Alfred Wegener Institute
for Polar and Marine Research
Bremerhaven, Germany

The Carbon Cycle during the Pleistocene

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—

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Guy Munhoven, Université de Lìege, Belgium

HELMHOLTZ
ASSOCIATION

Outline

The global record of atmospheric CO_2

EPICA — European Project for Ice Coring in Antarctica

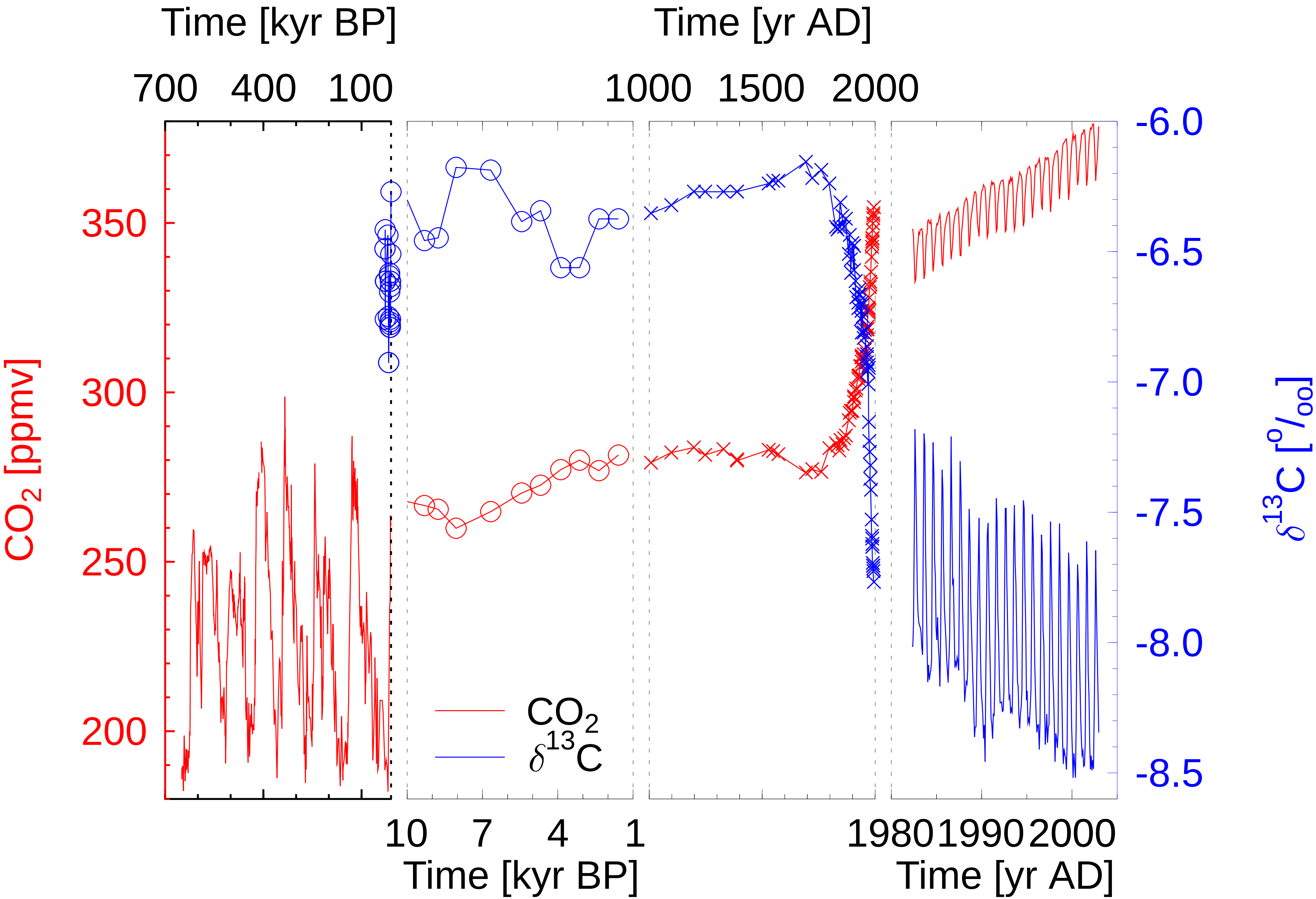
The global carbon cycle and the box model BICYCLE

Time-dependent processes: motivations and simulation results

Combined scenarios

Open questions

Conclusions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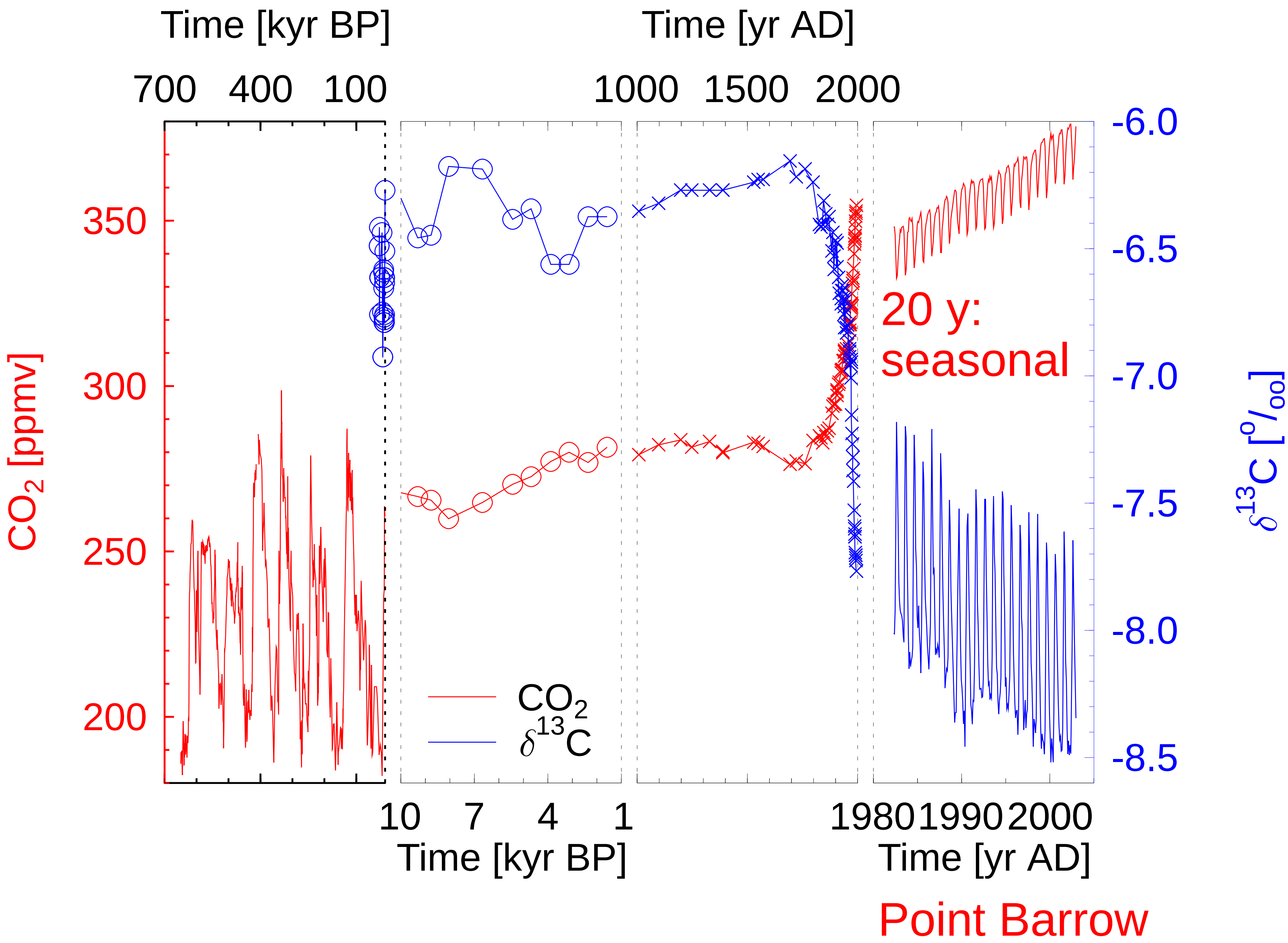
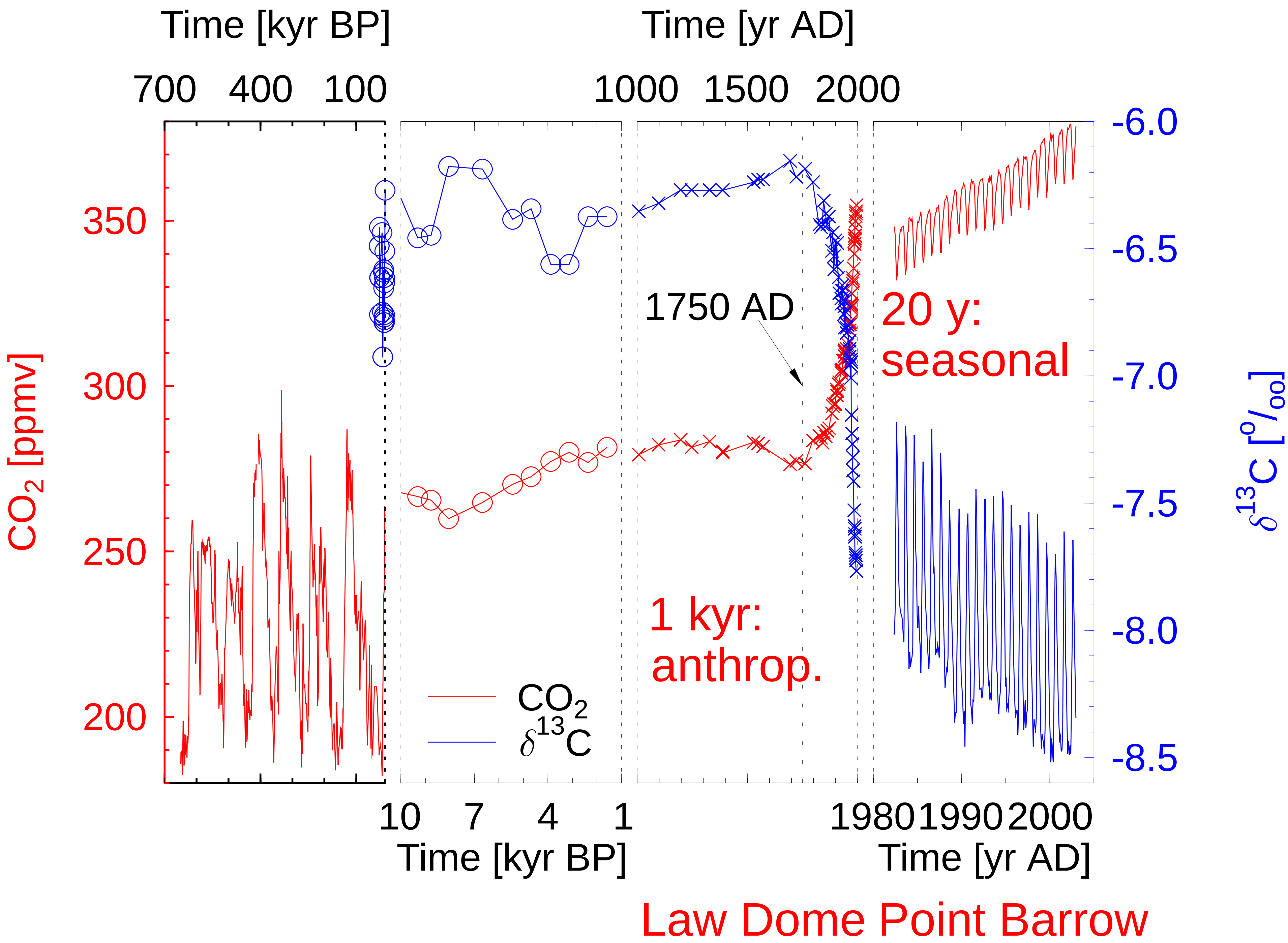
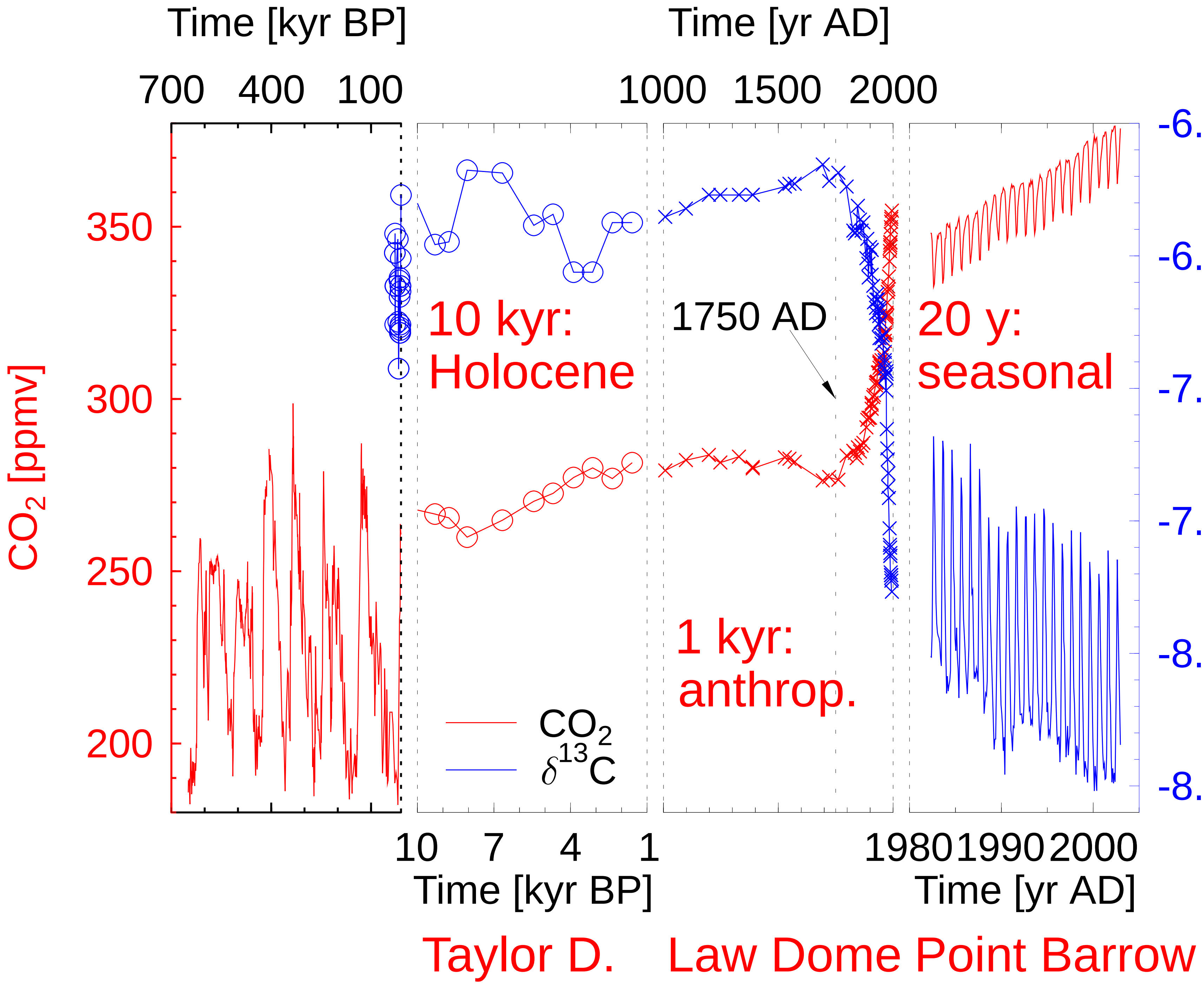
Time [yr AD]
700 400 100
1000 1500 2000
-6.0
-6.5
-7.0
-7.5
-8.0
-8.5
350
300
250
200
CO2 [ppmv]
δ13C [‰]
CO2
δ13C
10 7 4 1
1980 1990 2000
Time [kyr BP]
Time [yr AD]



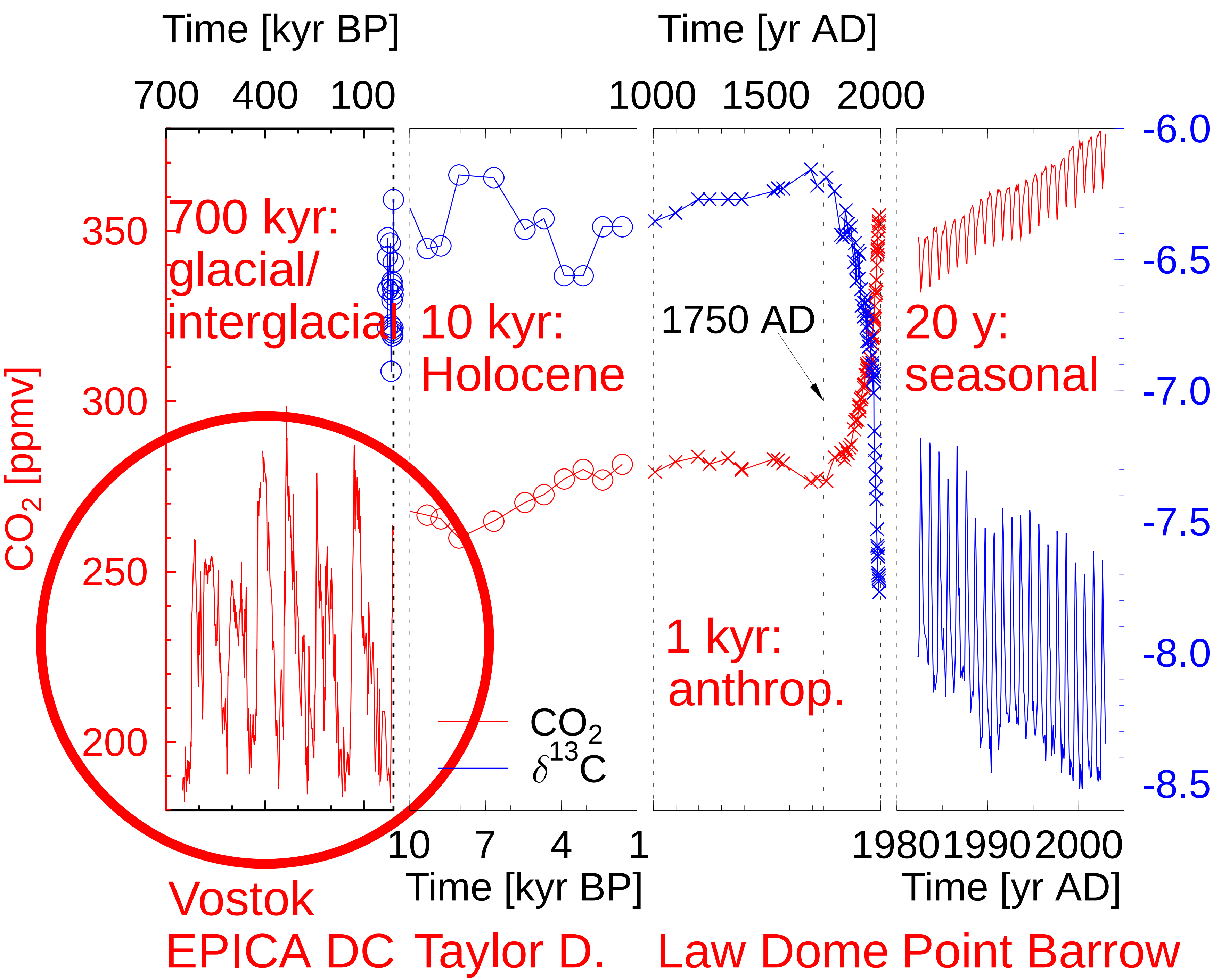
Keeling and Whorf, 2005; Keeling et al., 2005.



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



Smith et al., 1999



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

Radiative Forcing of Greenhouse Gases — Today

Gas	Current Amount	Increase	Radiative forcing ($W\ m^{-2}$) < 1750	Radiative forcing ($W\ m^{-2}$) 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
CFCs	268 ppt			0.31
Preindustrial Greenhouse Forcing			146	
Anthropogenic Greenhouse Forcing				2.66
Total Greenhouse Forcing			148.66	

Global surface temperature (energy balance without GHG): $-18°C$

Global surface temperature (measured in 20th century): $+16°C$

Total Greenhouse Forcing (148.66 W/m^2) explains ΔT of 34 K.

$\Rightarrow$ Anthropogenic Forcing (2.66 W/m^2) explains ΔT of 0.6 K.

(which is in agreement with observations during the last 150 years)

Radiative Forcing of Greenhouse Gases — LGM

Agent	Radiative forcing ($W\ m^{-2}$)
Preindustrial Greenhouse Gases	+146
Anthropogenic Greenhouse Gases	+2.66
LGM	
GHG (CO_2 + CH_4 + N_2O)	−2.8
Dust	−1.4
Ice sheets (Albedo)	−3.0
Vegetation (Albedo)	−1.2
LGM sum	−8.4

⇒ Anthropogenic GHG forcing is of the same order but opposite sign than GHG foring during LGM.

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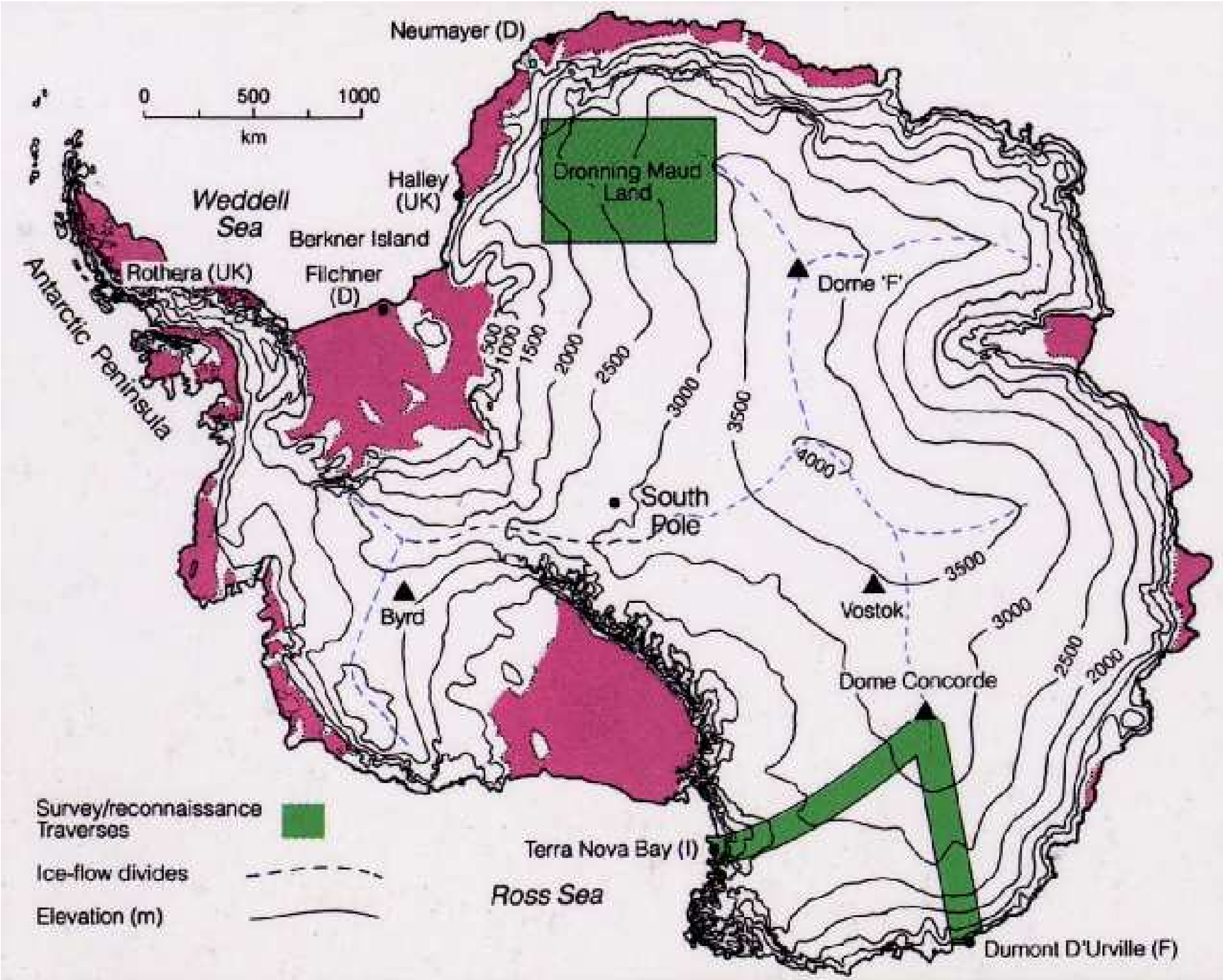
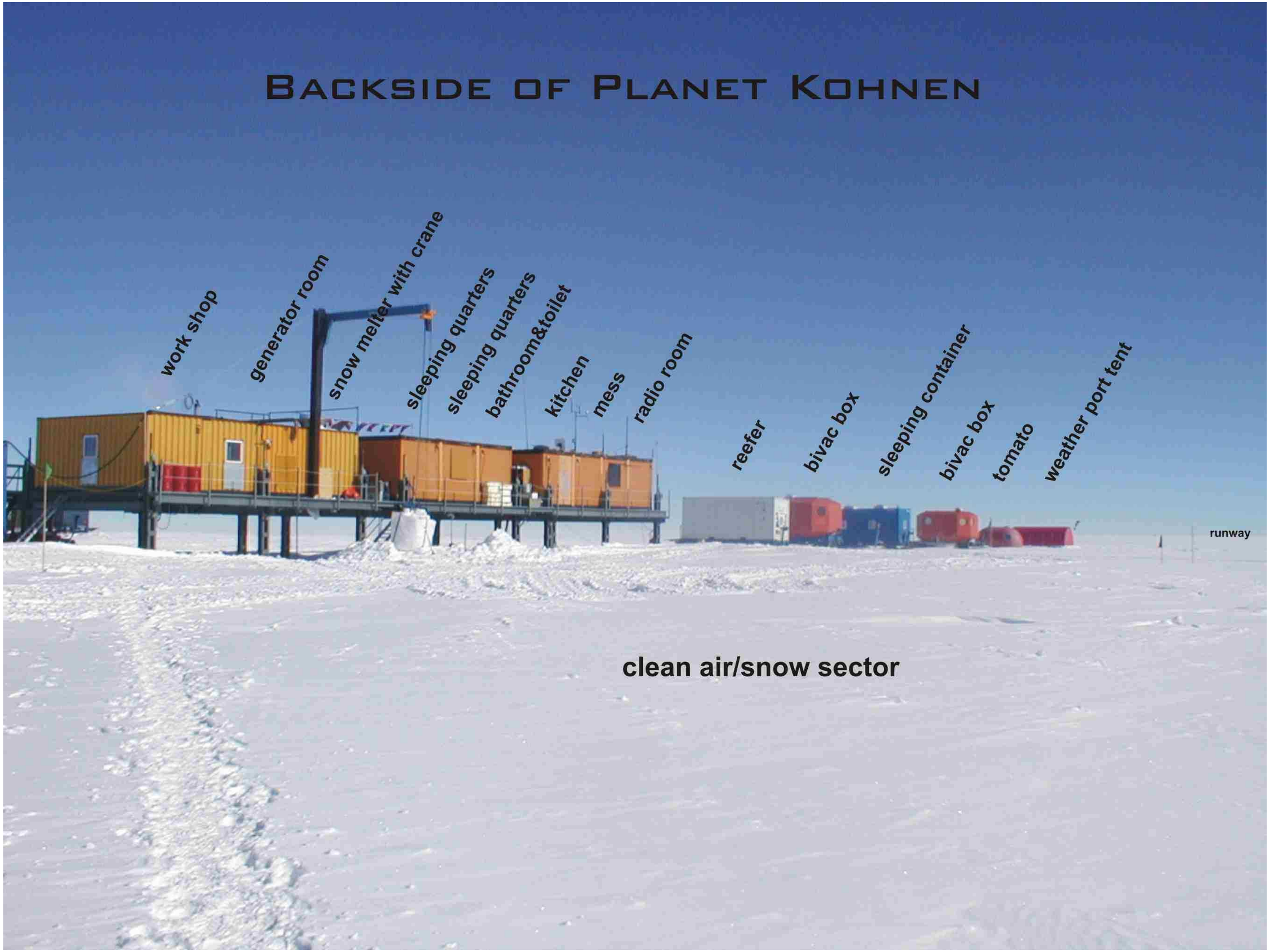


