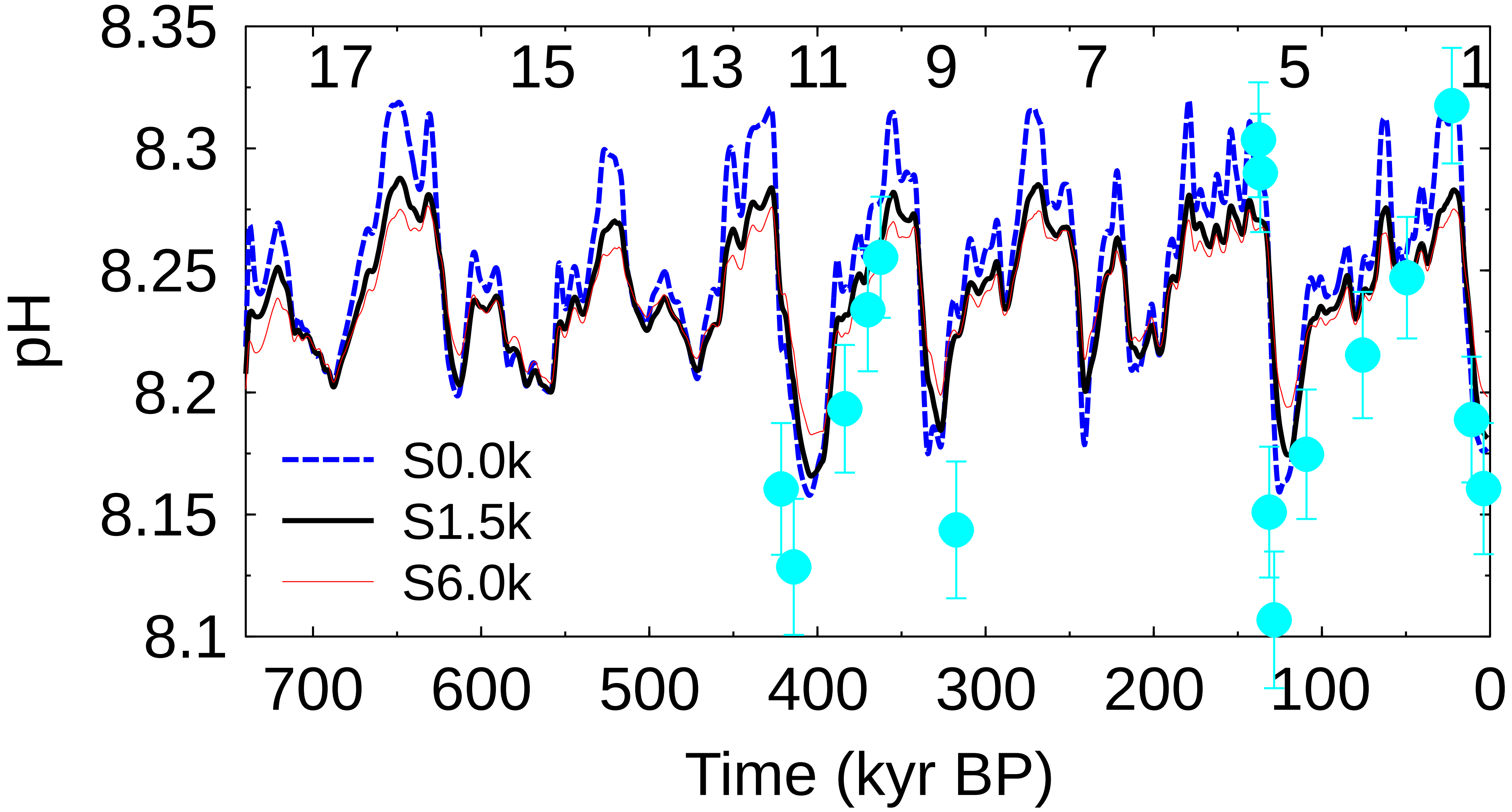
Termination VI, VII: smaller contributions from OCEAN CIRCULATION and SST



Köhler and Fischer, 2006, Climate of the Past

pH

pH from δ^{11}B in surface waters of equatorial Atlantic
only pH reconstruction available so far



pH from Hönisch & Hemming 2005

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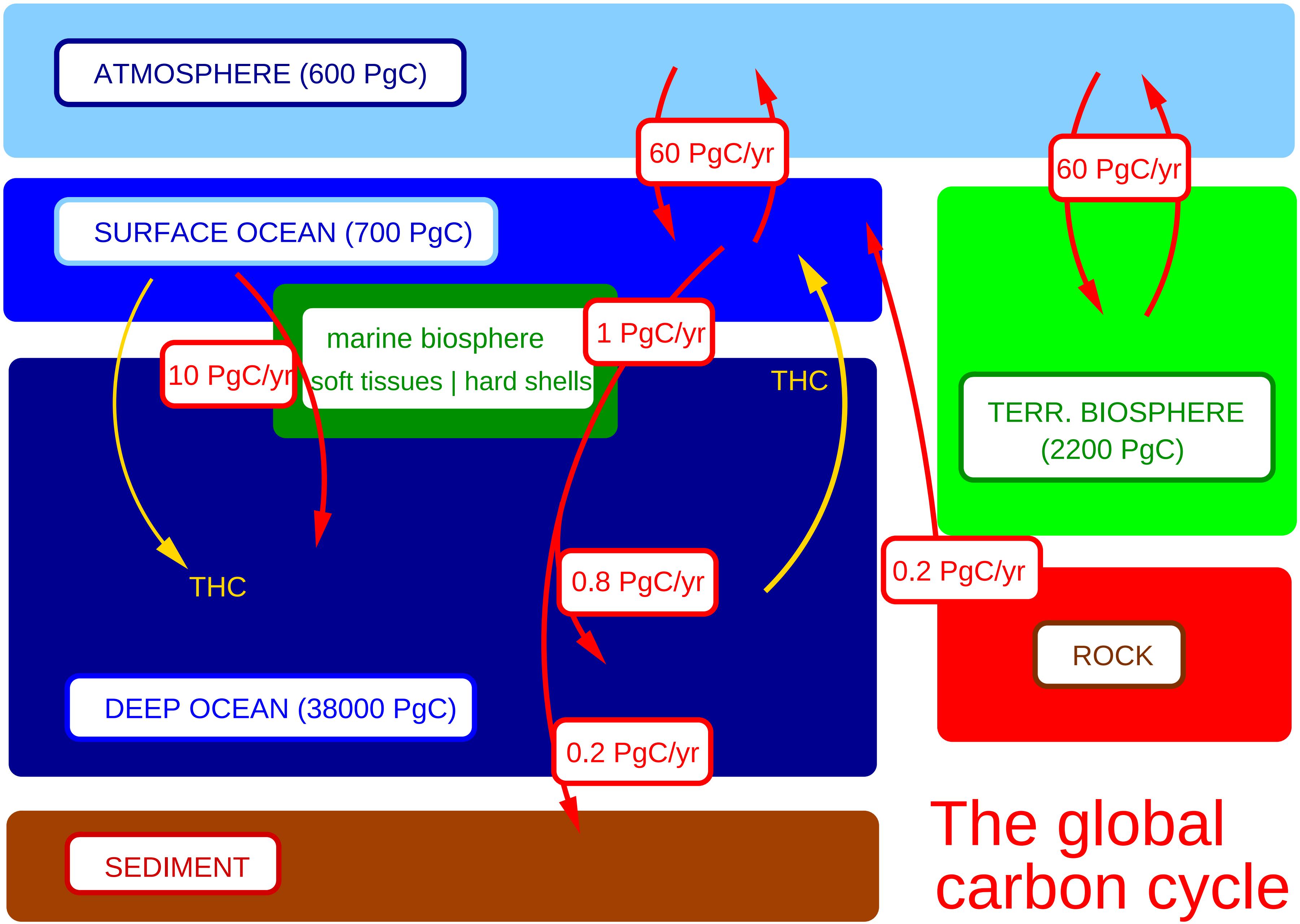
Missing: process-based sediment model; variation in riverine input



ATMOSPHERE (600 PgC)

60 PgC/yr

60 PgC/yr

SURFACE OCEAN (700 PgC)

marine biosphere

soft tissues | hard shells

10 PgC/yr

1 PgC/yr

THC

THC

TERR. BIOSPHERE
(2200 PgC)

0.8 PgC/yr

0.2 PgC/yr

ROCK

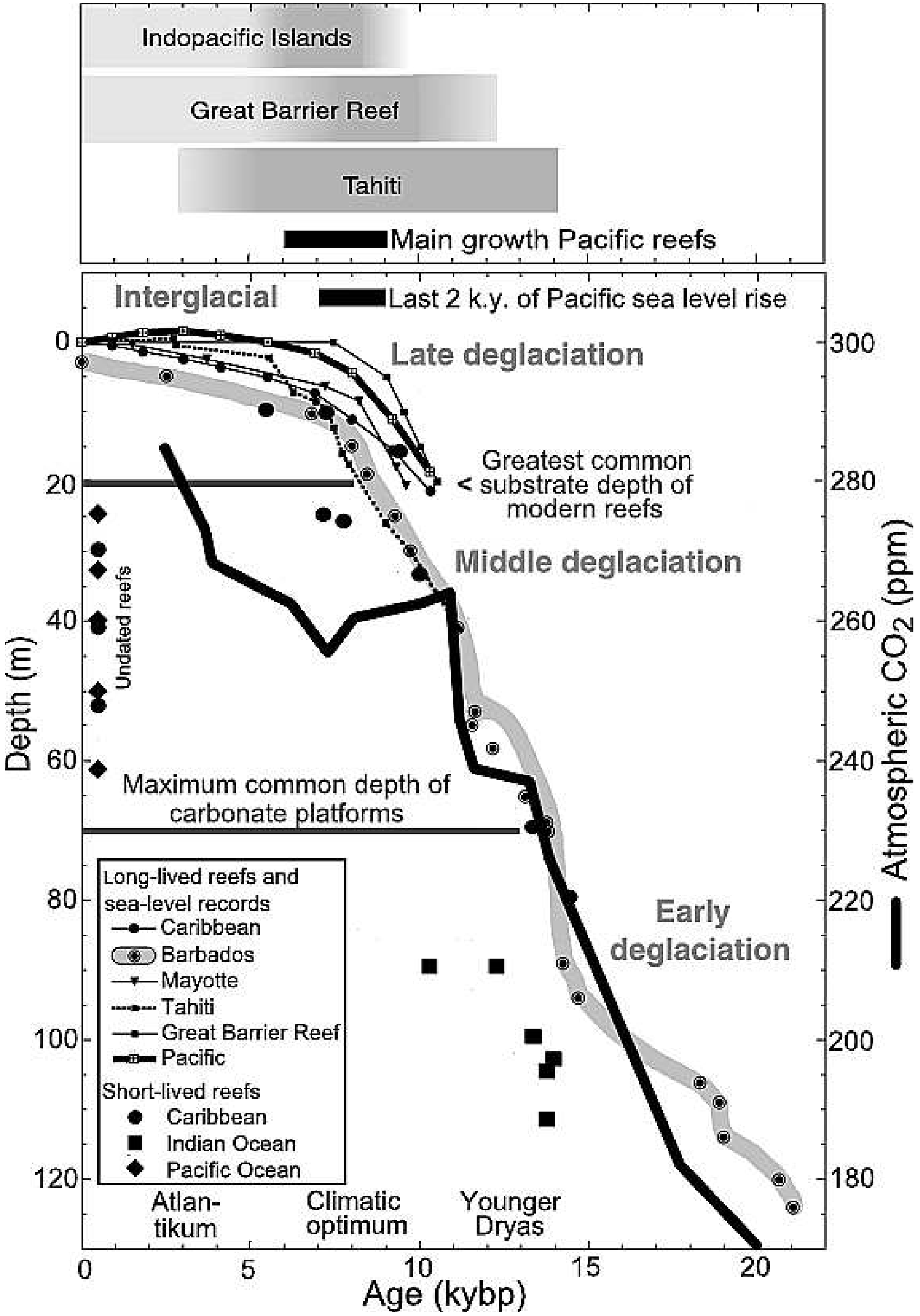
DEEP OCEAN (38000 PgC)

0.2 PgC/yr

SEDIMENT

The global carbon cycle

Coral reefs



CO_2 and sea level

Coral reef growth started after

MWP 1A (14 kyr BP)

sea level $>$ 70 m below present

main coral growth in the Holocene

Vecsei & Berger , 2004

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Take Home Messages

1.

2.

3.

4.

5.

Take Home Messages

1. There are reasonable data- and model-based evidences **which** processes were influencing the global carbon cycle on glacial/interglacial timescales.
2.
3.
4.
5.

Take Home Messages

1. There are reasonable data- and model-based evidences **which** processes were influencing the global carbon cycle on glacial/interglacial timescales.
2. The way **how** they are treated in a model depends on its architecture. Prescribing climate (box models) vs. internally calculated climate variability (climate models). More important is the agreement with paleo data sets.
3.
4.
5.

Take Home Messages

1. There are reasonable data- and model-based evidences **which** processes were influencing the global carbon cycle on glacial/interglacial timescales.
2. The way **how** they are treated in a model depends on its architecture. Prescribing climate (box models) vs. internally calculated climate variability (climate models). More important is the agreement with paleo data sets.
3. Not only the amplitudes, but also the timing of changes need to be addressed to quantify **what** impacts individual processes have on CO_2.
4.
5.

Take Home Messages

1. There are reasonable data- and model-based evidences **which** processes were influencing the global carbon cycle on glacial/interglacial timescales.
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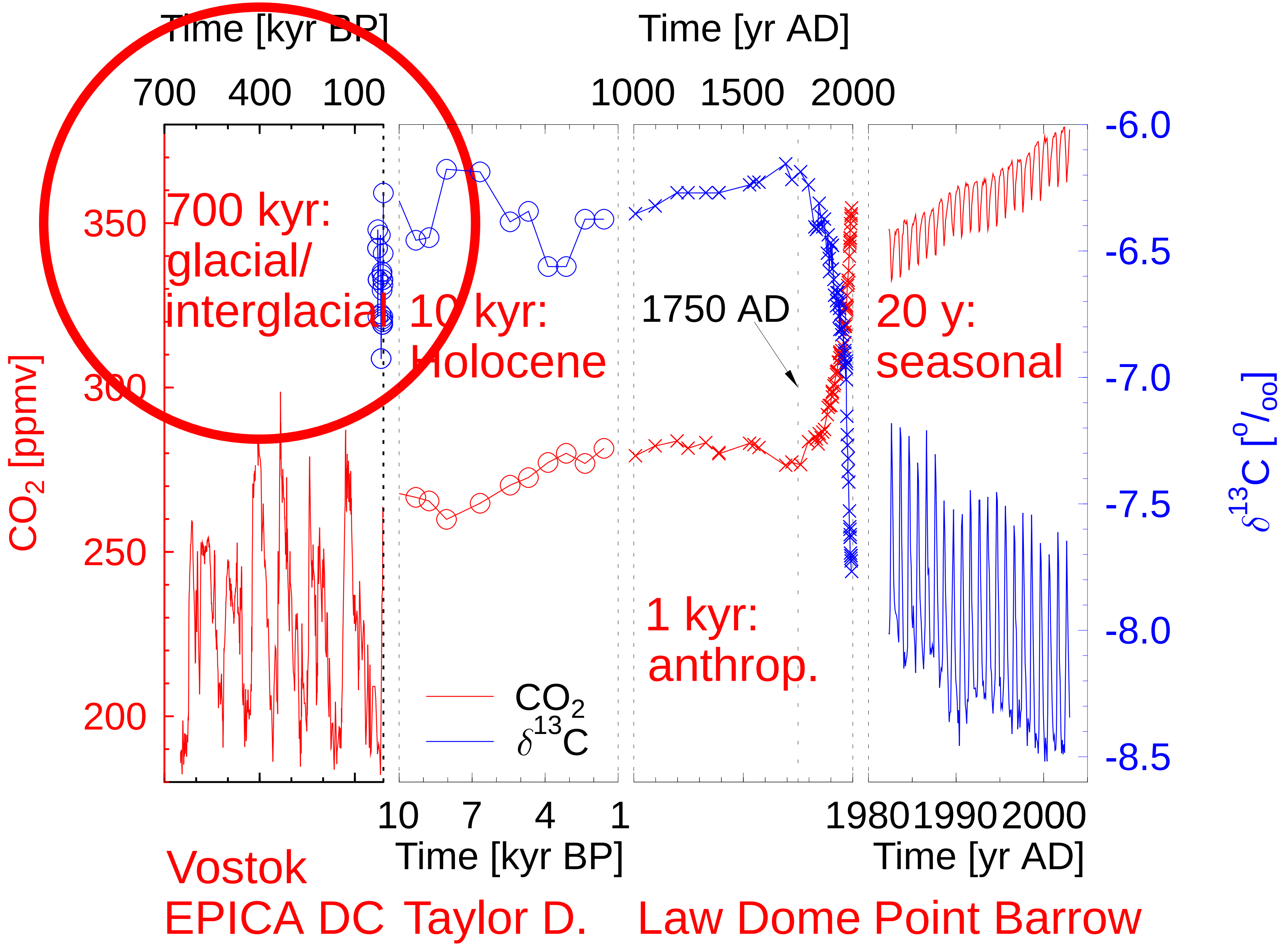
4. Simulation results are always model-dependent, but the amplitudes of individual contributions can be estimated with simple models such as BICYCLE.
5.

