Alfred Wegener Institute
for Polar and Marine Research
Bremerhaven, Germany

Carbon cycle and the Mid Pleistocene Transition: The Southern Ocean Decoupling Hypothesis

Peter Köhler

Berger Symposium on Climate Change, Louvain-la-Neuve, Belgium — May 2008

In cooperation with:

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HELMHOLTZ ASSOCIATION

Outline

The data

The model

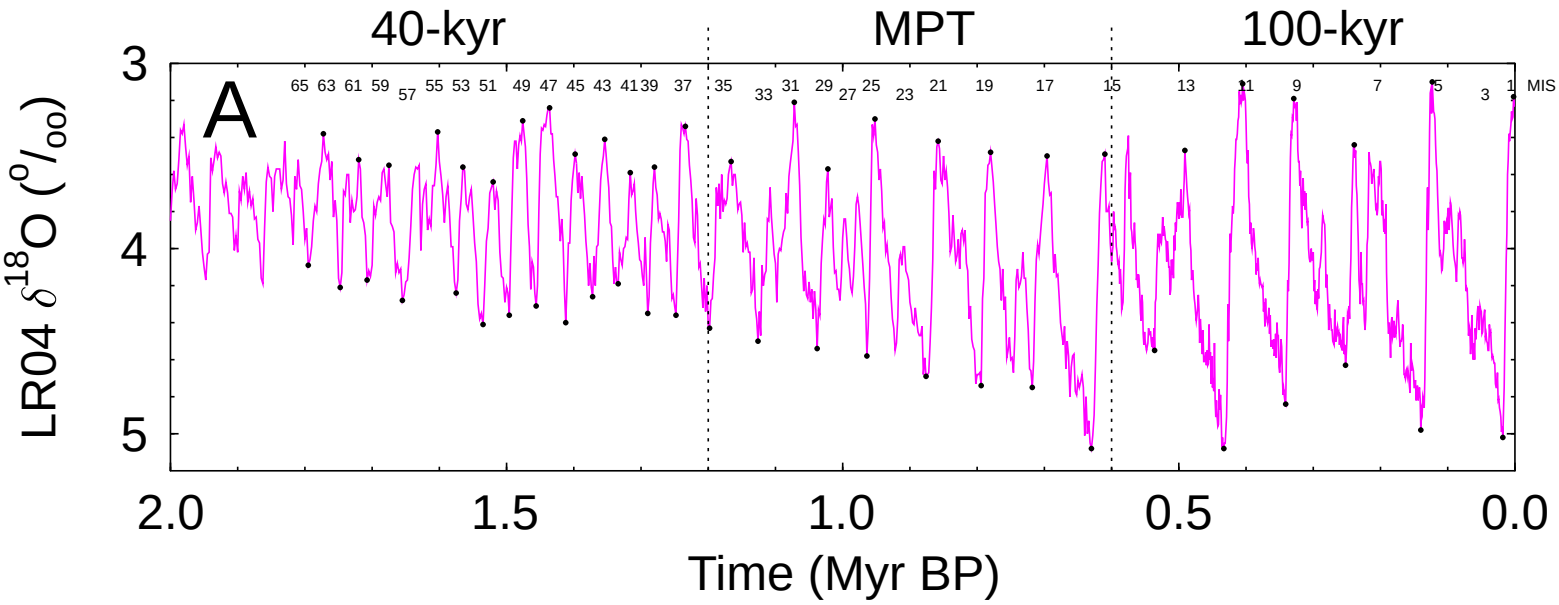
The EPICA Time Window

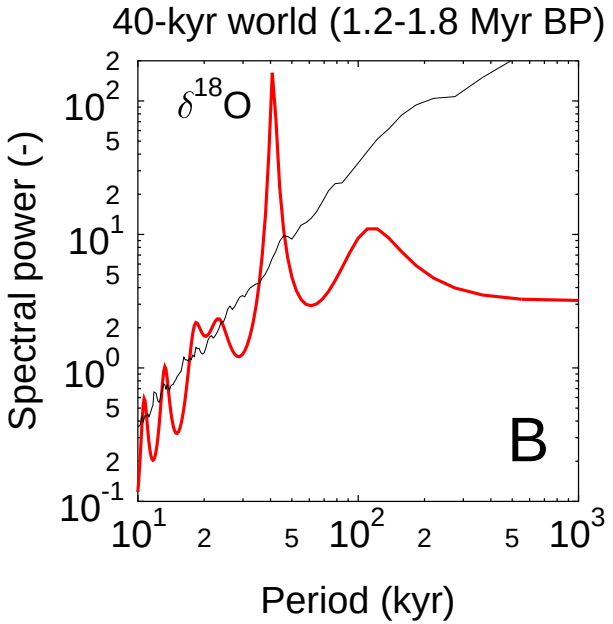
The Southern Ocean Decoupling Hypothesis

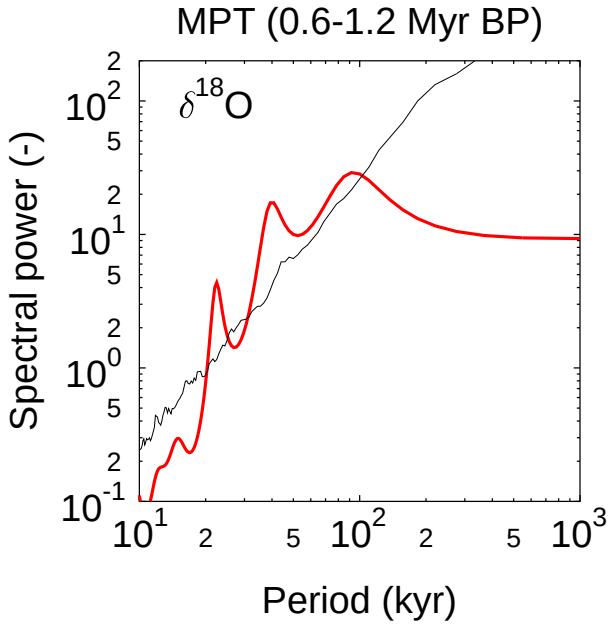
Other Theories

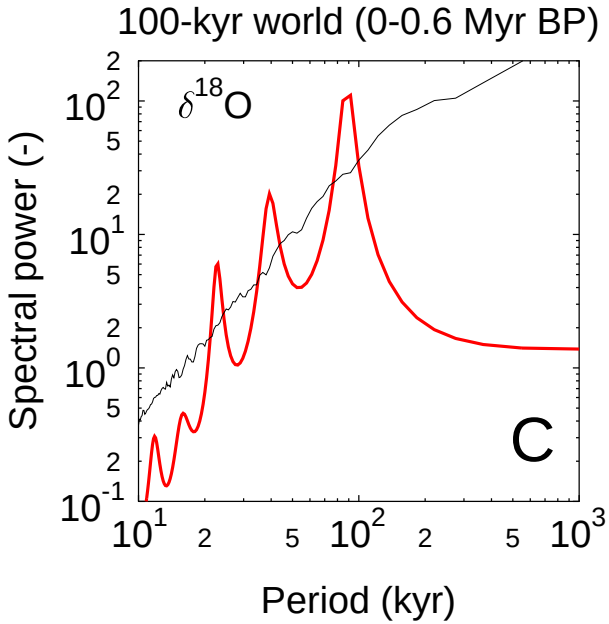
Take-home messages

Paleo Reconstructions — Climate



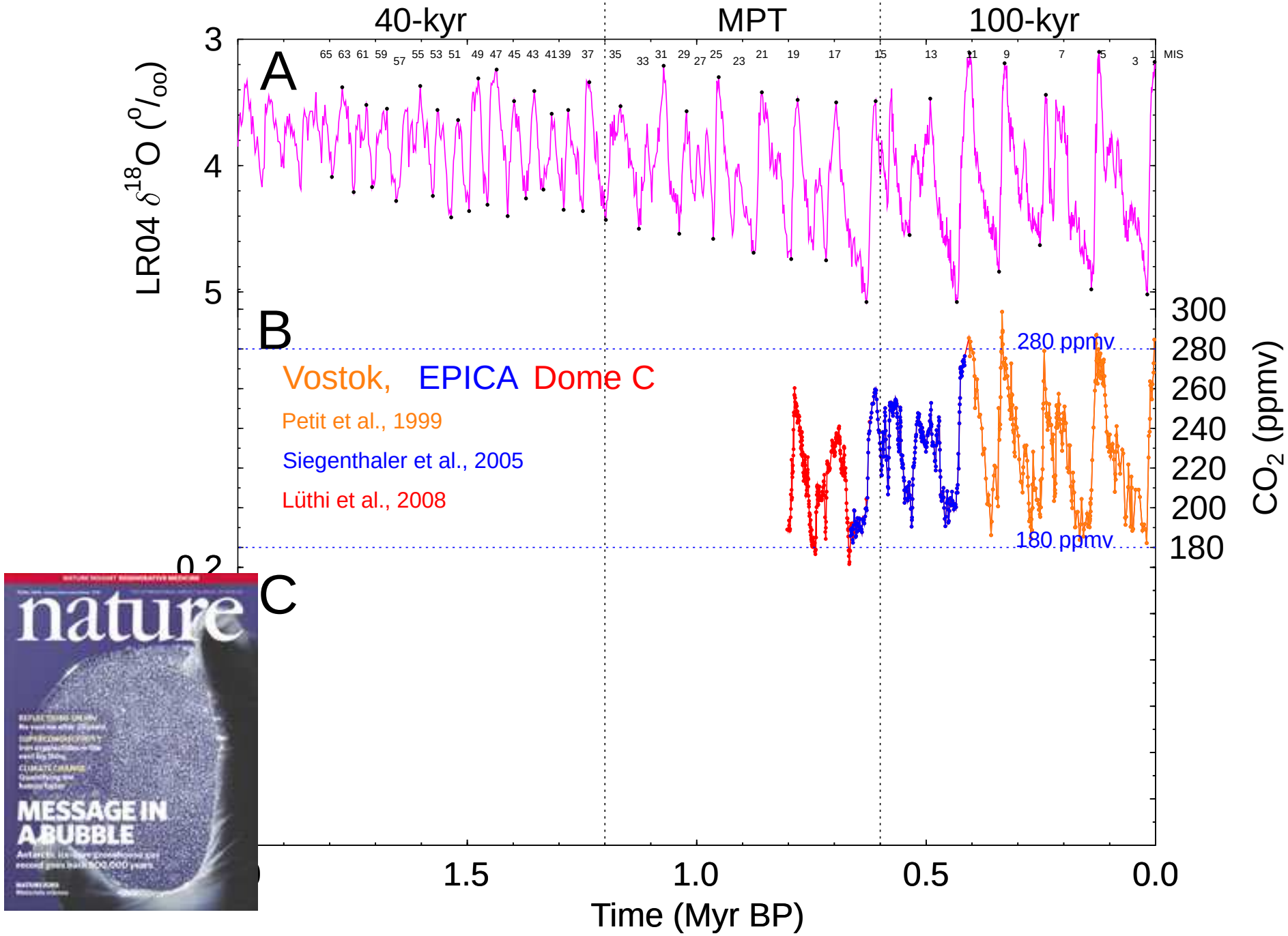






Benthic δ^{18}O stack LR04 (Lisiecki and Raymo, 2005)

Paleo Reconstructions — Carbon Cycle



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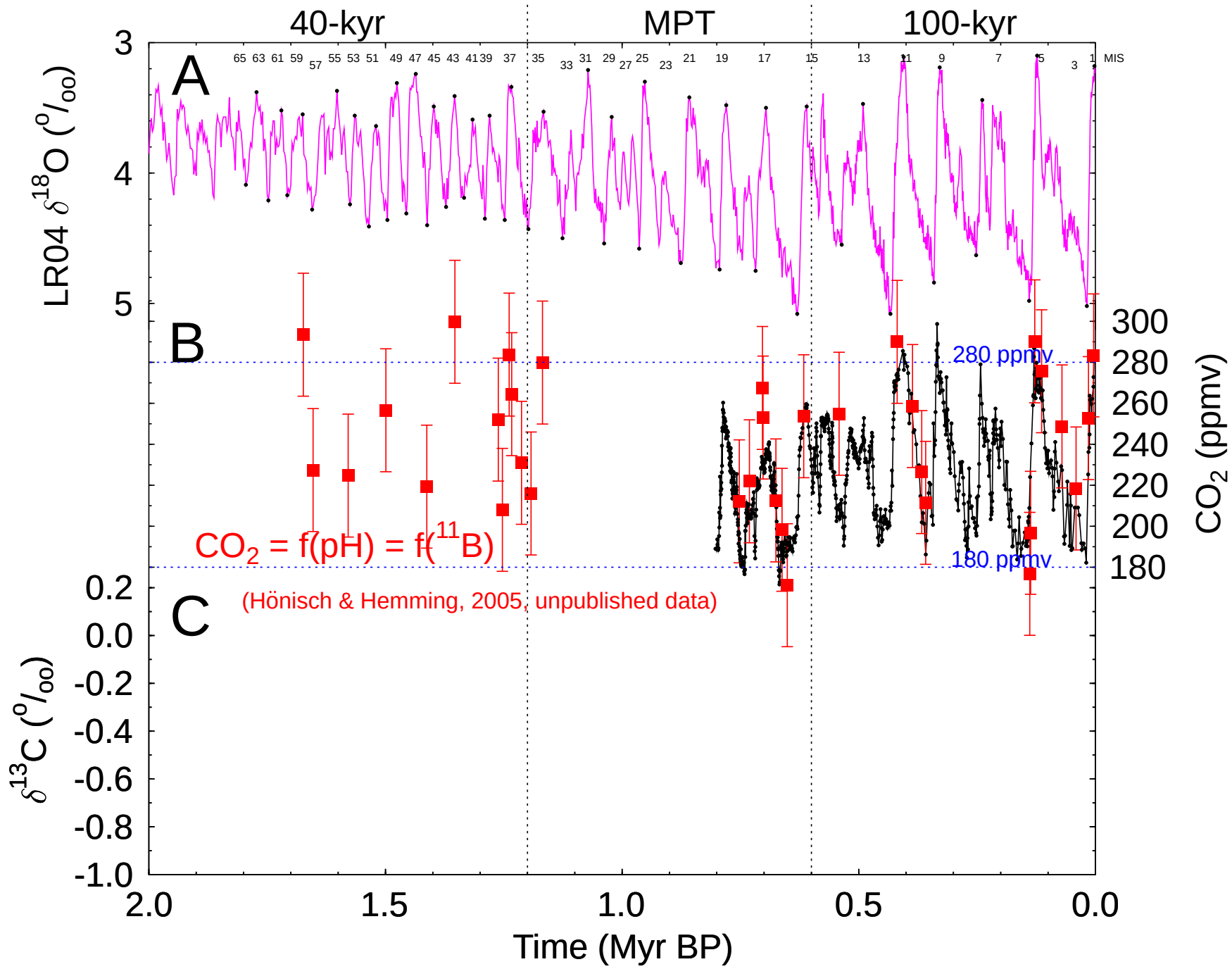

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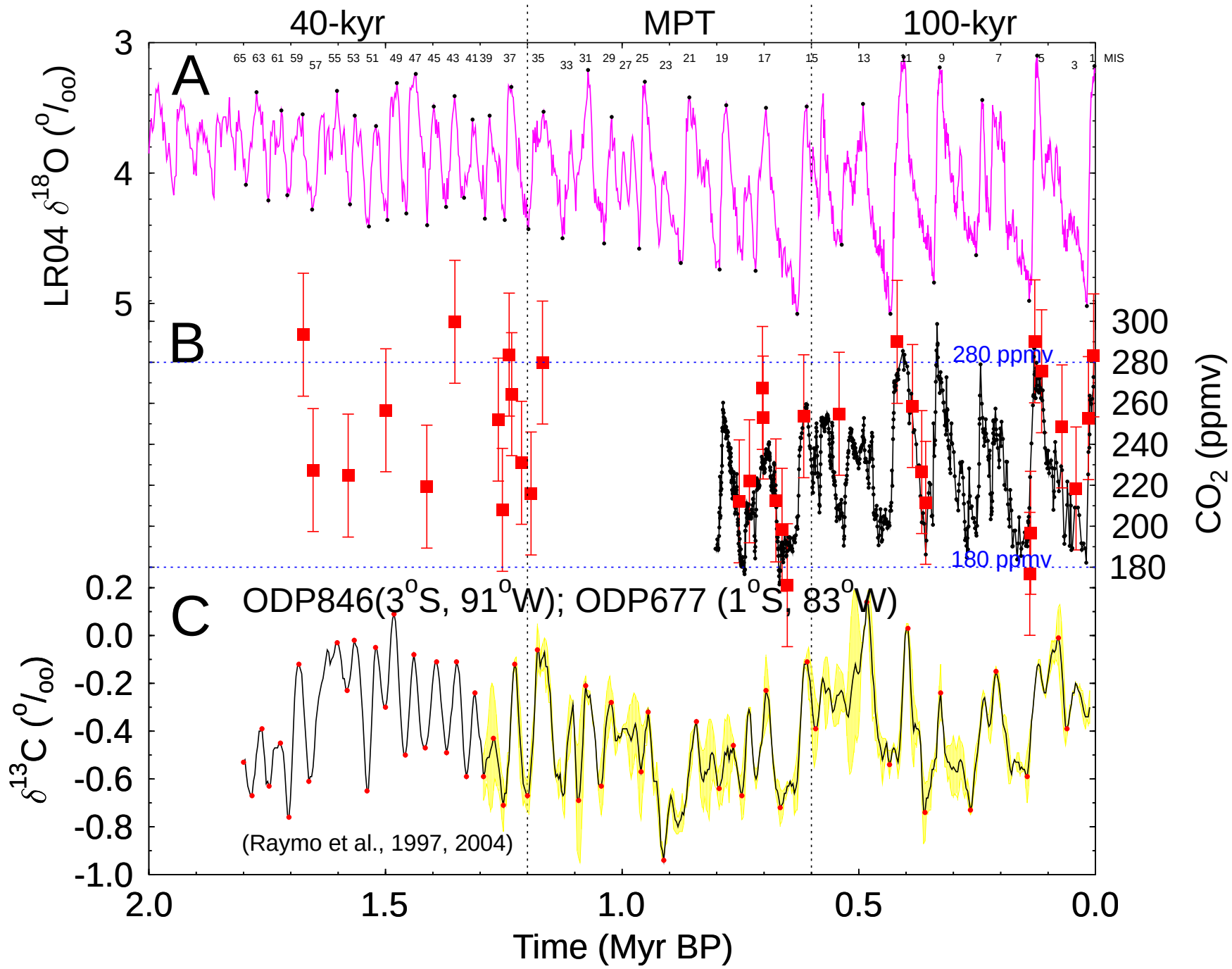