EPICA drilling sites:

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

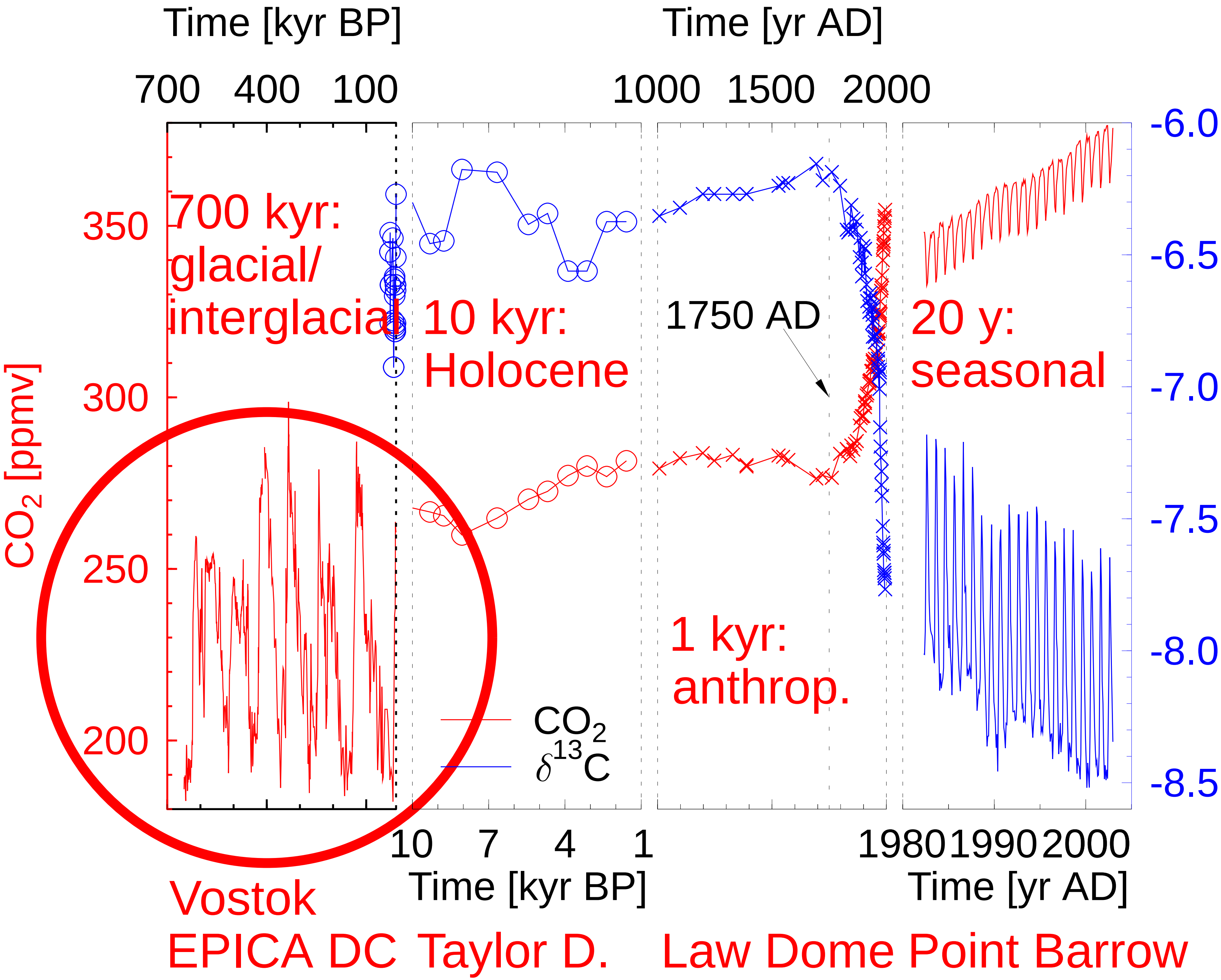
Dronning Maud Land (EDML): high accumulation rate, high resolution



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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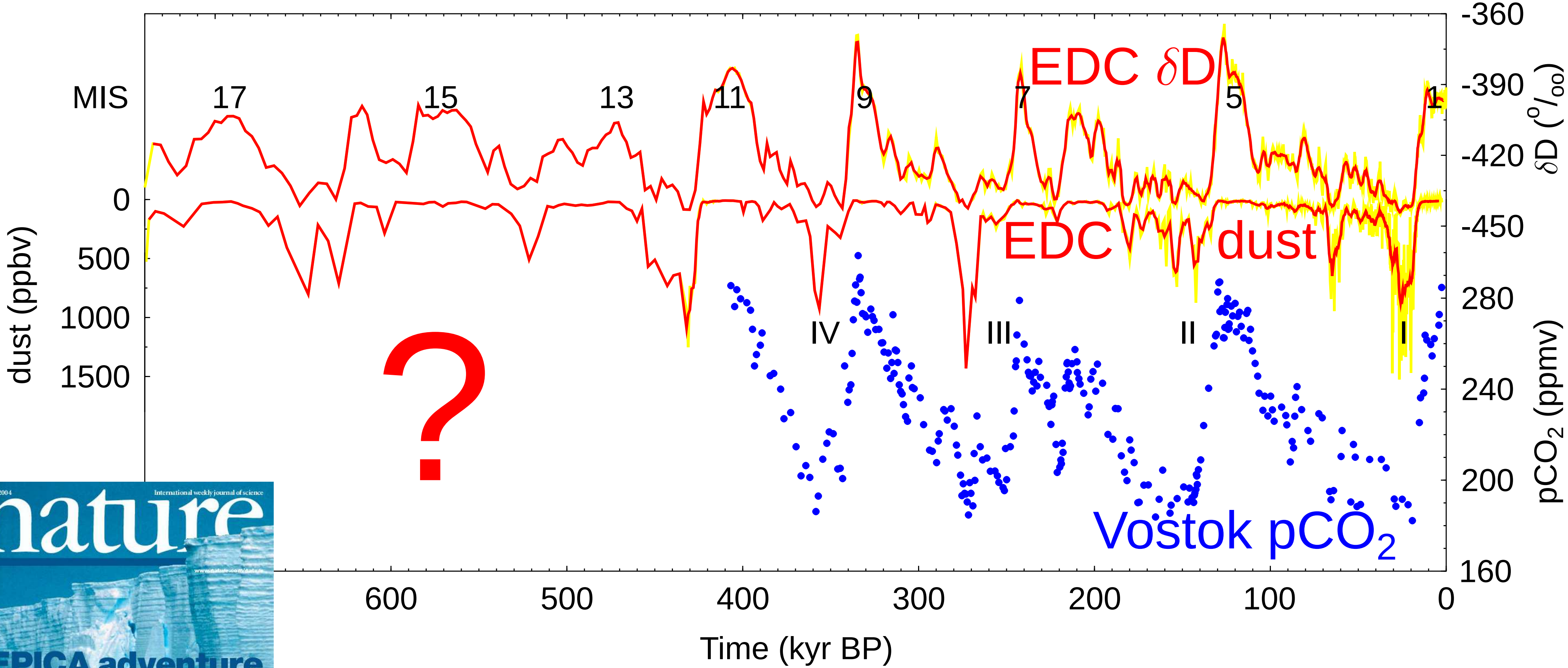
1000
1500
2000
-6.0
-6.5
-7.0
-7.5
-8.0
-8.5
350
300
250
200
CO2 [ppmv]
δ13C [o/oo]
700 kyr:
glacial/
interglacial
10 kyr:
Holocene
1750 AD
20 y:
seasonal
1 kyr:
anthrop.
CO2
δ13C
10
7
4
1
1980
1990
2000
Time [kyr BP]
Time [yr AD]
Vostok
EPICA DC
Taylor D.
Law Dome
Point Barrow

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

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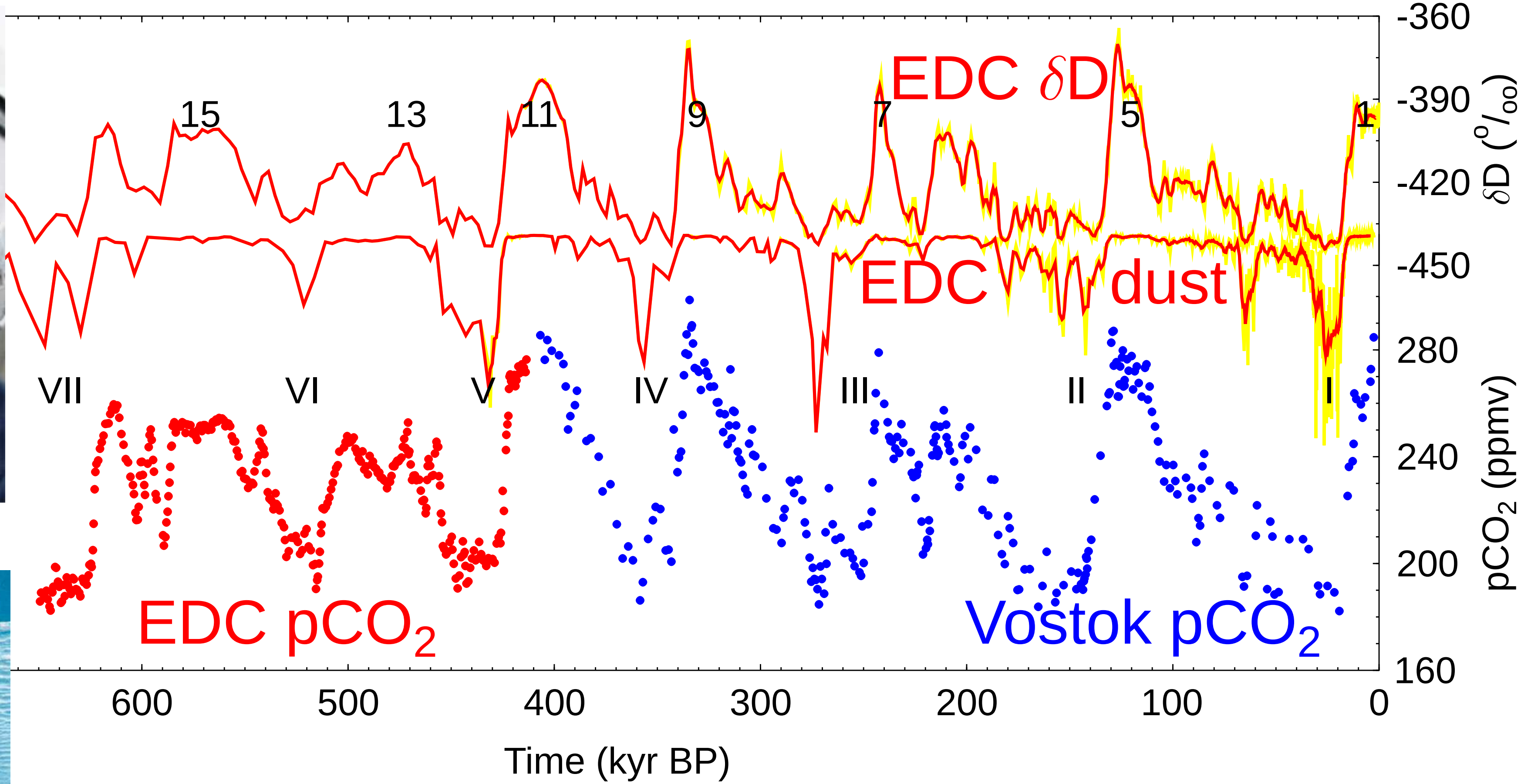
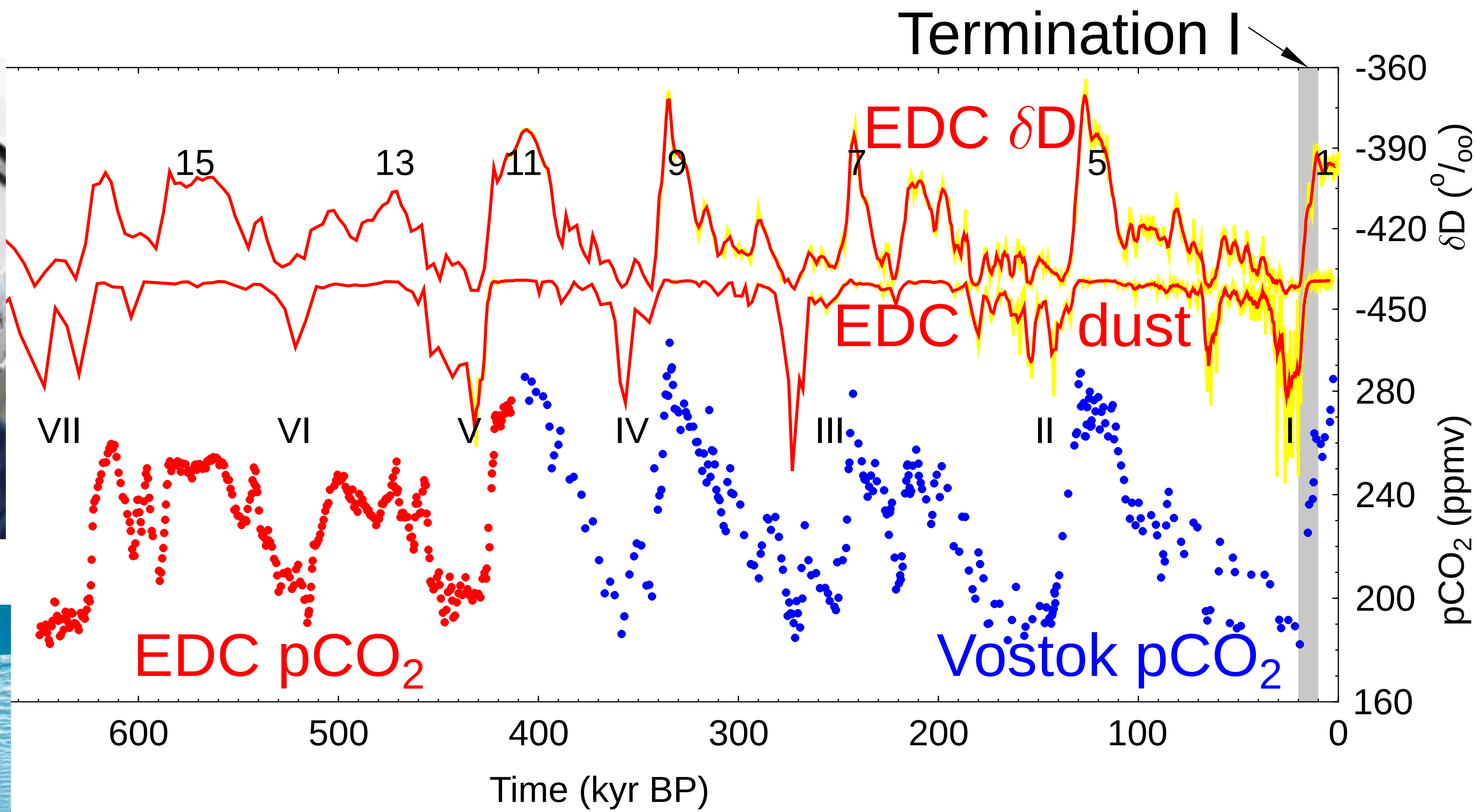