Take Home Messages

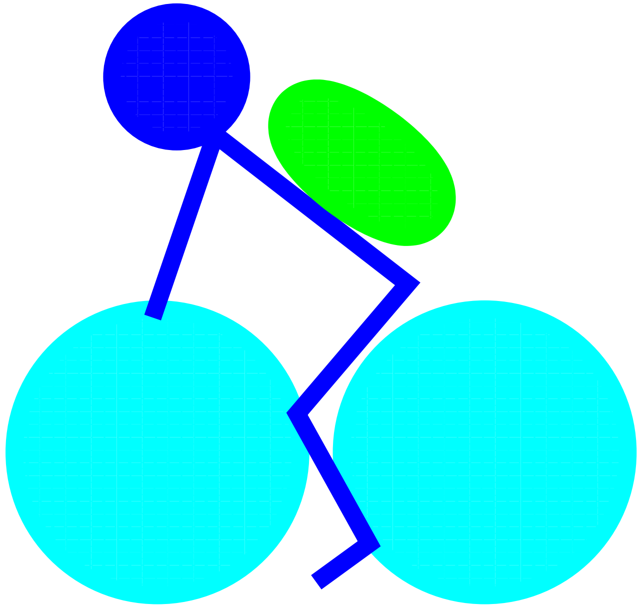
1. There are reasonable data- and model-based evidences **which** processes were influencing the global carbon cycle on glacial/interglacial timescales.
2. The way **how** they are treated in a model depends on its architecture. Prescribing climate (box models) vs. internally calculated climate variability (climate models). More important is the agreement with paleo data sets.
3. Not only the amplitudes, but also the timing of changes need to be addressed to quantify **what** impacts individual processes have on CO_2.
4. Simulation results are always model-dependent, but the amplitudes of individual contributions can be estimated with simple models such as BICYCLE.
5. Are our findings for Termination I of general nature?

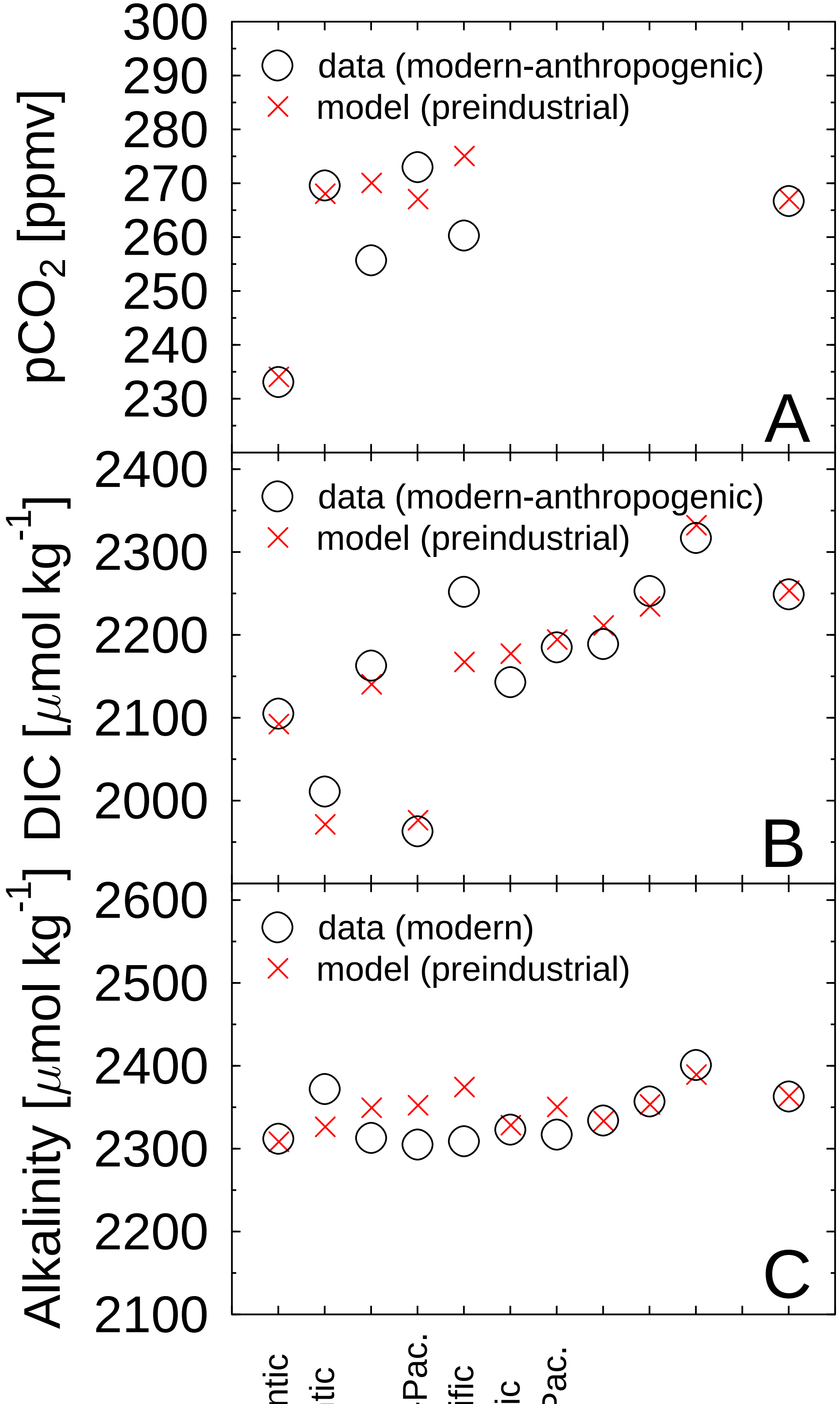
Future $\delta^{13}C$ data might verify or falsify our approach.



The End of an Ice Core (EDML): refrozen water entering borehole from below

THANK YOU FOR YOUR ATTENTION



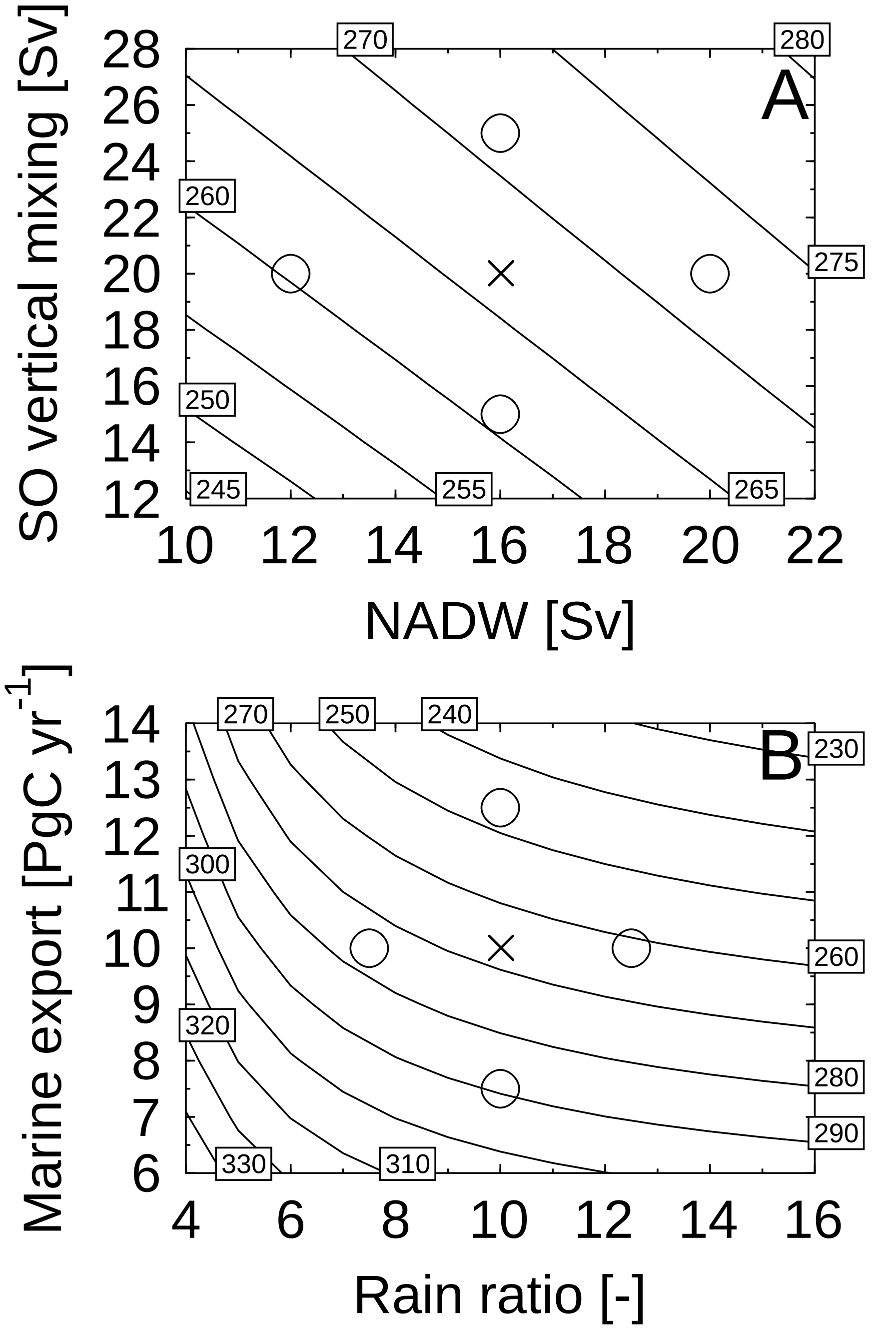


Data versus Model

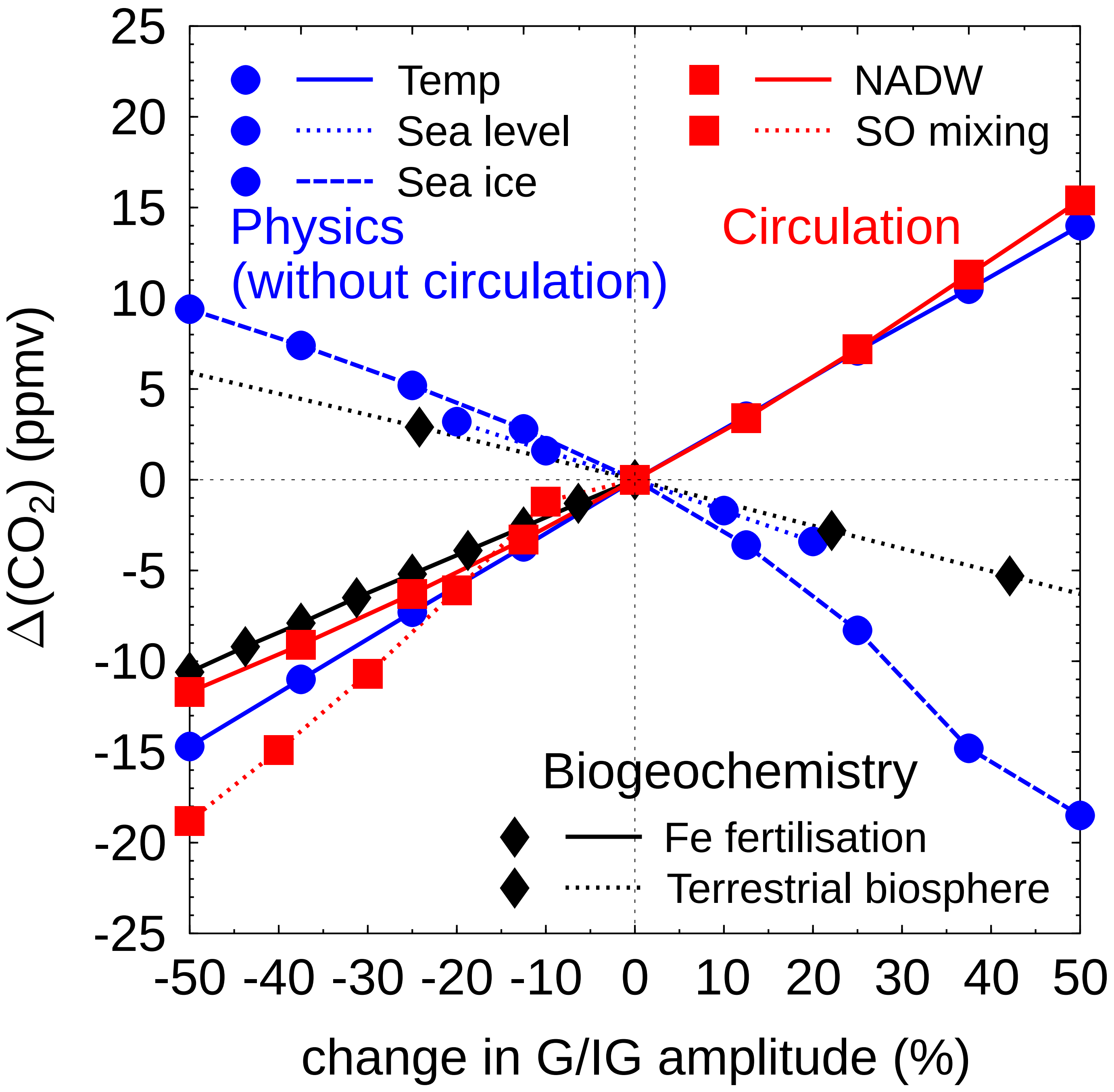
data from

Takahashi et al., 2002; Key et al., 2004

Sensitivity Analysis



Robustness of BICYCLE



Considered processes contributing to $p\mathrm{CO}_2$ change

Process		**Amplitude** (REF vs. LGM)	**Forced by**
Physics			
Ocean temperatures		+(3–5) K	plank. δ^{18}O, EDC δD
Salinity / sea level		+120 m	benthic δ^{18}O SPECMAP
Gas exchange rates / sea ice		× 0.5	f(SST)
Ocean circulation			
NADW formation		16 vs. 10 Sv	benthic δ^{18}O, δ^{13}C
NADW formation / Heinrich events		shutdown	Ice rafted debris (IRD)
Southern Ocean vertical mixing		29 vs. 9 Sv	f(SOSST)
Biogeochemistry			
Fe fertilisation		export prod. −10%	EDC dust
Terrestrial biosphere		+(400–1000) PgC	δ^{13}C, models
$CaCO_3$ chemistry	AOB:	−(1500–2100) PgC	lysocline

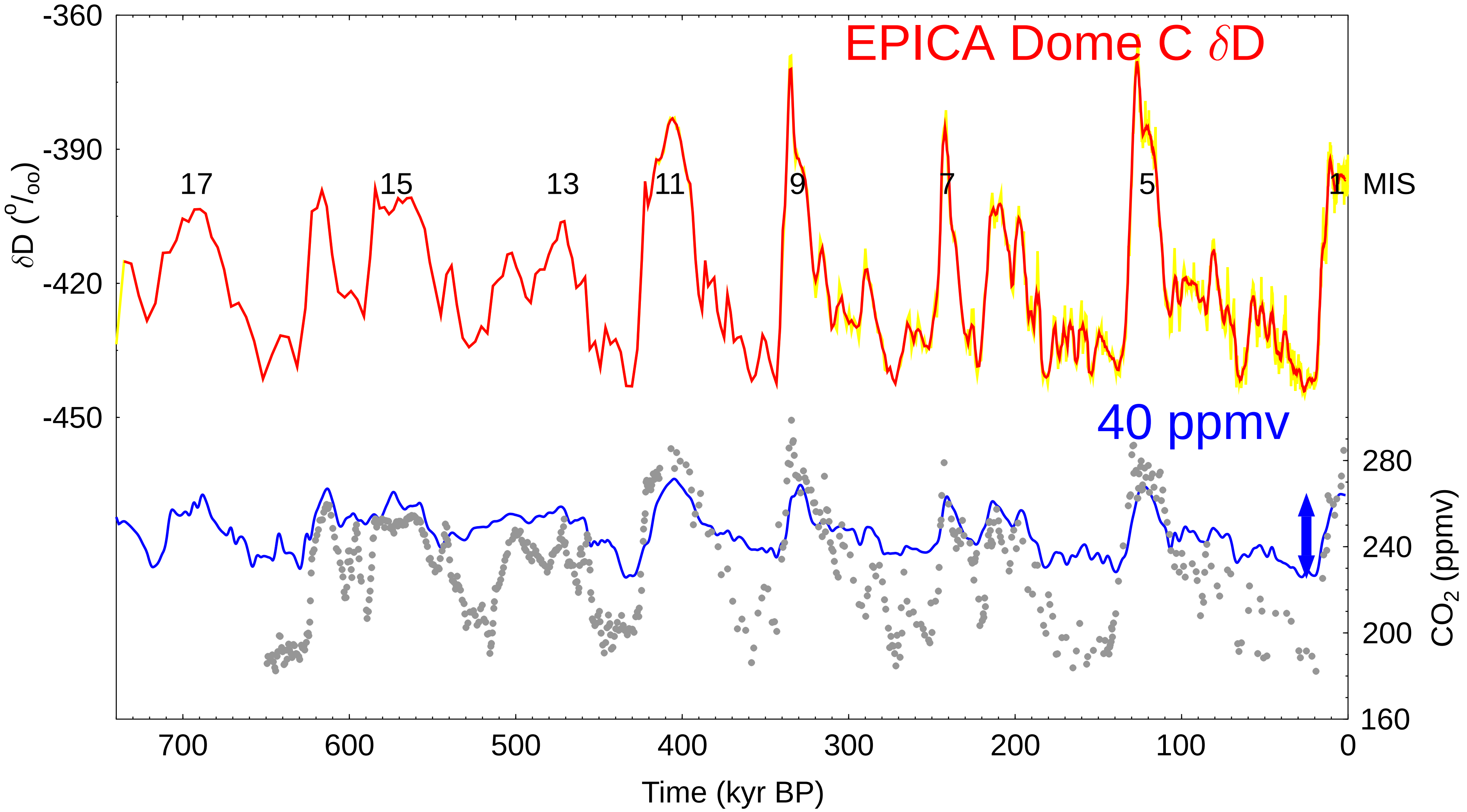
Contributions to $p\mathrm{CO}_2$ change during Termination I