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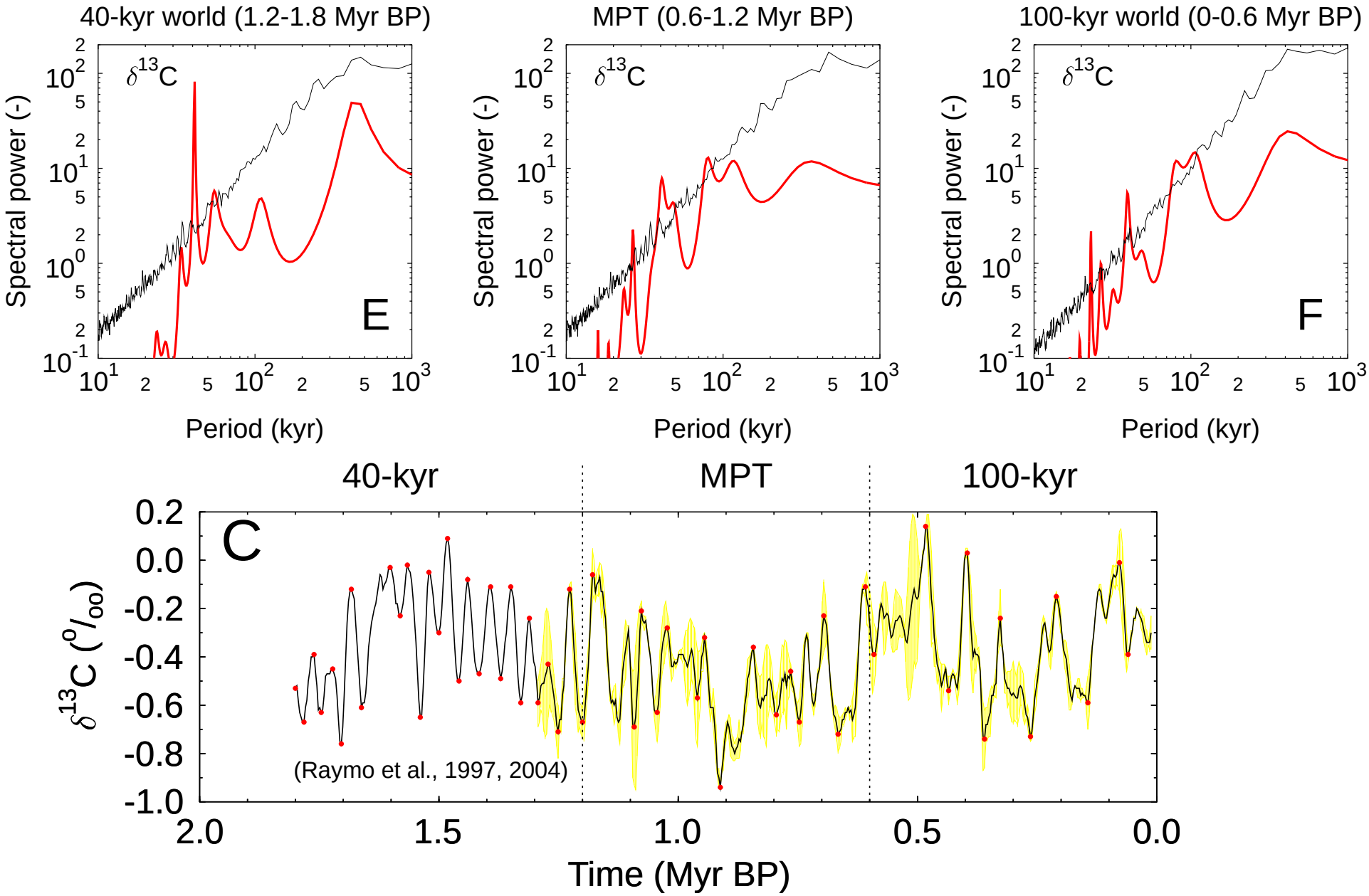
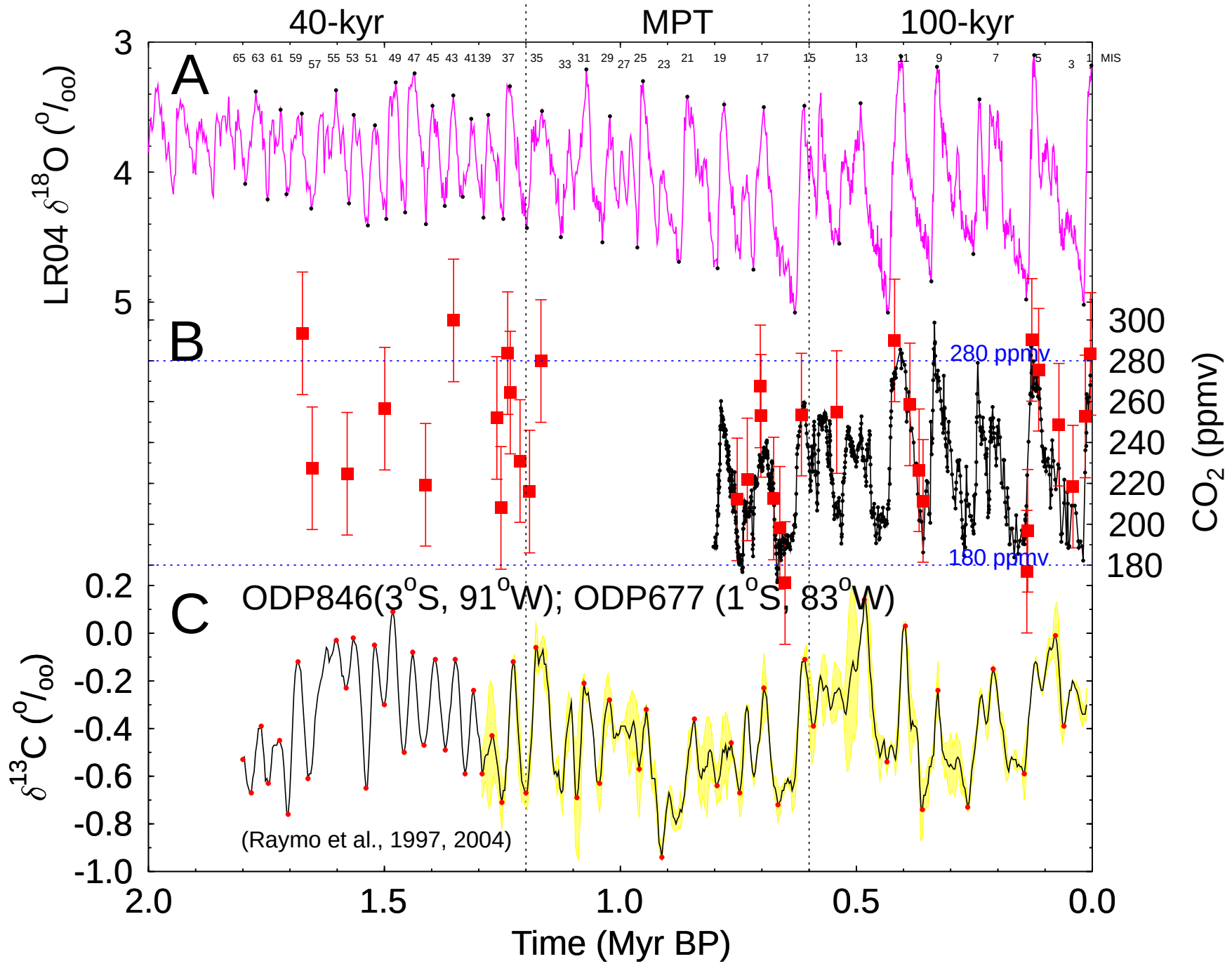


Variation in Glacial/Interglacial Amplitudes



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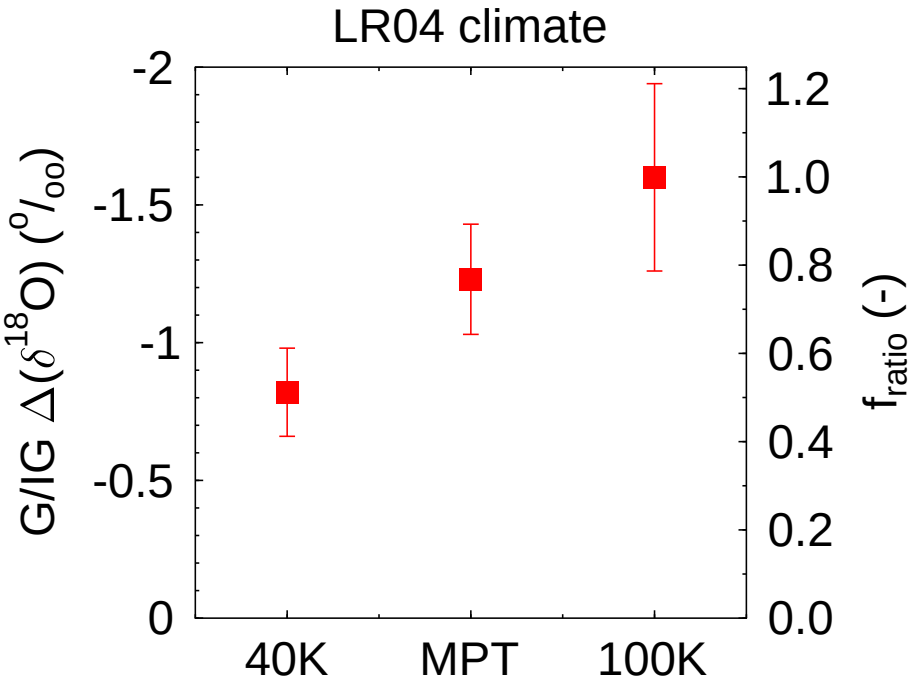

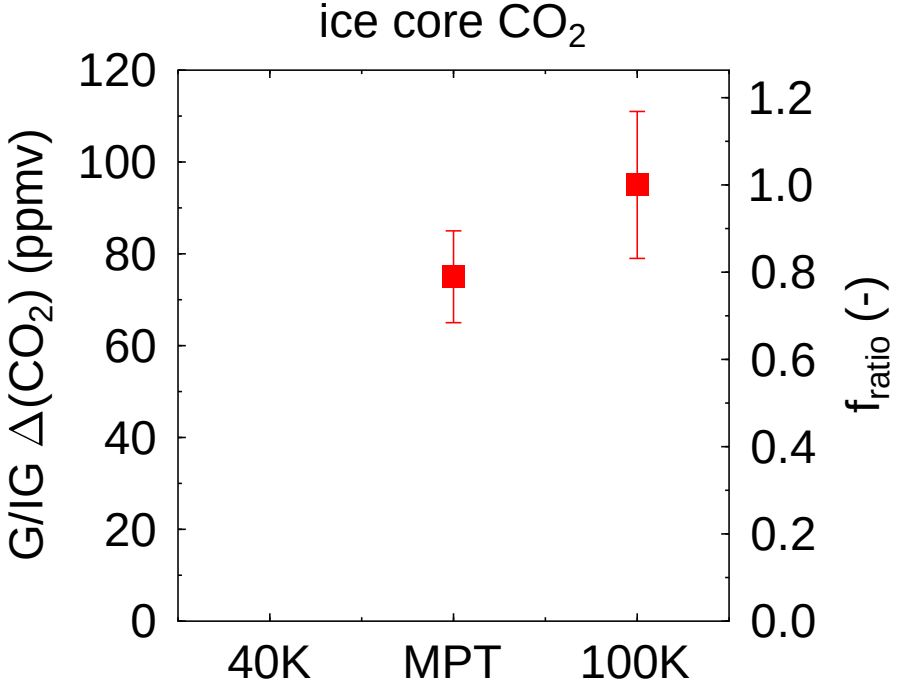

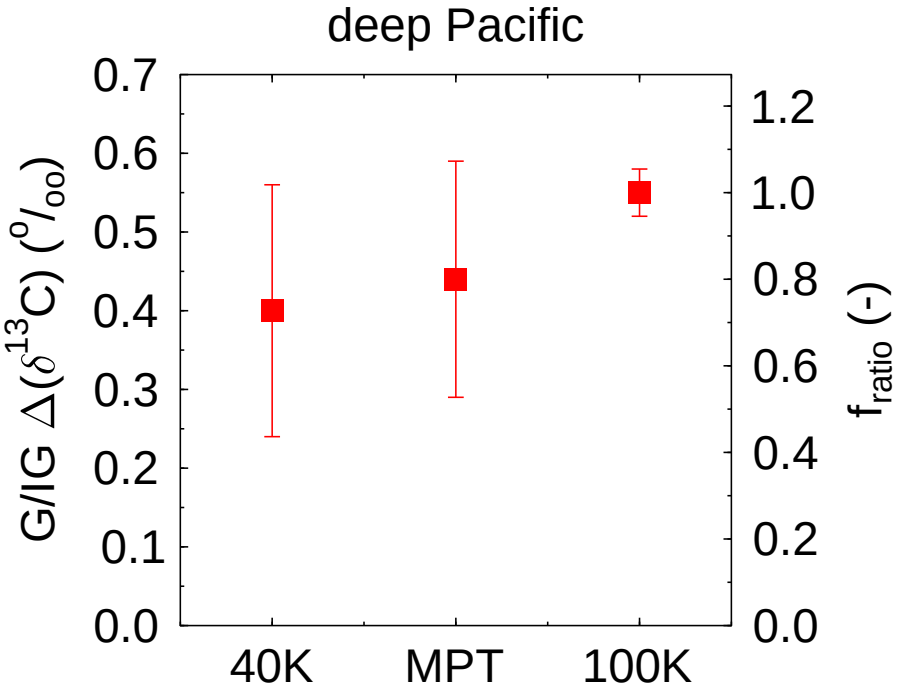

right y-axis: $f_{\text{ratio}} = \frac{\Delta_{\text{40k,MPT}}}{\Delta_{\text{100k}}}$

reduced G/IG amplitude in 40k:

climate (LR04): $\sim$ 50% of 100k
carbon (CO_2): ???
carbon ($\delta^{13}C$): $\sim$ 70% of 100k