EPICA, 2004; Petit et al., 1999

Siegenthaler et al., 2005

The EPICA challenge

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

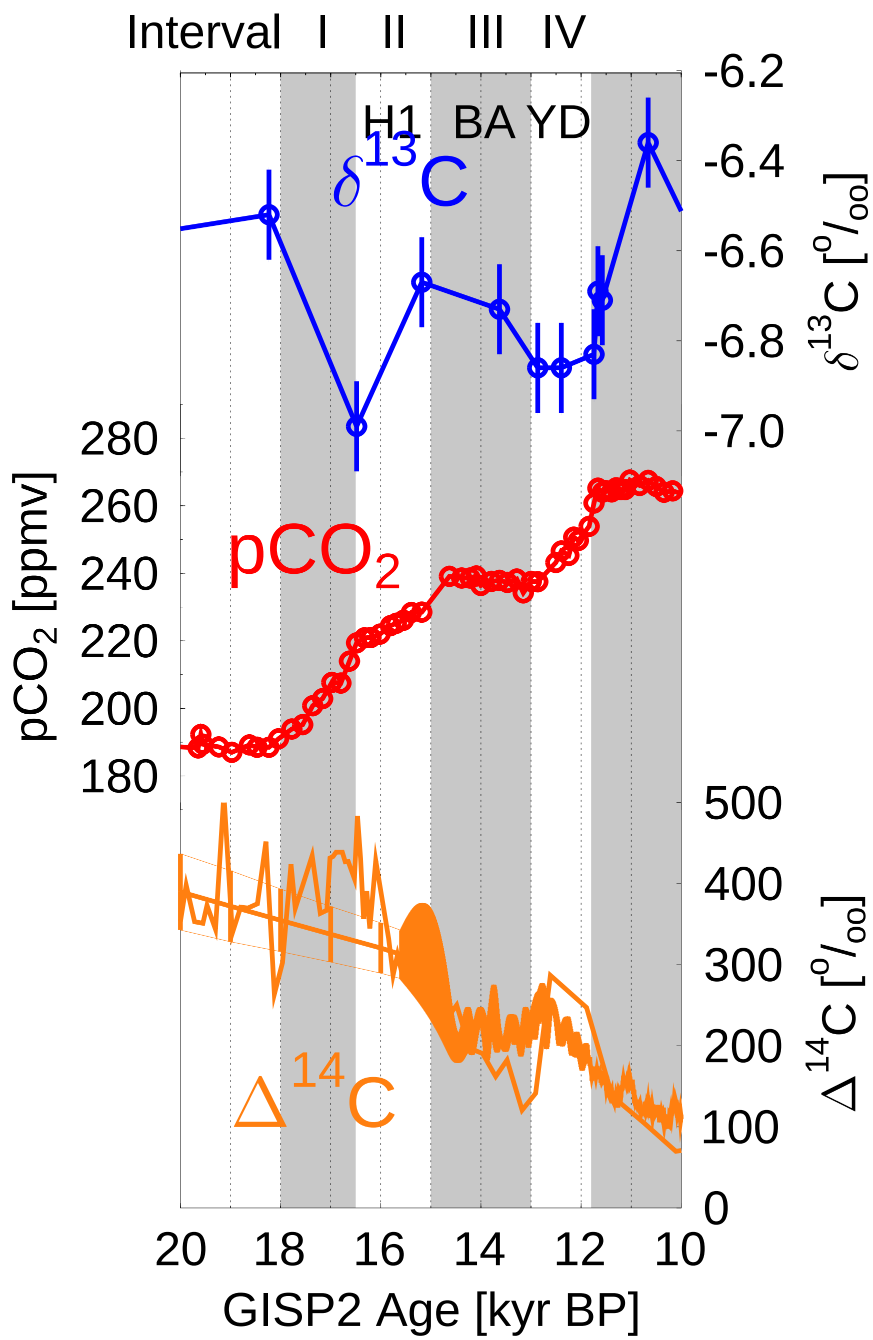


EPICA, 2004; Petit et al., 1999
Siegenthaler et al., 2005

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



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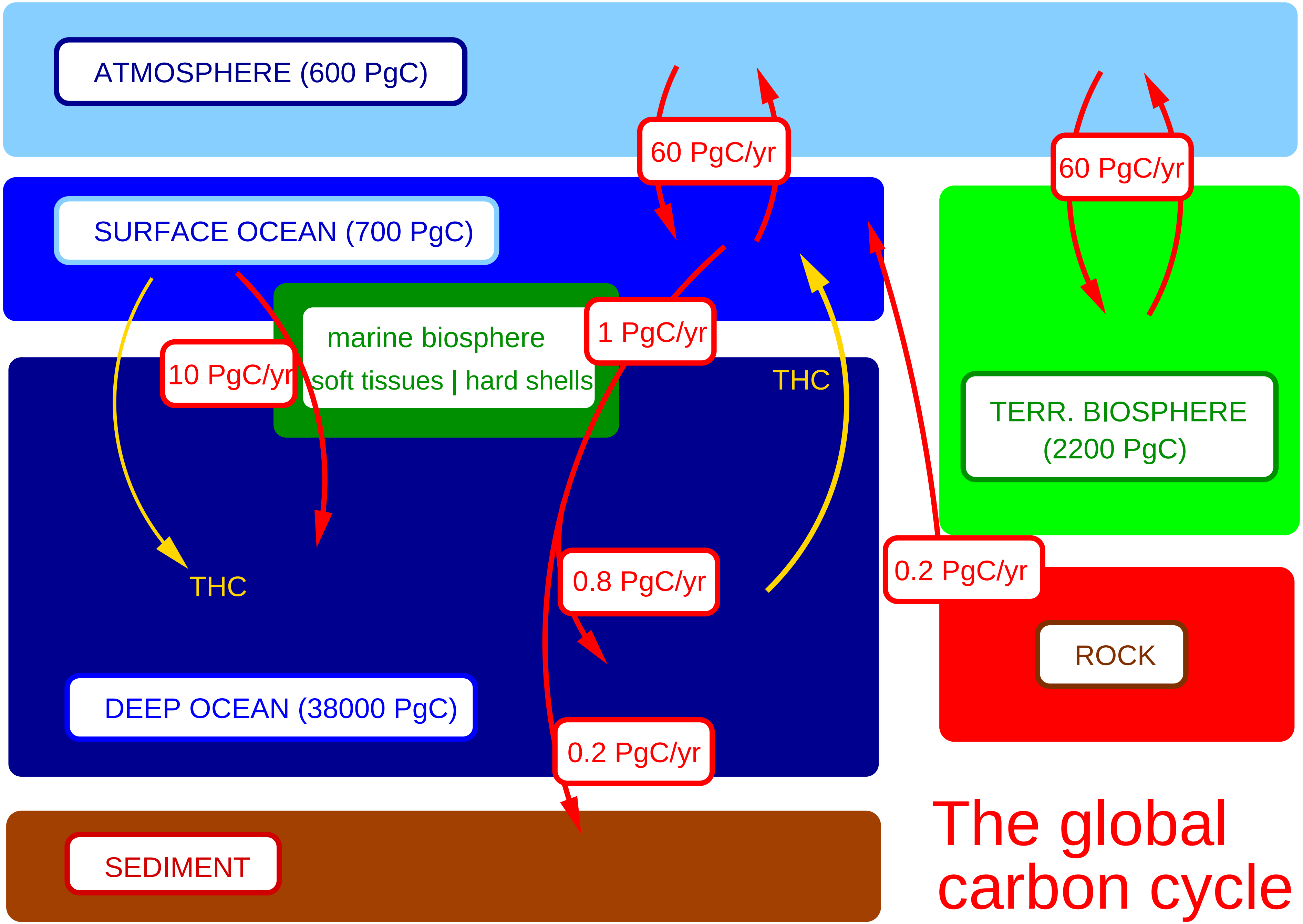
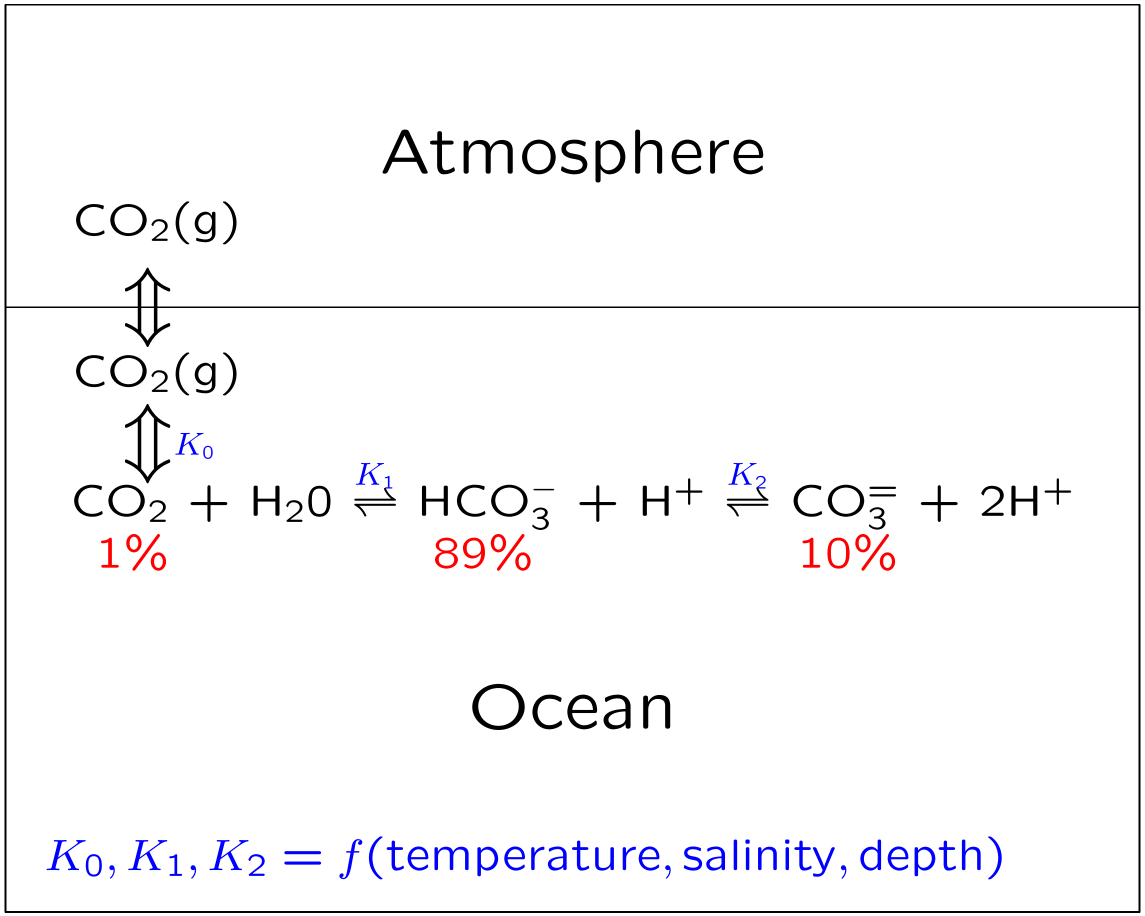


The global carbon cycle

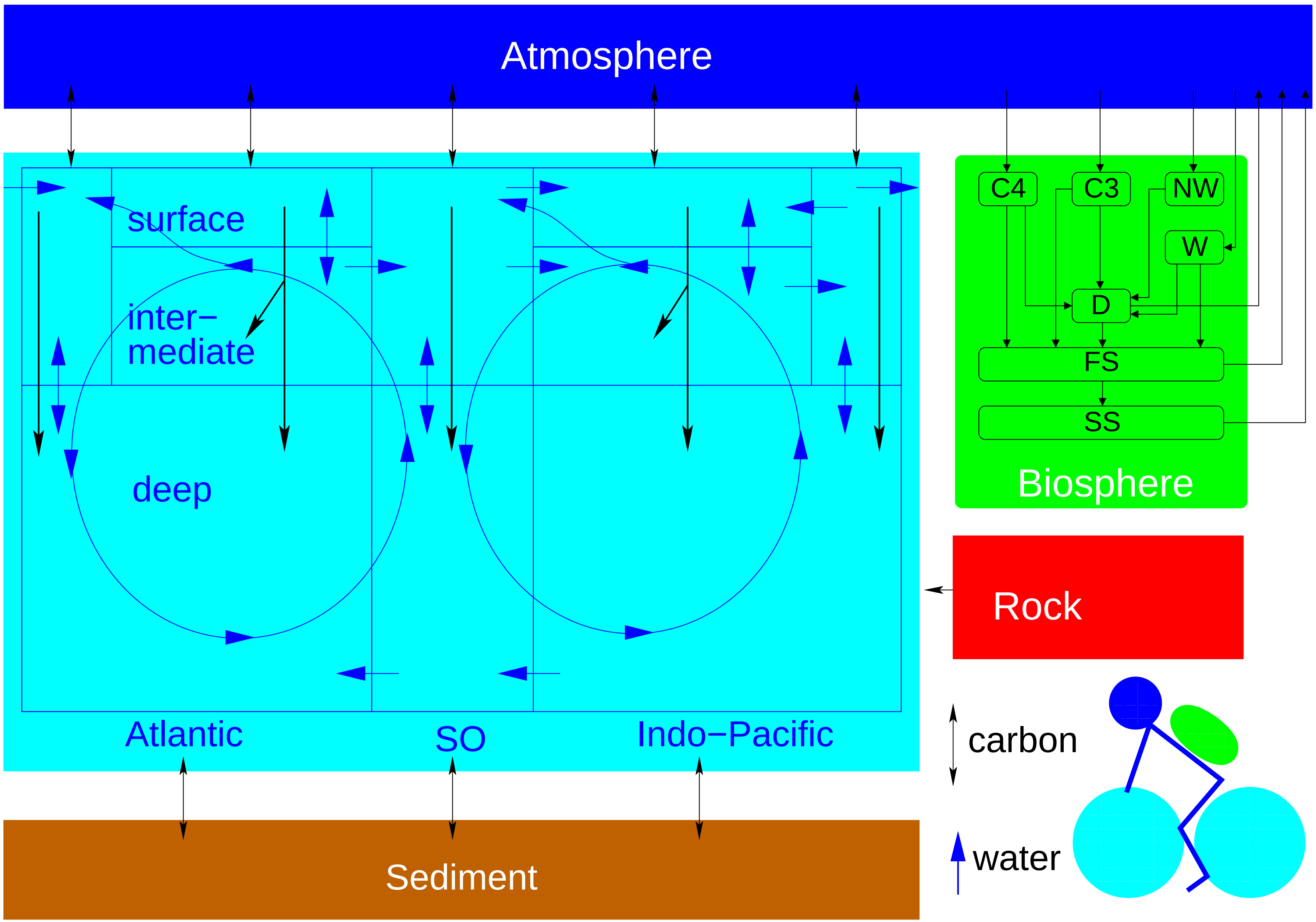
preindustrial reservoir sizes and annual fluxes

Carbonate System in the Ocean

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



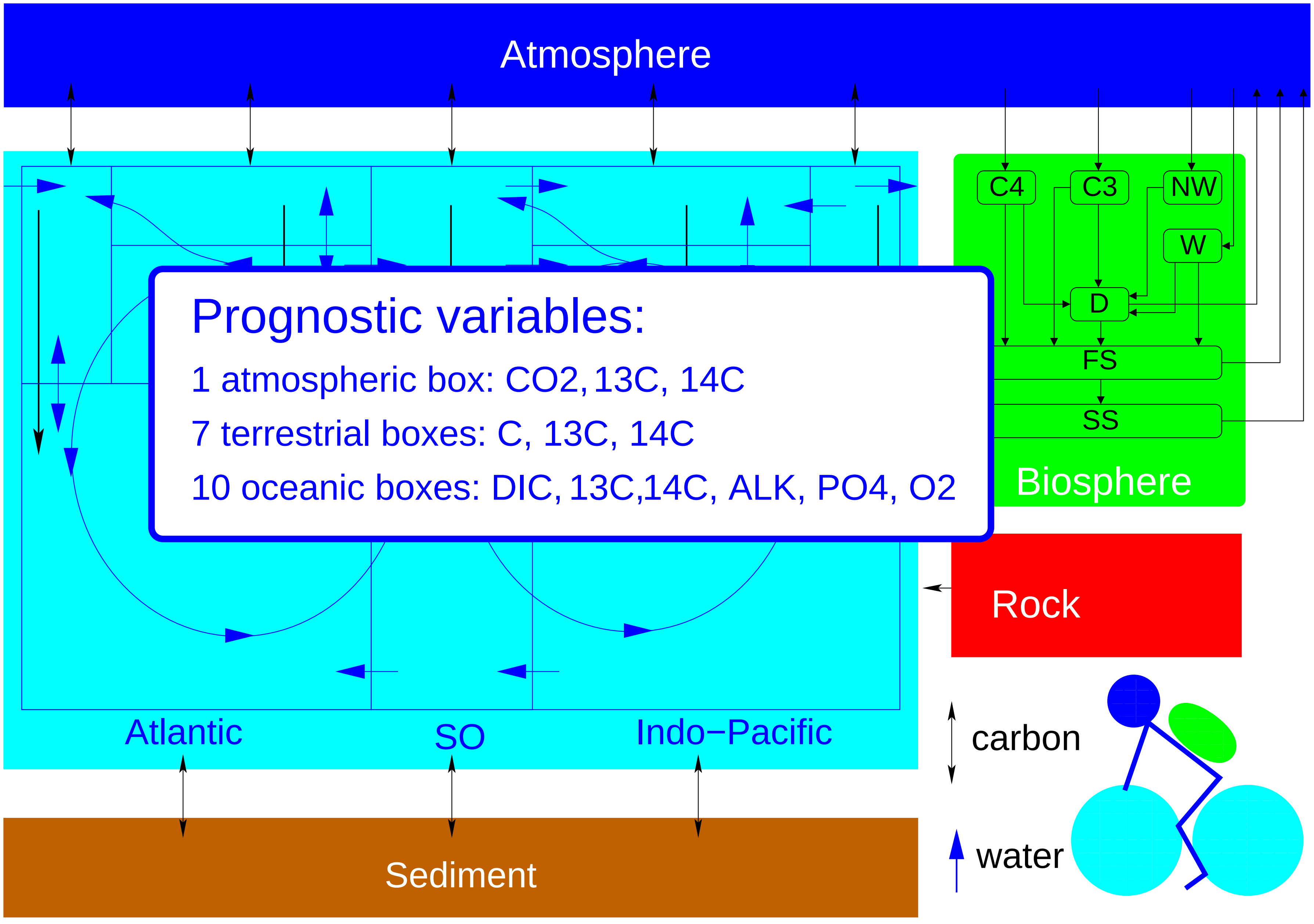
after Zeebe and Wolf-Gladrow, 2001



Box model of the Isotopic Carbon cYCLE

BICYCLE

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



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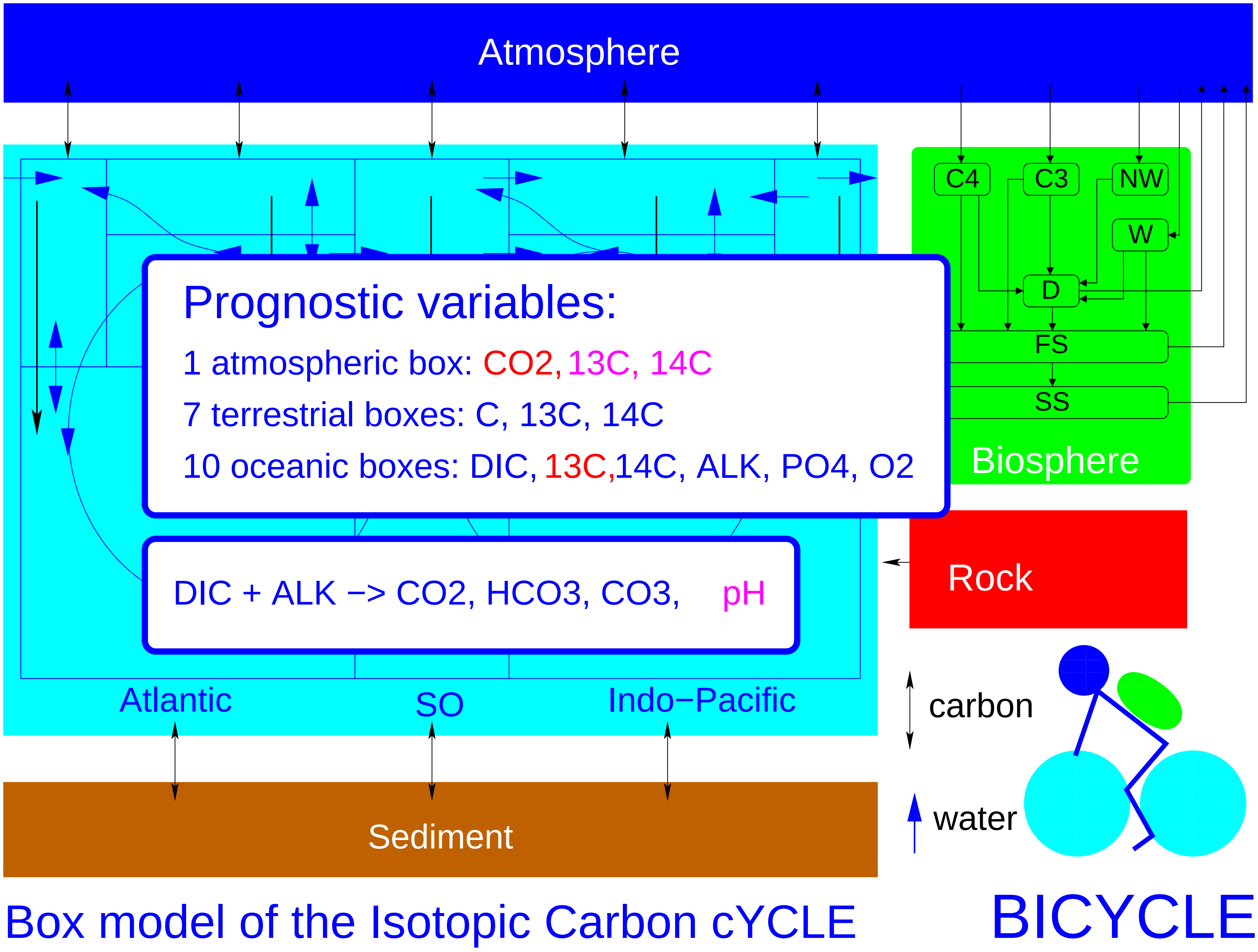

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Overall objective and procedure for time-dependent simulations

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

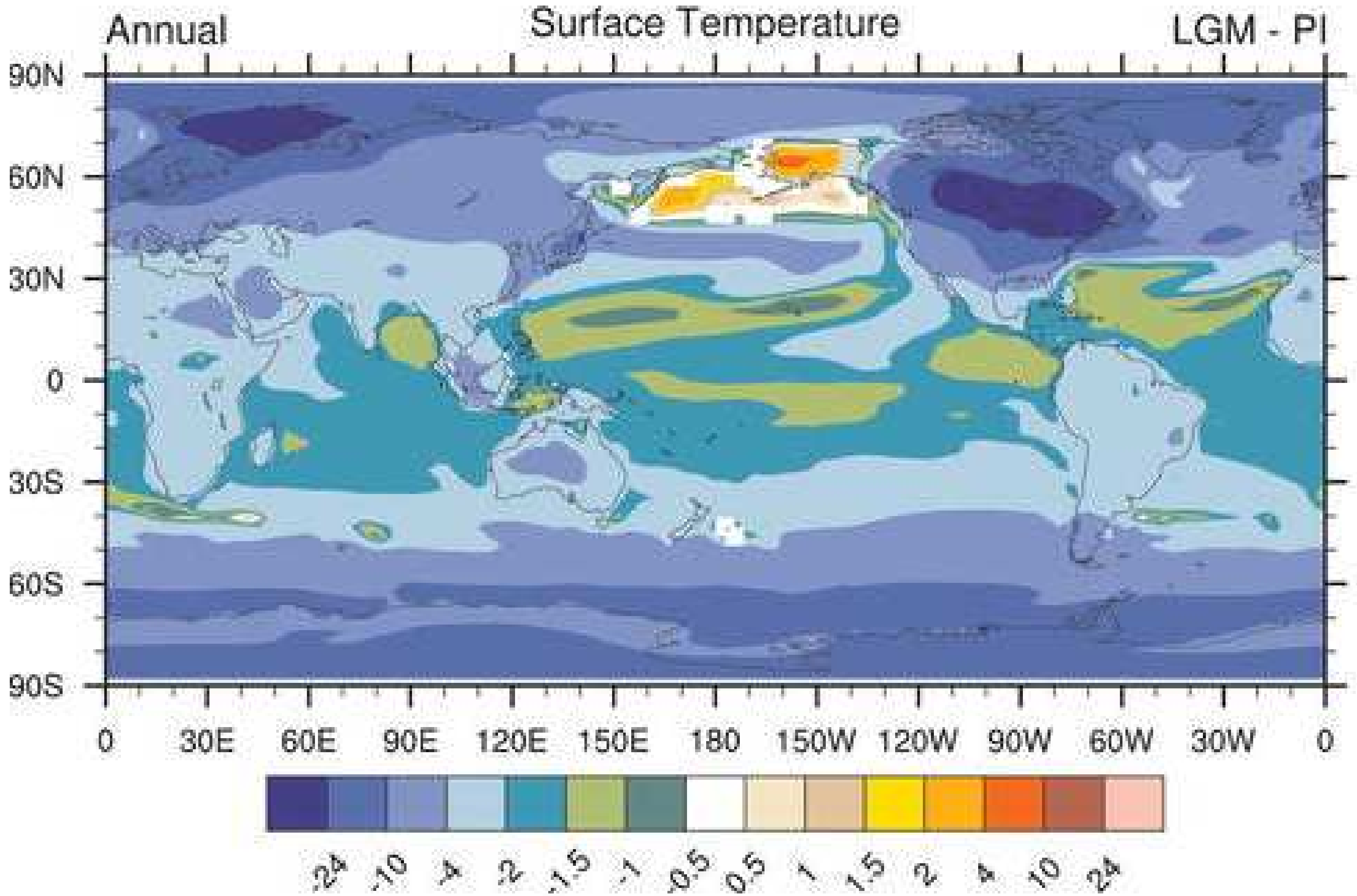
4 NADW formation
5 Southern Ocean ventilation

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



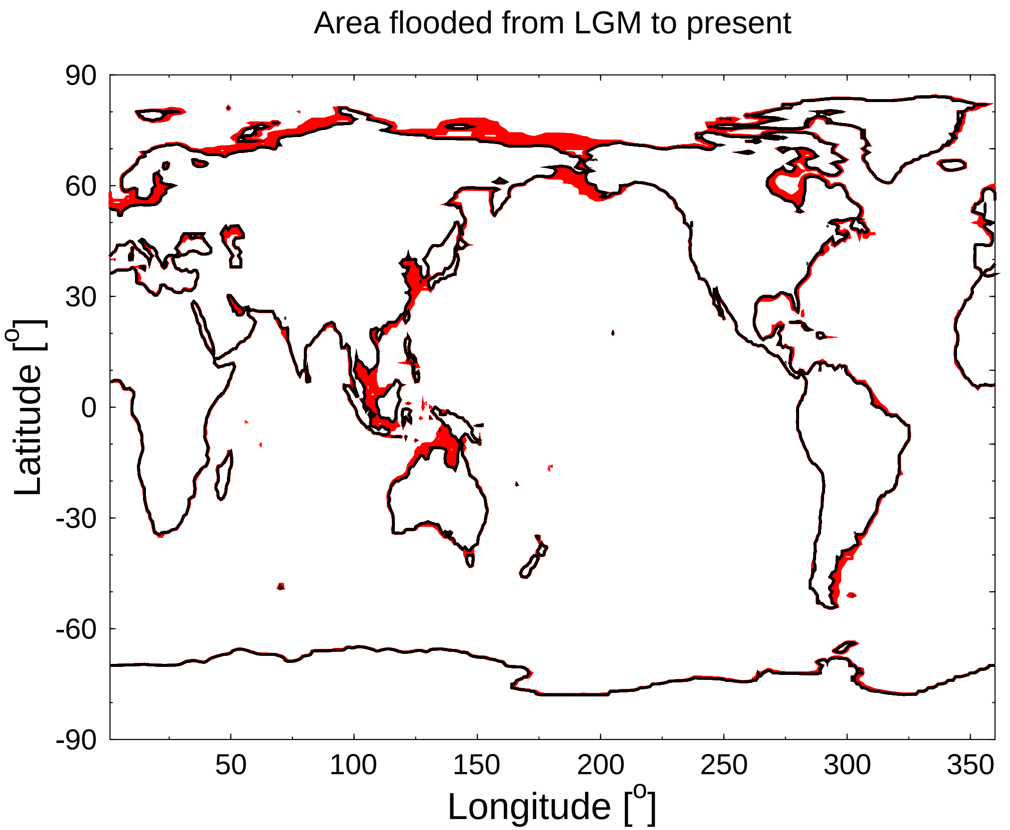
Otto-Bliesner et al., 2006

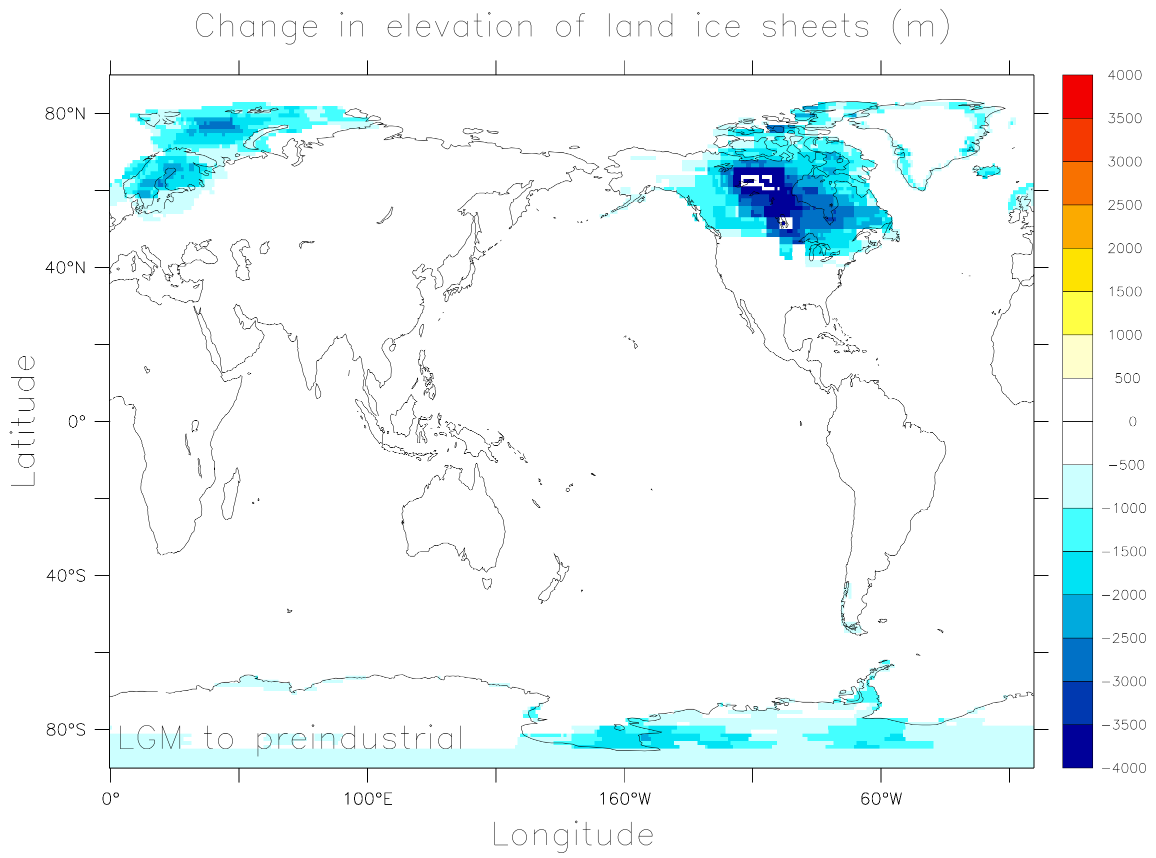
Time-dependent processes:

	Which	How (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:

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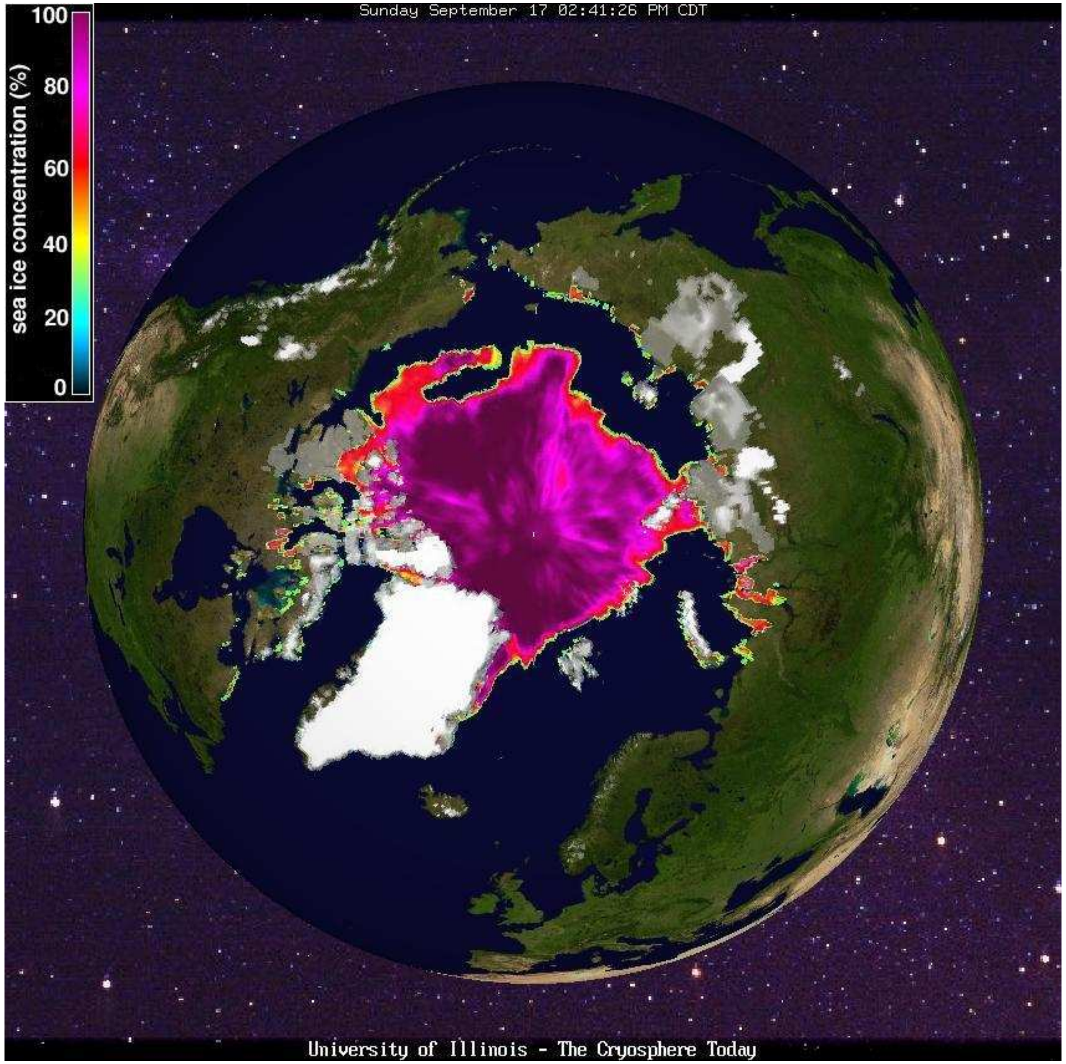
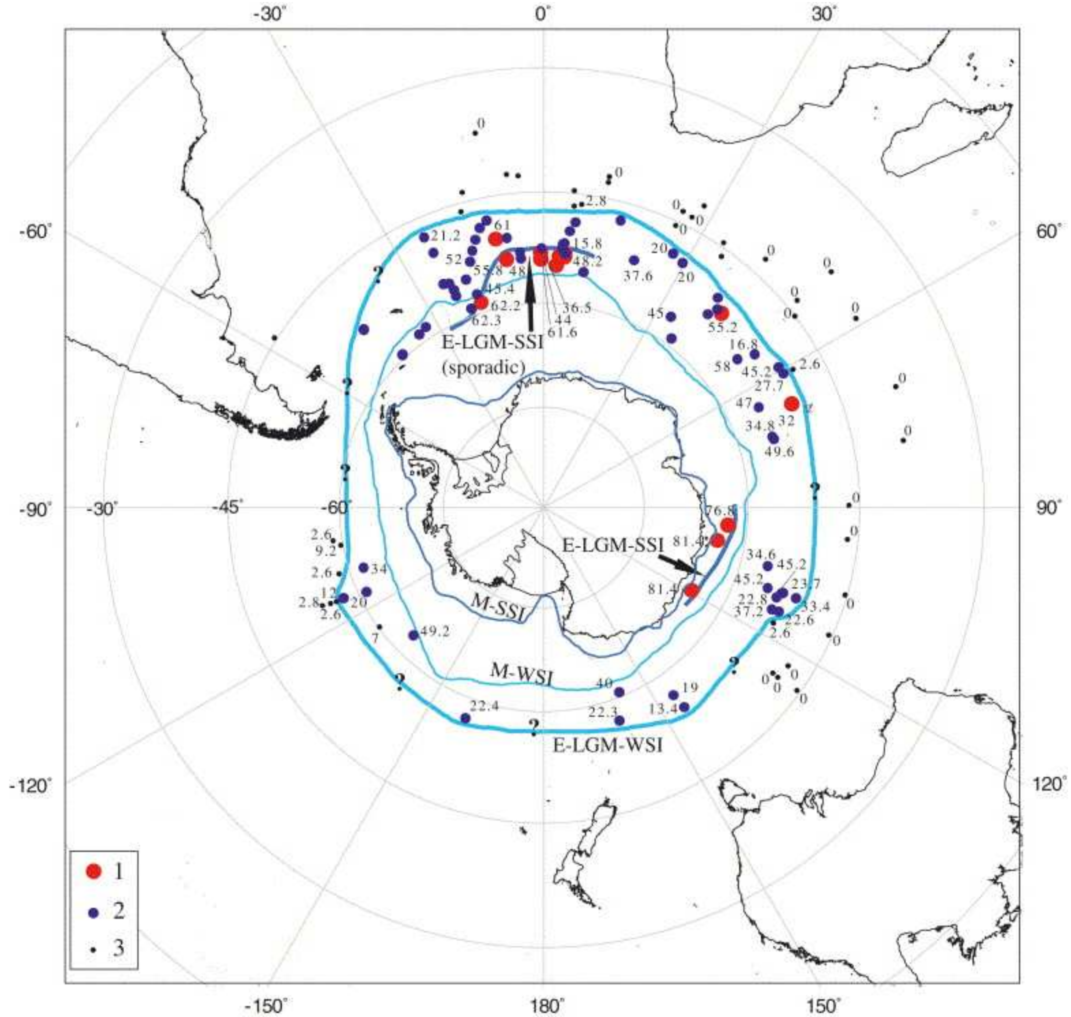
3 Gas Exchange / Sea Ice

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

Dynamics coupled to temperature in the high latitude surface boxes

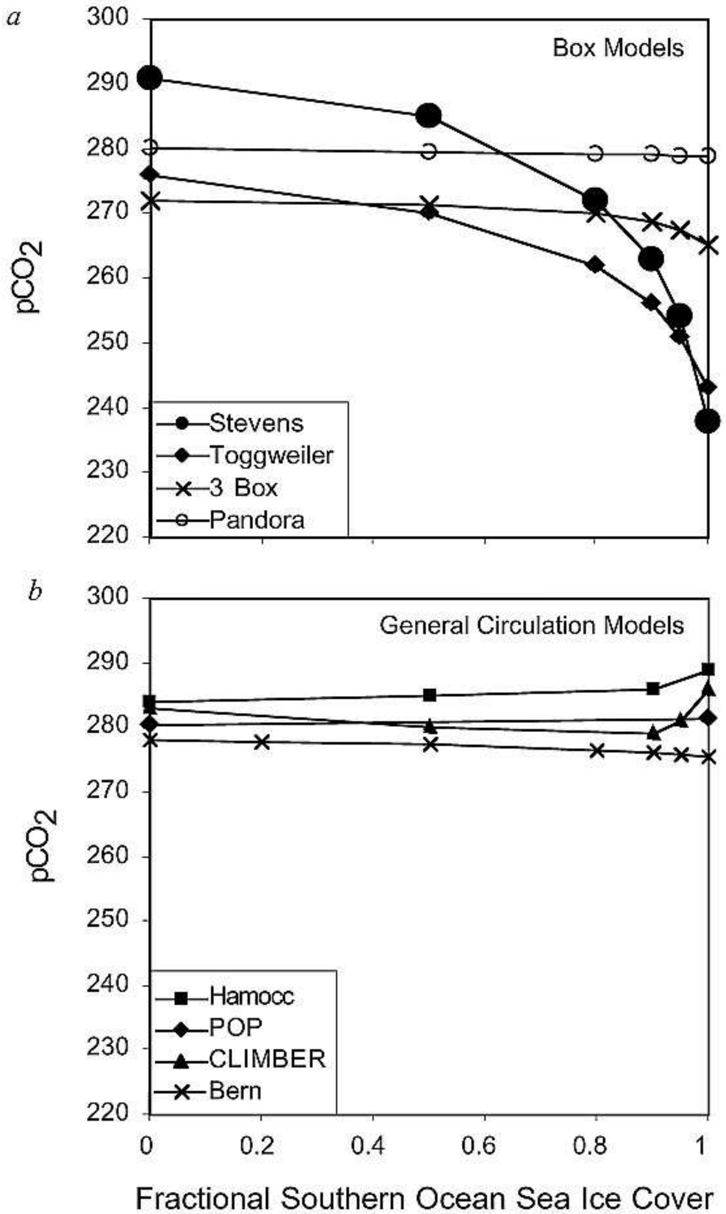




Arctic (present): The Cryosphere Today (www)

Antarctic (LGM) Gersonde et al., 2005

3 Gas Exchange / Sea Ice



Model comparions came to ambiguous results

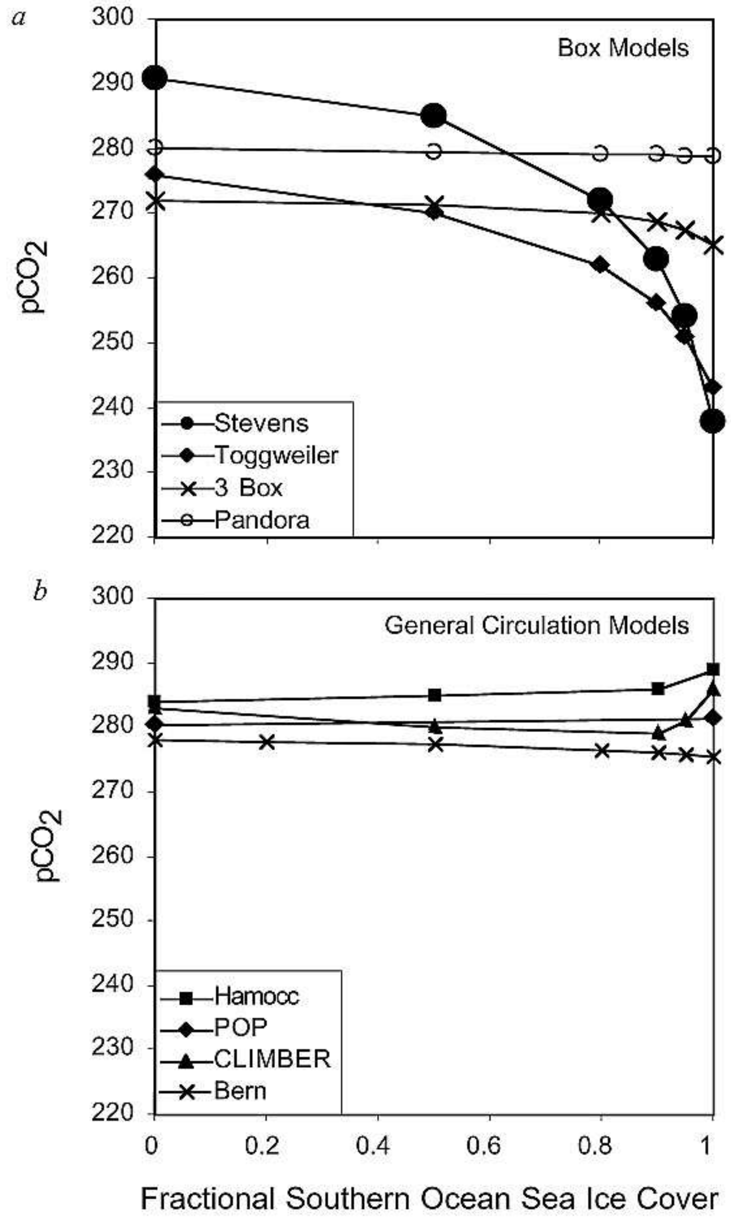
Box models: full sea ice cover in SO reduces CO_2

General Circulation Models: only small changes

Archer et al., 2003

BICYCLE

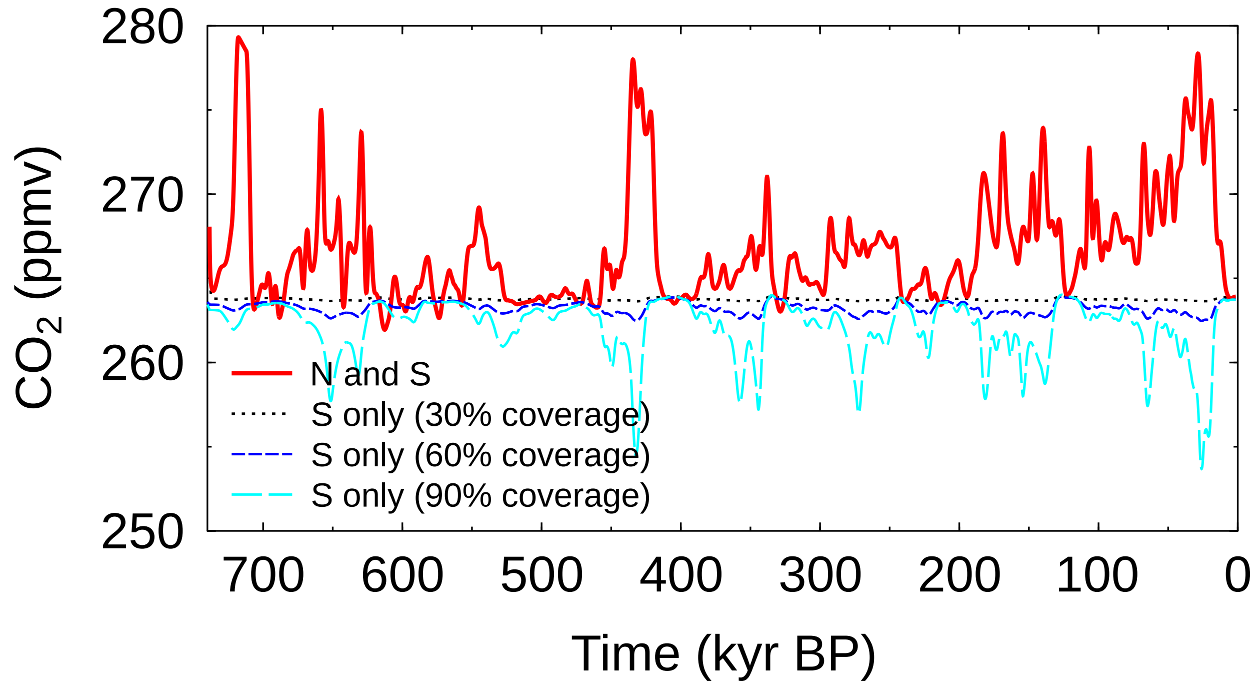
3 Gas Exchange / Sea Ice



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

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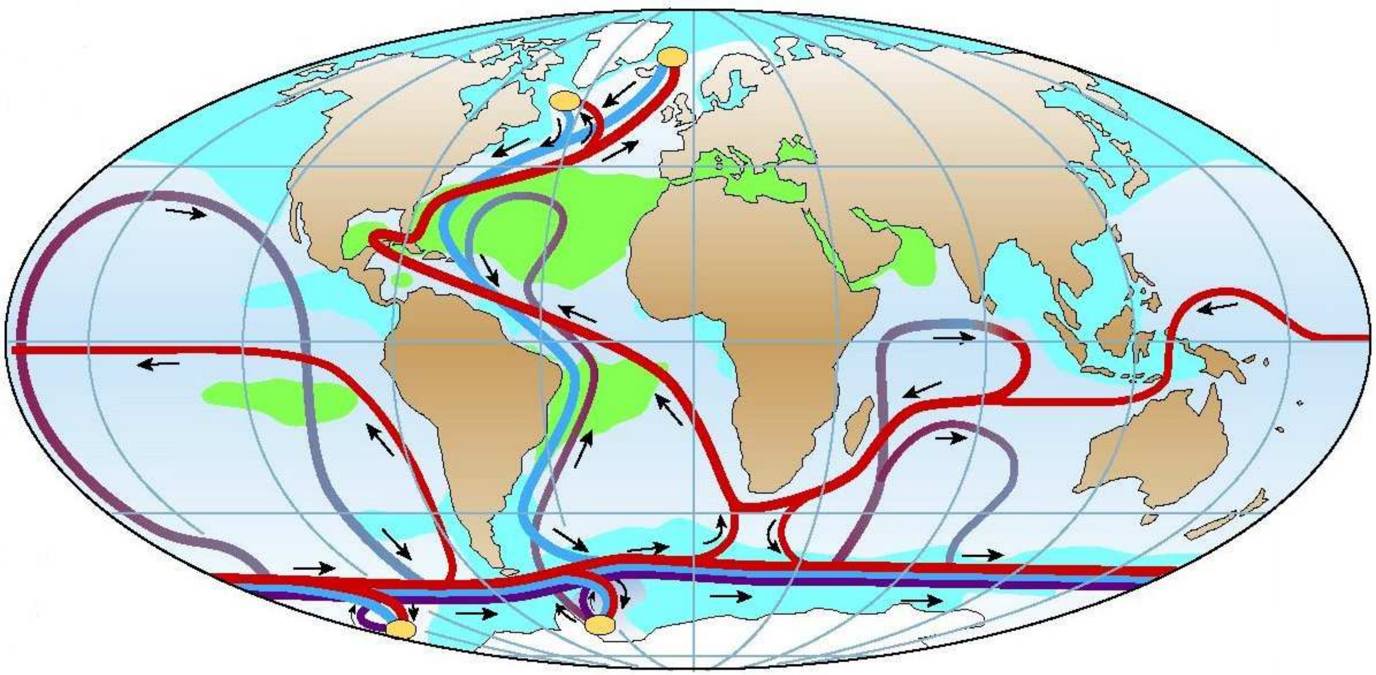
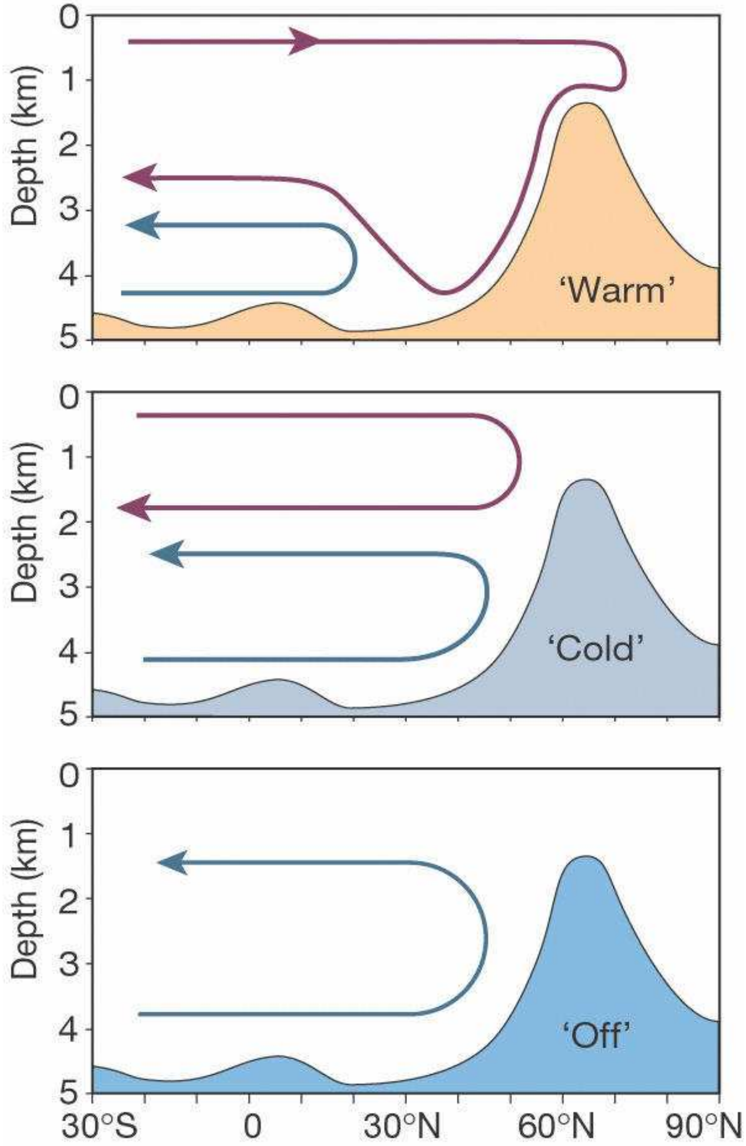
4 North Atlantic Deep Water (NADW) Formation

Conveyor belt



Changes in Atlantic THC

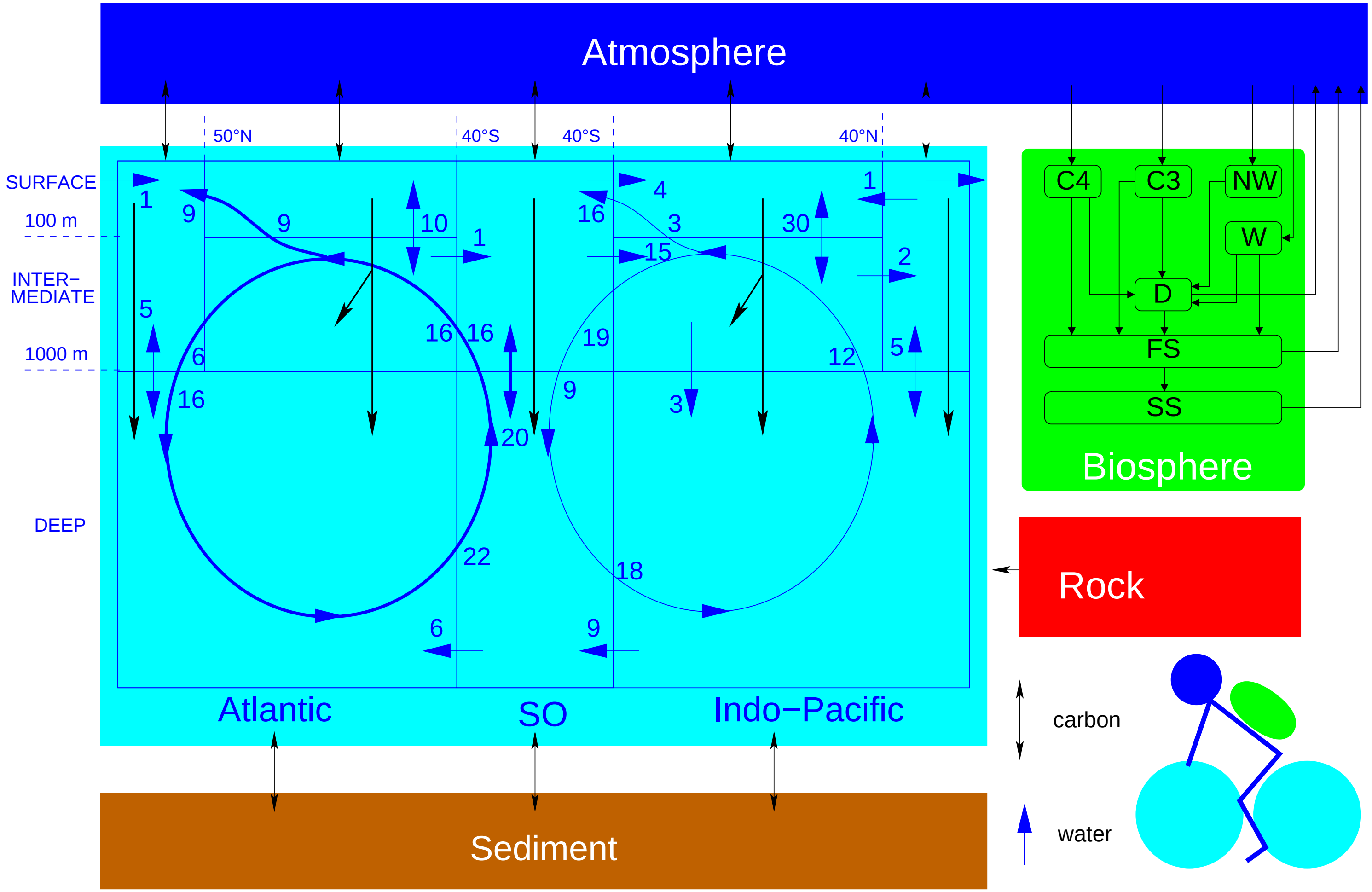


Rahmstorf, 2002

4 North Atlantic Deep Water (NADW) Formation

Preindustrial circulation: World Ocean Circulation Experiment (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