Process	**$\Delta p\mathrm{CO}_2$ (ppmv)** single process	in combined scenarios
Physics		
Ocean temperatures	+38	+24
Salinity / sea level	−16	−11
Gas exchange rates / sea ice	−14	−11
Ocean circulation		
NADW formation	+13	+16
Southern Ocean vertical mixing	+30	+37
Biogeochemistry		
Fe fertilisation	+20	+27
Terrestrial biosphere	−19	−21
CaCO_3 chemistry	+4	+44

1 Temperature

Temperature rise during Termination I: 3–5 K

EPICA Dome C is one example of 7 temperature curves feeding the model

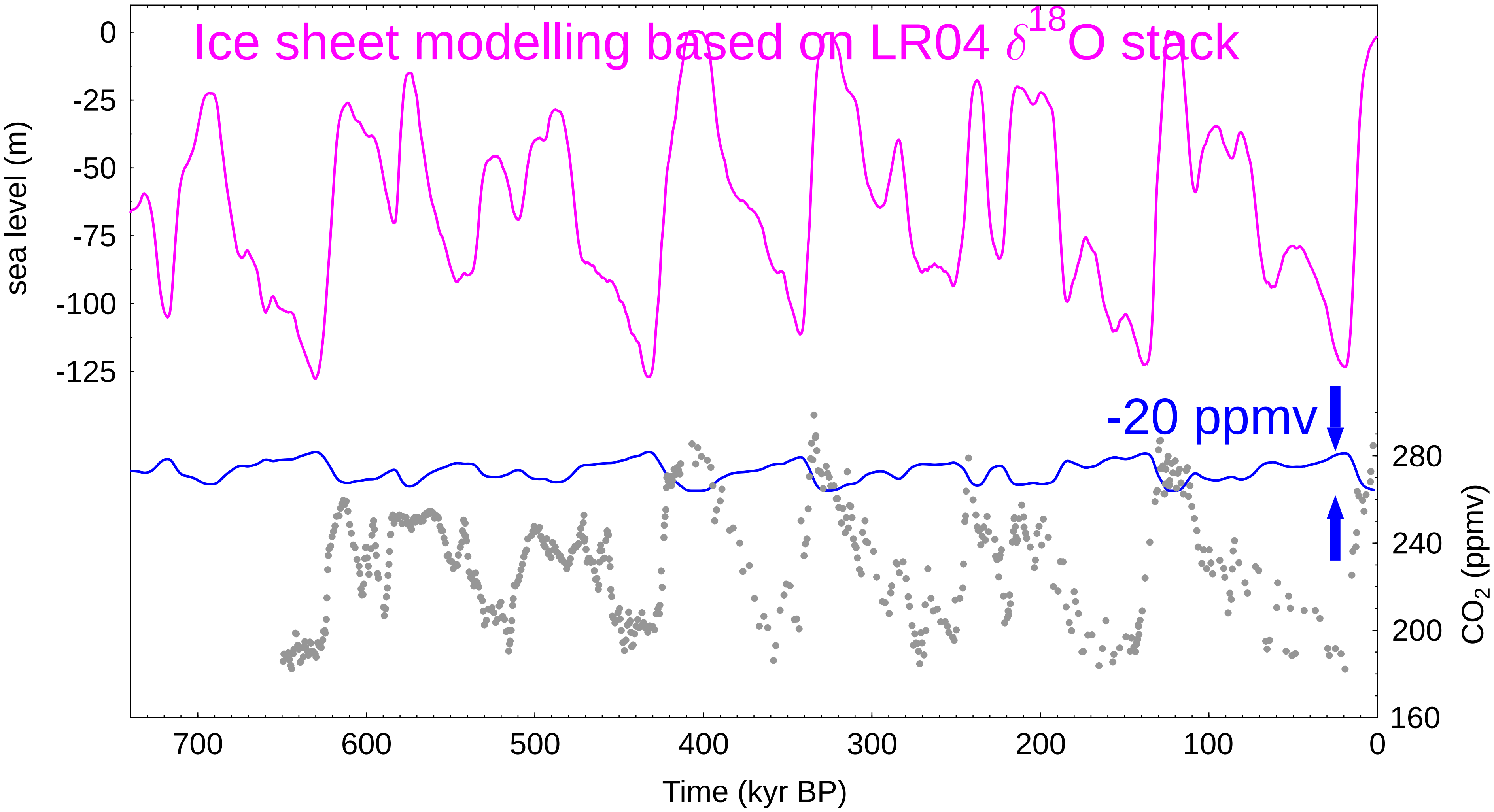


EPICA, 2004

2 Sea Level / Salinity

Sea level rise during Termination I: 125 m

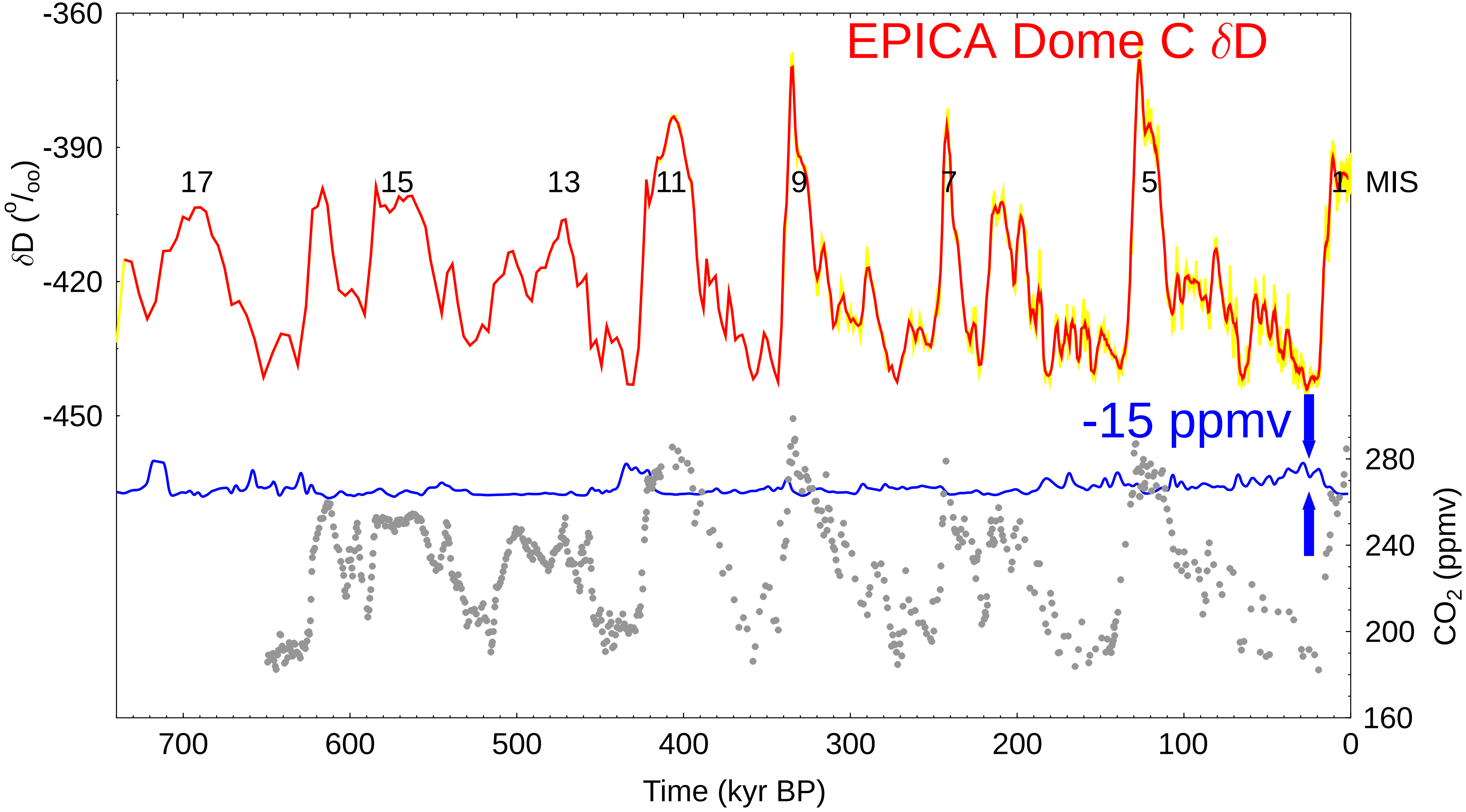
Salinity dropped by 3%; ocean volume changes



Bintanja et al., 2005

3 Gas Exchange / Sea Ice

Sea ice shrunk by ~50% during Termination I

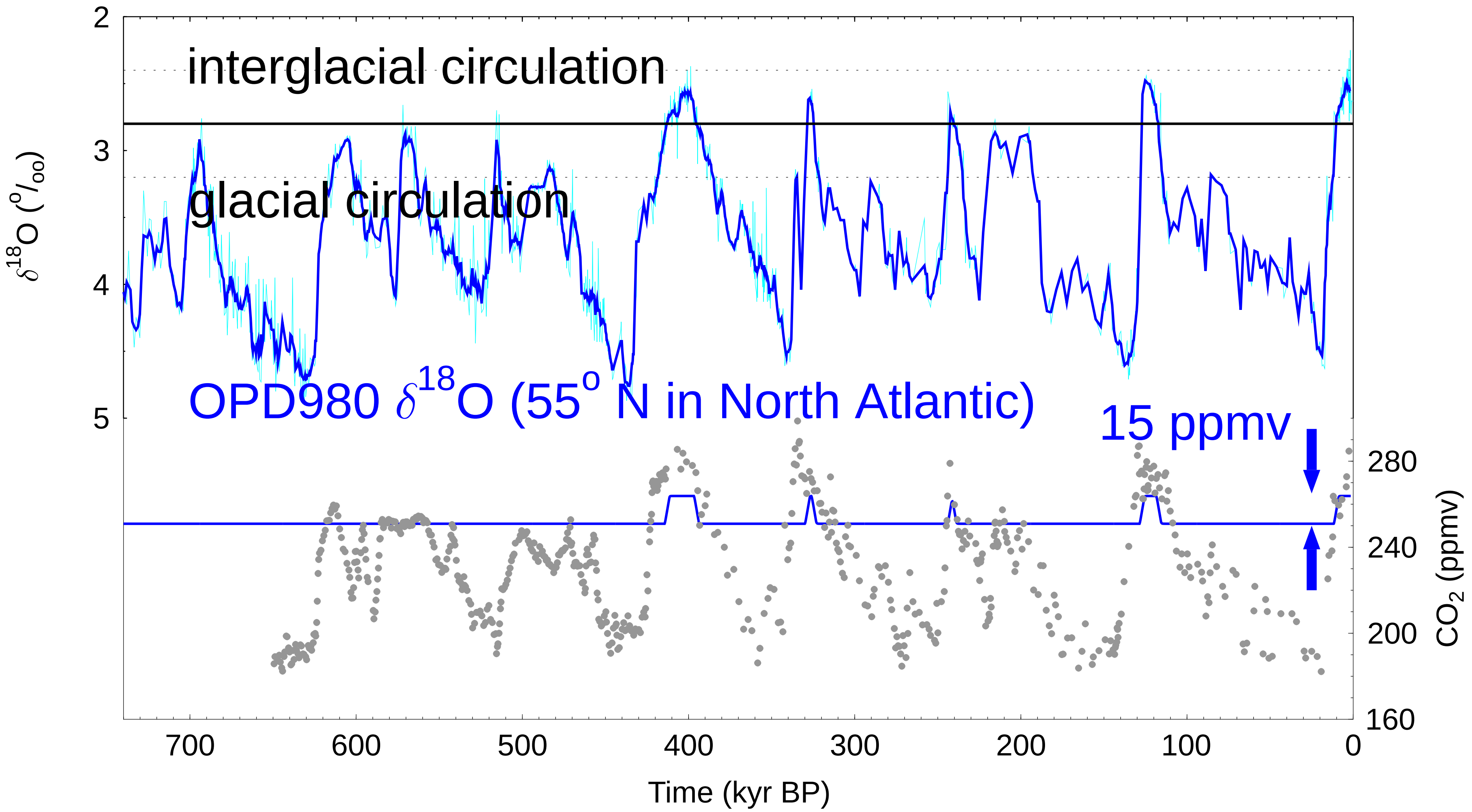


EPICA, 2004

4 NADW Formation

Switch from glacial to interglacial circulation

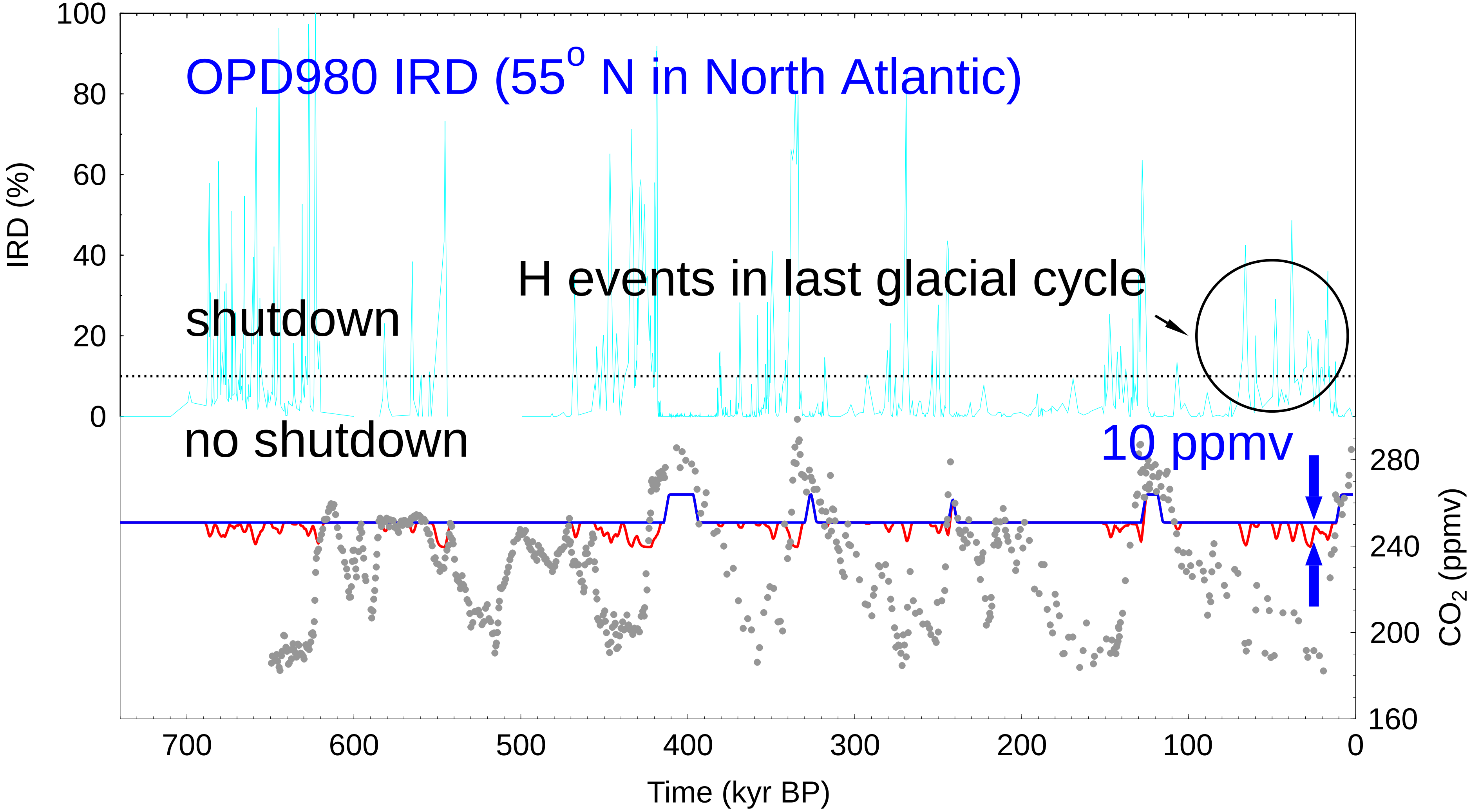
Only direct effect of change in ocean circulation