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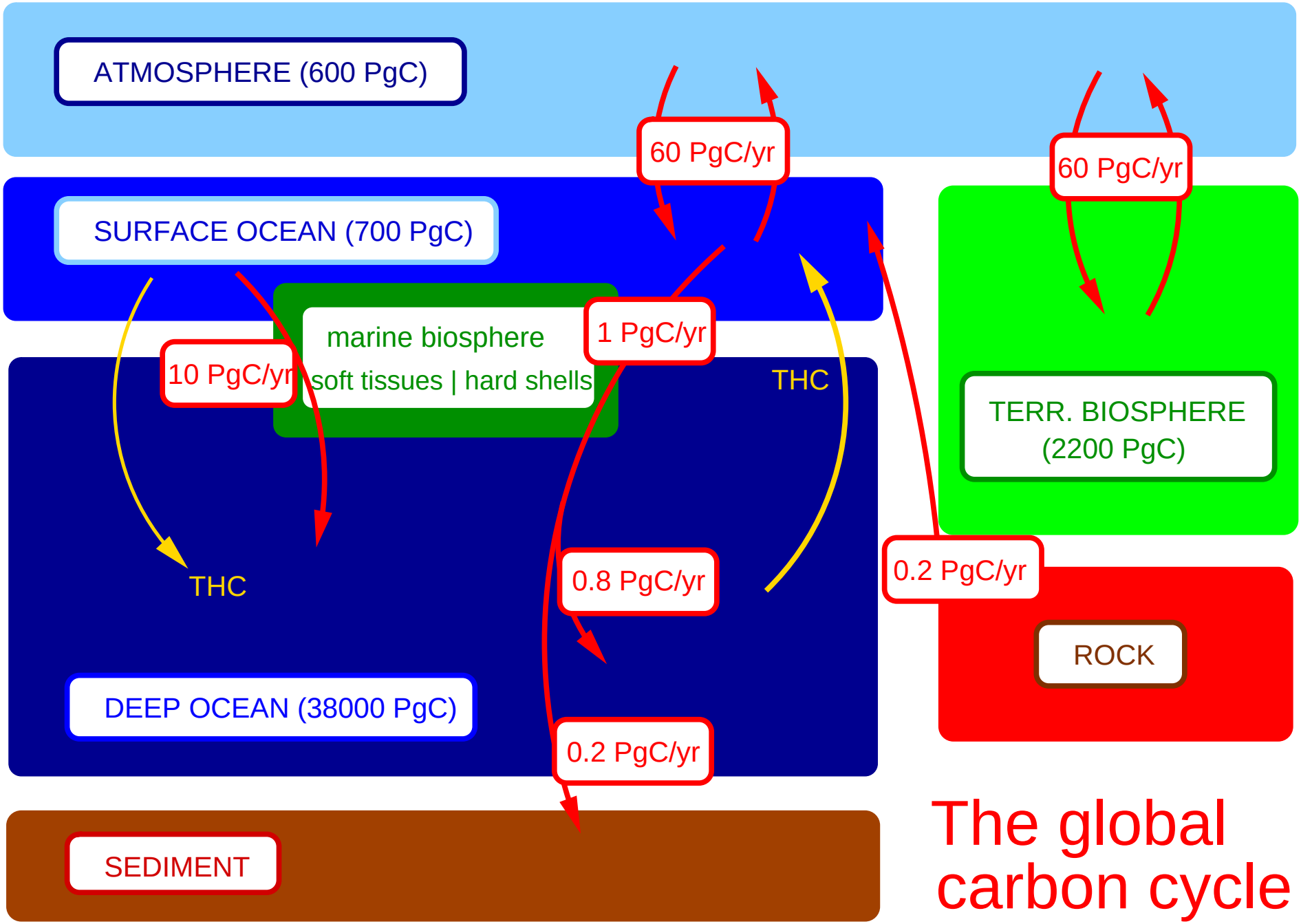
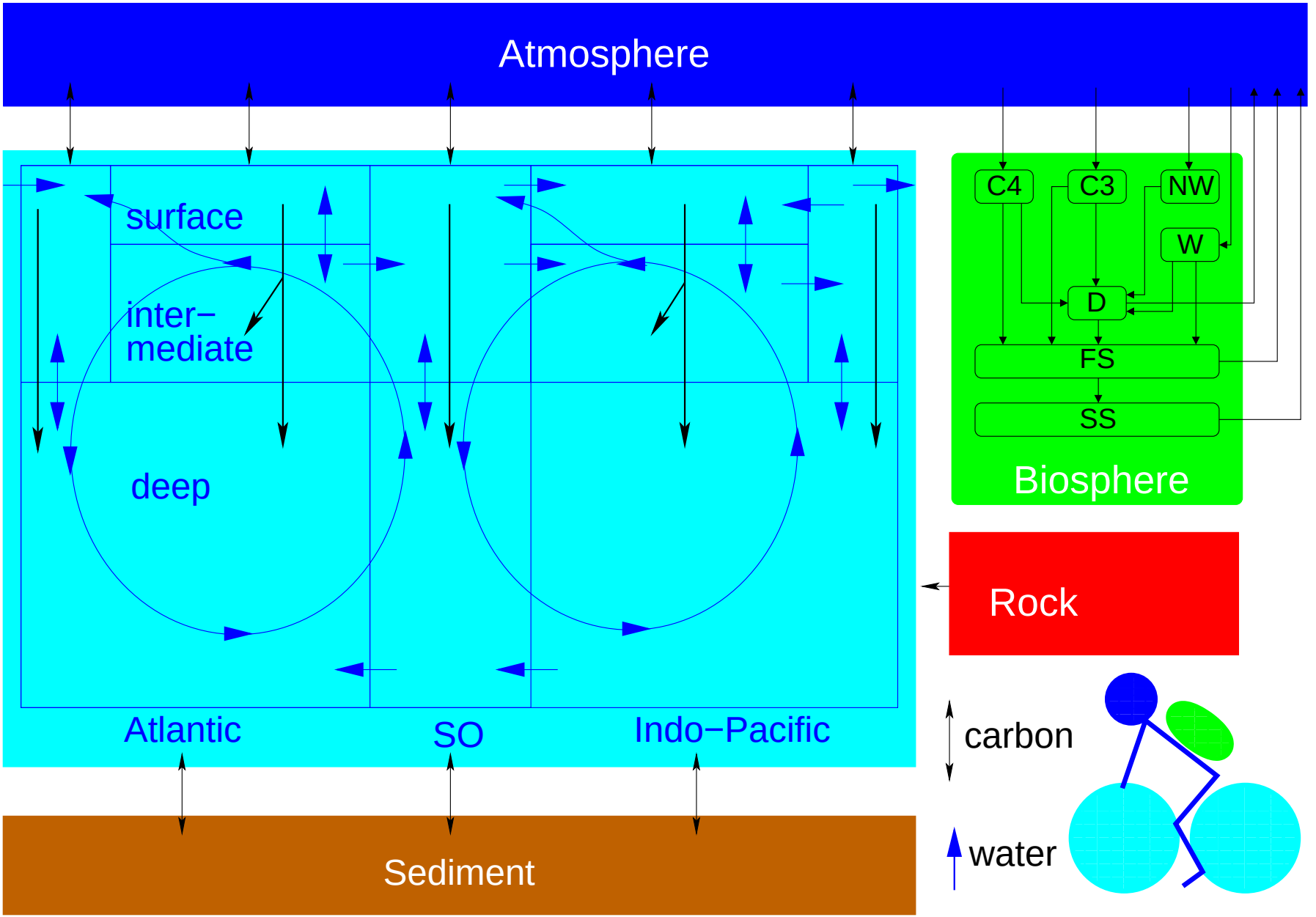


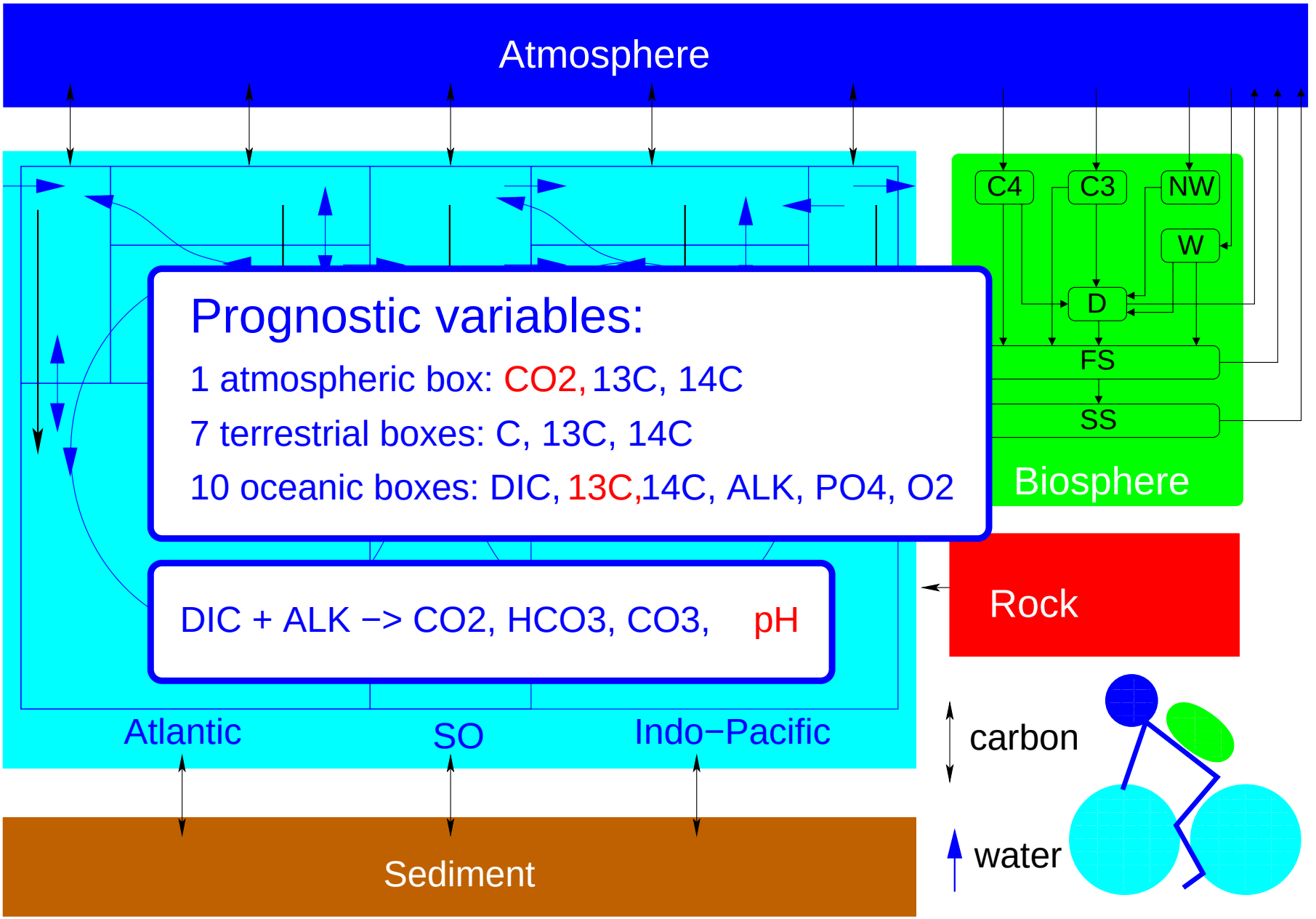
preindustrial reservoir sizes and annual fluxes



Box model of the Isotopic Carbon cYCLE

BICYCLE

Köhler et al. (2005, submitted), Köhler & Fischer (2006)



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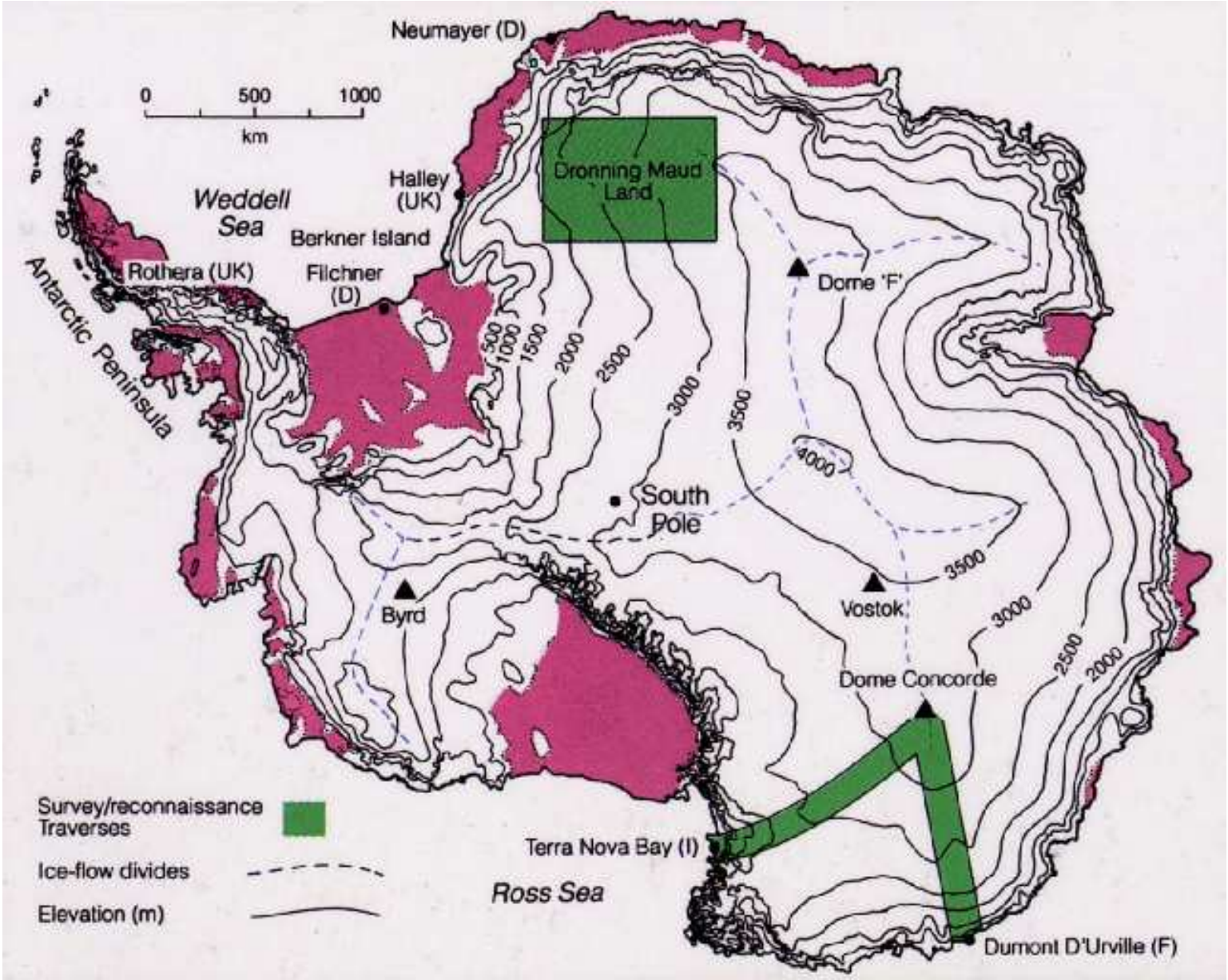


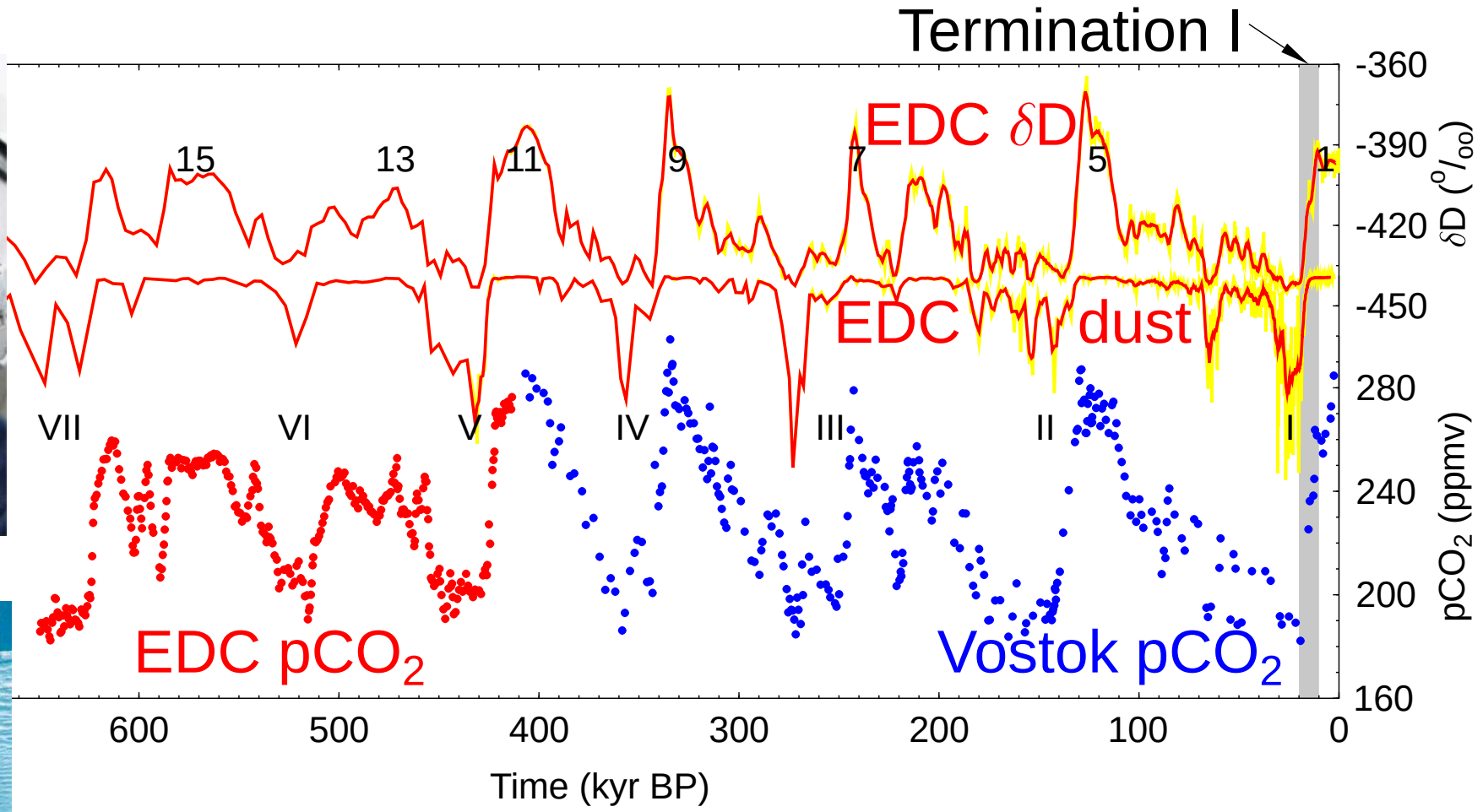
EPICA drilling sites:

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

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

The EPICA Time Window

Carbon cycle model simulations based on results for Termination I



EPICA, 2004; Petit et al., 1999

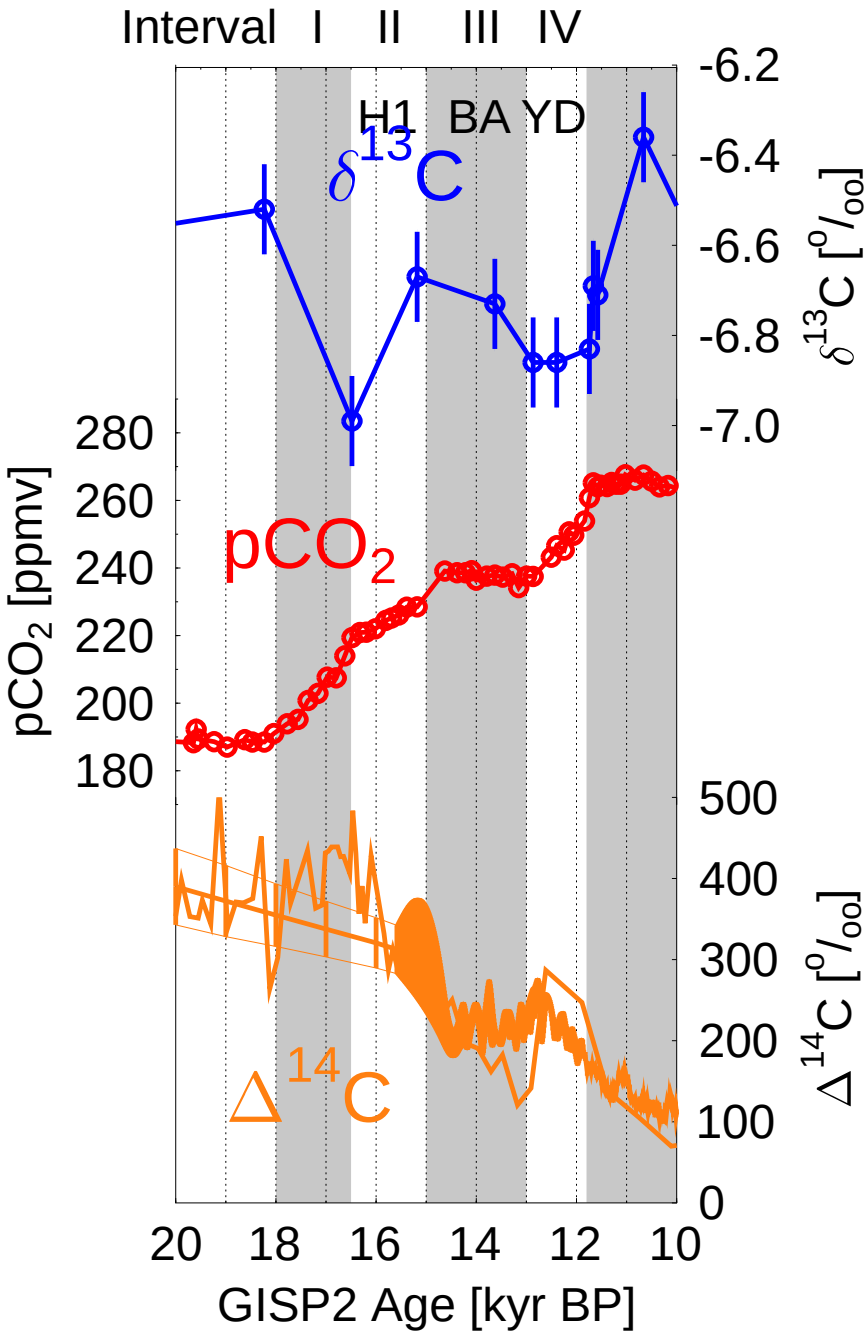
Siegenthaler et al., 2005

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



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?

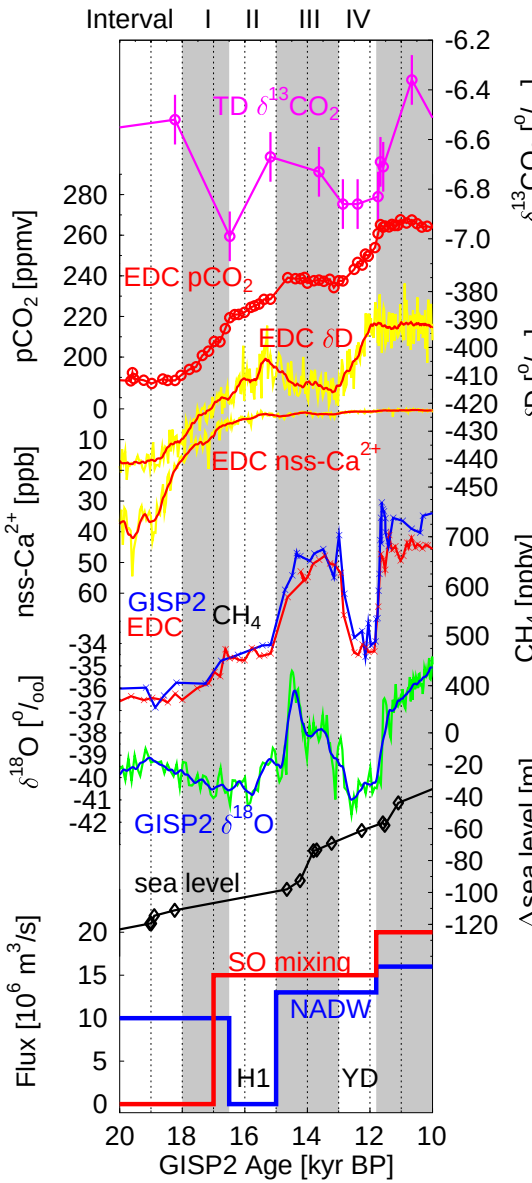
Time-dependent processes:

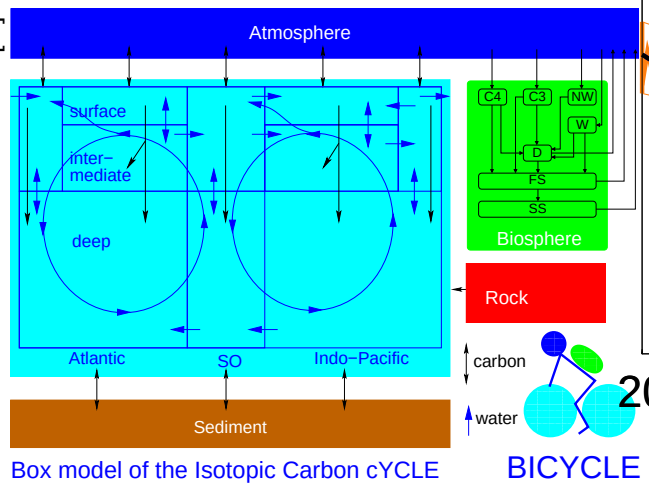
	Which	**How** (T I)	**What** (ppmv)	**?**
	Physics (without ocean circulation)			
1	Temperature	+(3–5) K	+30	!
2	Sea level / salinity	+125 m	−15	!
3	Gas exchange / sea ice	−50%	−15	?
	Ocean circulation			
4	NADW formation	+6 Sv	+15	!/? (off)
5	Southern Ocean ventilation	+20 Sv	+35	o
	Biogeochemistry			
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	?
	Sum		+75	
	Sum (without sea ice)		+90	
	Vostok (incl. Holocene rise)		+103	

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





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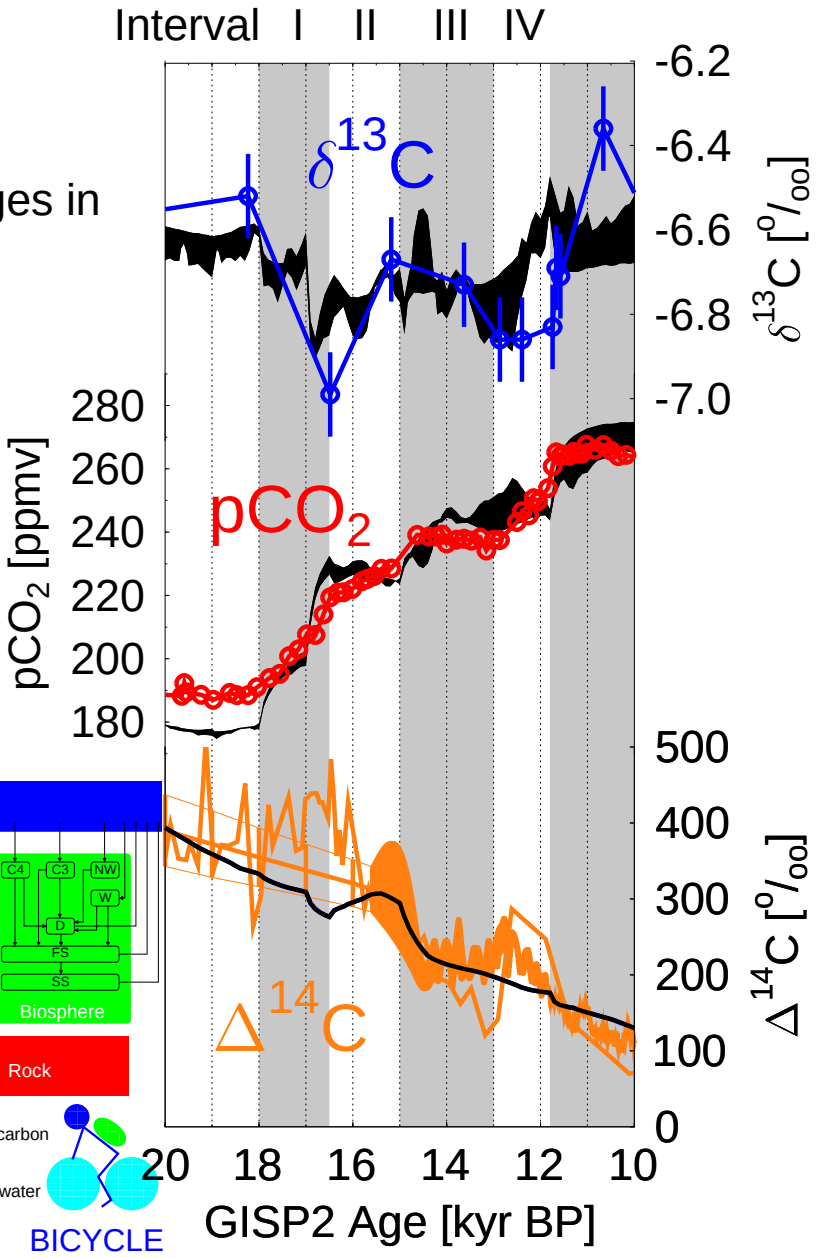


Forcing ⇒ Model ⇒ Results

Köhler et al. (2005) Global Biogeochemical Cycles

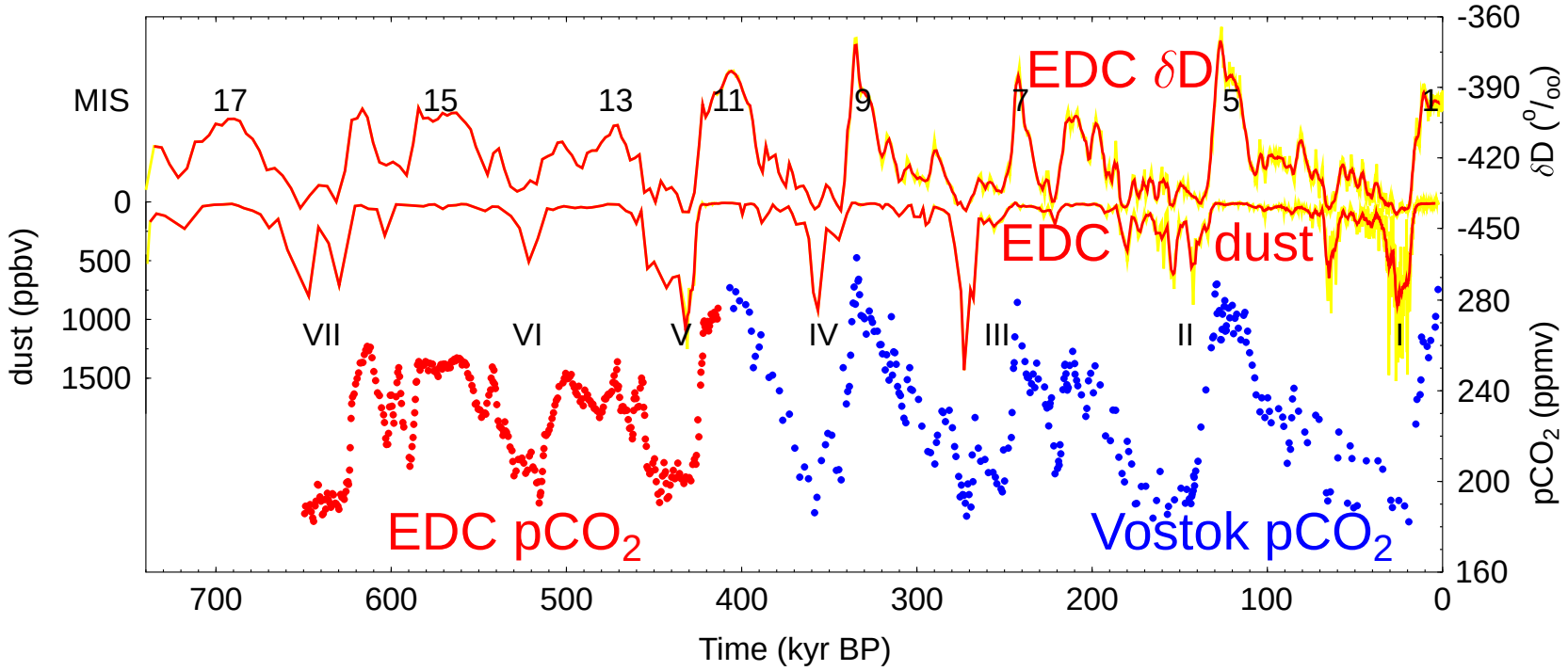
The EPICA Time Window

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

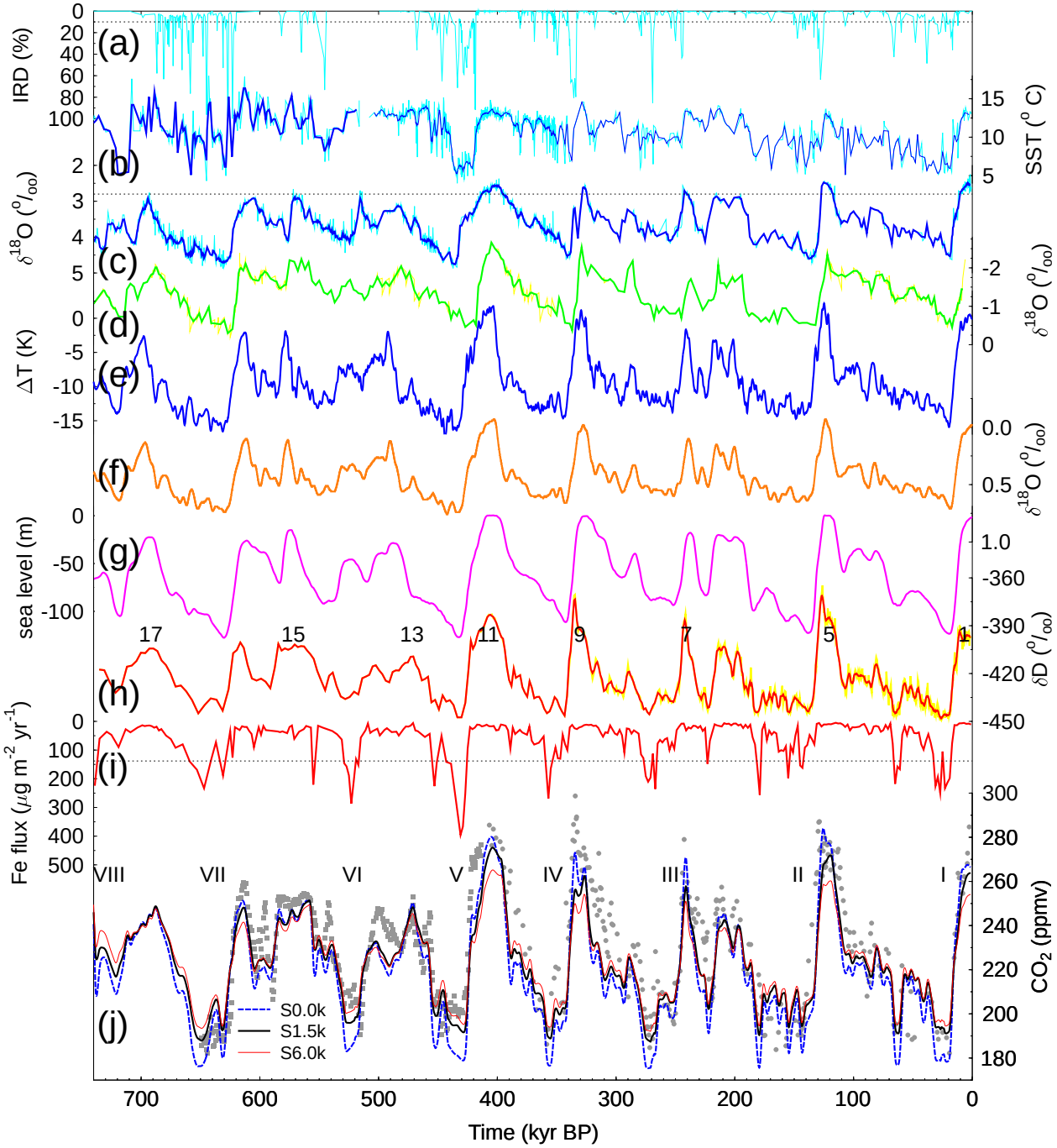
f: deep sea ΔT

g: sea level

h: SO SST

i: Fe fert.