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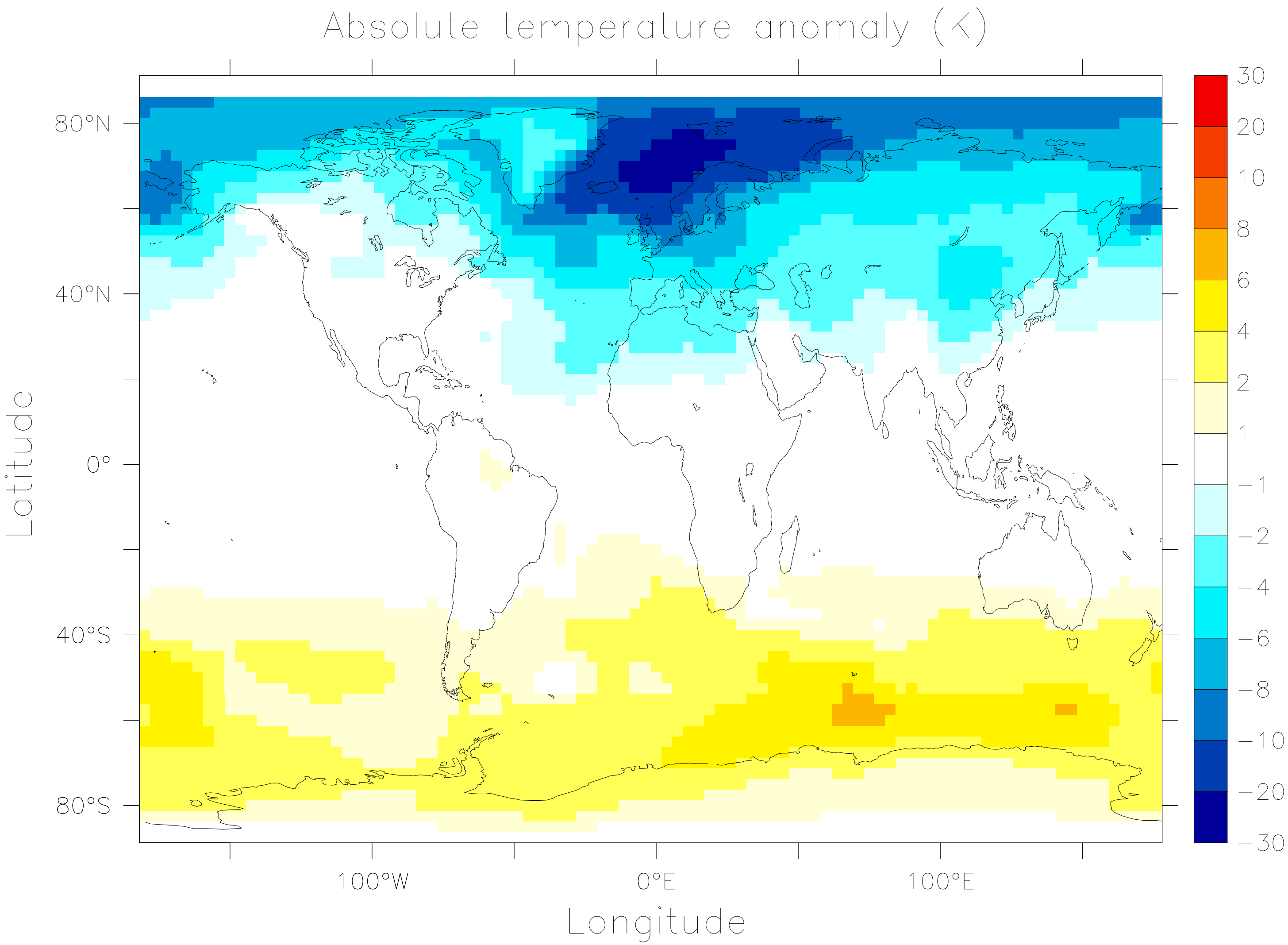
4 Indirect effects of shutdown of NADW (not in BICYCLE)

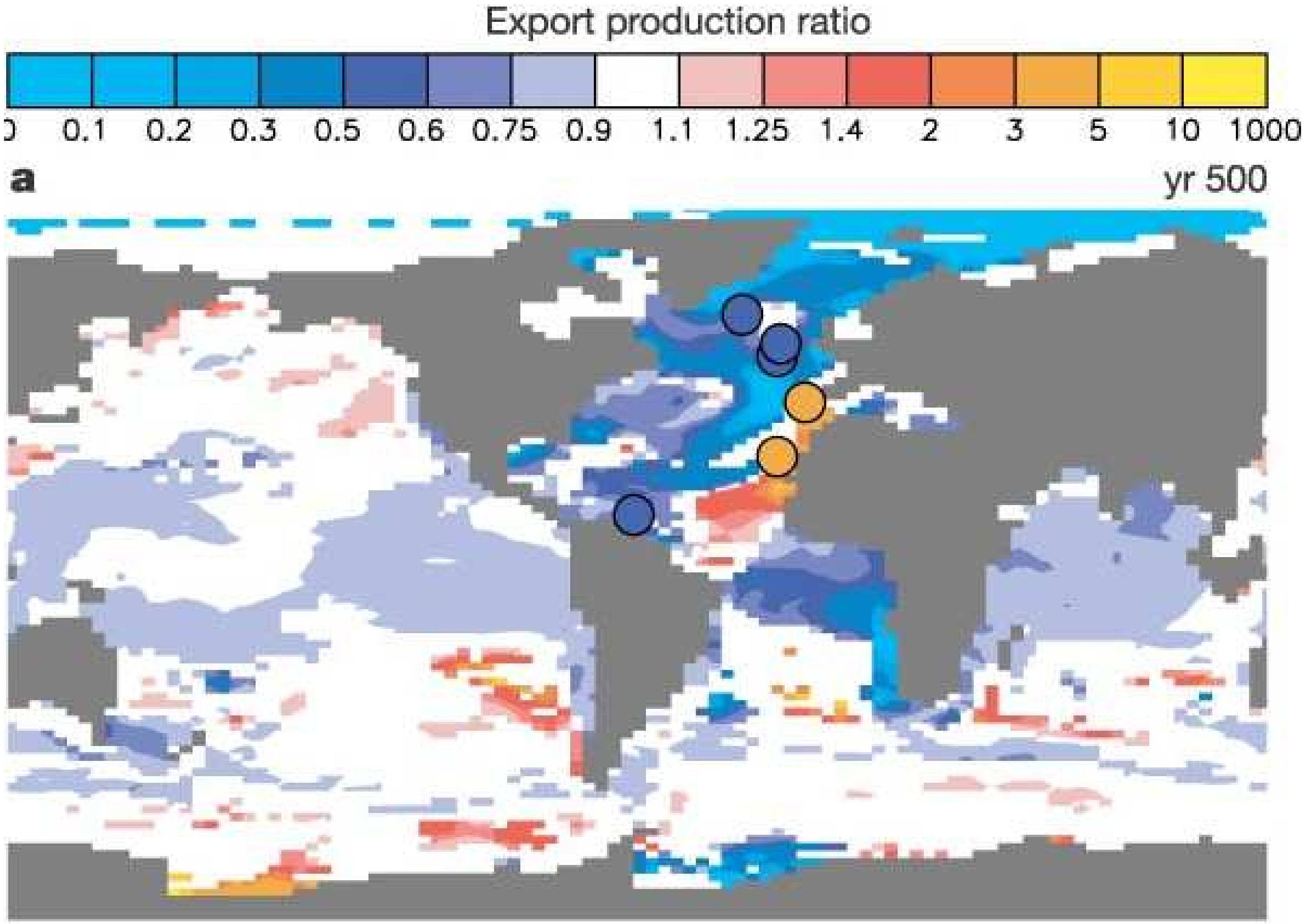
Additionally, a NADW shutdown would lead to cooling in Eurasia
Temperature anomalies simulated with climate model ECBILT-CLIO



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%

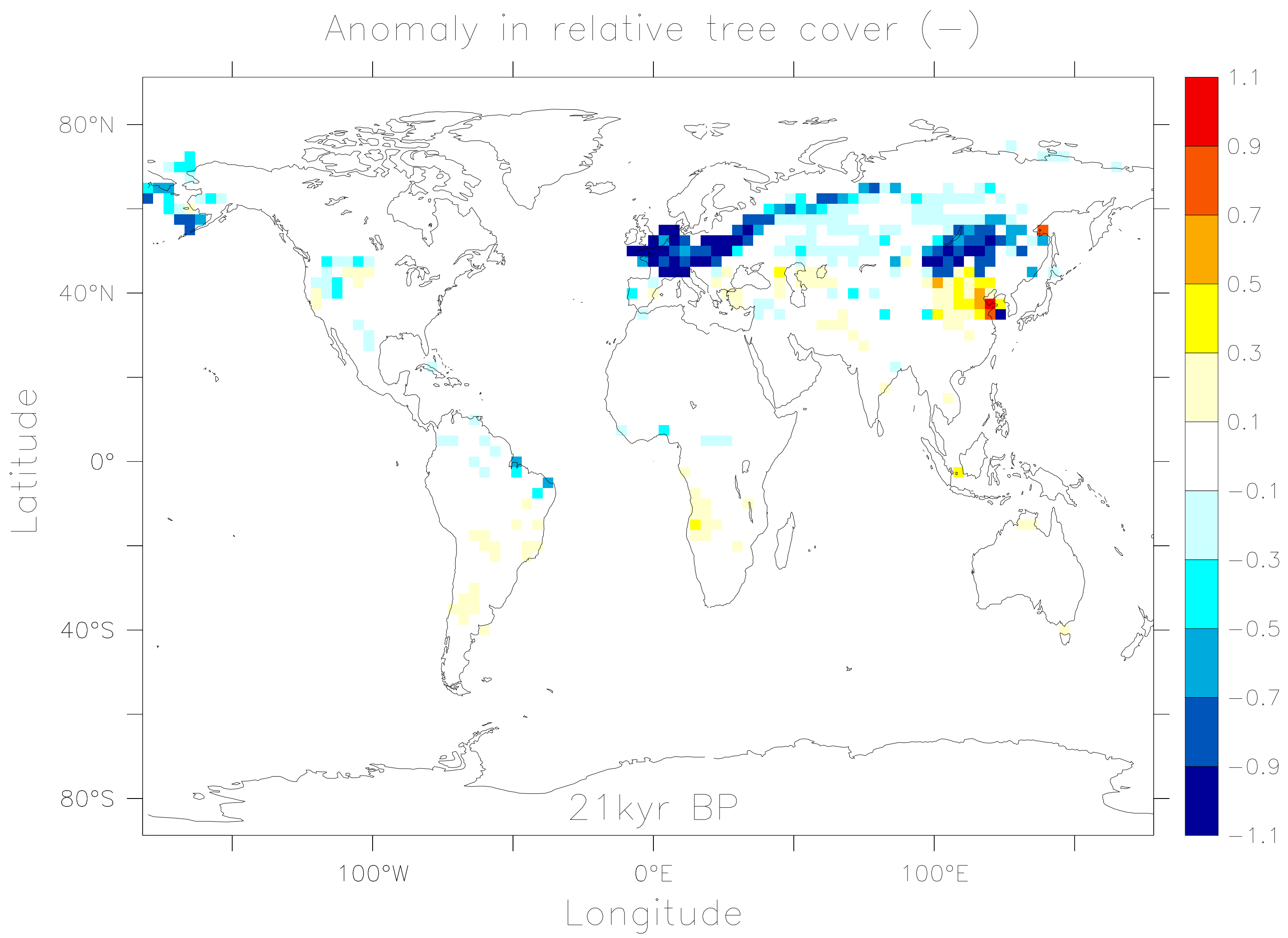


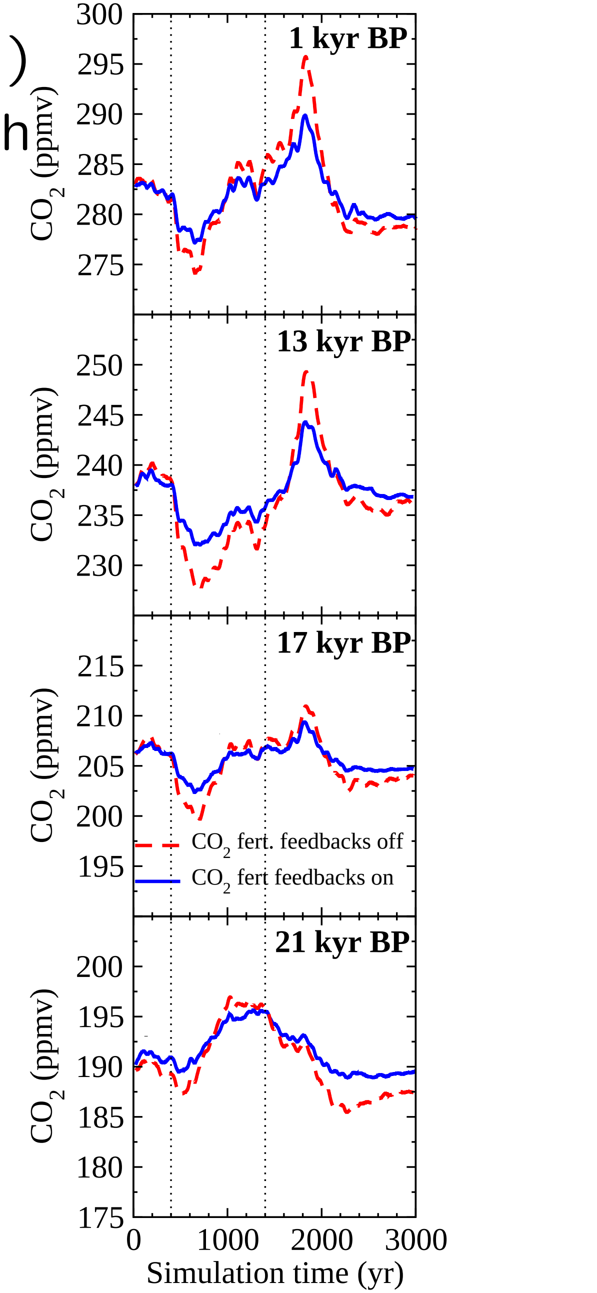
Schmittner, 2005

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			
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5	Southern Ocean ventilation			
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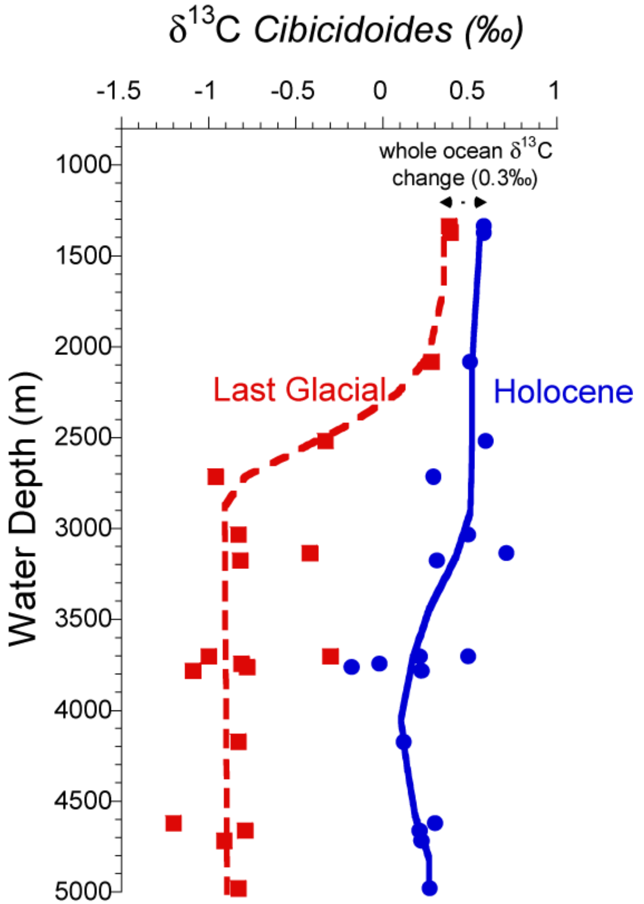
8	$CaCO_3$ chemistry			

5 Southern Ocean Ventilation

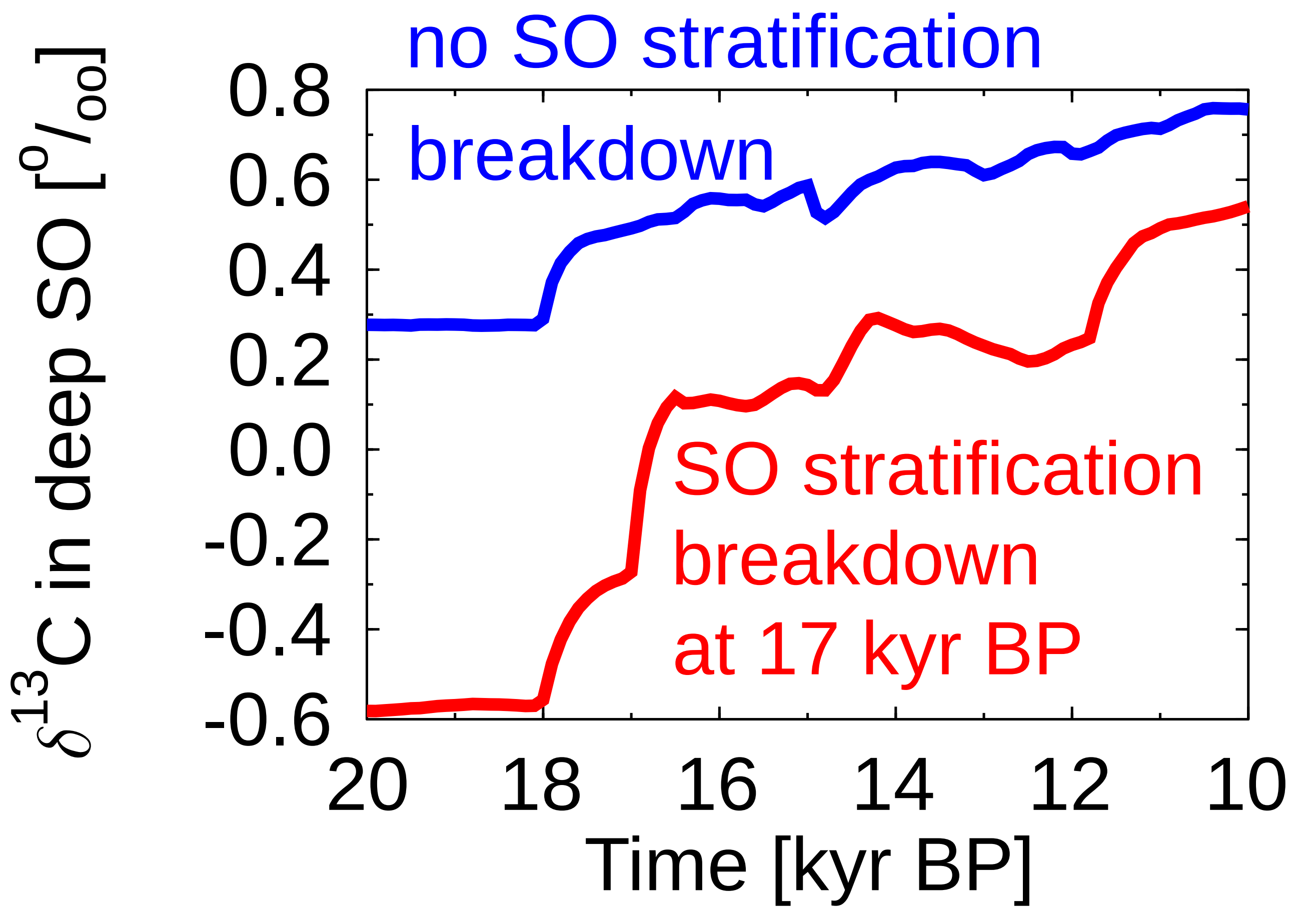
How to explain $\Delta\delta^{13}$C(PRE-LGM)=+1.2‰ in deep Southern Ocean?

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

Different hypotheses on the physical cause behind it (work in progress)



Hodell et al, 2003



Köhler, et al., 2005, Global Biogeochemical Cycles

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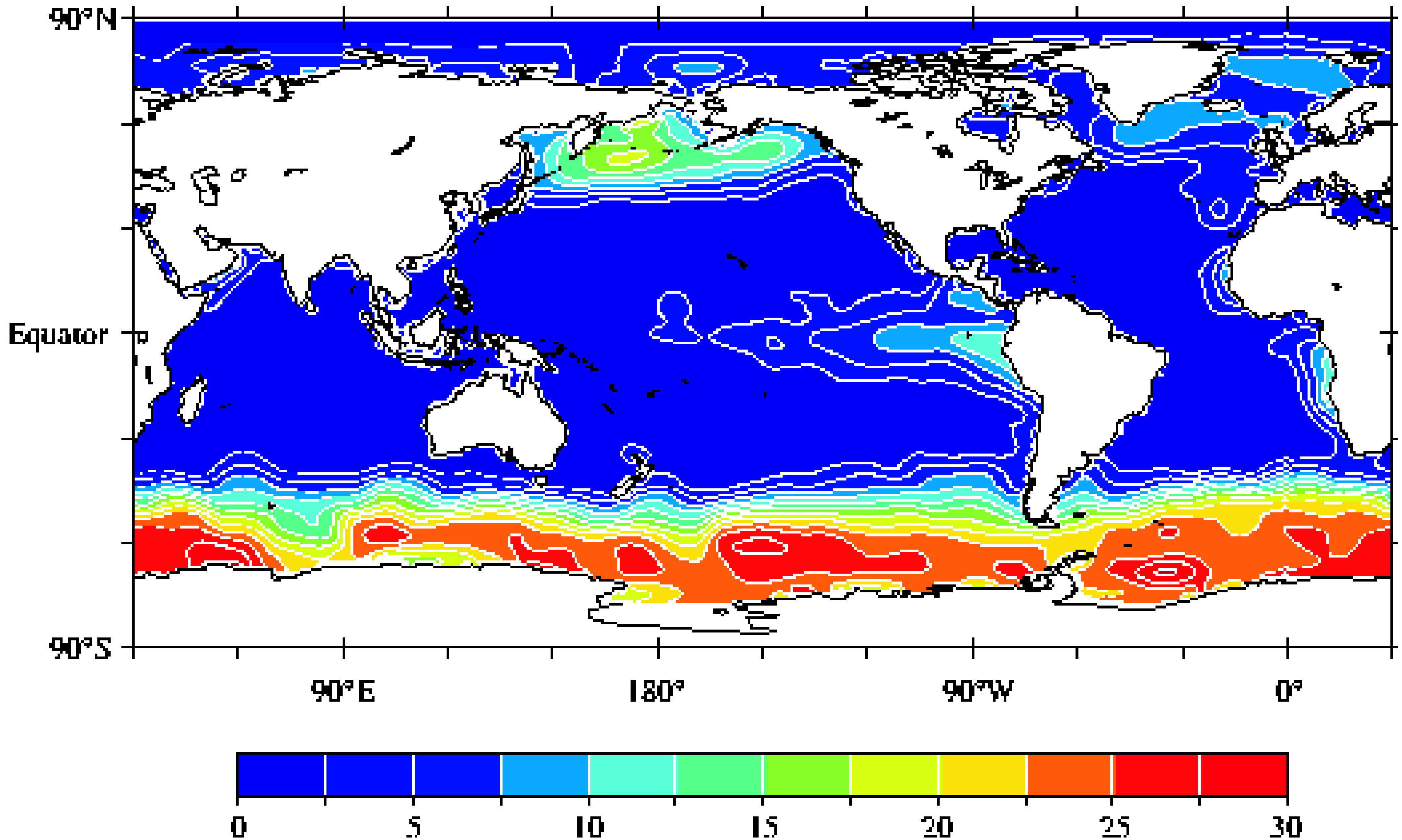
6 Marine Biota / Iron fertilisation