McManus et al., 1999; Wright & Flower, 2002

4 Shutdown in NADW Formation

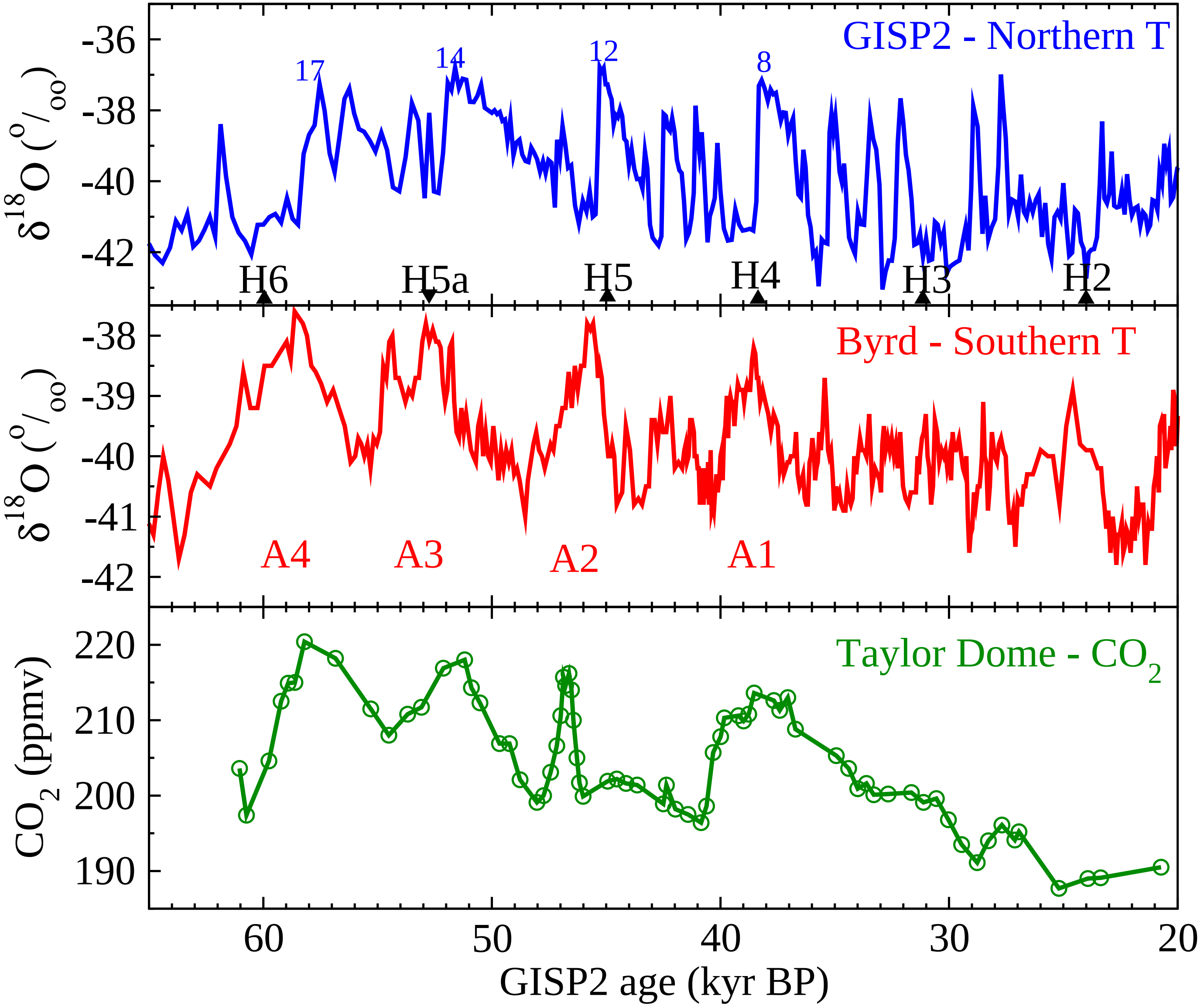
Ice rafted debris (IRD): Shutdown of NADW formation
In BICYCLE this influences nutrients, but not T, S, sea ice



McManus et al., 1999; Wright & Flower, 2002

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

Temperature anomalies follow the concept of a bipolar seesaw

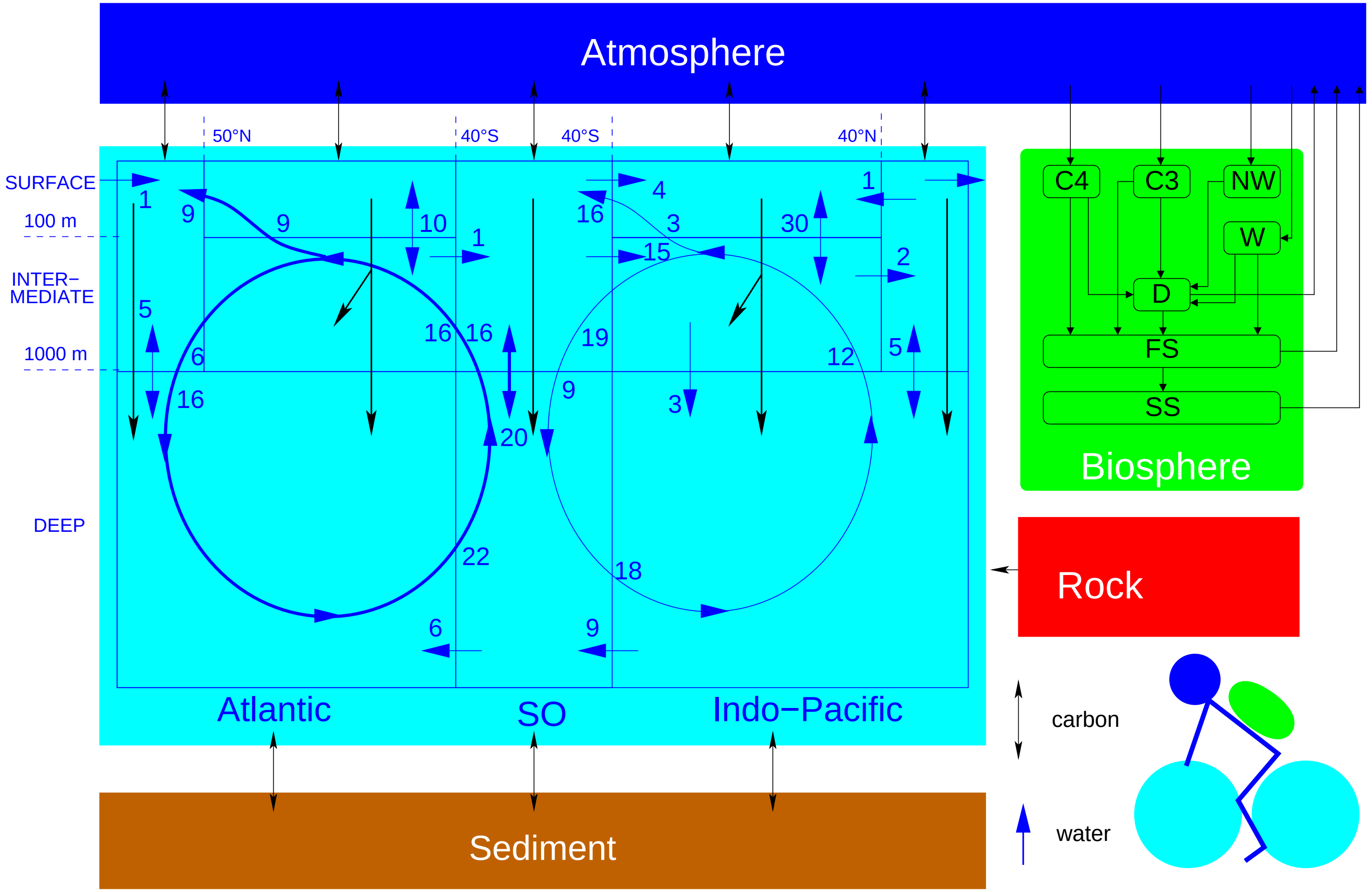


Johnsen et al., 1972; Grootes & Stuiver, 1997; Indermühle et al., 2000

5 Southern Ocean Ventilation

Preindustrial circulation: WOCE data

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



Box model of the Isotopic Carbon cYCLE

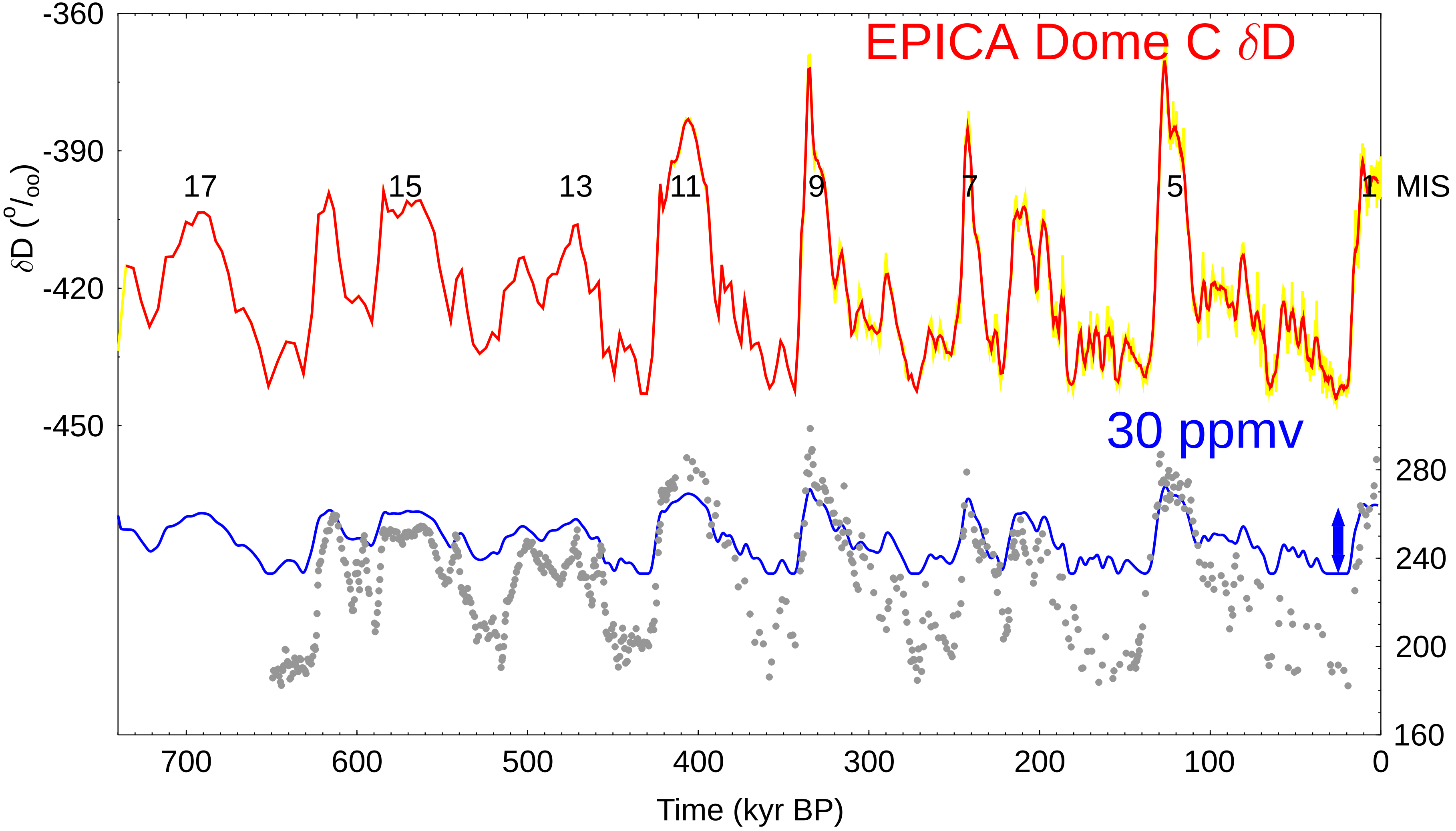
BICYCLE

Circulation after Ganachaud & Wunsch, 2000

5 Southern Ocean Ventilation

Probably cause: northwards shift of westerly winds (e.g. Toggweiler et al., 2006)

Southern Ocean vertical mixing = f(SO SST) = f(EDC δD)