j: CO_2

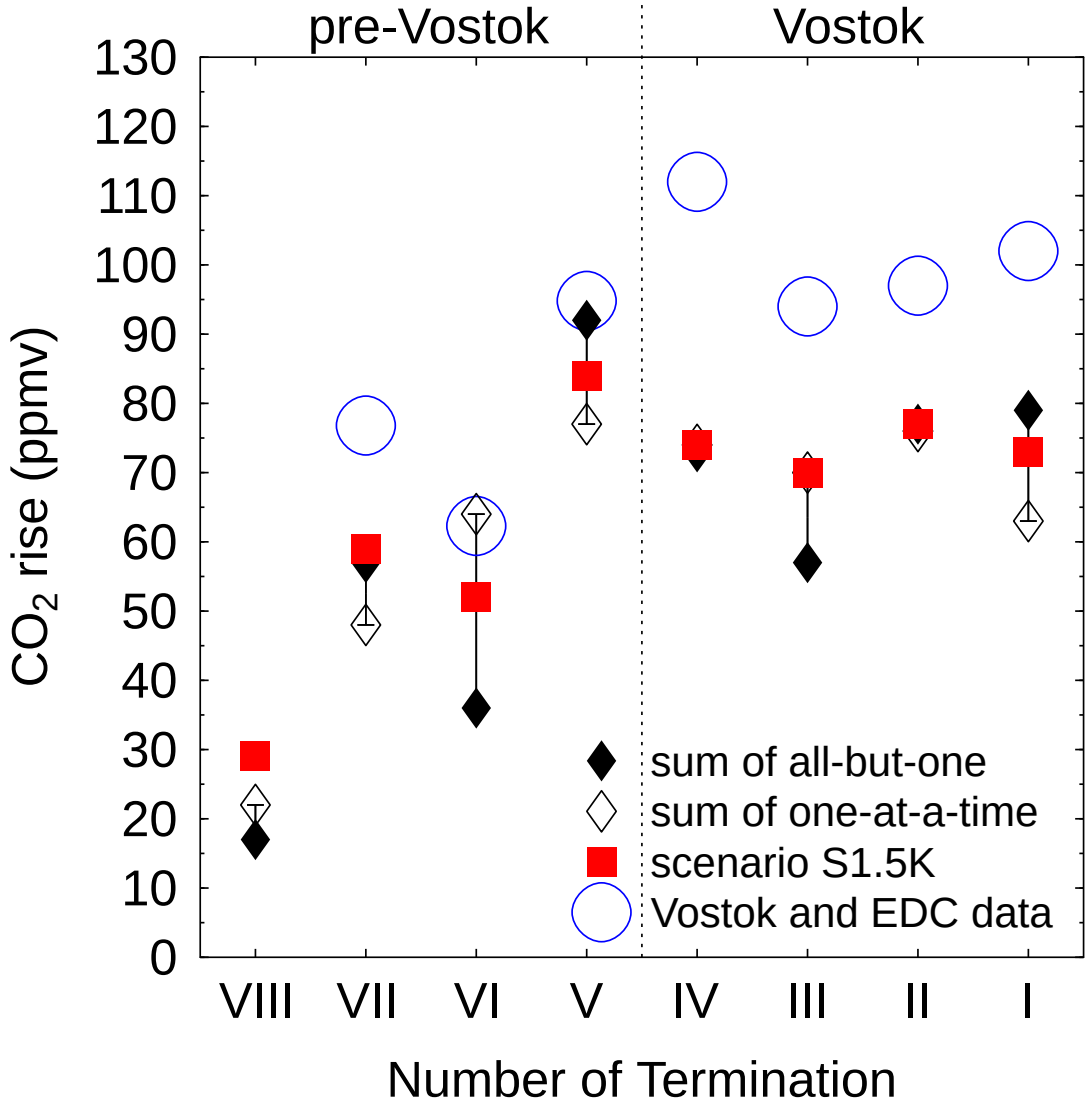


Köhler and Fischer, 2006, Climate of the Past

Terminations I-VIII

combined simulation vs. ice core data

~20 ppmv per Termination are missing



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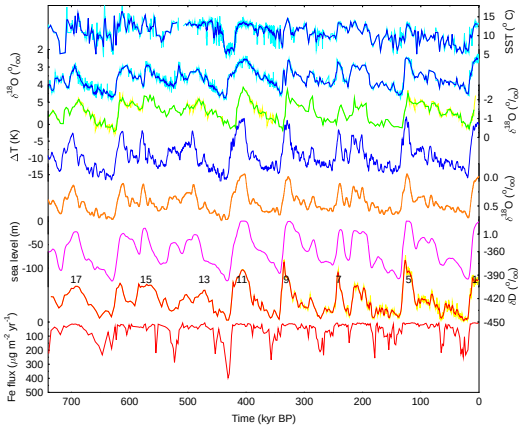
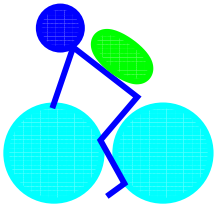
Beyond EPICA — Forcings

OLD EPICA 740kyr

Köhler & Fischer (2006)



⇒  ⇒ CO_2, $\delta^{13}C$

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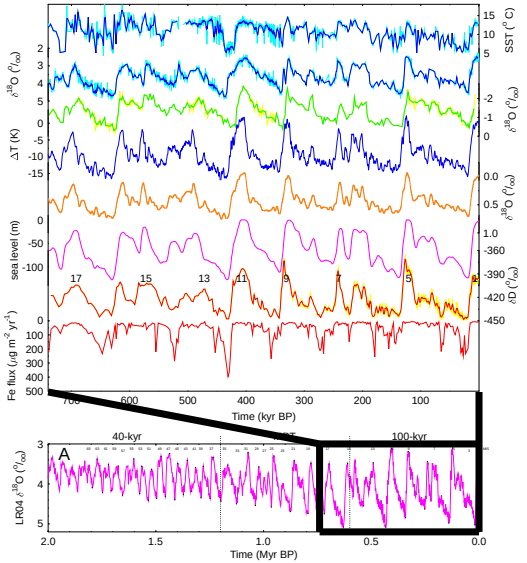
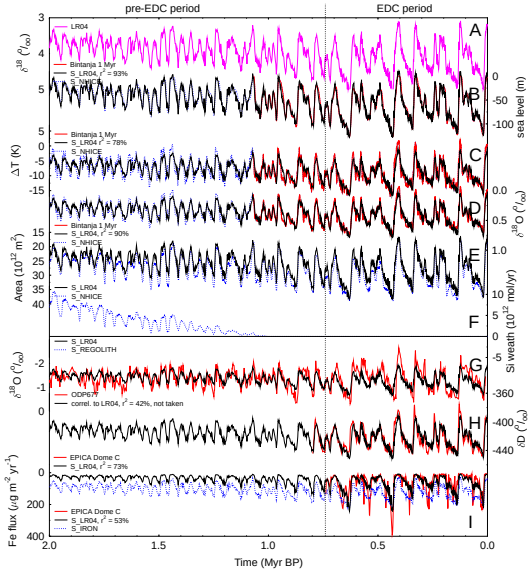
740 kyr



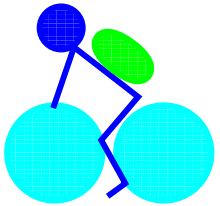
2 Myr



NEW MPT 2 Myr

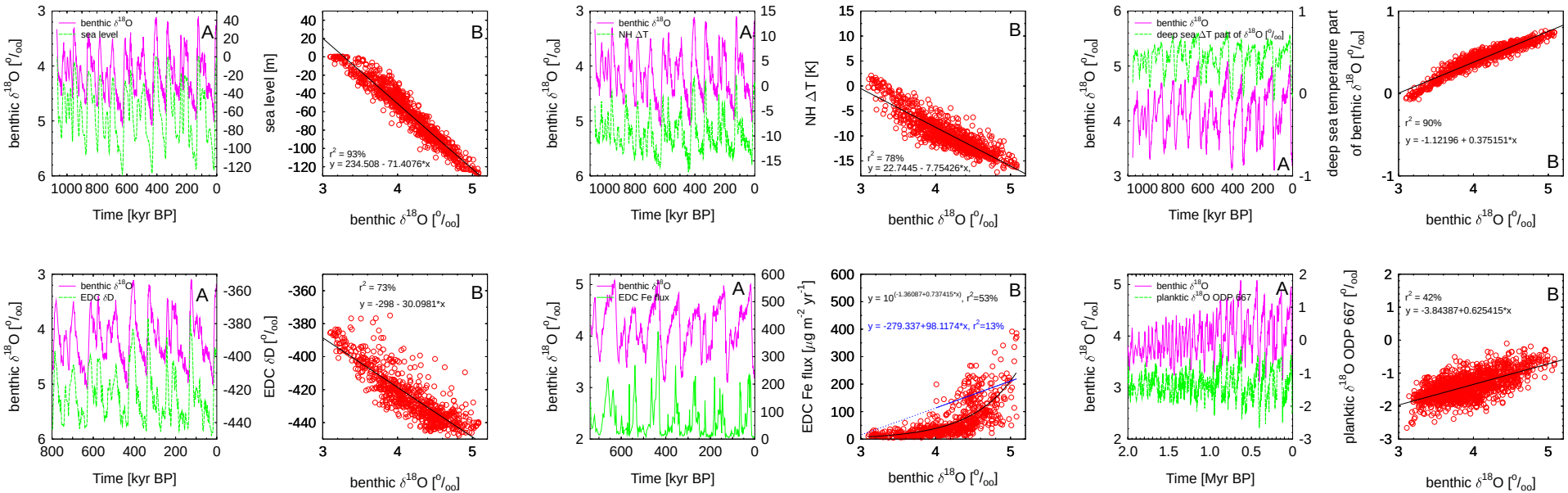
this study

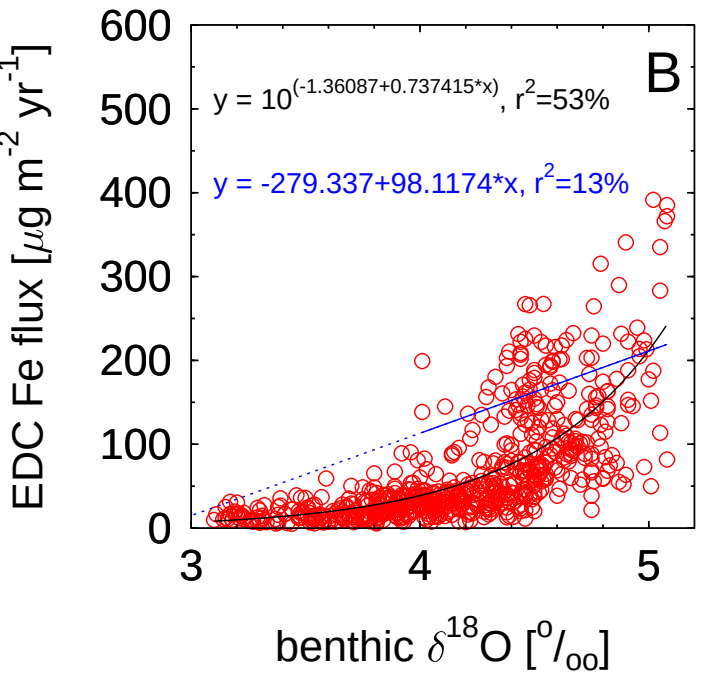
LR04-based

⇒  ⇒ CO_2, $\delta^{13}C$

⇒ LR04-based forcing is a Null Hypothesis

Regressions between LR04 and other Records





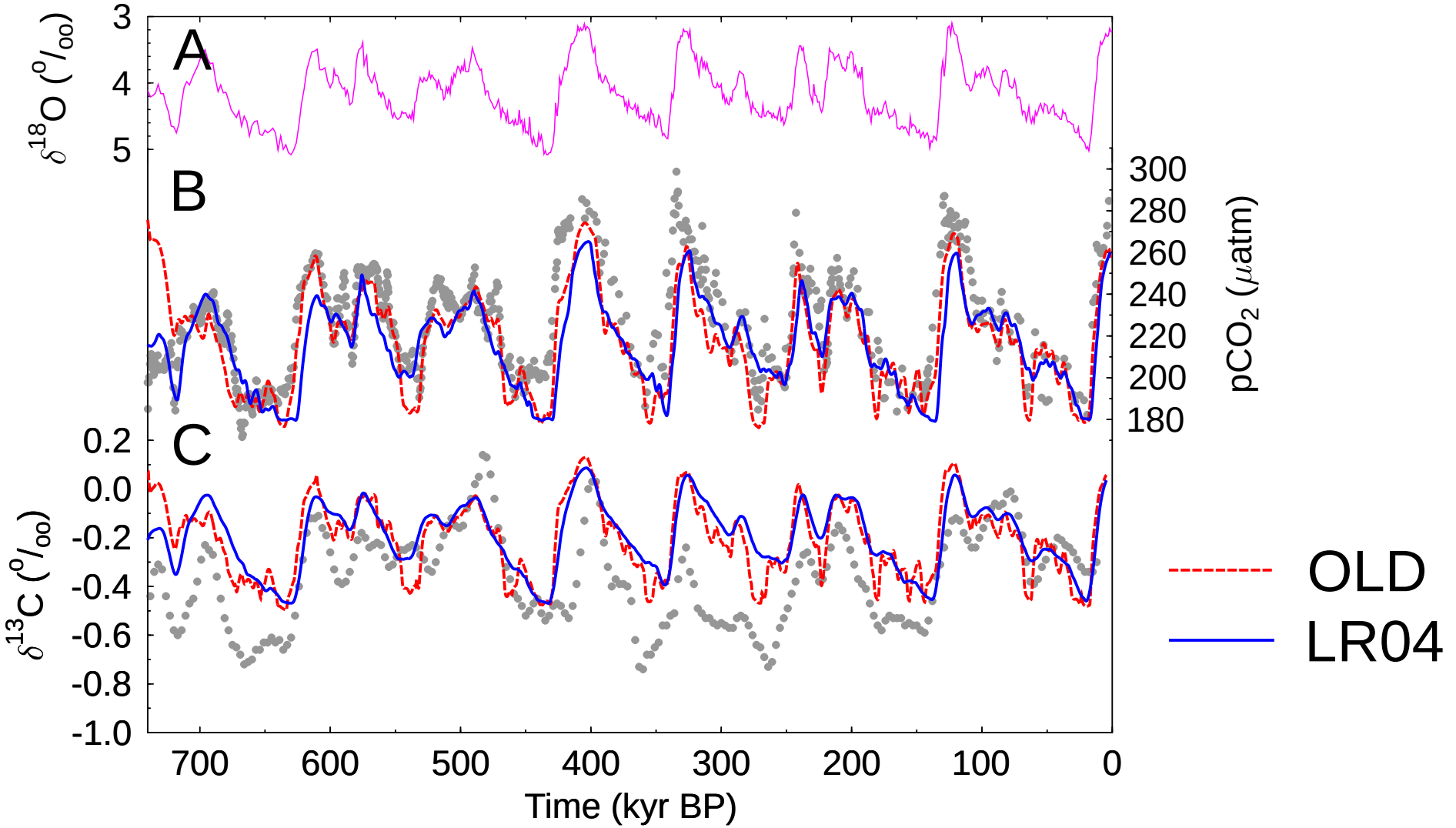
Underlying assumption:

Climate change is similarly related to LR04 in 40k and 100k world

(1) Regression is in general good ($r^2 = 93, 78, 90, 73, 53, 42\%$).

(2) Most difficult is Fe flux to Antarctica (two approaches, see left).