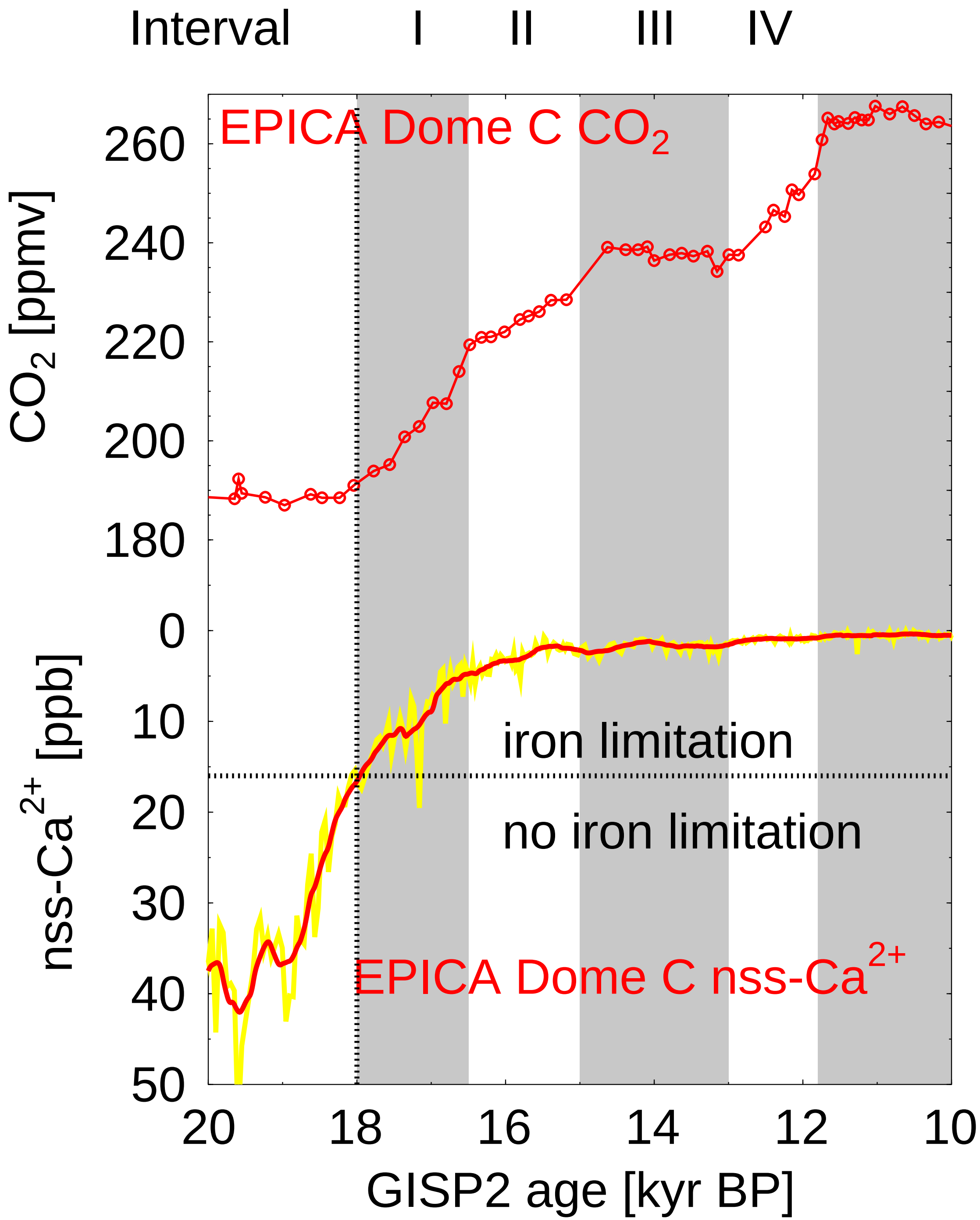
Marine biological productivity might be Fe limited
in high nitrate low chlorophyll (HNLC) areas (Martin, 1990)



surface nitrate (μmol kg^{-1})

(Conkright et al, 1994)

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

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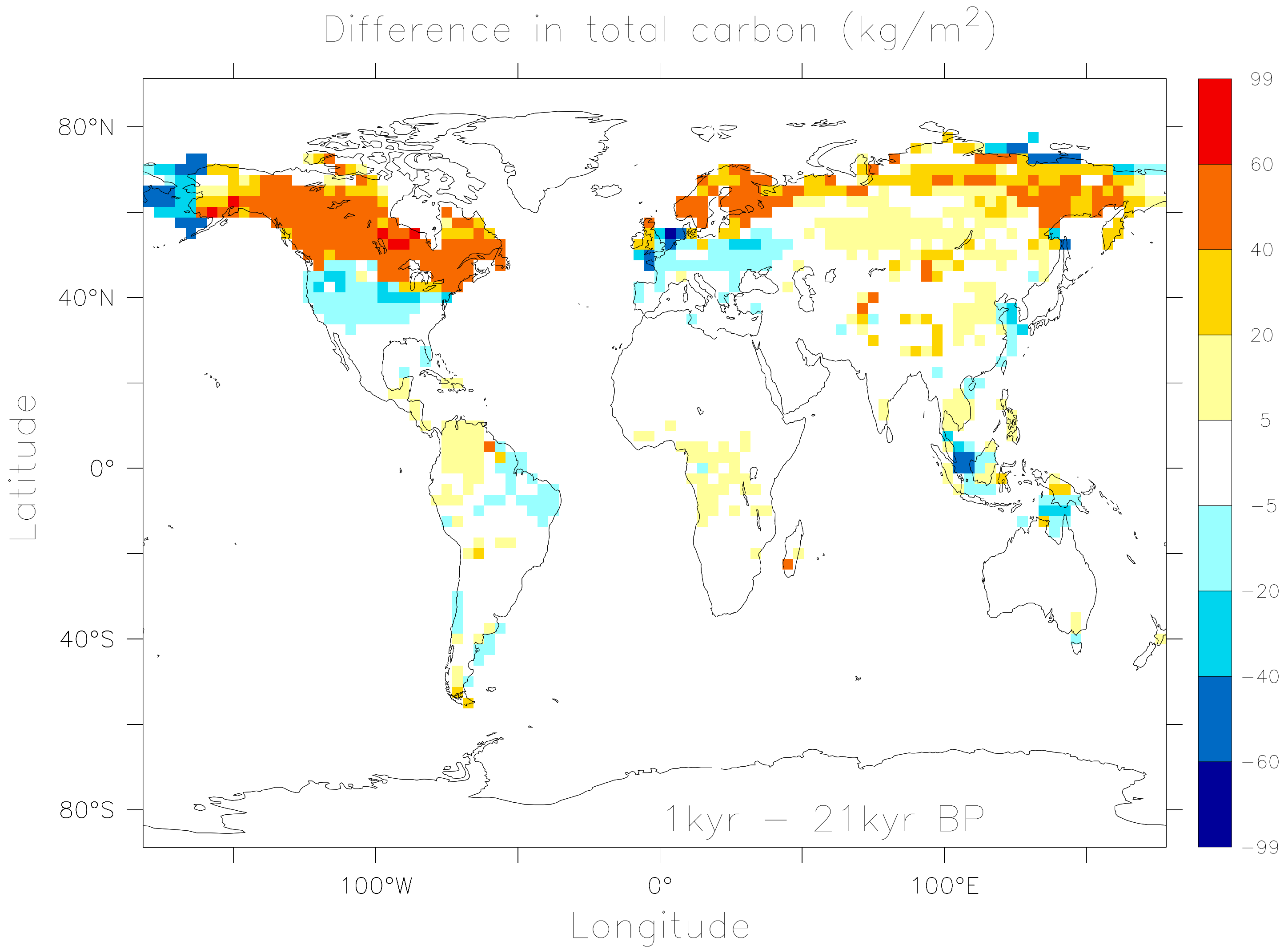
	Biogeochemistry			
6	Marine biota / iron fertilisation	−2 PgC yr^{-1}	+20	?
7	Terrestrial carbon storage			
8	$CaCO_3$ chemistry			

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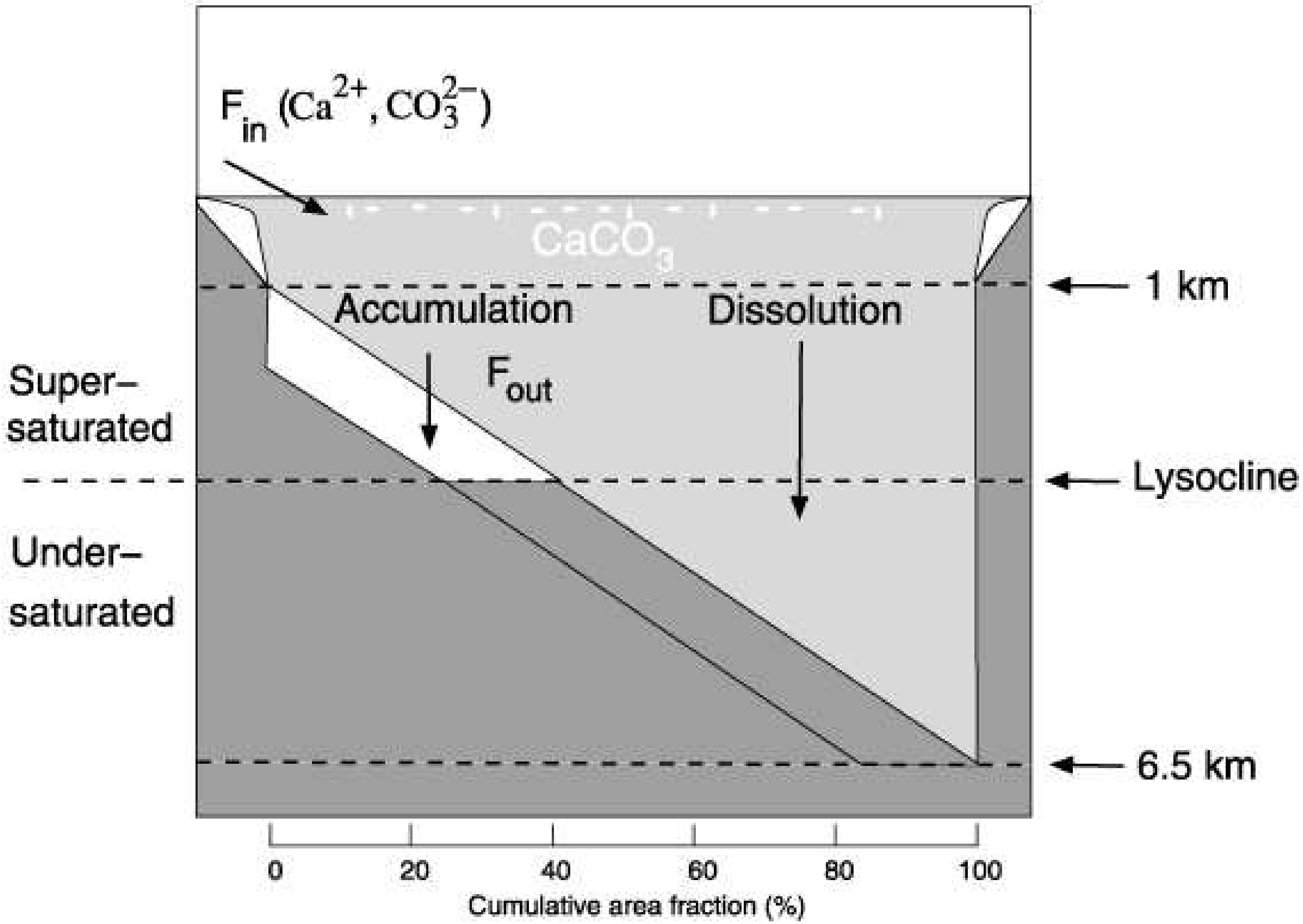
	Biogeochemistry			
6	Marine biota / iron fertilisation	−2 PgC yr^{-1}	+20	?
7	Terrestrial carbon storage	+500 PgC	−15	!
8	$CaCO_3$ chemistry			

8 Carbonate compensation

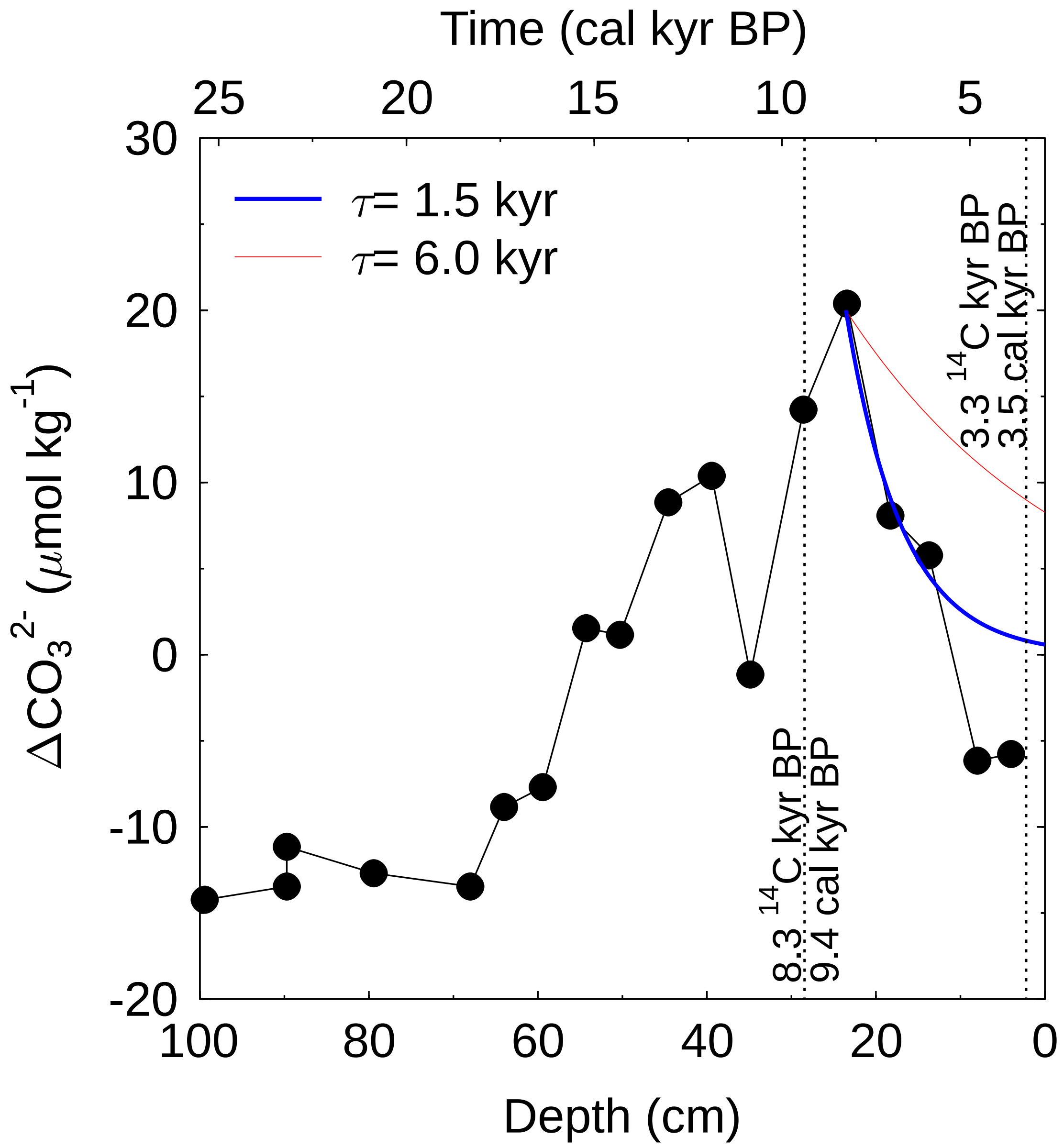
Dissolution / accumulation of $CaCO_3$ depends on deep ocean $[CO_3^{2-}]$



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	!
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)	**?**
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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	

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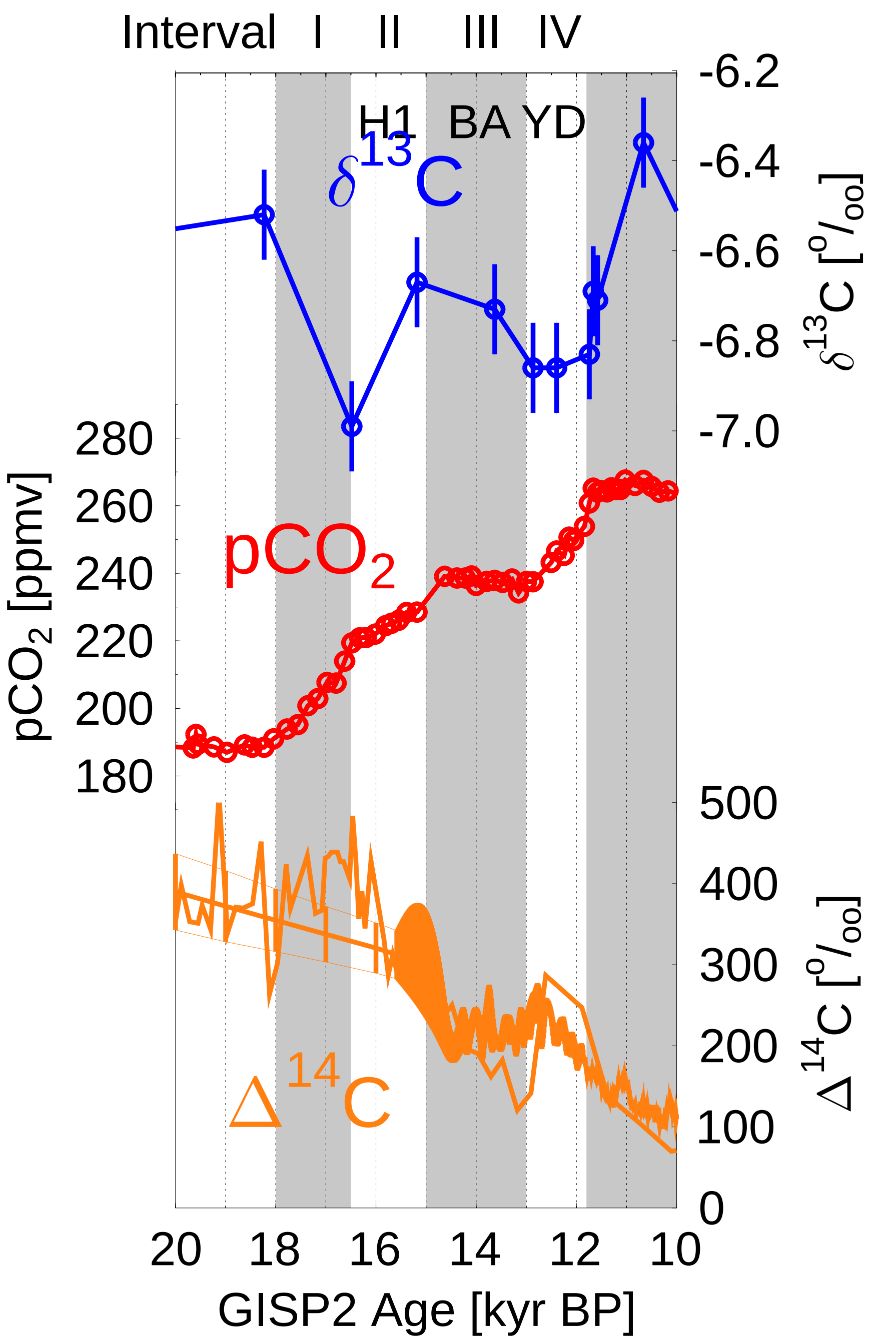
Atmospheric carbon during Termination I

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

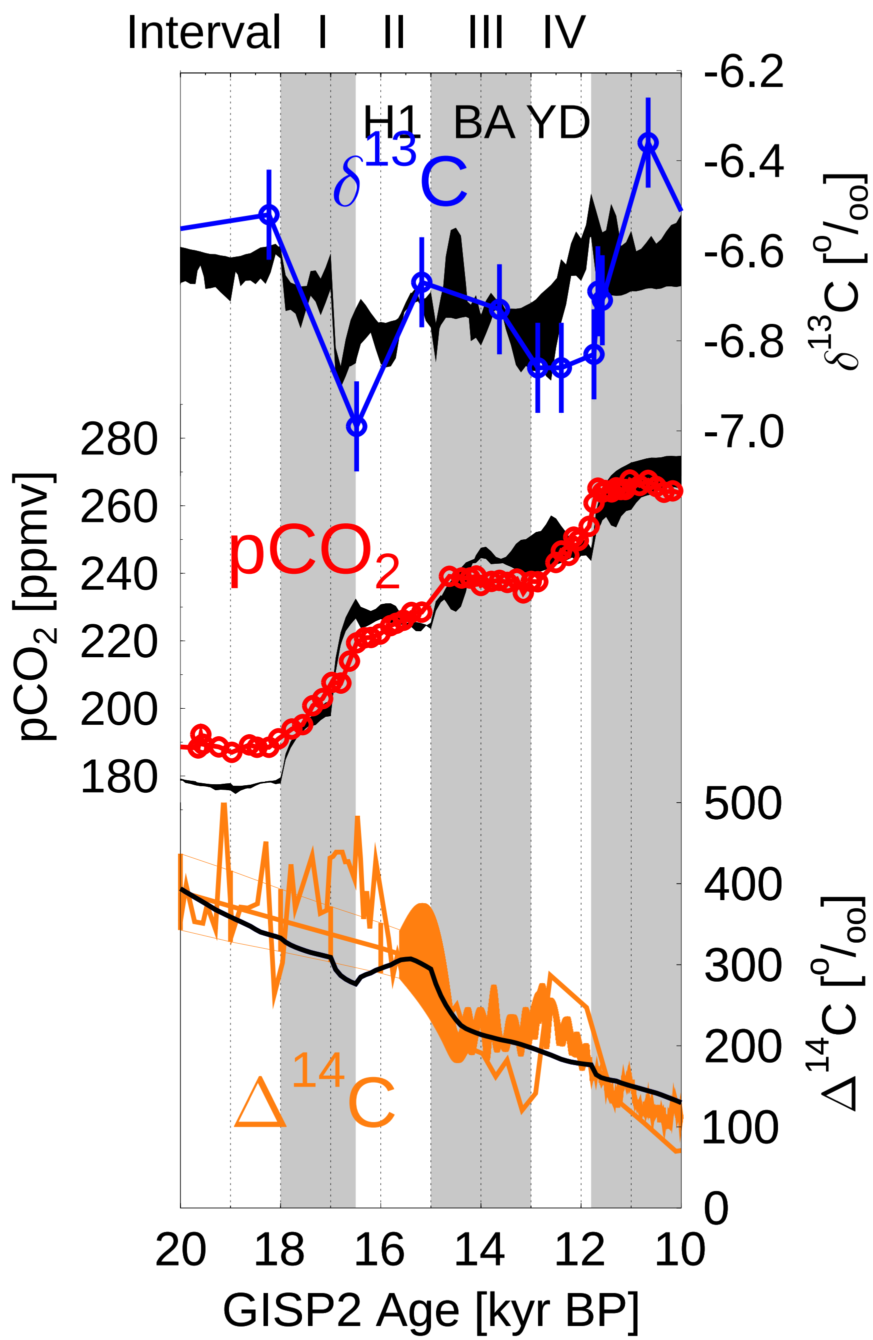
Smith et al., 1999; Monnin et al., 2001;
Stuiver et al., 1998; Hughen et al., 2004