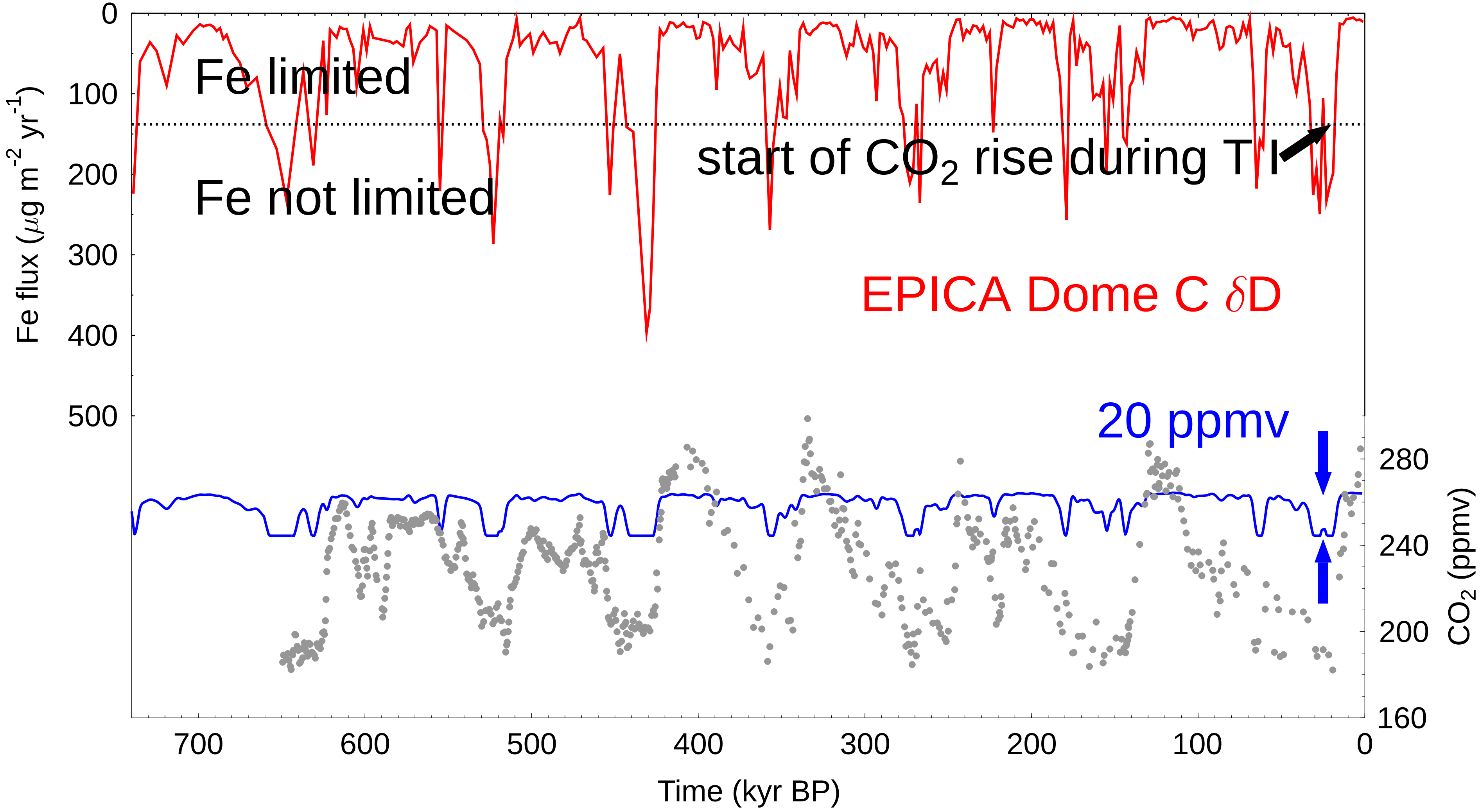


EPICA, 2004

6 Marine Biota / Iron fertilisation

Aeolian dust input to Antarctica / the Southern Ocean

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

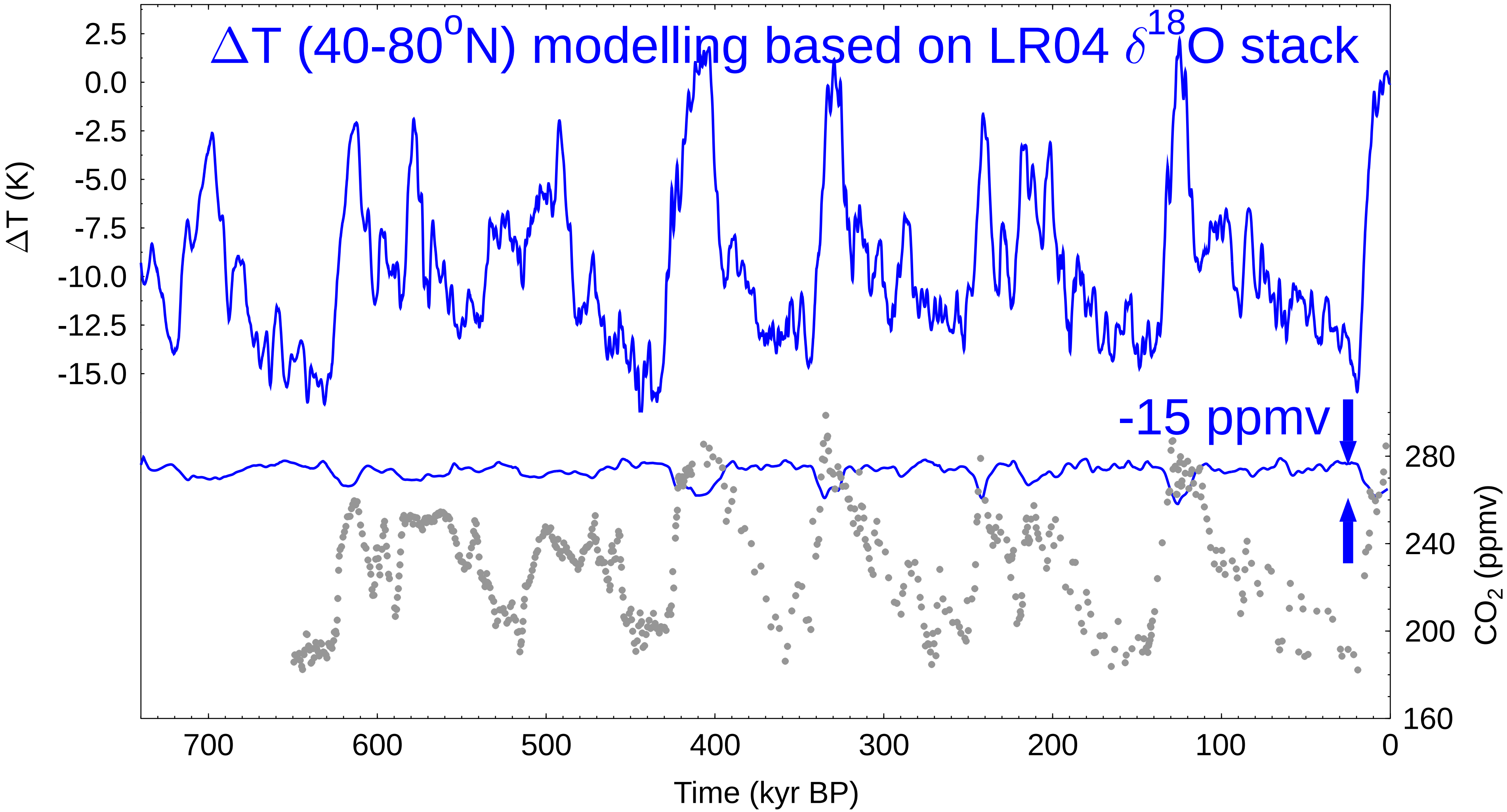


Wolff et al., 2006

7 Terrestrial Carbon Storage

$$\mathrm{NPP} = f(\mathrm{CO_2}, \mathrm{climate})$$

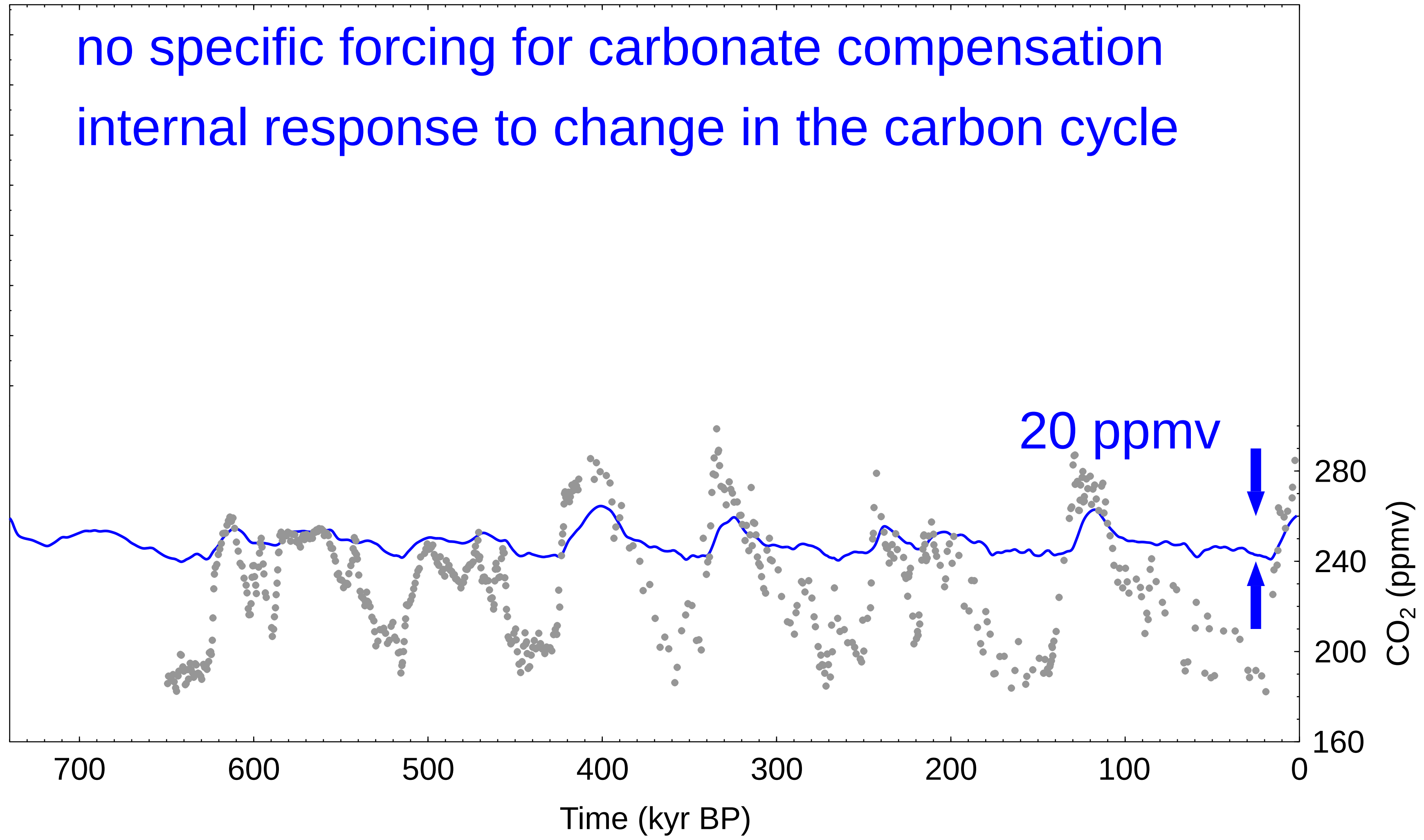
$$\Delta\mathrm{C\text{-}TB}\ (\mathrm{PRE-LGM}) = 500\ \mathrm{PgC}$$



Bintanja et al., 2005

8 Carbonate compensation

$(\tau = 1.5 \text{ kyr})$

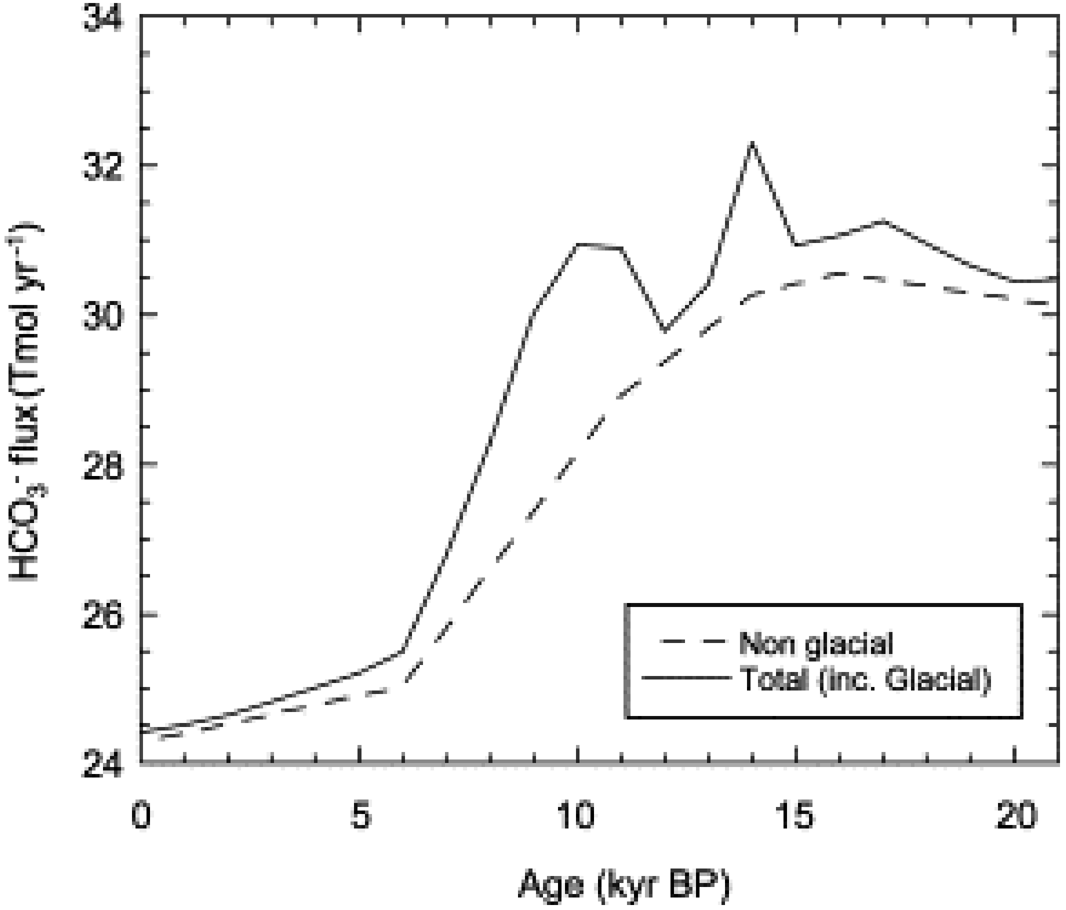


no specific forcing for carbonate compensation

internal response to change in the carbon cycle

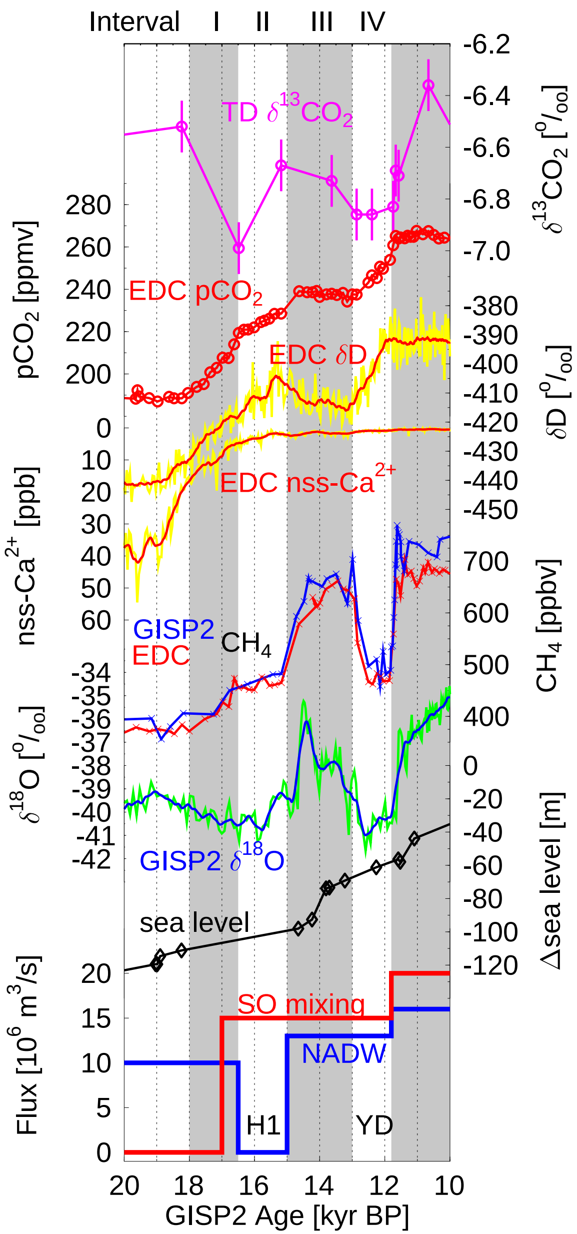
Terrestrial weathering and $CaCO_3$ chemistry