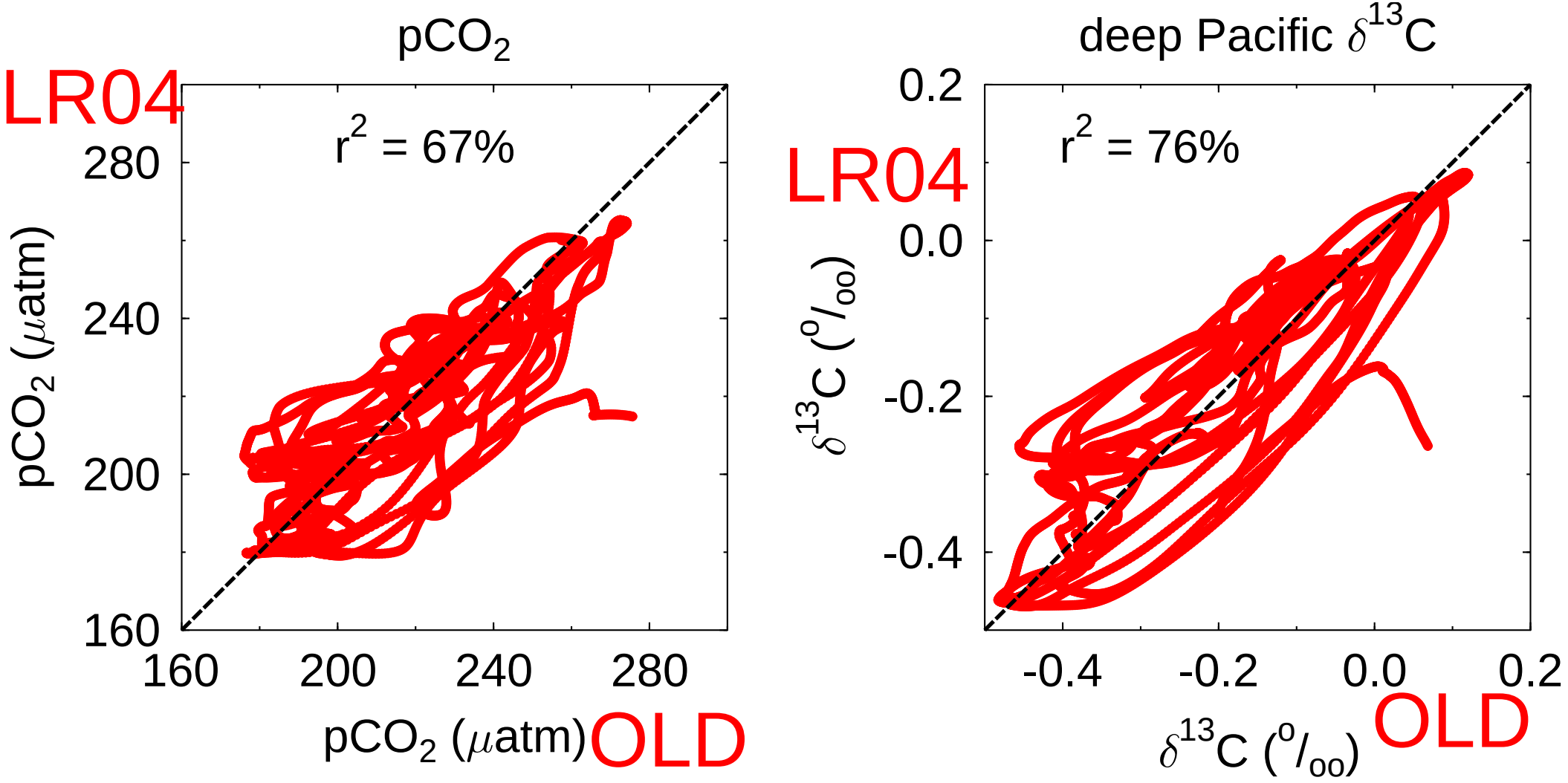
Ground-truthing of LR04-based approach



(1) Simulated glacial/interglacial amplitudes of original approach are about 85% of those in the data sets.

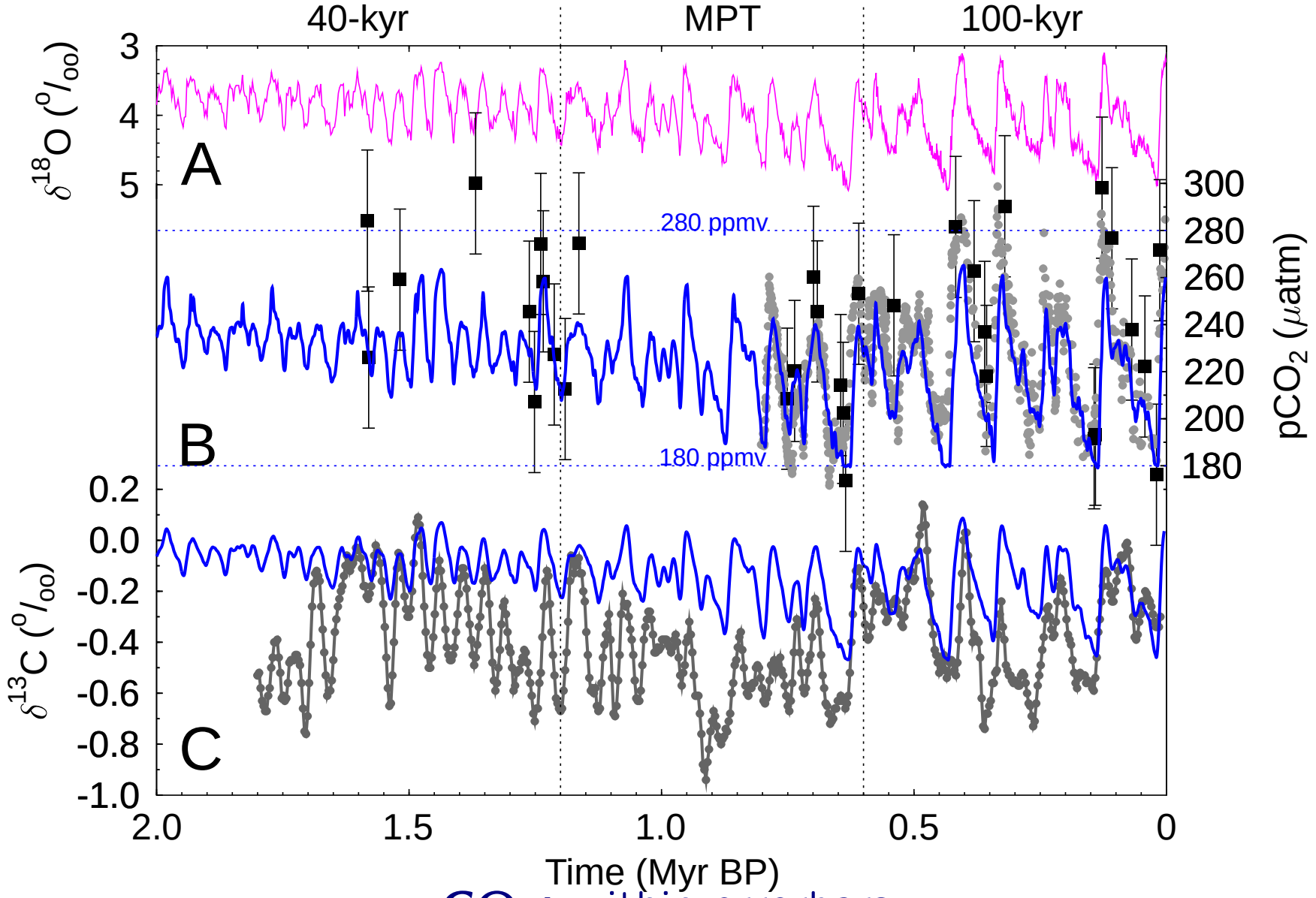
(2) 400-kyr cycle in δ^{13}C (eccentricity) is not covered by simulations.

Ground-truthing of LR04-based approach



LR04-based approach loses about 10%
of the glacial/interglacial amplitudes in both pCO_2 and $\delta^{13}C$.

Null Hypothesis

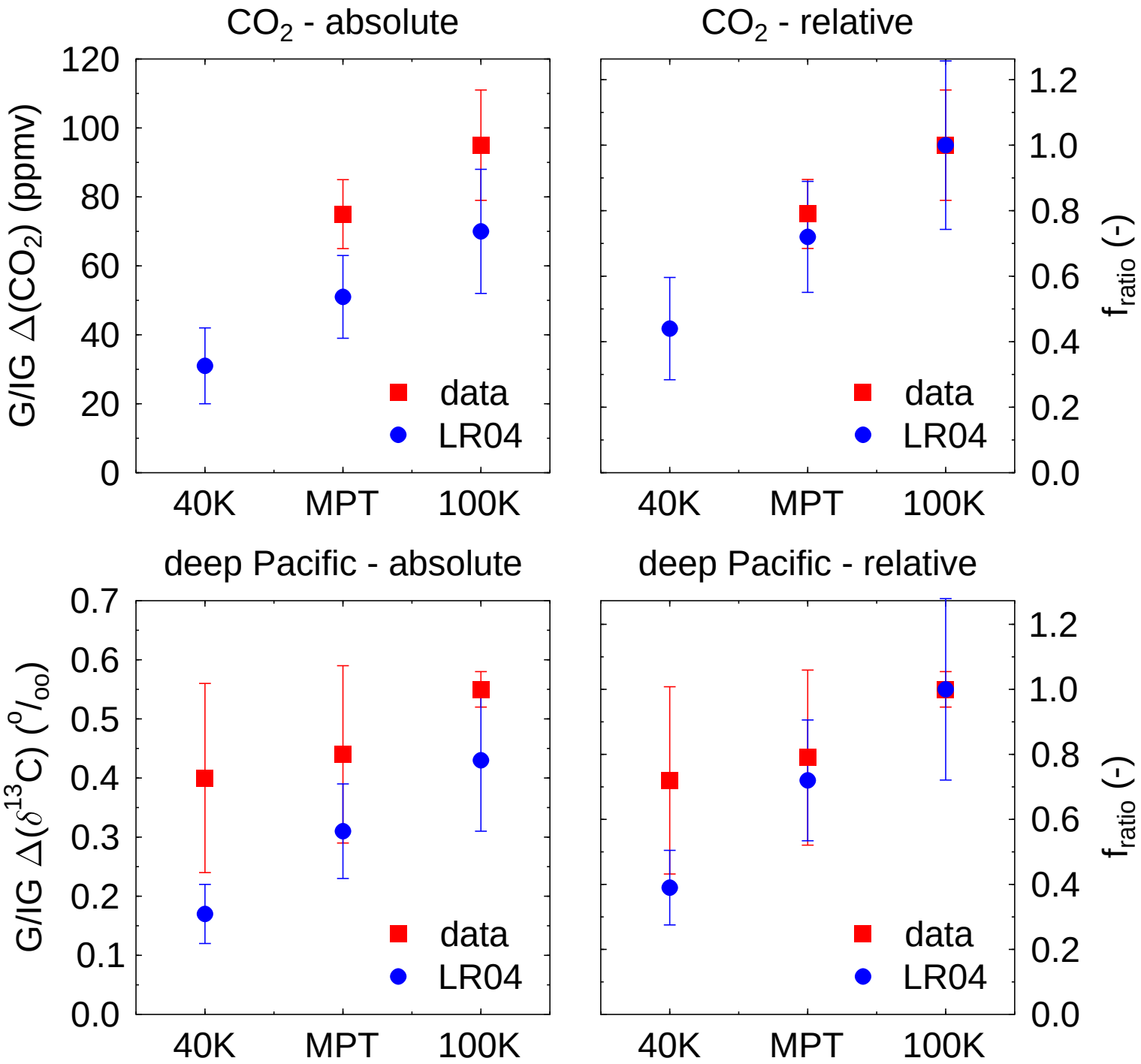


$p\mathbf{CO_2}$**:** within errorbars;

$\delta^{13}\mathbf{C}$**:** amplitudes in 40-kyr world too small

$\Rightarrow$ **Reject Null Hypothesis**

Variation in Glacial/Interglacial Amplitudes



Improving the Null Hypothesis

LR04 regression function between LR04 and climate records
Null Hypothesis

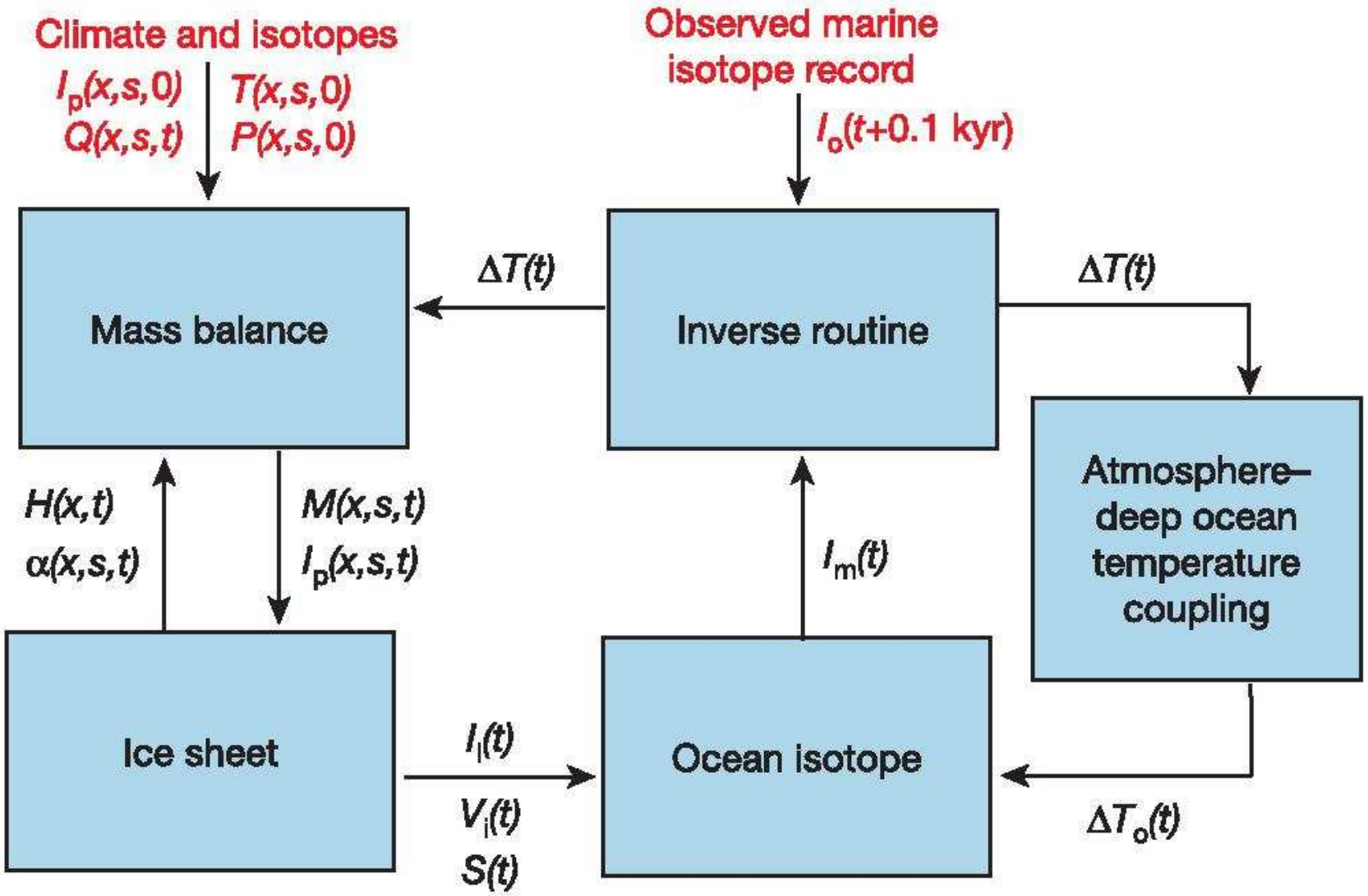
Improving the Null Hypothesis

LR04	regression function between LR04 and climate records
Null Hypothesis	
IRON	alternative regression for Fe flux (Southern Ocean marine export production)

Improving the Null Hypothesis

LR04 **Null Hypothesis**	regression function between LR04 and climate records
IRON	alternative regression for Fe flux (Southern Ocean marine export production)
NHICE	Sea level, ΔT in deep ocean and northern hemisphere from Bintanja & van de Wal (submitted)

Northern Hemispheric Ice Sheets
Bintanja et al. (2005, submitted)



Deconvolute LR04 stacked $\delta^{18}O$ into climate variables

($\Delta T_{\text{deepocean}}$, $\Delta T_{\text{atmosphere}}$, size of ice sheets, sea level)

Improving the Null Hypothesis

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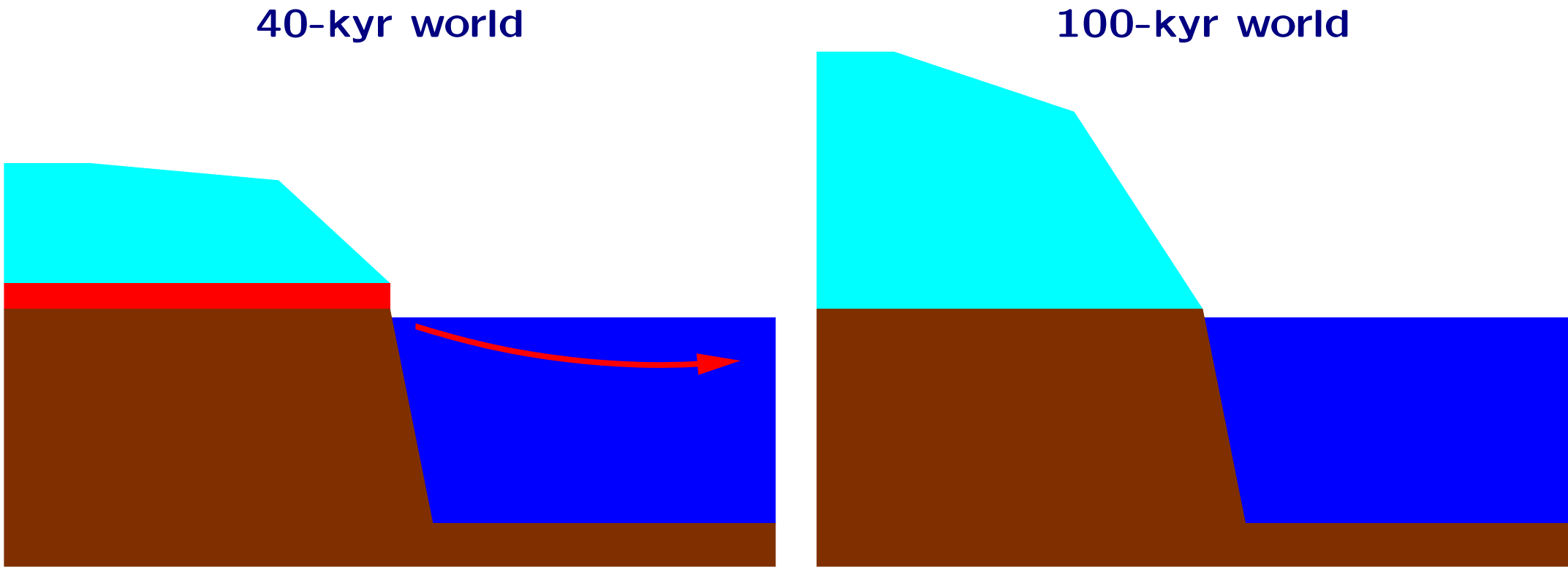
NHICE	Sea level, ΔT in deep ocean and northern hemisphere from Bintanja & van de Wal (submitted)
REGOLITH	as NHICE + *Regolith Hypothesis* (Clark et al., 2007), additionally changing silicate weathering rates between 2 and 1 Myr BP