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



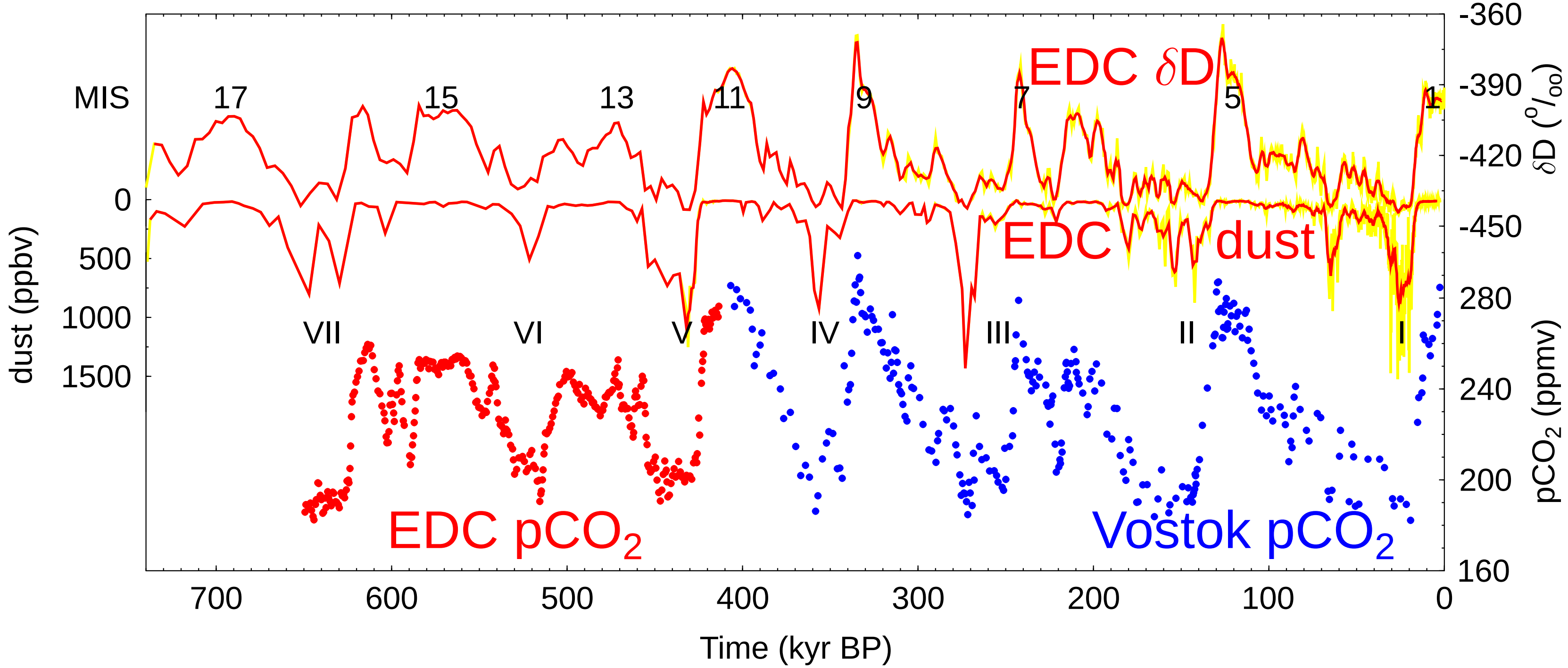
The EPICA challenge

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

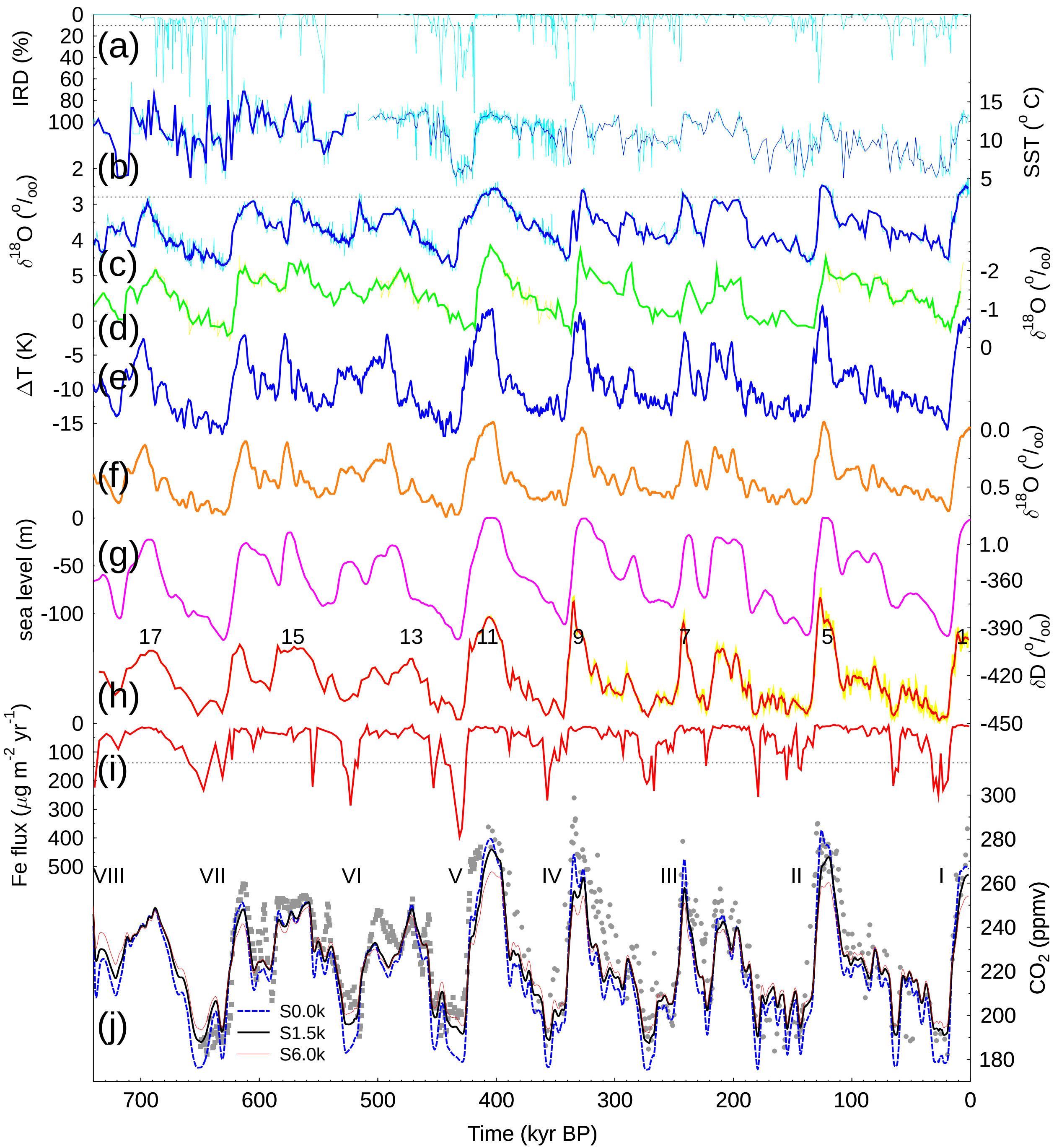
f: deep sea ΔT

g: sea level

h: SO SST

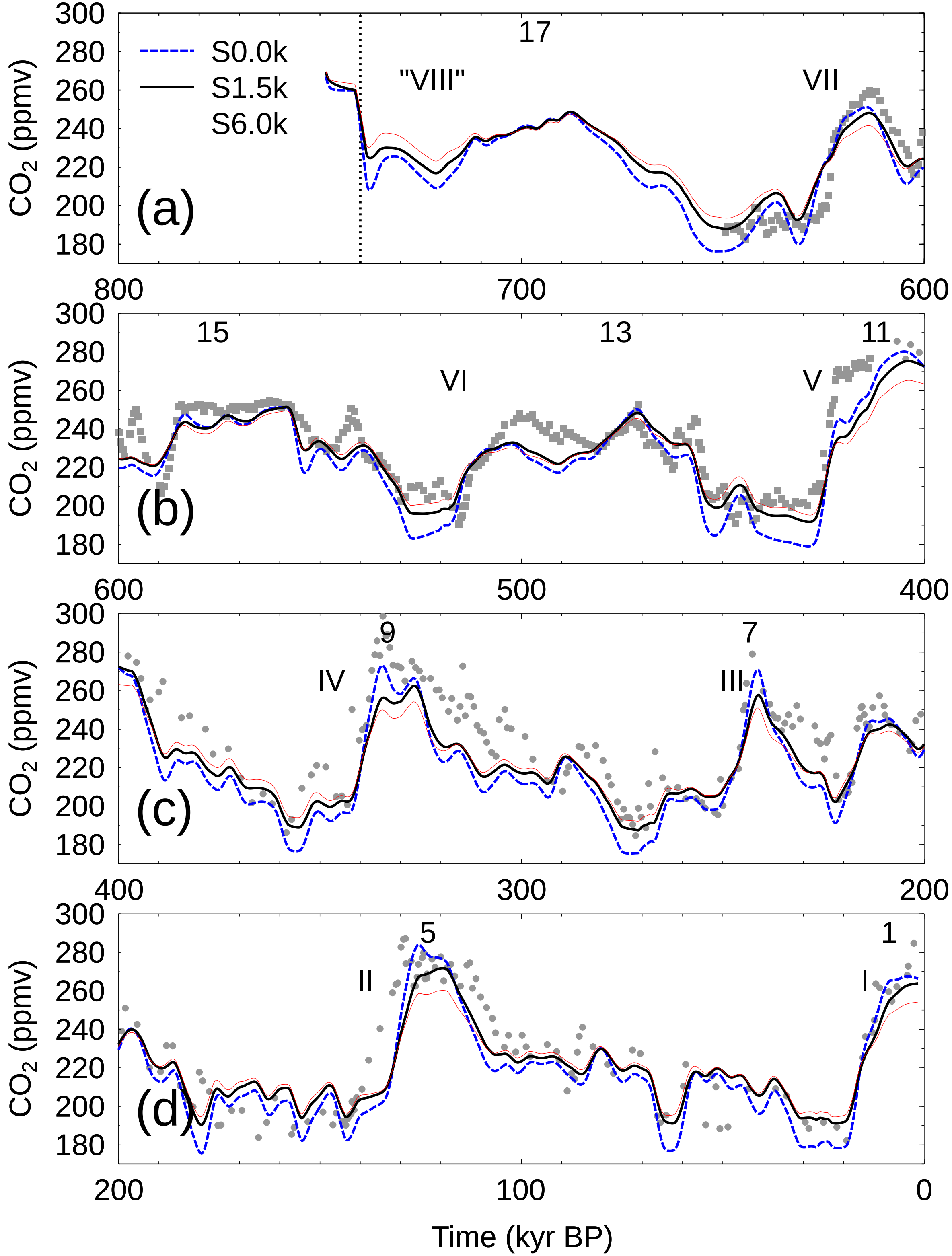
i: Fe fert.

j: CO_2



Köhler and Fischer, 2006, Climate of the Past

The EPICA challenge



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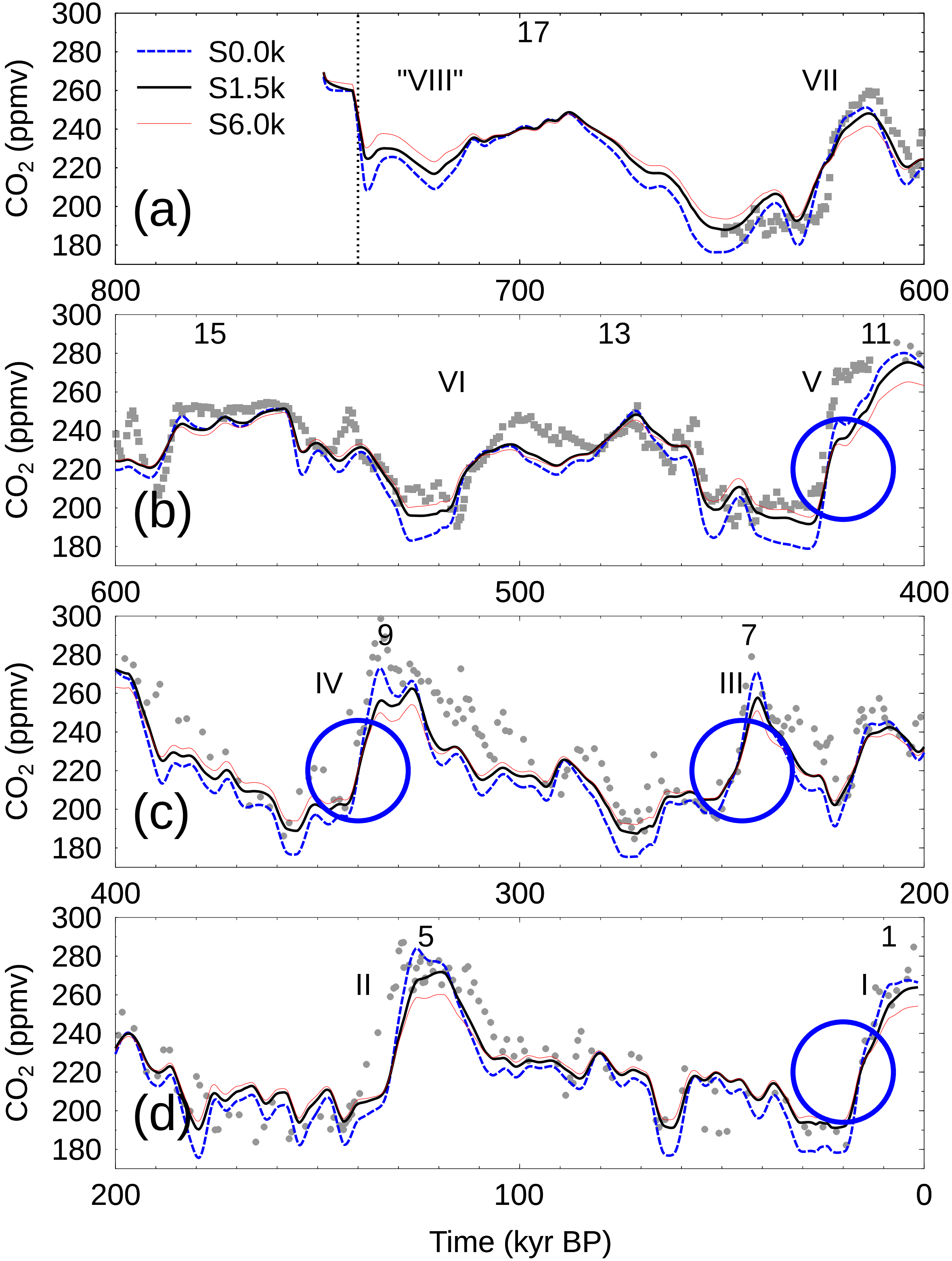
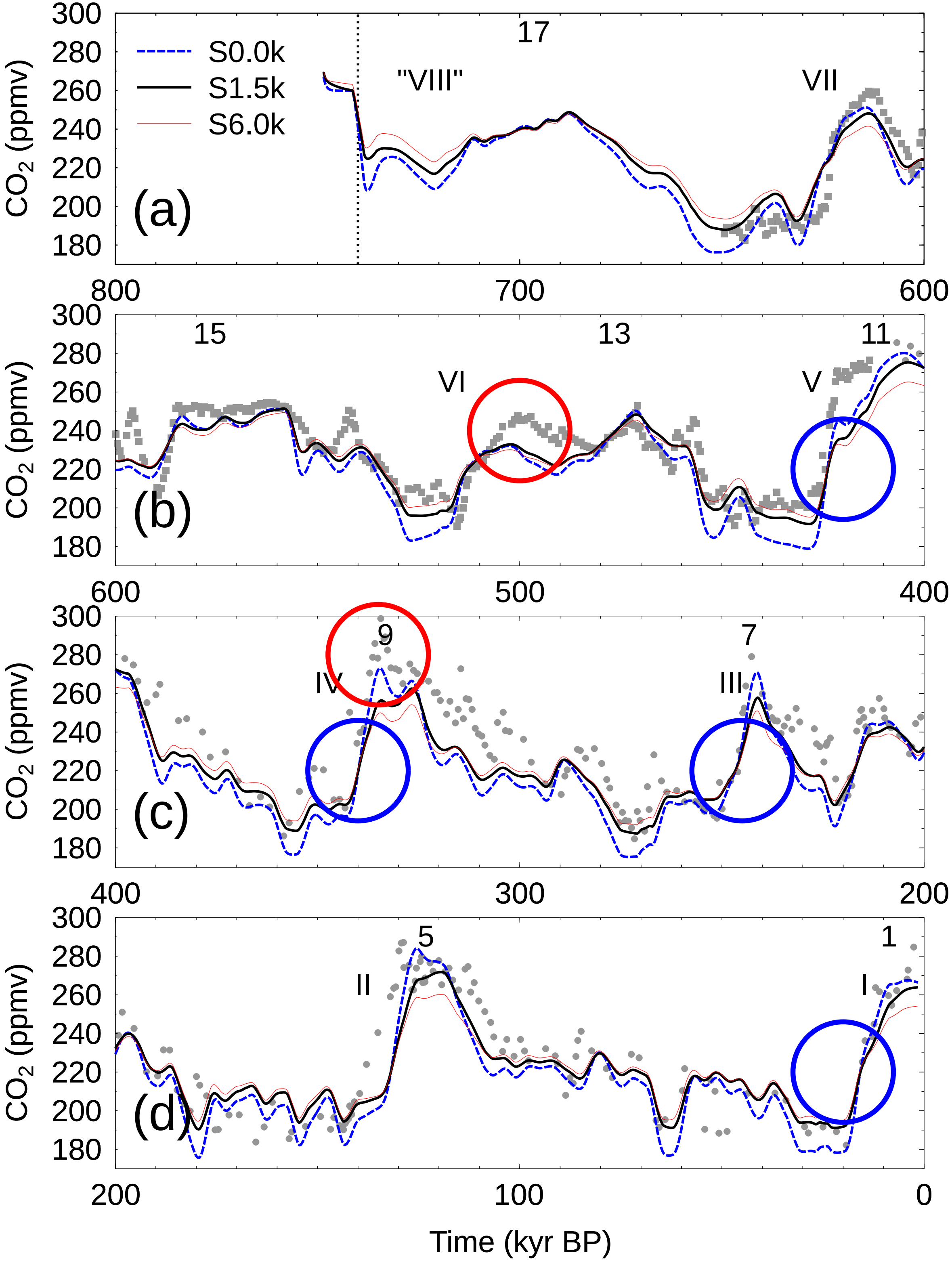


The EPICA challenge

1. Terminations I, III, IV, V

Köhler and Fischer, 2006,

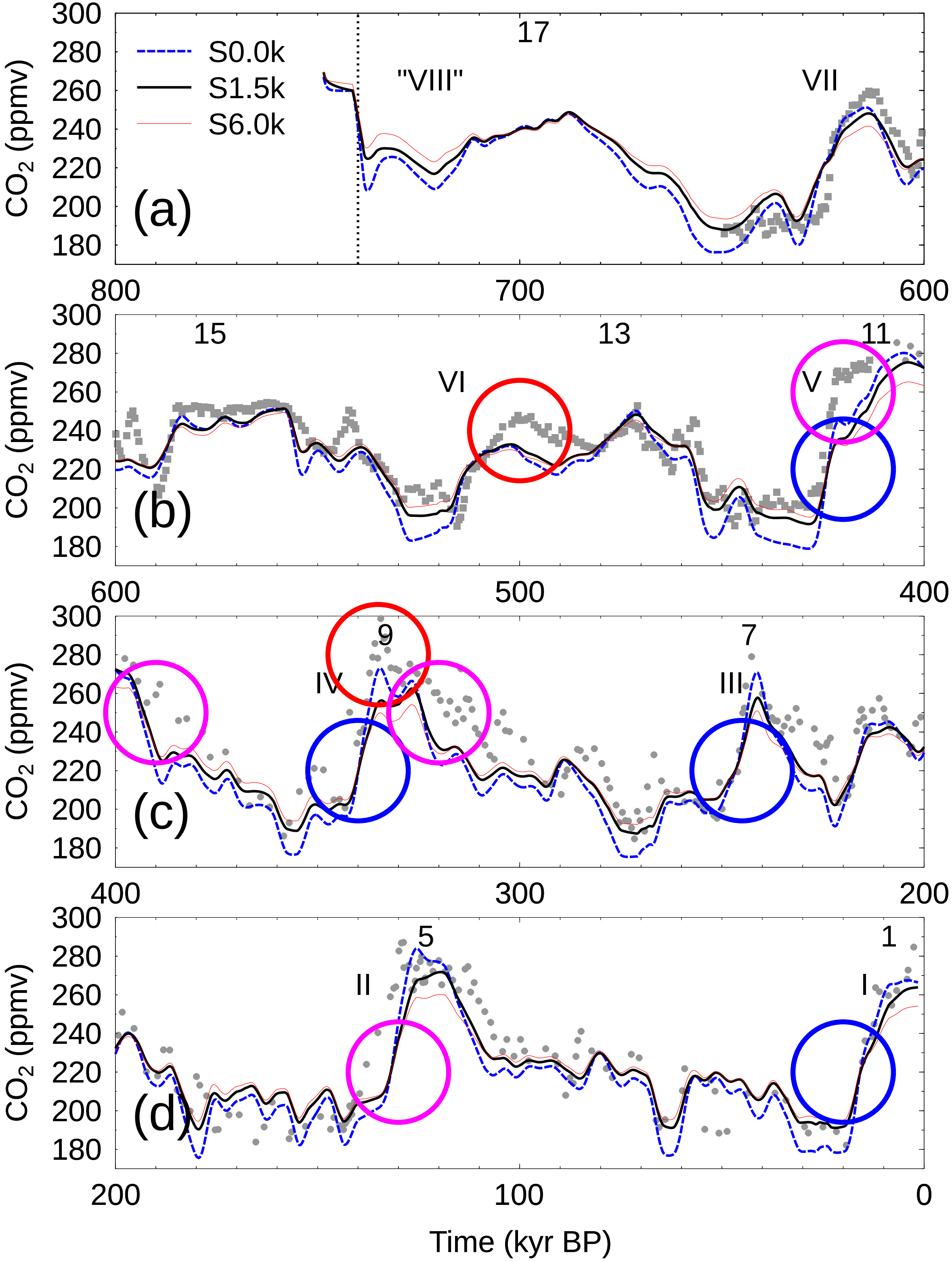
Climate of the Past



The EPICA challenge

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

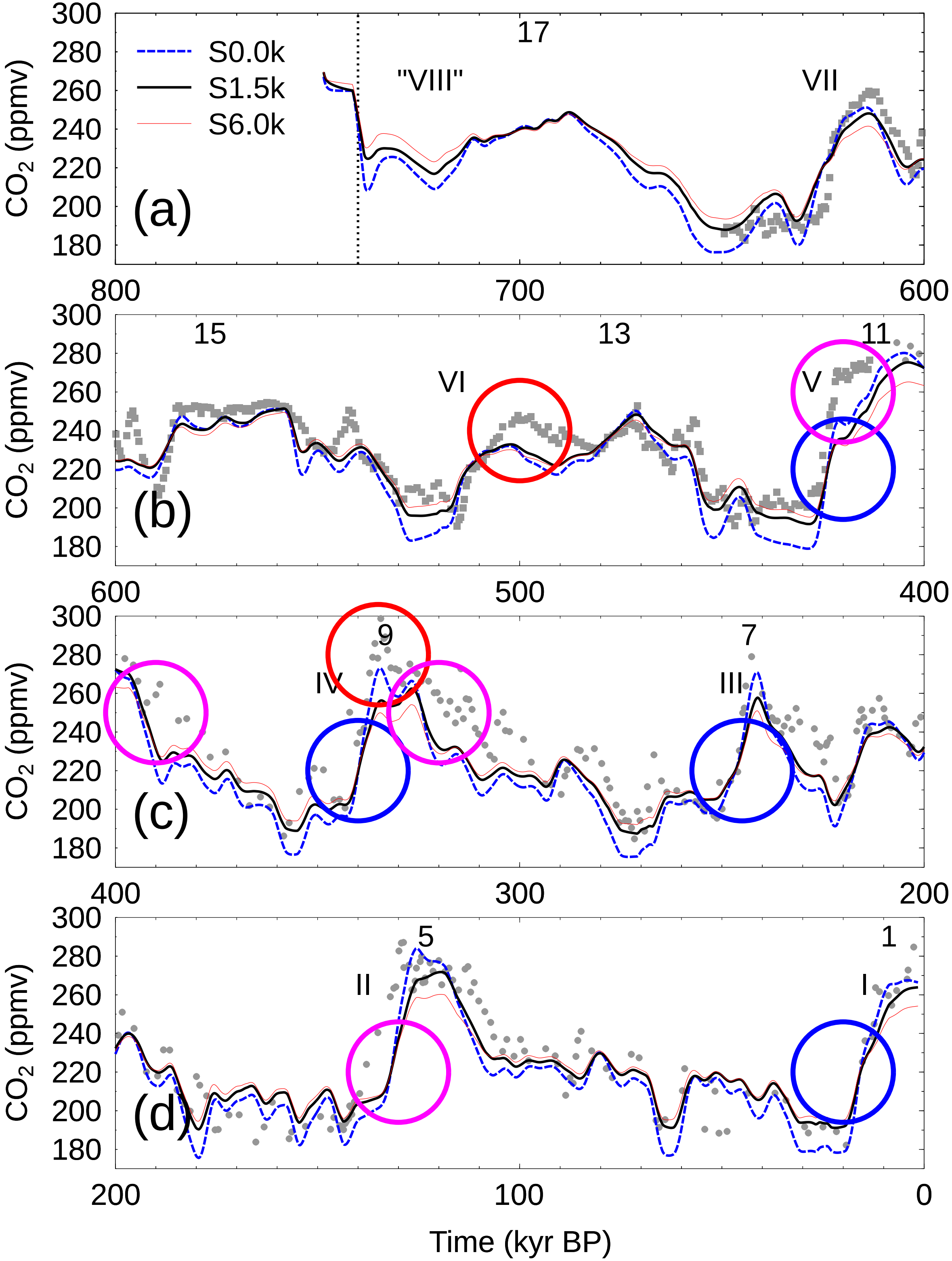
Köhler and Fischer, 2006, Climate of the Past



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?