Variation in riverine input of HCO_3^-
Process-based sediment model



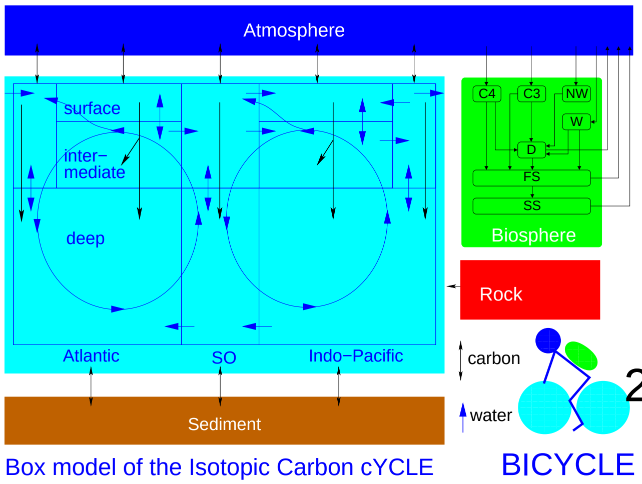
Jones et al., 2002

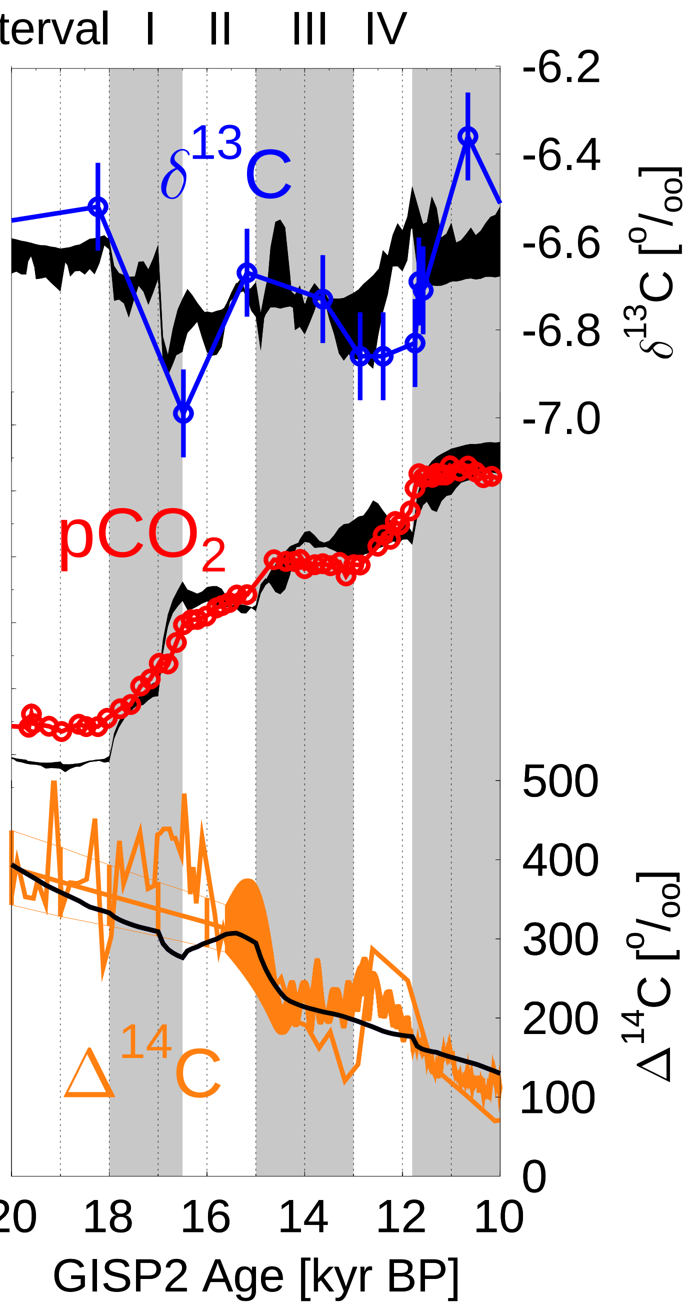
Termination I



Assumptions on changes in

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



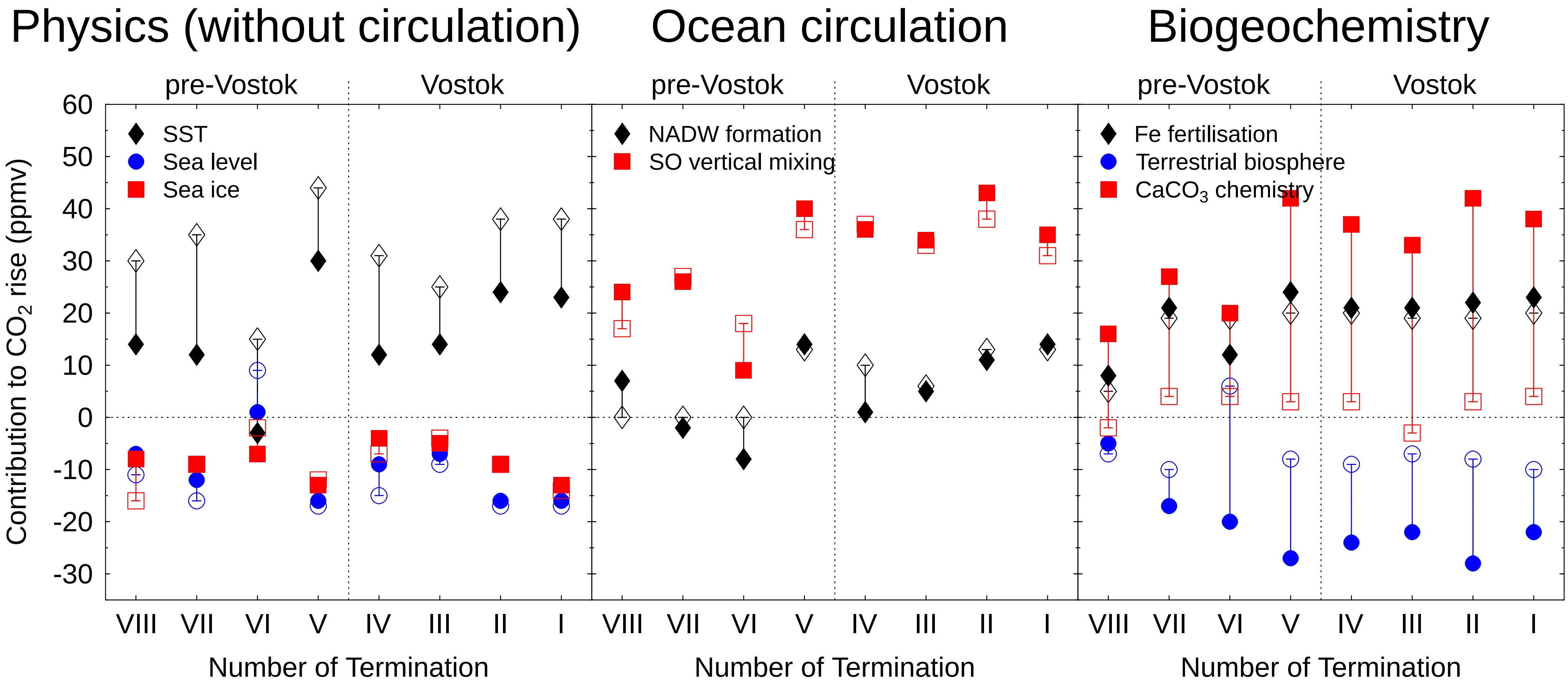


Forcing ⇒ Model ⇒ Results

Köhler et al., 2005, Global Biogeochemical Cycles

Processes during Terminations I-VIII

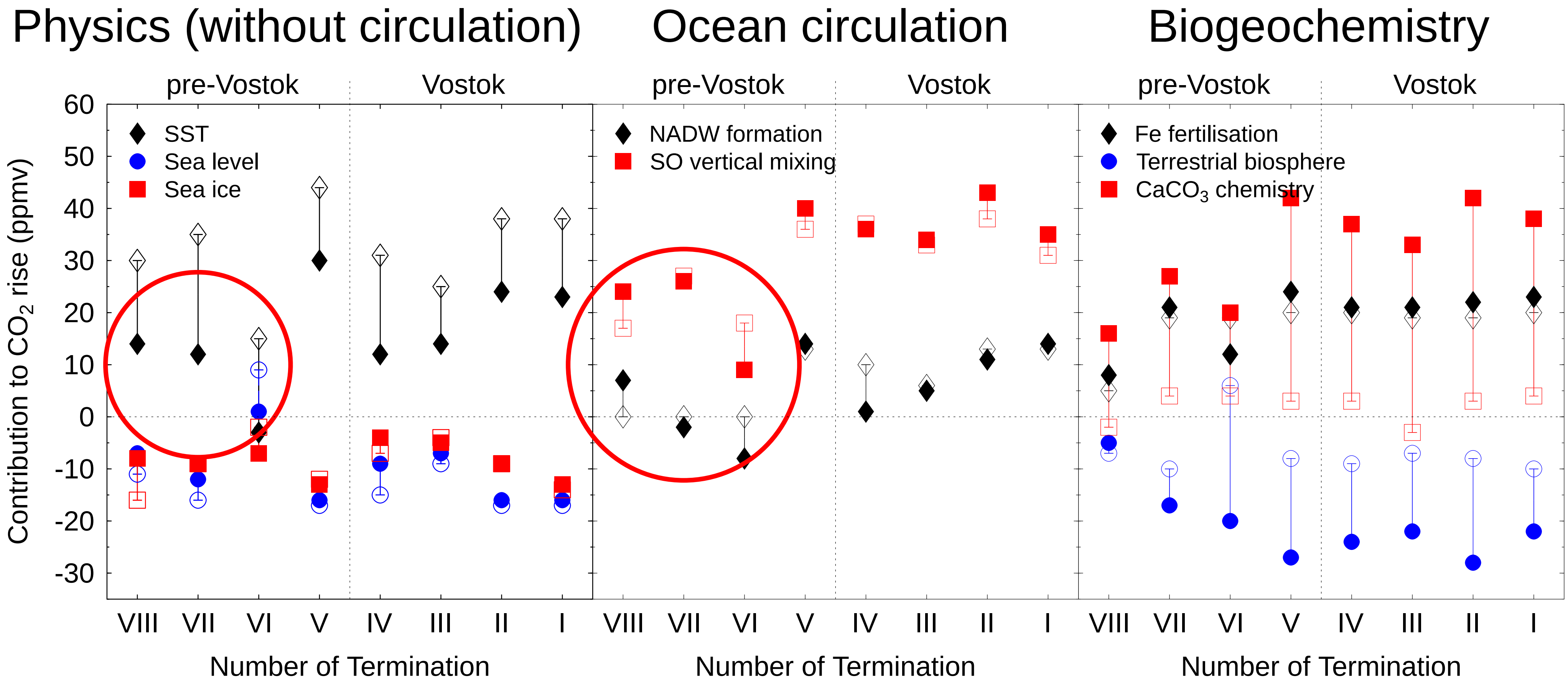
Two different estimates of individual contribution
Concentrate on CLOSED symbols



Köhler and Fischer, 2006, Climate of the Past

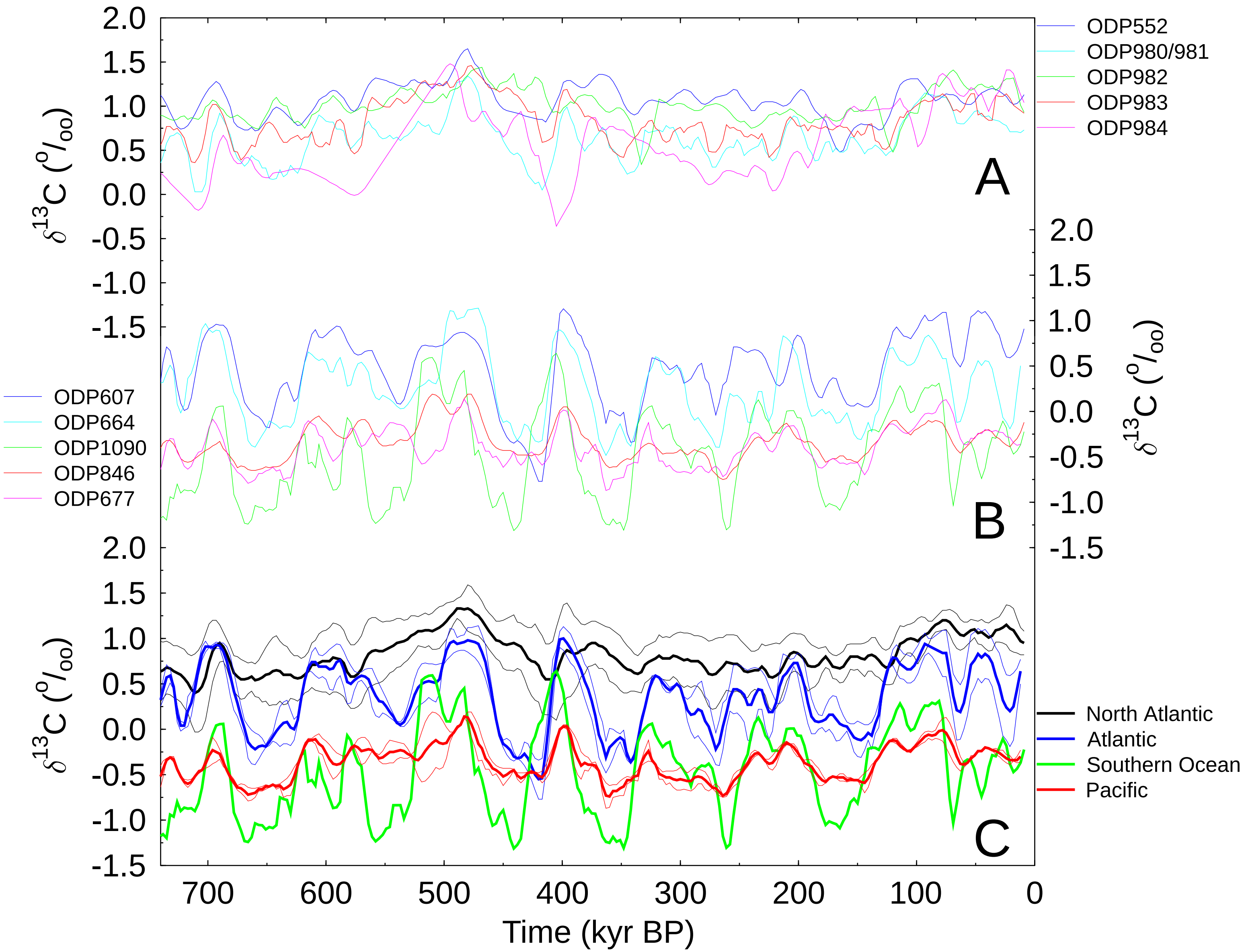
Processes during Terminations I-VIII

Smaller contributions from OCEAN CIRCULATION and SST
prior to Termination V



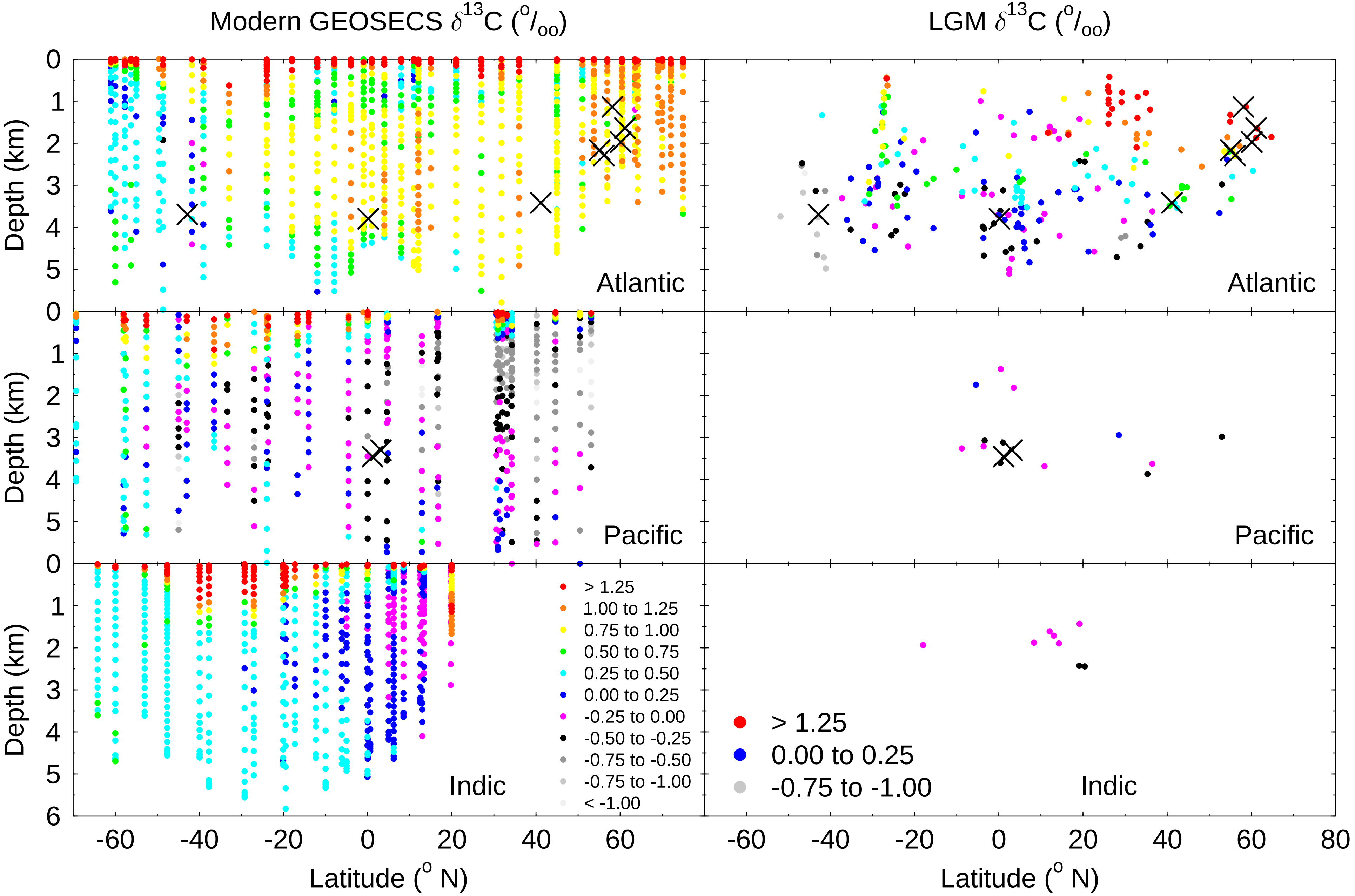
Köhler and Fischer, 2006, Climate of the Past

Benthic ^{13}C cycle



Köhler, Fischer, Paleoceanography, in prep.

2. Benthic δ^{13}C: How respresentative are single cores?



Kroopnick 1985, Boyle 1992, Bickert & Mackensen 2003, Curry & Oppo 2005

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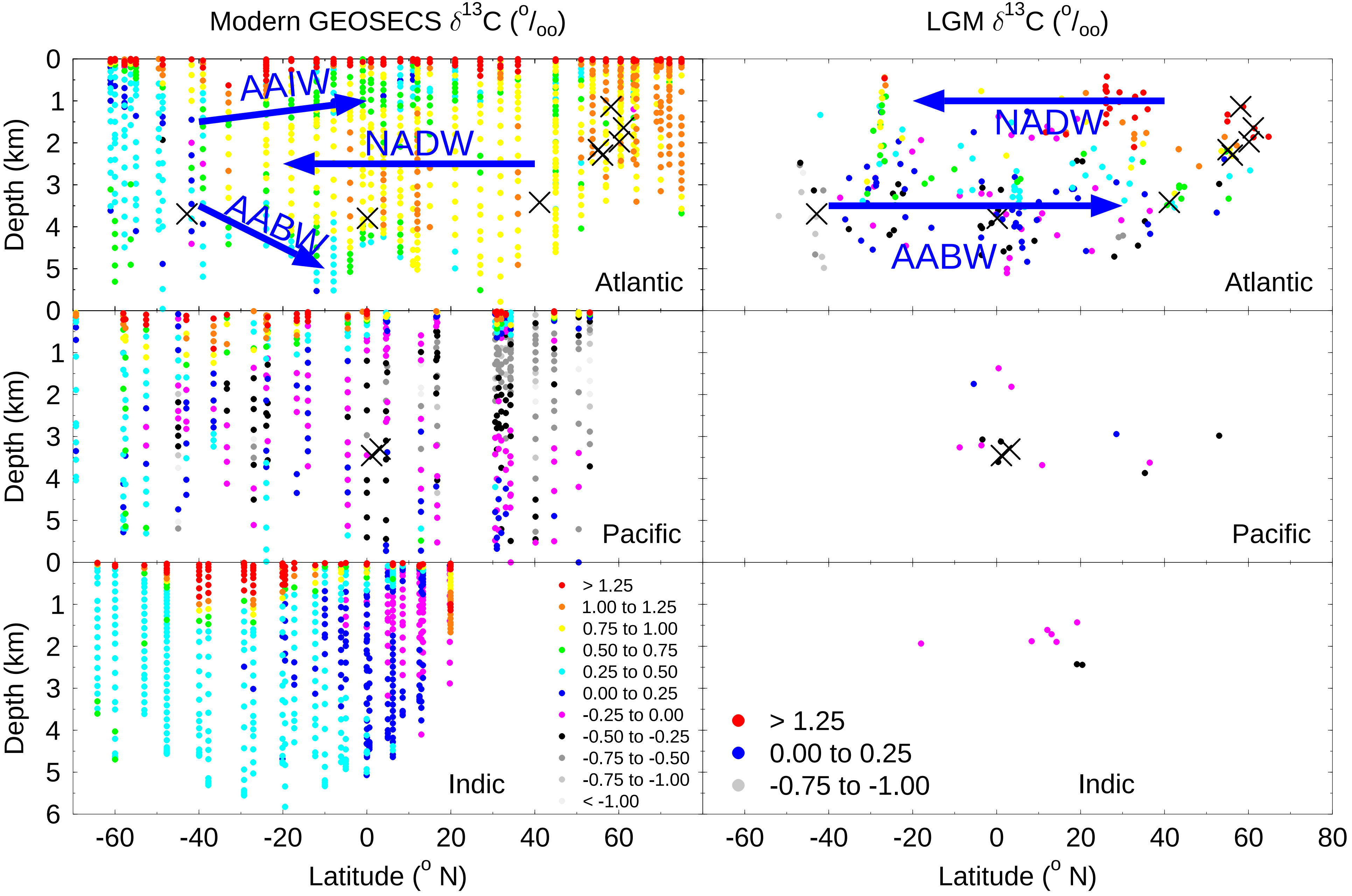
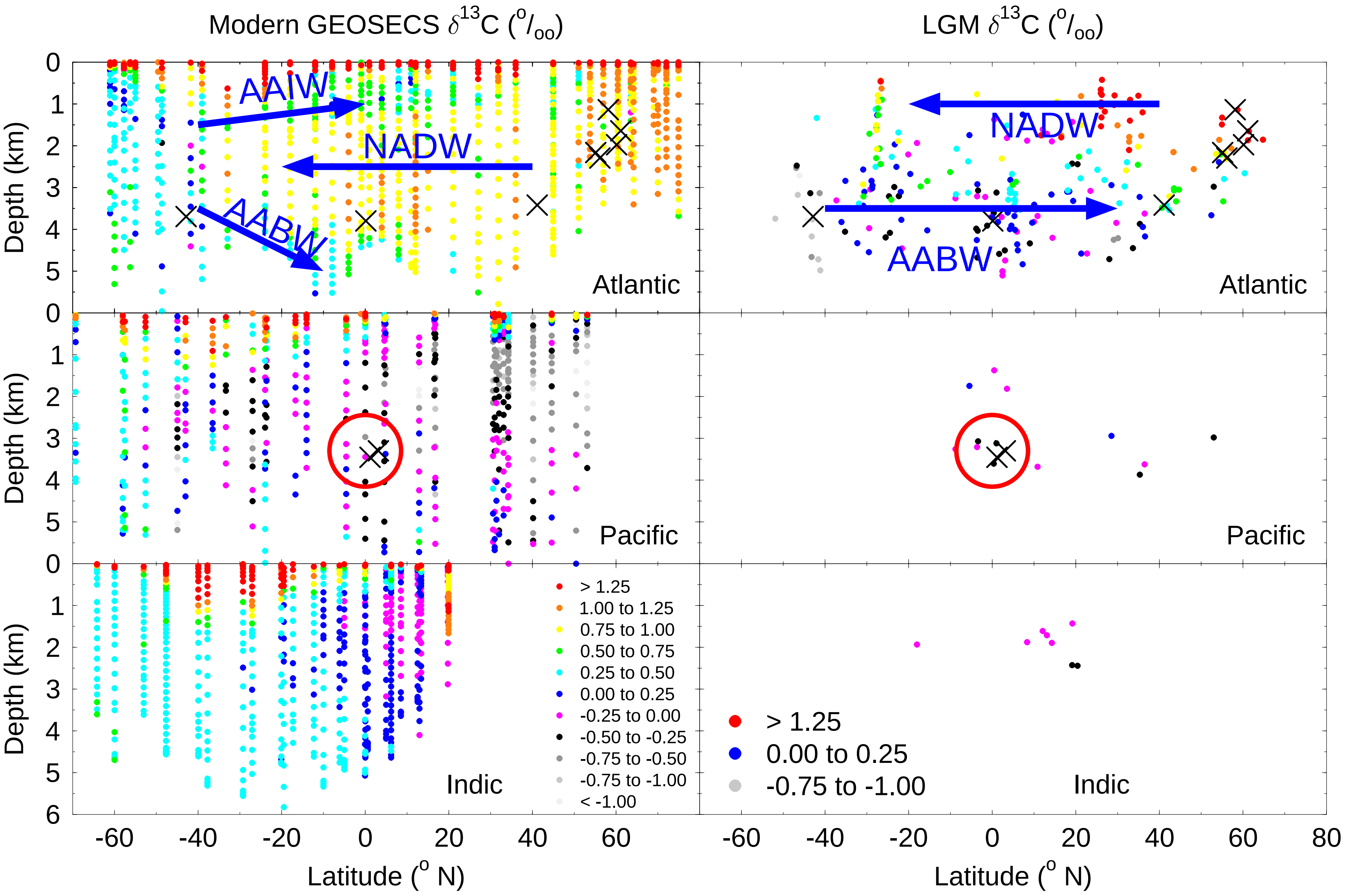