Regolith Hypothesis
Clark et al. (2007)



small	$\Delta\delta^{18}O$	large
small	NH ice sheet	large
yes	bedrock regolith	no
yes	silicate weathering due to regolith erosion	no

$\Rightarrow$ Impacts of weathering on Carbon Cycle

Improving the Null Hypothesis

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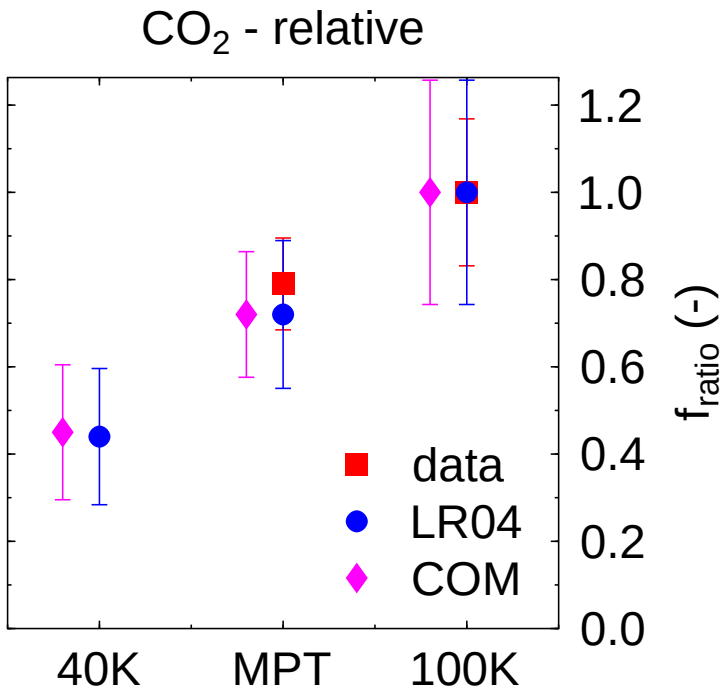
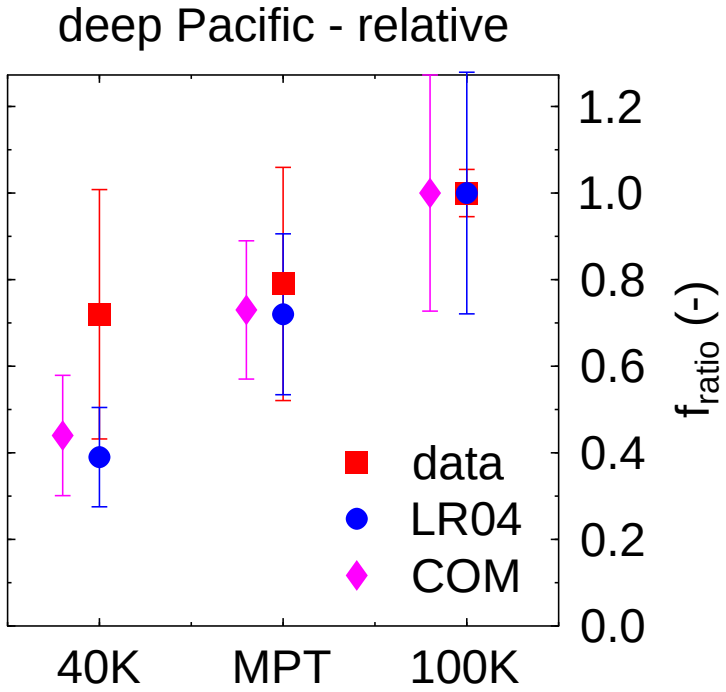
IRON	alternative regression for Fe flux (Southern Ocean marine export production)
NHICE	Sea level, ΔT in deep ocean and northern hemisphere from Bintanja & van de Wal (submitted)
REGOLITH	as NHICE + *Regolith Hypothesis* (Clark et al., 2007), additionally changing silicate weathering rates between 2 and 1 Myr BP
COM	combining all

Variation in Glacial/Interglacial Amplitudes

Nearly no improvements
in simulated deep ocean $\delta^{13}C$
and atmospheric CO_2
through additional assumptions
(scenario COM).





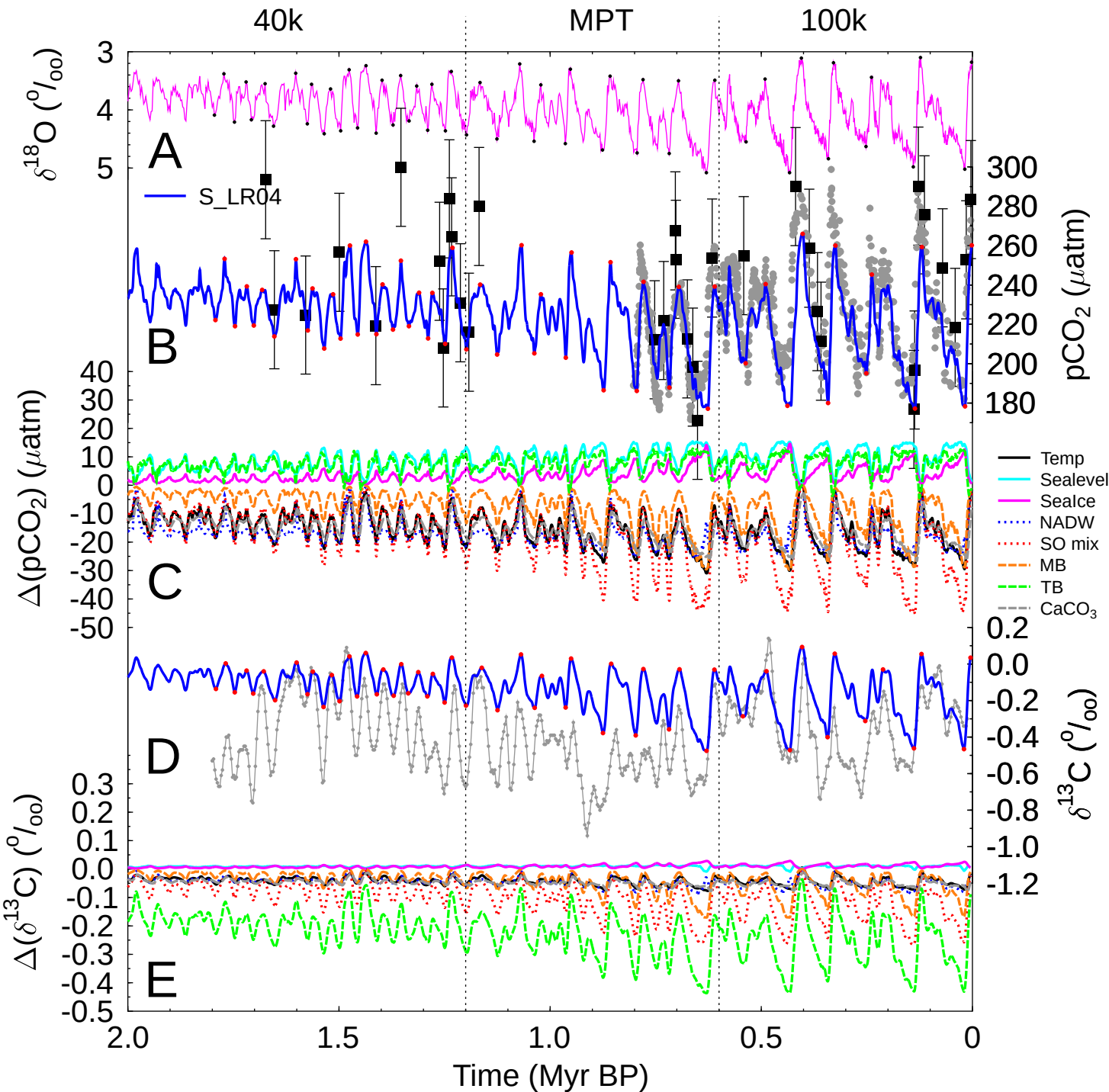
Looking for Responsible Processes...

Southern Ocean processes

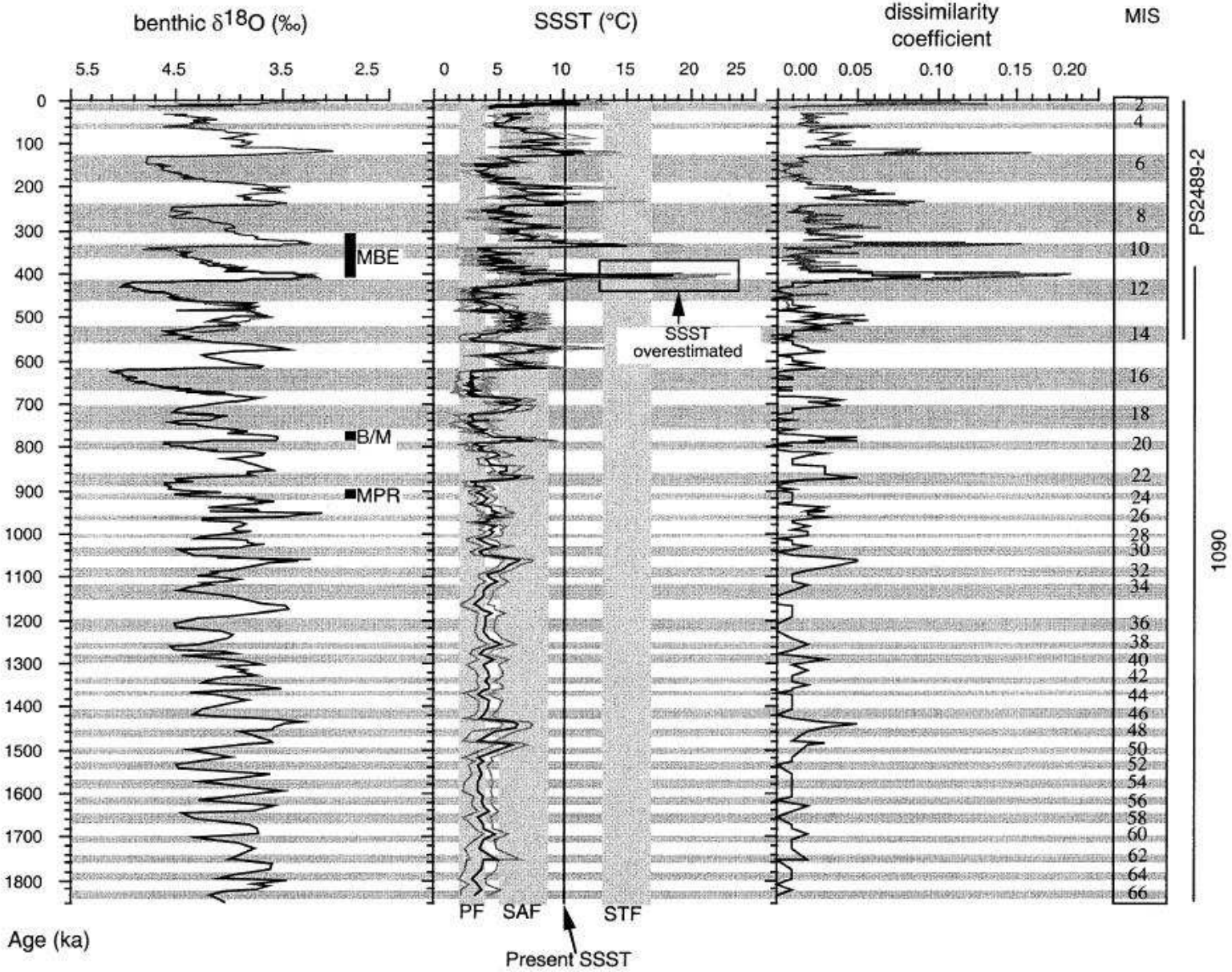
vertical mixing
biological pump

change most over MPT.

Or
Terrestrial biosphere
For what reason?



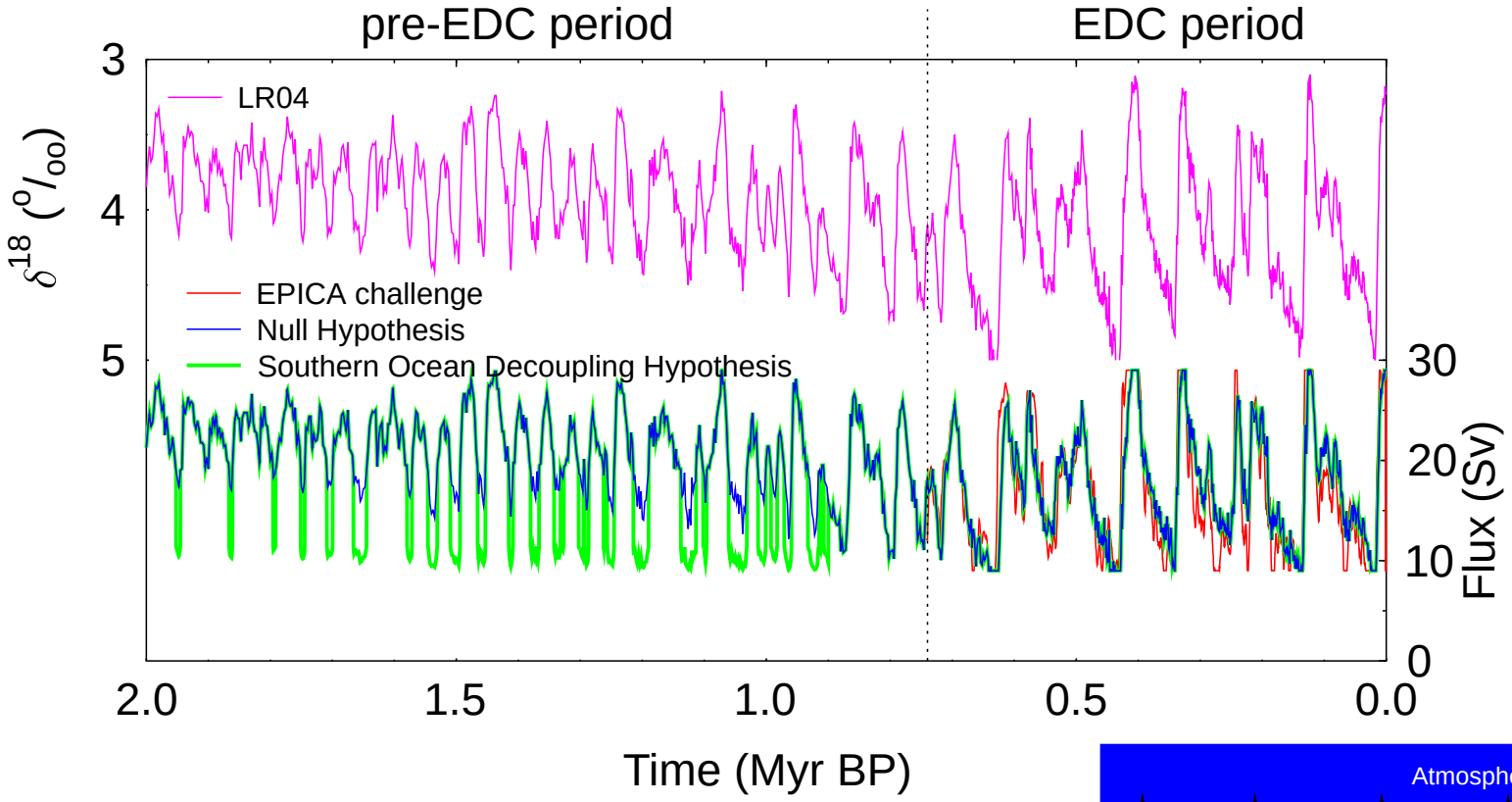
Summer SST in the Southern Ocean OPD 1090



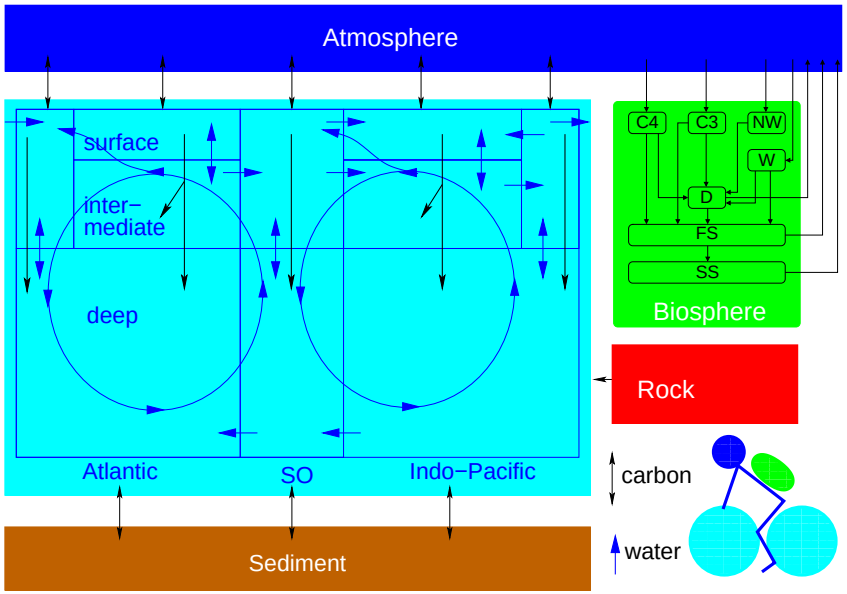
Modern Analog Technique applied on planktonic foraminifers.