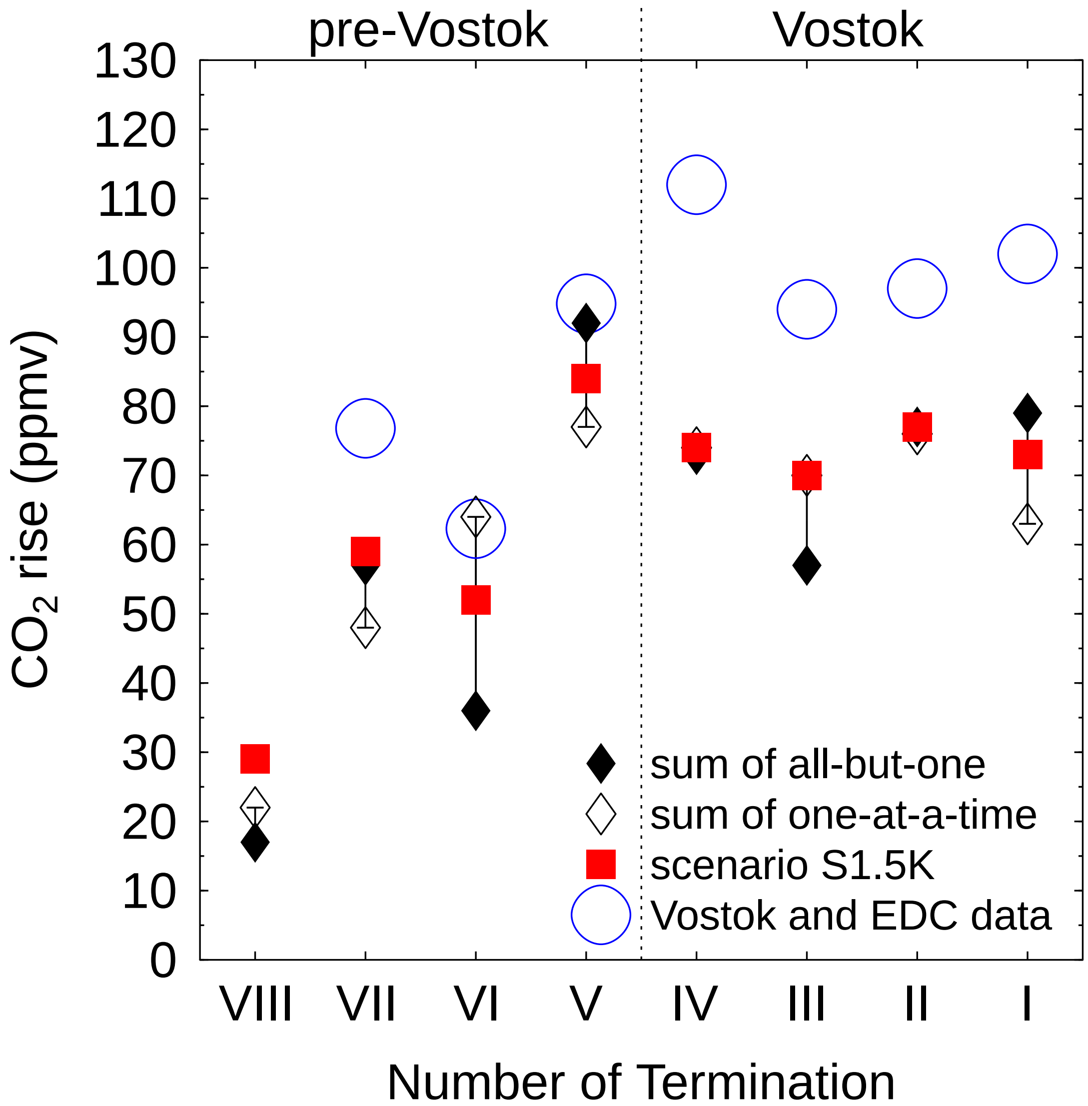
C: Are our findings for Termination I of general nature?

Köhler and Fischer, 2006, Climate of the Past

Terminations I–VIII

combined simulation vs. ice core data

∼20 ppmv per Termination are missing

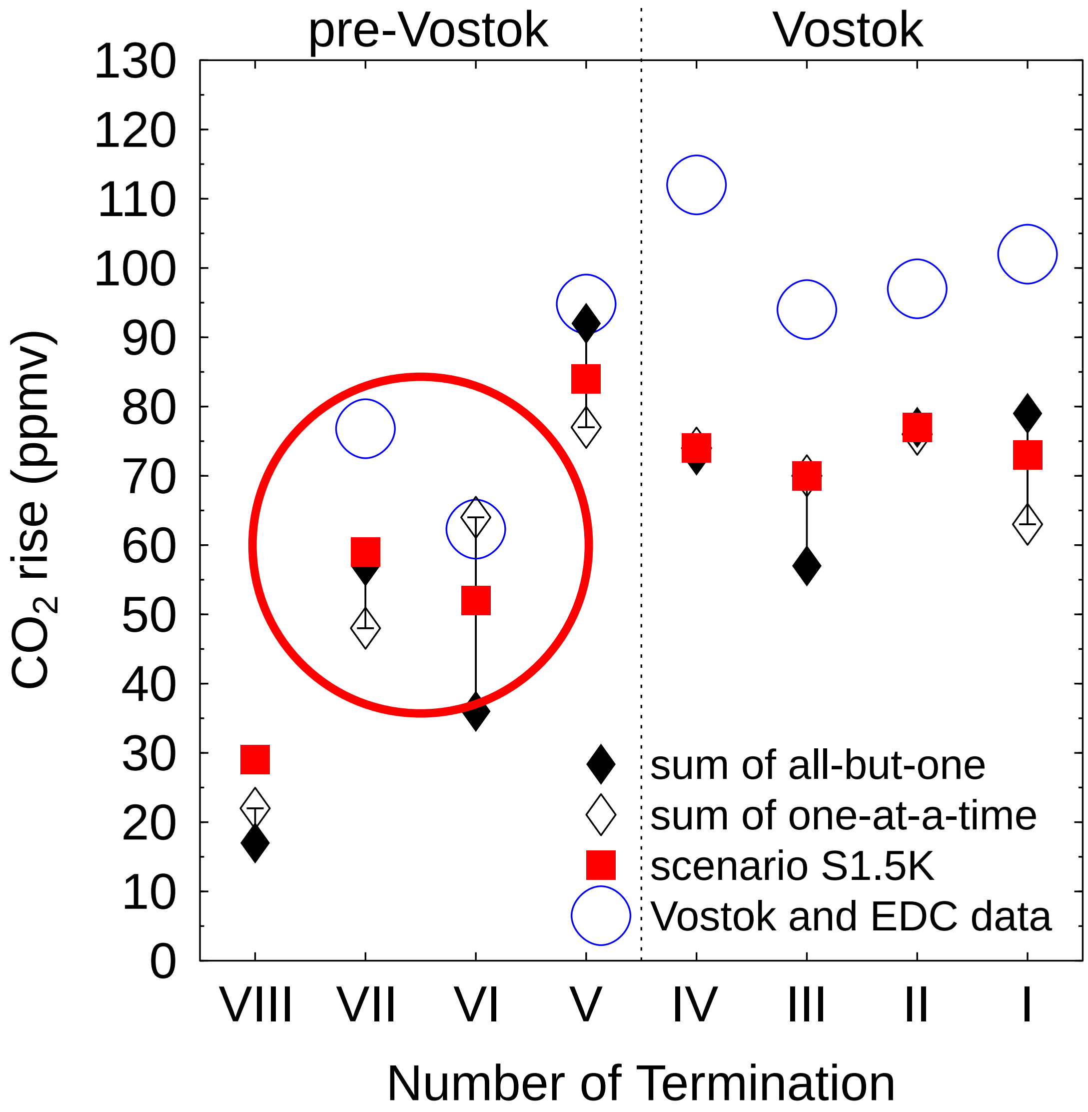


Köhler and Fischer, 2006, Climate of the Past

Terminations I–VIII

combined simulation vs. ice core data

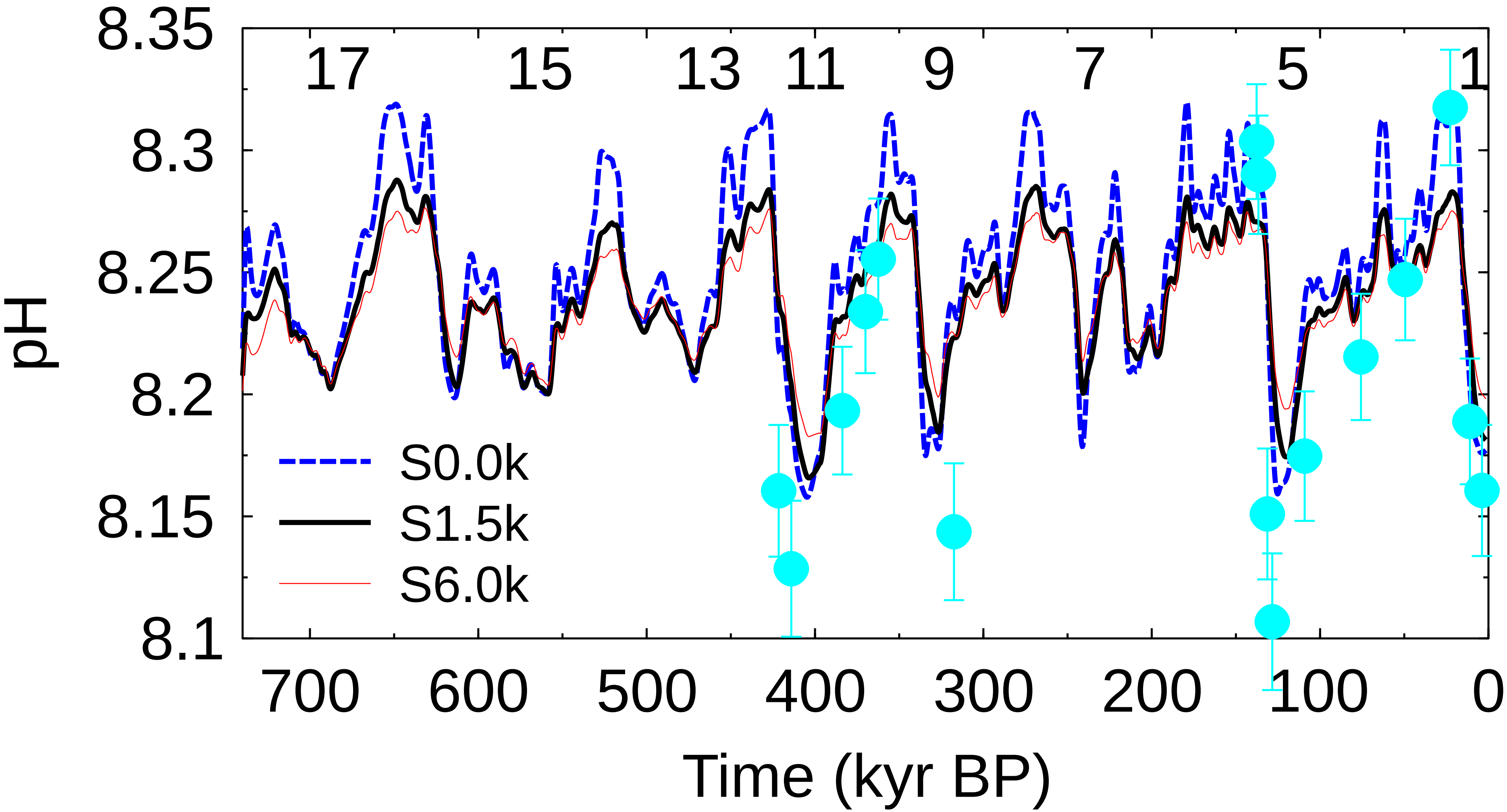
Termination VI, VII: smaller contributions from OCEAN CIRCULATION and SST



Köhler and Fischer, 2006, Climate of the Past

pH

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



pH from Hönisch & Hemming 2005

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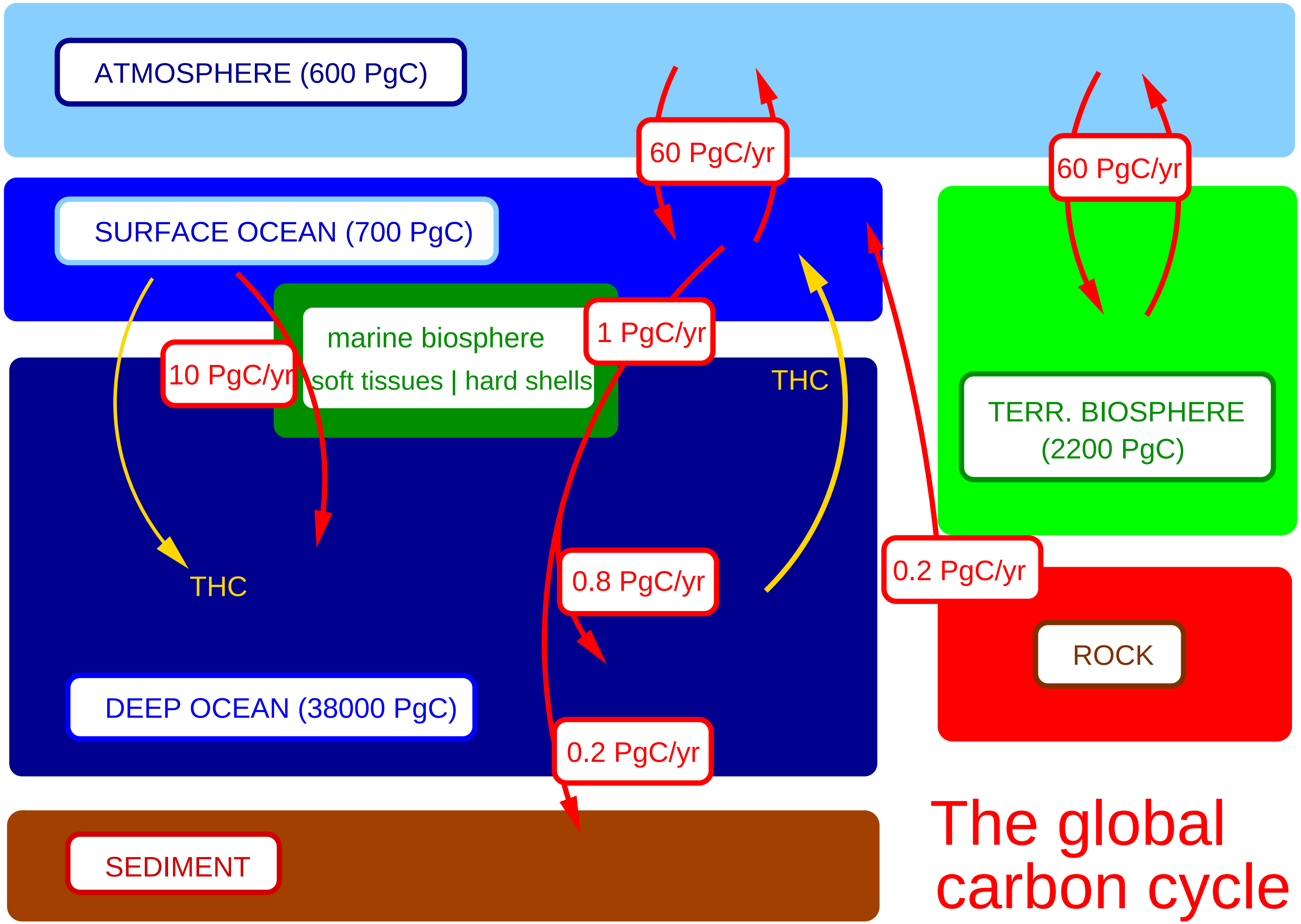
Missing processes

- process-based sediment model (work in progress)
- riverine input of continental weathering



Continental Weathering

Two effects of continental weathering:

1. a sink for atmospheric CO_2
2. a source of HCO_3^- and alkalinity to the ocean

For steady state conditions :

riverine input = sedimentation output

Changes in the riverine input lead to changes in the sedimentation output (carbonate compensation) until a new equlibrium with equal input and output is established.

For investigations under changing climates (either 21st century or LGM) one would need :

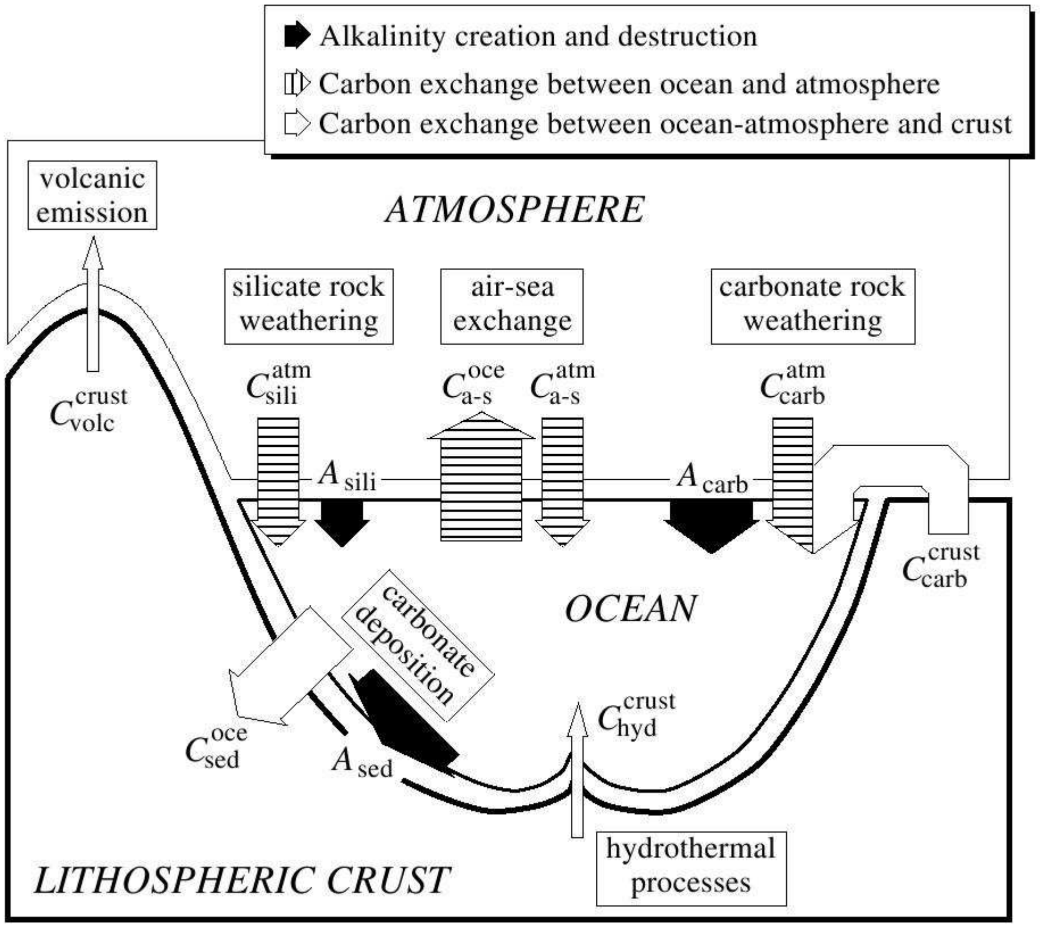
1. a climate model coupled to a model of continenal weathering
2. riverine inputs in an ocean carbon cycle model (incl sediments)

Continental Weathering II

Two different processes:

- Carbonate weathering: C supply from atmosphere and continental crust
- Silicate weathering: C supply from atmospheric CO_2 only

  ⇒: Outgassing from ocean. Changes in alkalinity are more important than for the changes in the C budget itself.

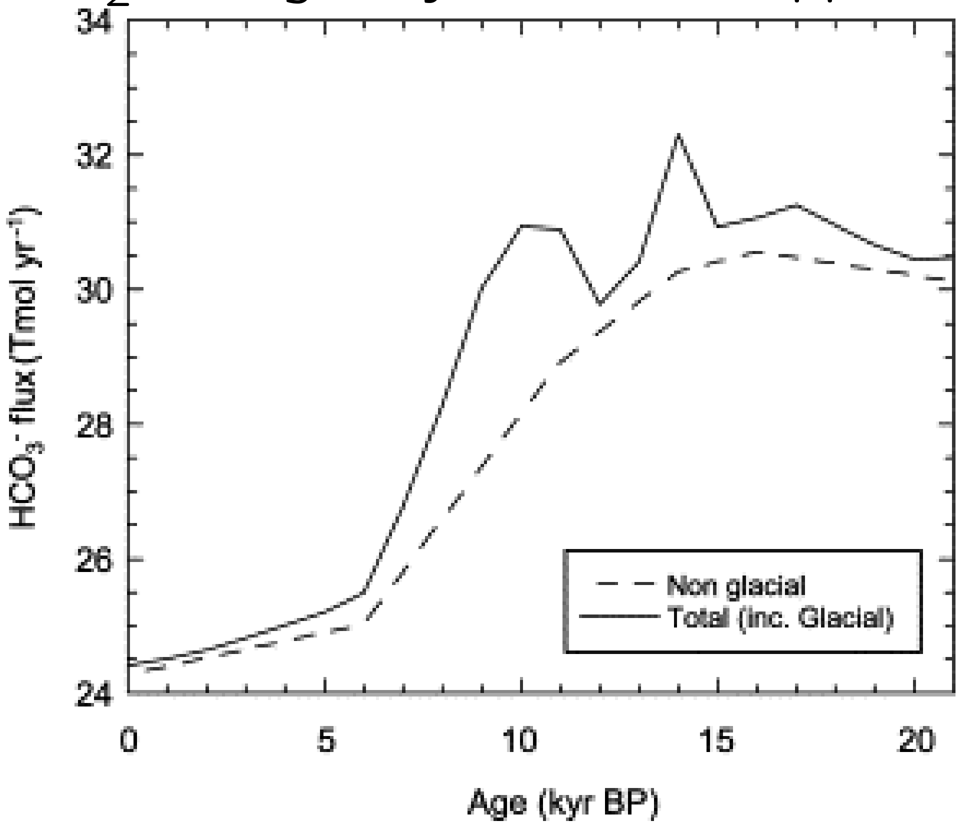


(Munhoven 1997)

Continental Weathering III

Work on changes in continental weathering during the last 20 000 yr:

- Munhoven 2002: CO_2 changes by 6 to 12 ppmv
- Jones et al 2002: CO_2 changes by less than 6 ppmv



Shortcomings:

- Weathering: underlying lithology (incl resolution)
- Carbon cycle: simplified model

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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.

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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.

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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.
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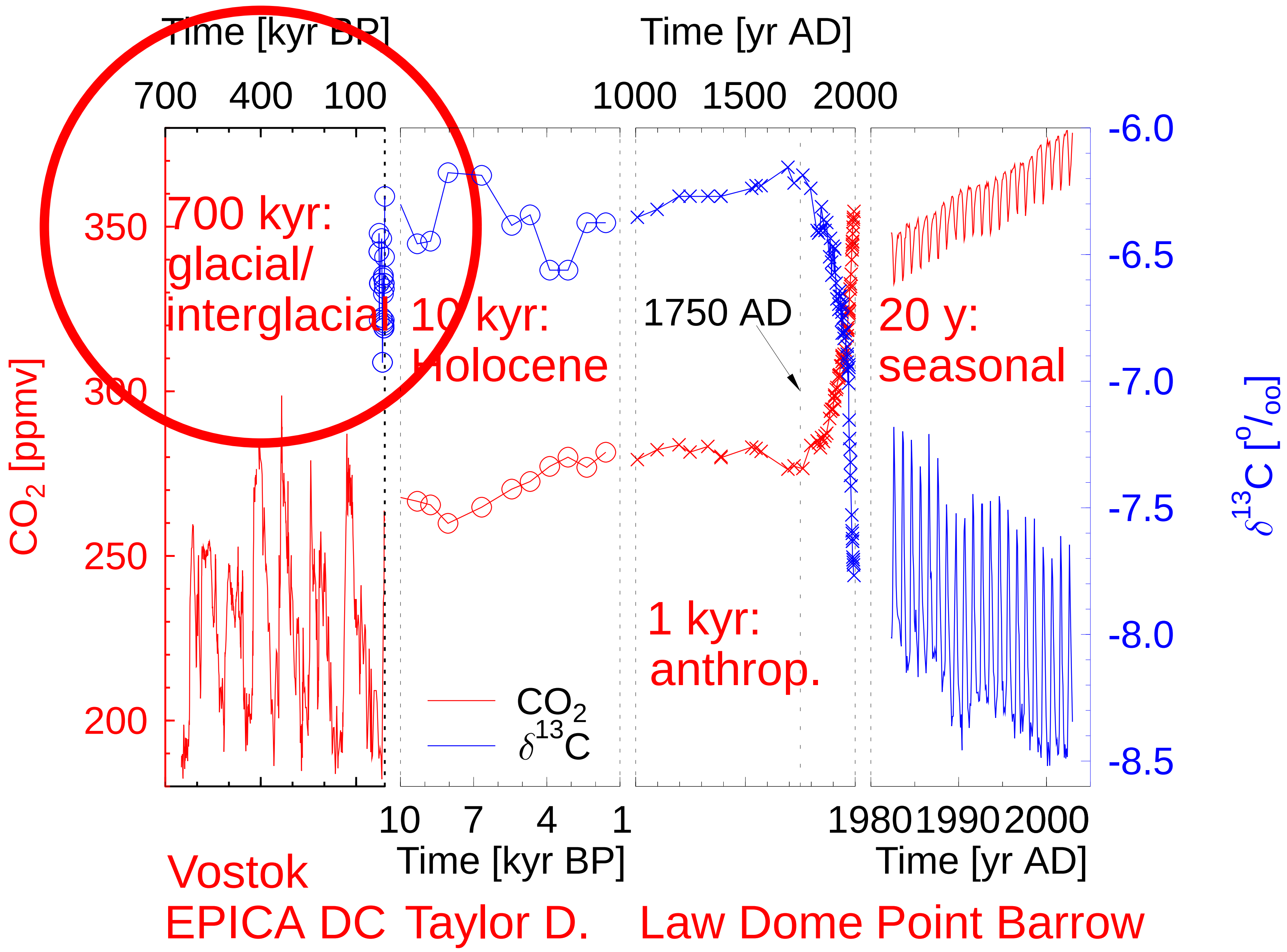
3. Not only the amplitudes, but also the timing of changes need to be addressed to quantify **what** impacts individual processes have on CO_2.
4. Simulation results are always model-dependent, but the amplitudes of individual contributions can be estimated with simple models such as BICYCLE.
5. Are our findings for Termination I of general nature?

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



THANK YOU FOR YOUR ATTENTION