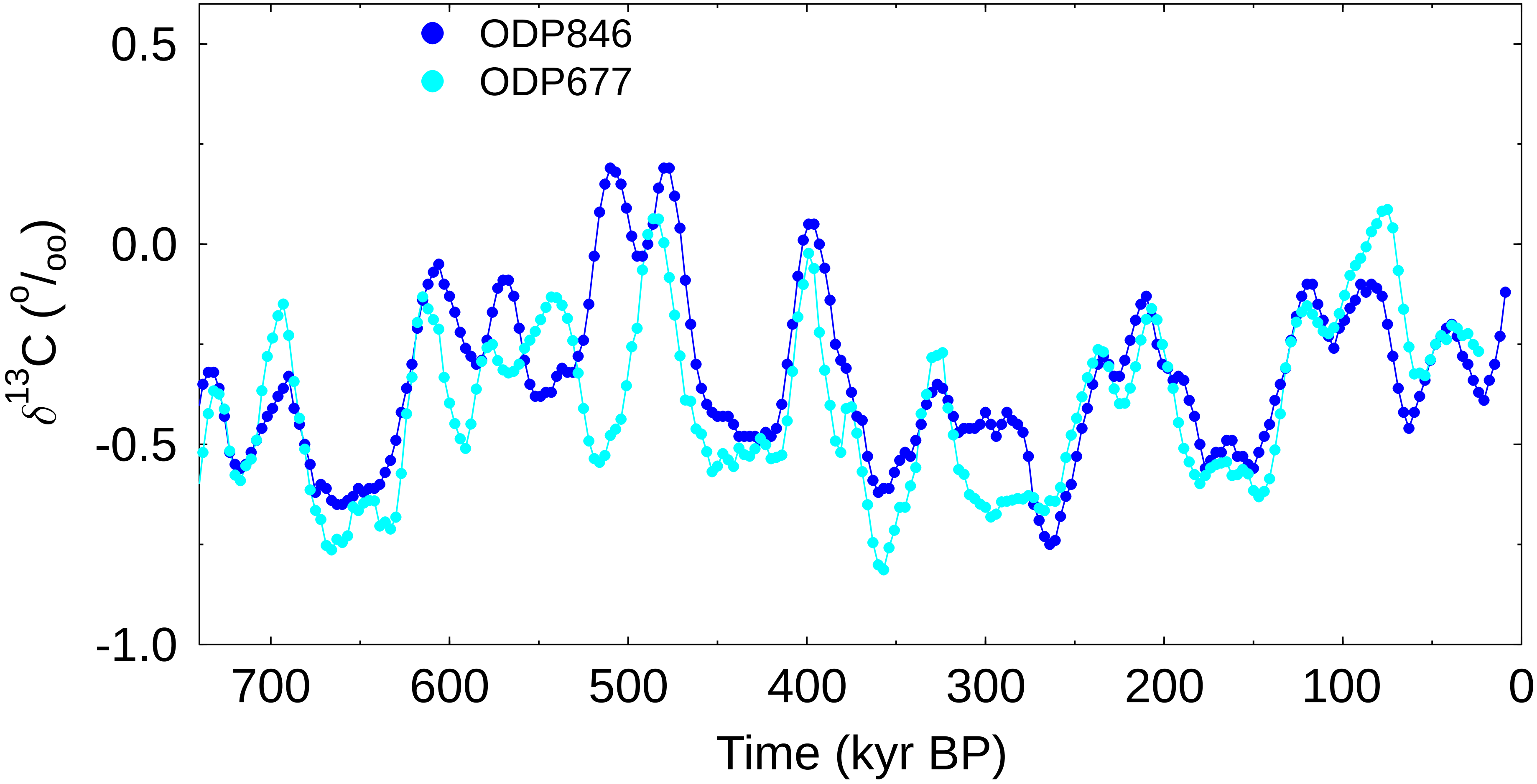
Deep Atlantic sites: water source shifts, not basin wide representative

2. Benthic $\delta^{13}C$: How respresentative are single cores?



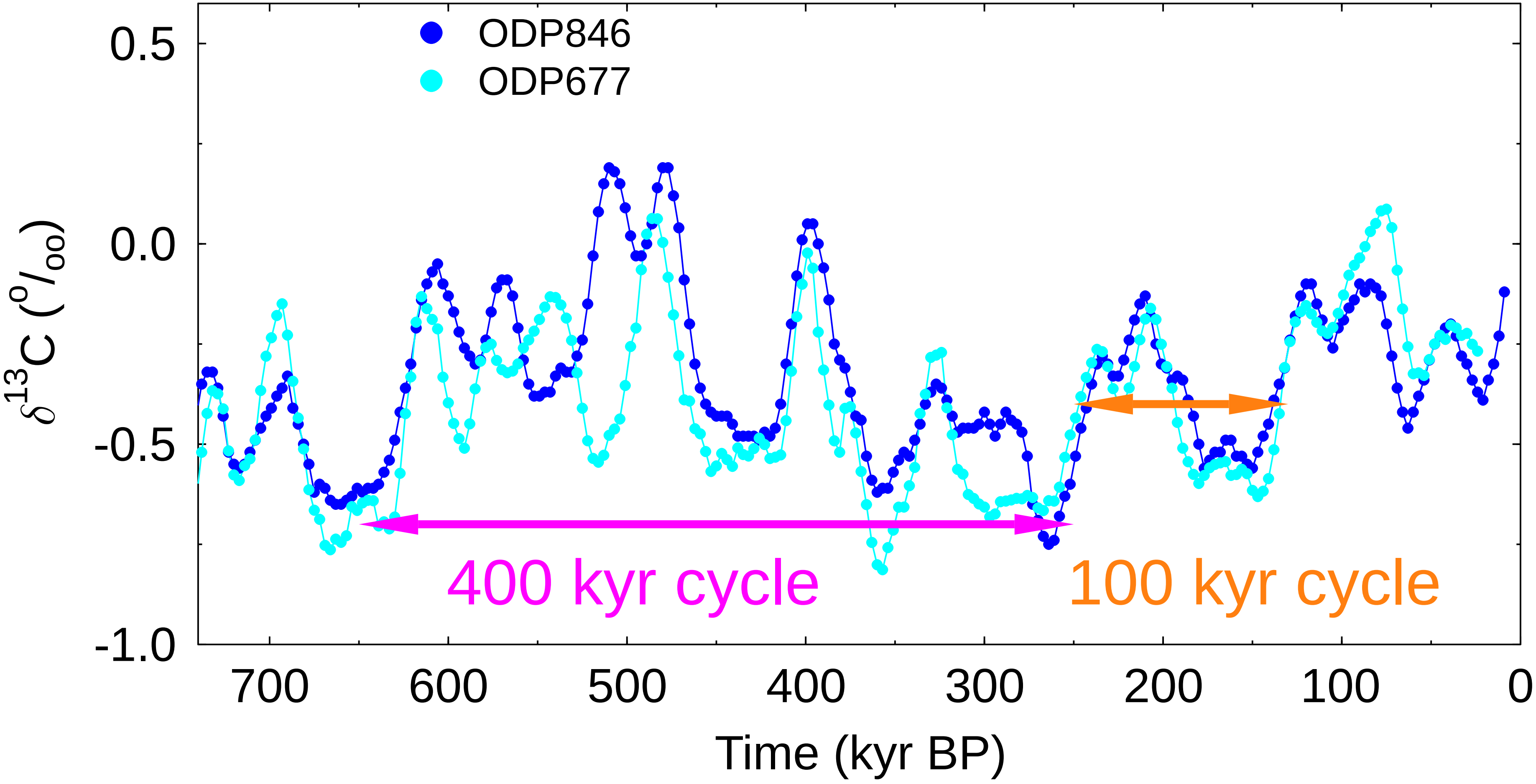
Deep Pacific sites: more homogeneous $\delta^{13}C$ distribution

2. Benthic δ^{13}C in the Deep Pacific Ocean



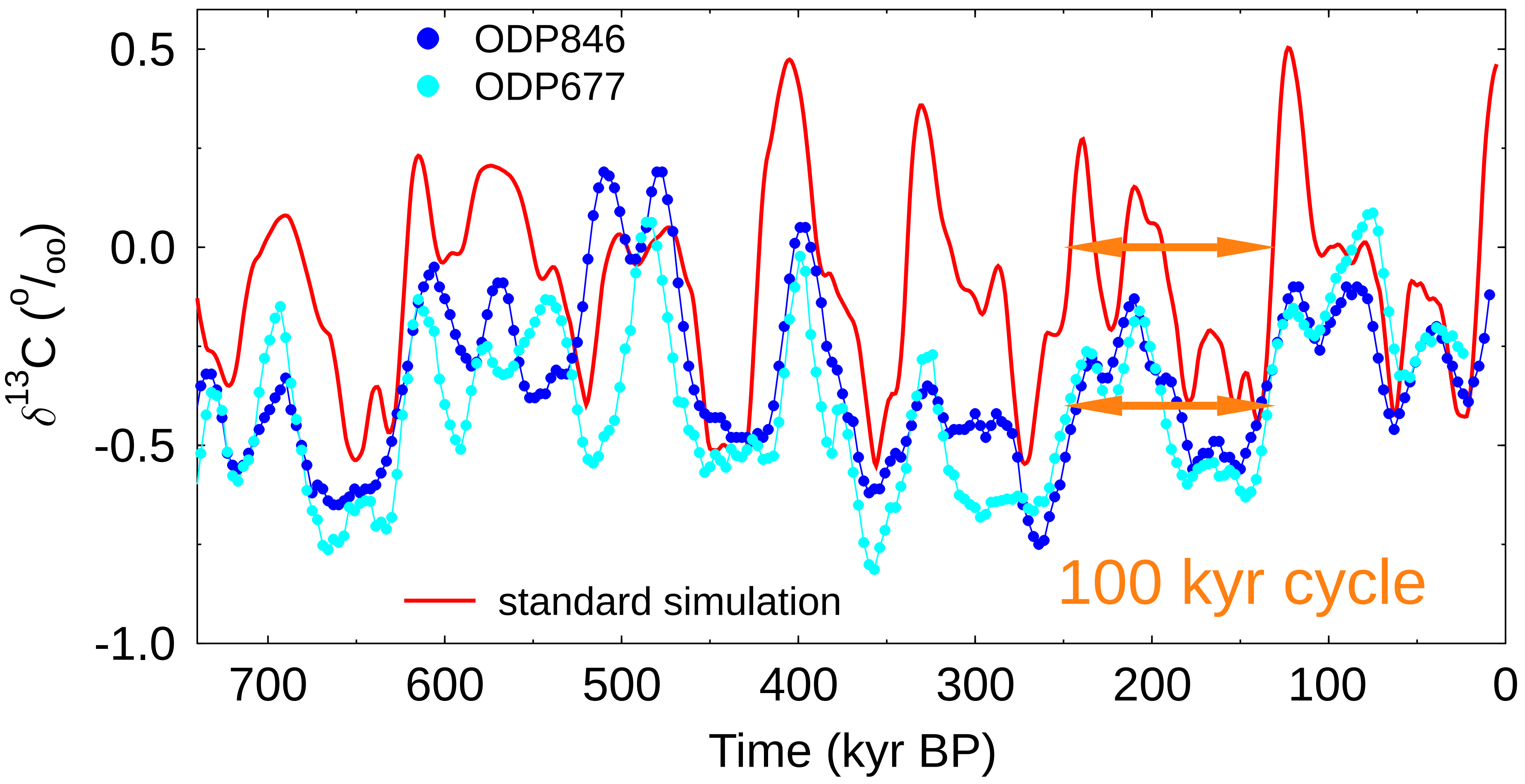
Raymo et al., 1997, 2004

2. Benthic δ^{13}C in the Deep Pacific Ocean



Raymo et al., 1997, 2004

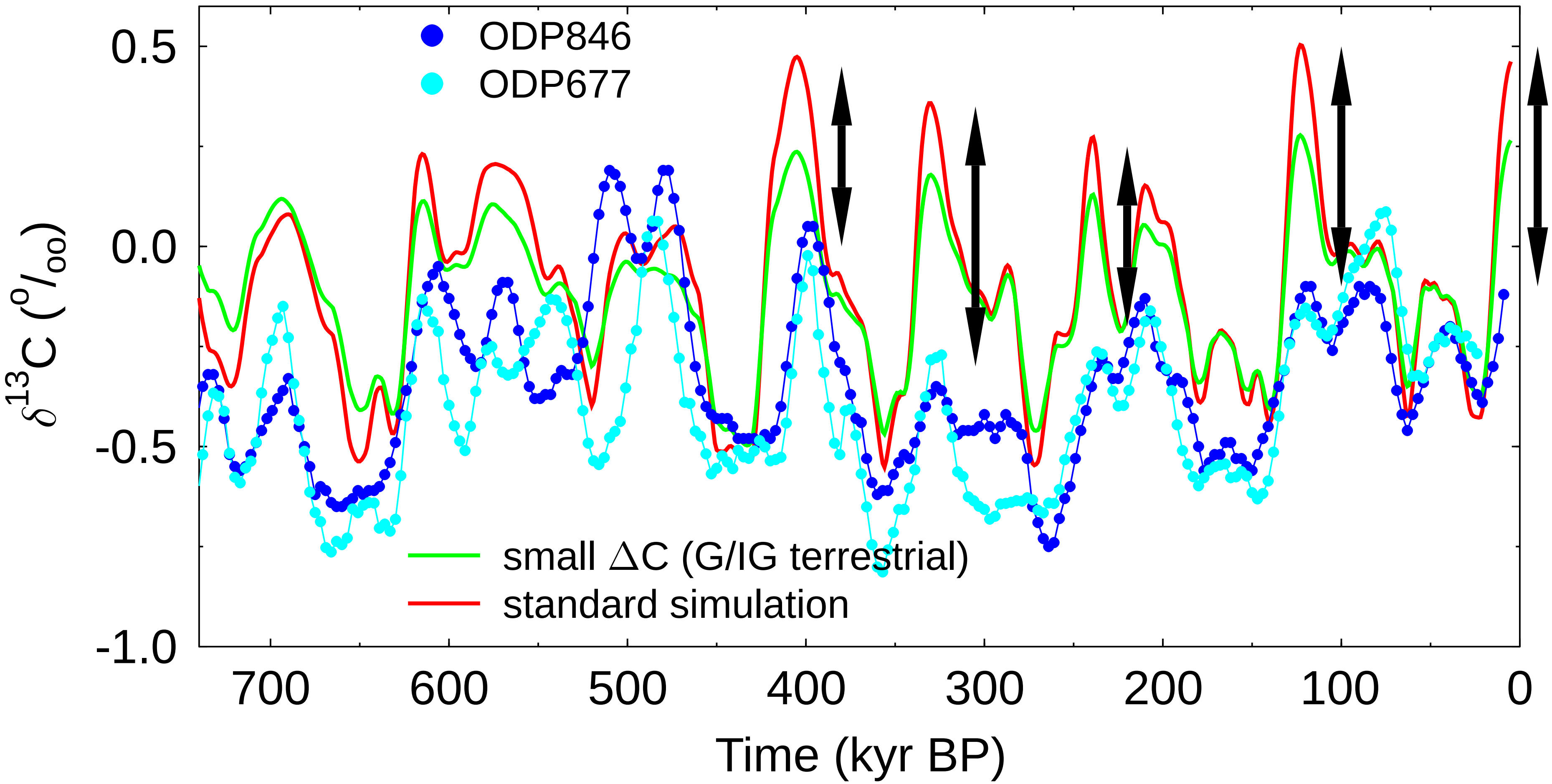
2. Benthic δ^{13}C in the Deep Pacific Ocean