Indeed smaller G/IG amplitude in 40k world (Becquey & Gersonde, 2002).

Revised Southern Ocean Vertical Mixing



Decoupling of
Southern Ocean SST and mixing
probably due to changed
cryosphere/ocean interaction.



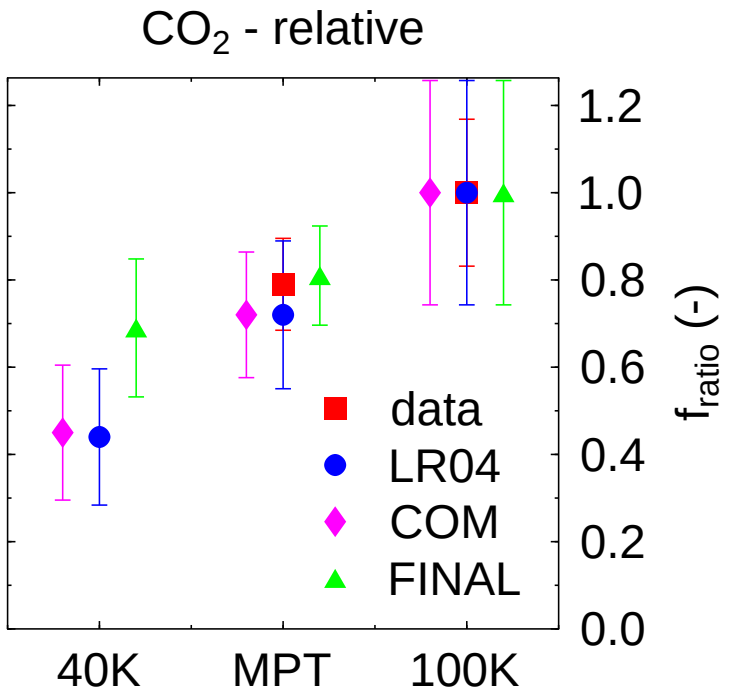
Box model of the Isotopic Carbon cYCLE

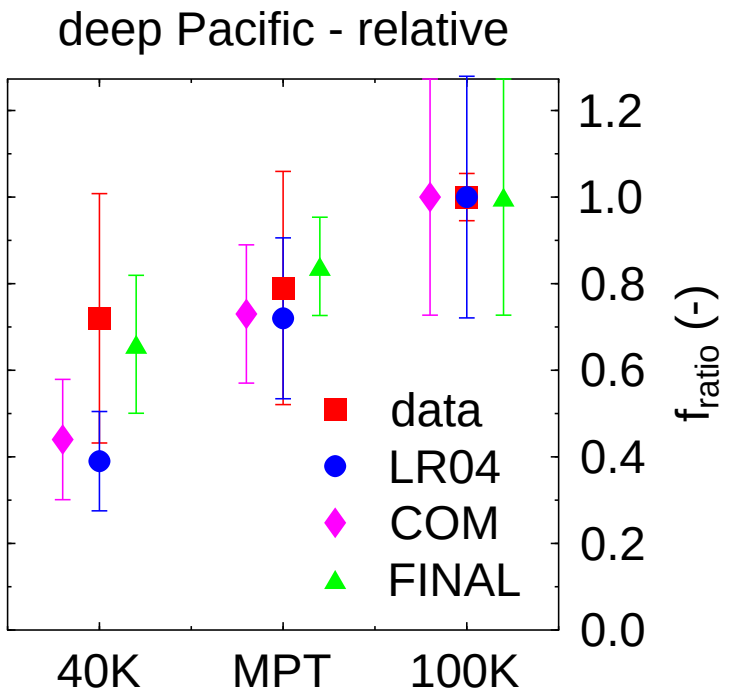
BICYCLE

Results for the Southern Ocean Decoupling Hypothesis

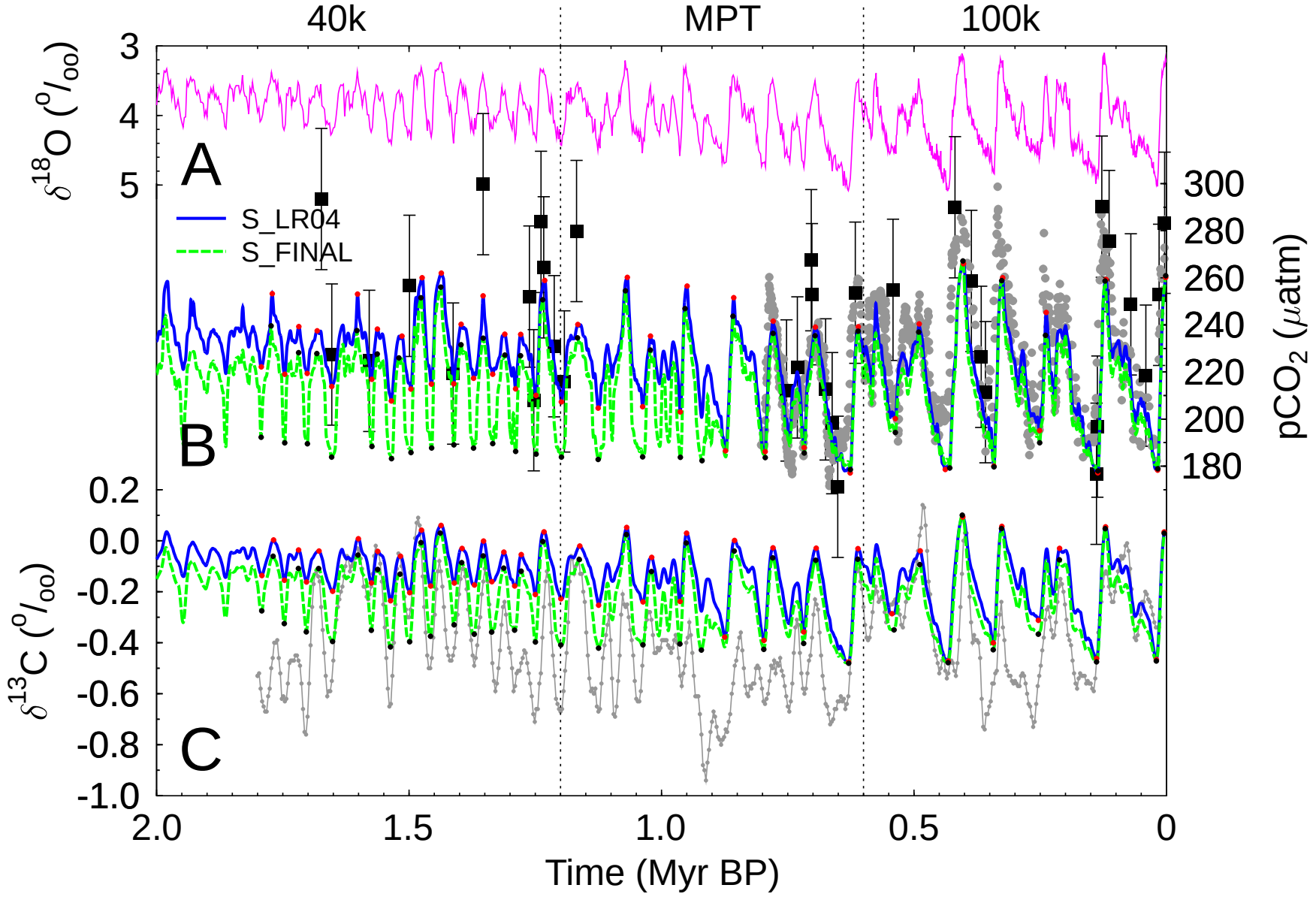
Large improvements
in simulated deep ocean $\delta^{13}C$
in scenario FINAL

A combination of all
previous improvements and the
Southern Ocean
Decoupling Hypothesis





Results for the Southern Ocean Decoupling Hypothesis



pCO_2: within errorbars (apart from 3 points)

$\delta^{13}C$: average G/IG amplitudes okay, $400 - 500$ kyr cycle missing

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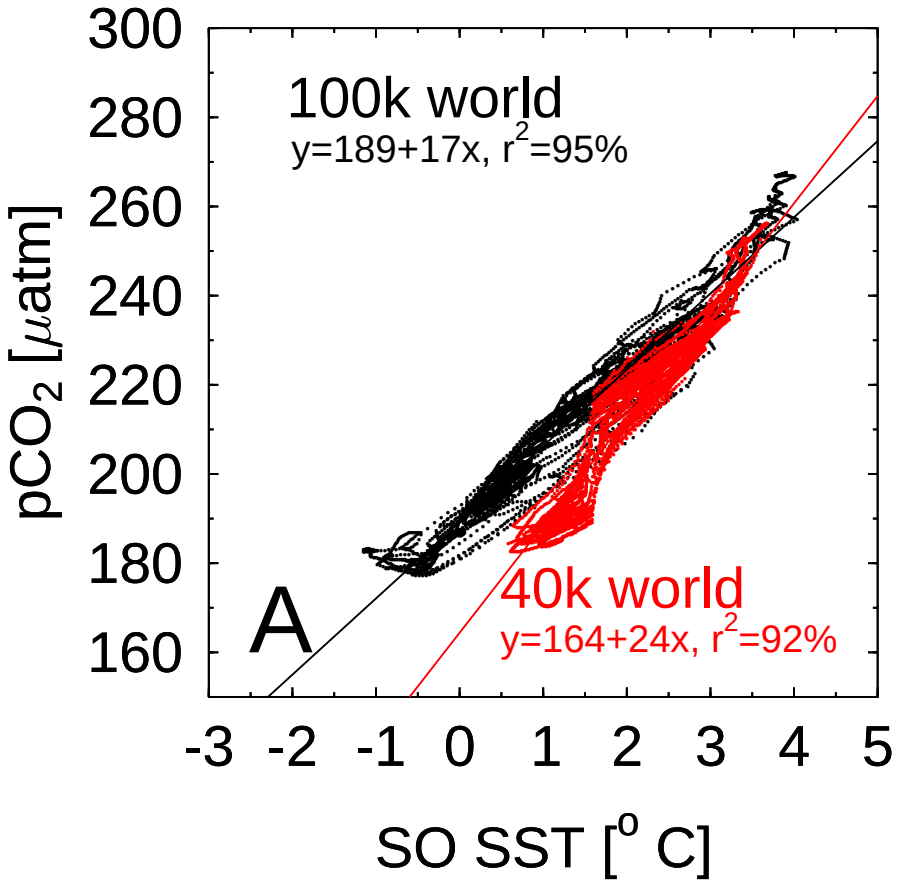

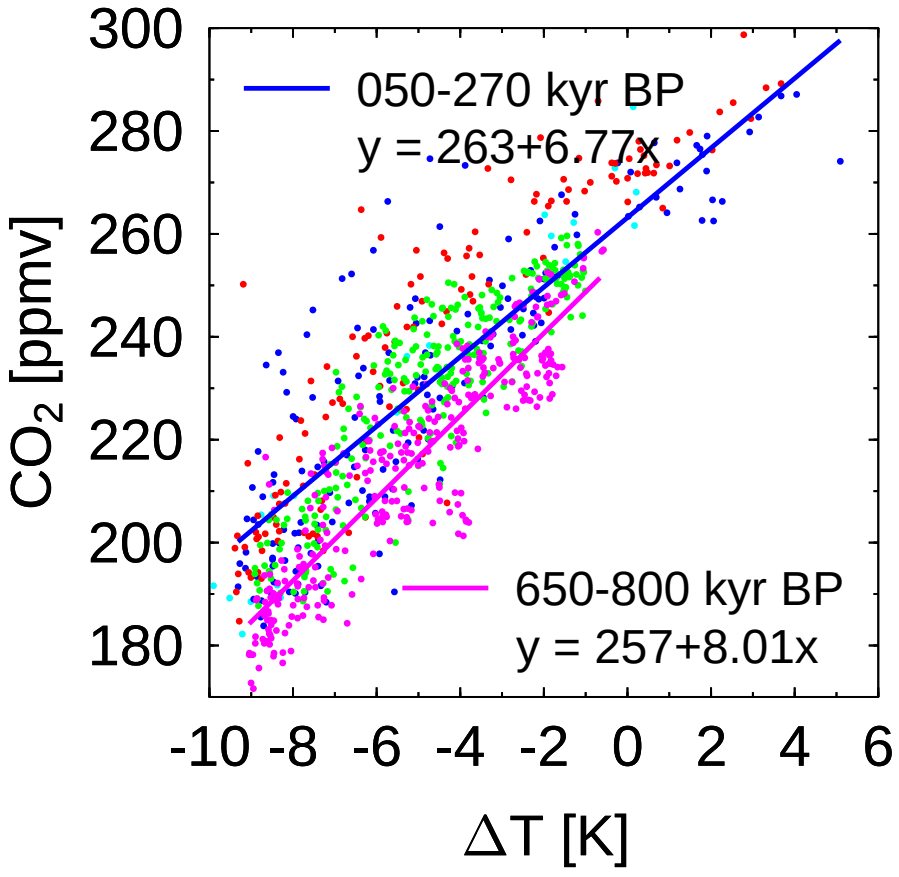

Consequence:

Decoupling of Antarctic ΔT (SO SST) and atmospheric CO_2.

Already to some extent seen in EPICA Dome C ice core data.

Outline

The data

The model

The EPICA Time Window

The Southern Ocean Decoupling Hypothesis

Other Theories

Take-home messages

Other Recent Hypotheses

Insolation Canon Hypothesis (Schulz & Zeebe, 2006):

Terminations (I – VII) are triggered by a canon of increased summer insolation in South and North.

$\Rightarrow$ **Weak support (change in SH) for SO Decoupling Hypothesis.**

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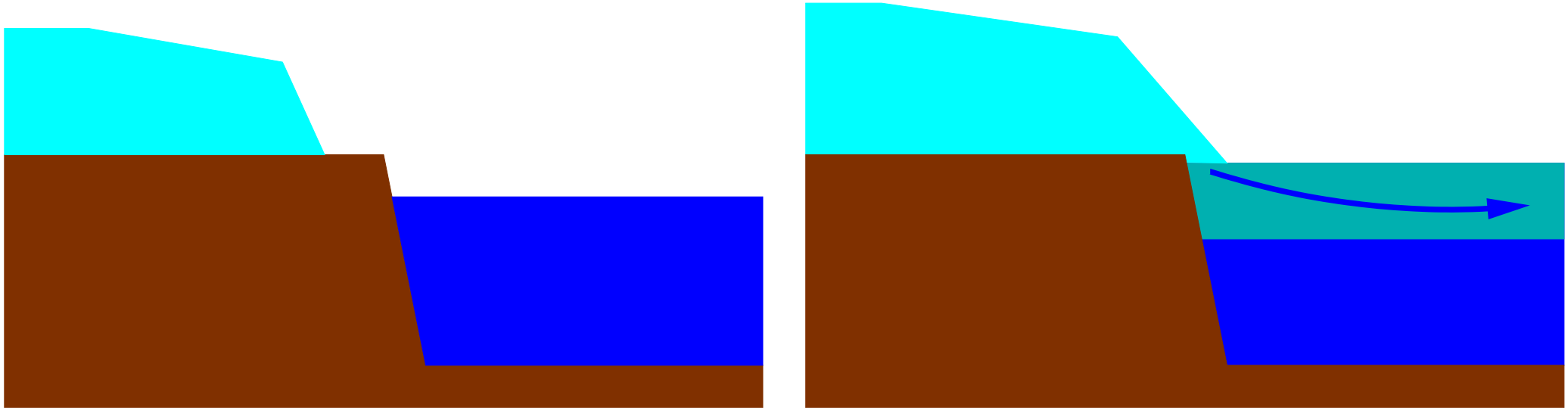
East Antarctic Ice Sheet (EAIS) Hypothesis (Raymo et al., 2006):

Smaller EAIS with continental ice margin (no shelves) in 40-kyr world

⇒ **Cryosphere/ocean interaction in SO, but with 20k periodicity.**

EAIS Hypothesis (Raymo et al., 2006)

40-kyr world **100-kyr world**



small	$\Delta\delta^{18}O$	large
warm	glacials ΔT	cold
small	EAIS	large
no	marine ice shelves	yes

Different freshwater input in Southern Ocean.

Detailed impact on ocean circulation difficult to estimate.

$\Rightarrow$ **Impacts through Southern Ocean circulation on Carbon Cycle**

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4. Alternative hypotheses on the MPT do not violate our hypothesis and give support to the importance of the Southern Ocean/Antarctica for the MPT.

5. We argue to include more often evidences from the carbon cycle (e.g. $\delta^{13}C$) in the interpretation of climate variations.

Thank you for your attention