100 kyr cycle: supported

400 kyr cycle: not found in simulations, sediment model missing

2. Benthic δ^{13}C in the Deep Pacific Ocean



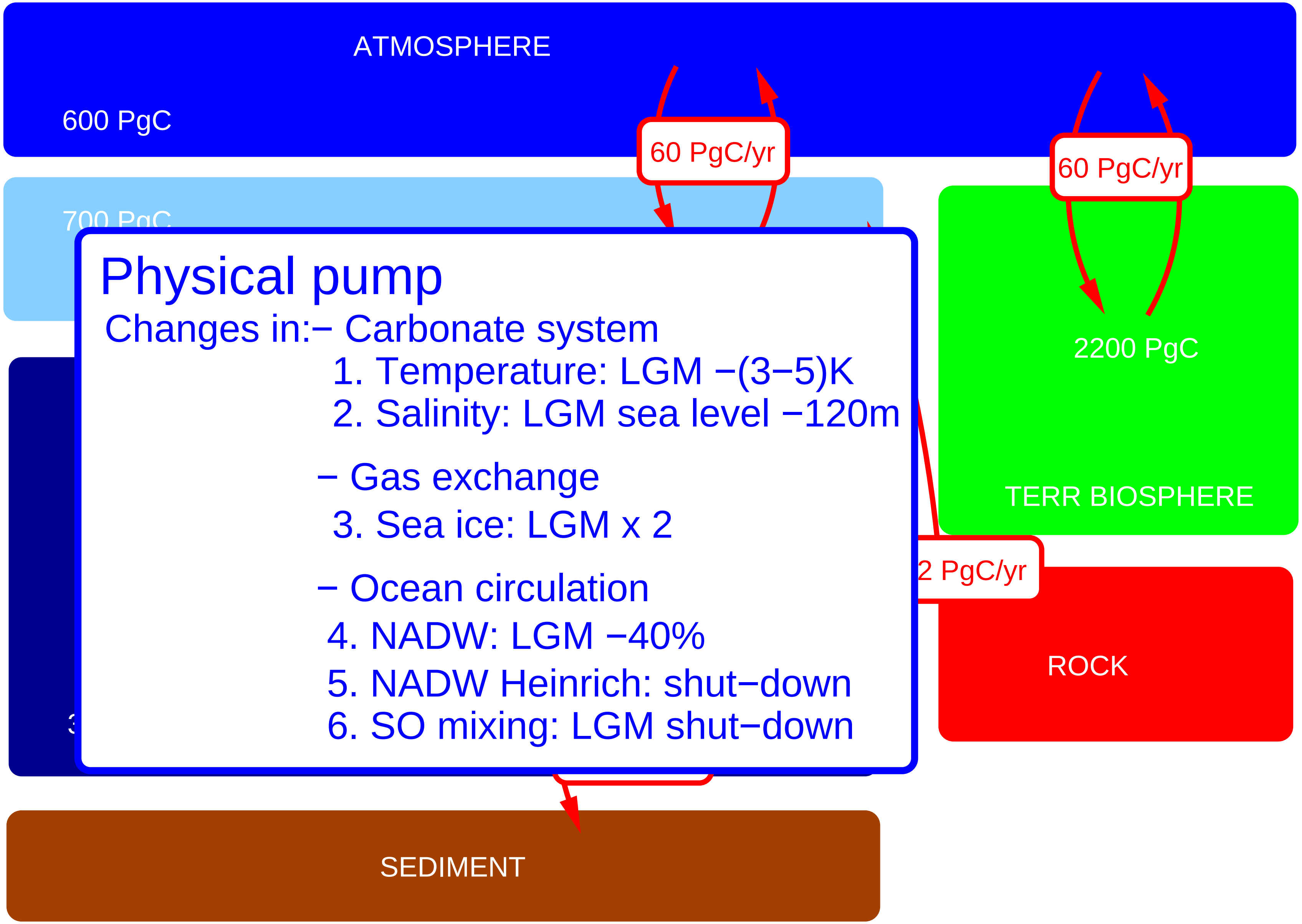
δ^{13}C during interglacials in the 100 kyr world:

– Terrestrial biosphere?

– Missing delay of $CaCO_3$ compensation by 10 kyr?

– Representative of time series for basin wide changes?

The Physical Pump



Physical pump

Changes in:− Carbonate system

1. Temperature: LGM −(3−5)K
2. Salinity: LGM sea level −120m

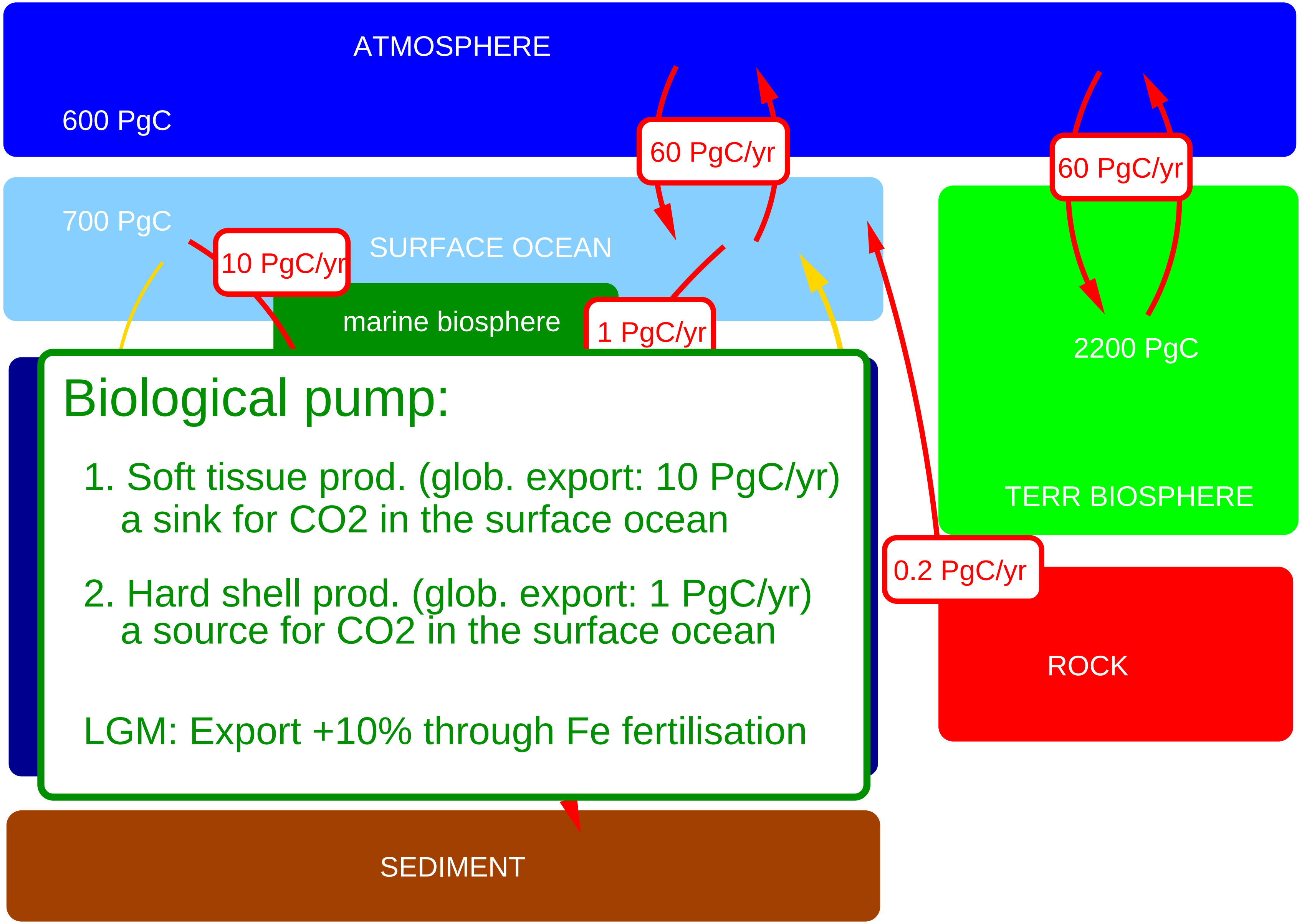
− Gas exchange

3. Sea ice: LGM x 2

− Ocean circulation

4. NADW: LGM −40%
5. NADW Heinrich: shut−down
6. SO mixing: LGM shut−down

The Biological Pump



ATMOSPHERE

600 PgC

60 PgC/yr

60 PgC/yr

700 PgC

SURFACE OCEAN

10 PgC/yr

marine biosphere

1 PgC/yr

2200 PgC

TERR BIOSPHERE

0.2 PgC/yr

ROCK

SEDIMENT

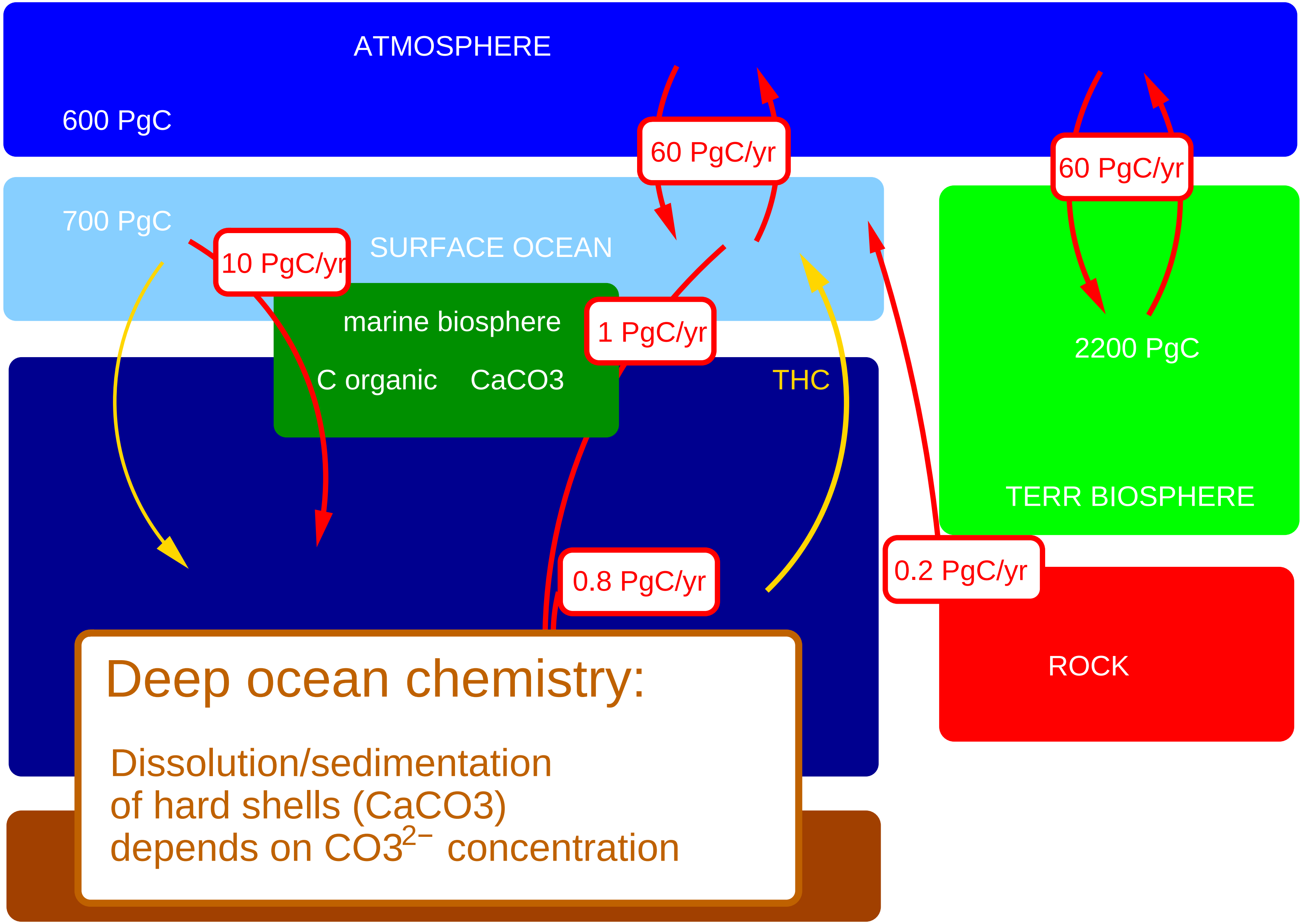
Biological pump:

1. Soft tissue prod. (glob. export: 10 PgC/yr)
   a sink for CO2 in the surface ocean

2. Hard shell prod. (glob. export: 1 PgC/yr)
   a source for CO2 in the surface ocean

LGM: Export +10% through Fe fertilisation

$CaCO_3$ chemistry



ATMOSPHERE

600 PgC

60 PgC/yr

60 PgC/yr

700 PgC

10 PgC/yr

SURFACE OCEAN

marine biosphere

C organic CaCO3

1 PgC/yr

THC

2200 PgC

TERR BIOSPHERE

0.8 PgC/yr

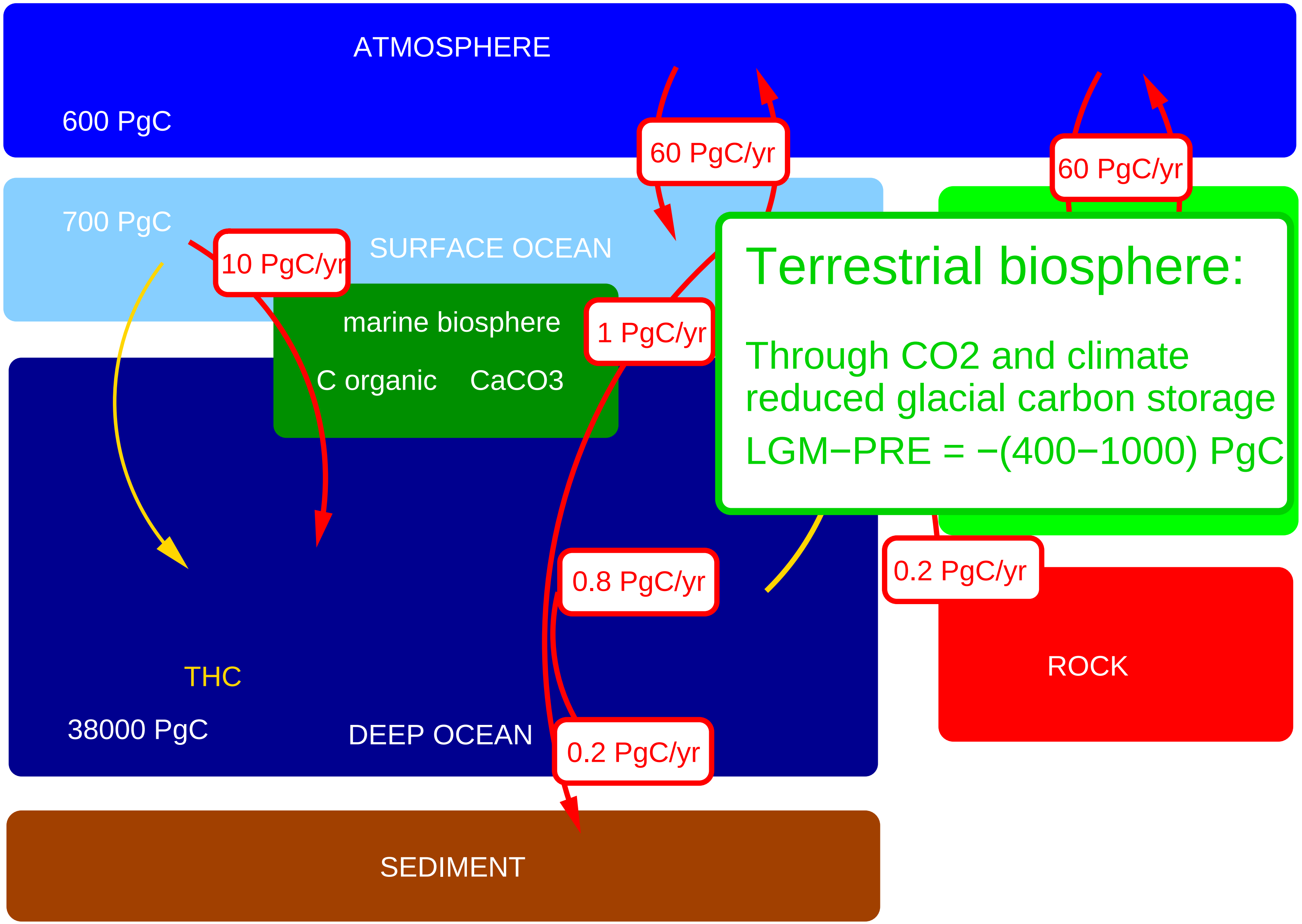
0.2 PgC/yr

ROCK

Deep ocean chemistry:

Dissolution/sedimentation
of hard shells (CaCO3)
depends on $CO3^{2-}$ concentration

The terrestrial biosphere



Terrestrial biosphere:

Through CO2 and climate
reduced glacial carbon storage
LGM−PRE = −(400−1000) PgC

Preindustrial ocean circulation