Southern Ocean buoyancy forcing of ventilation, and glacial-interglacial atmospheric CO_2 change

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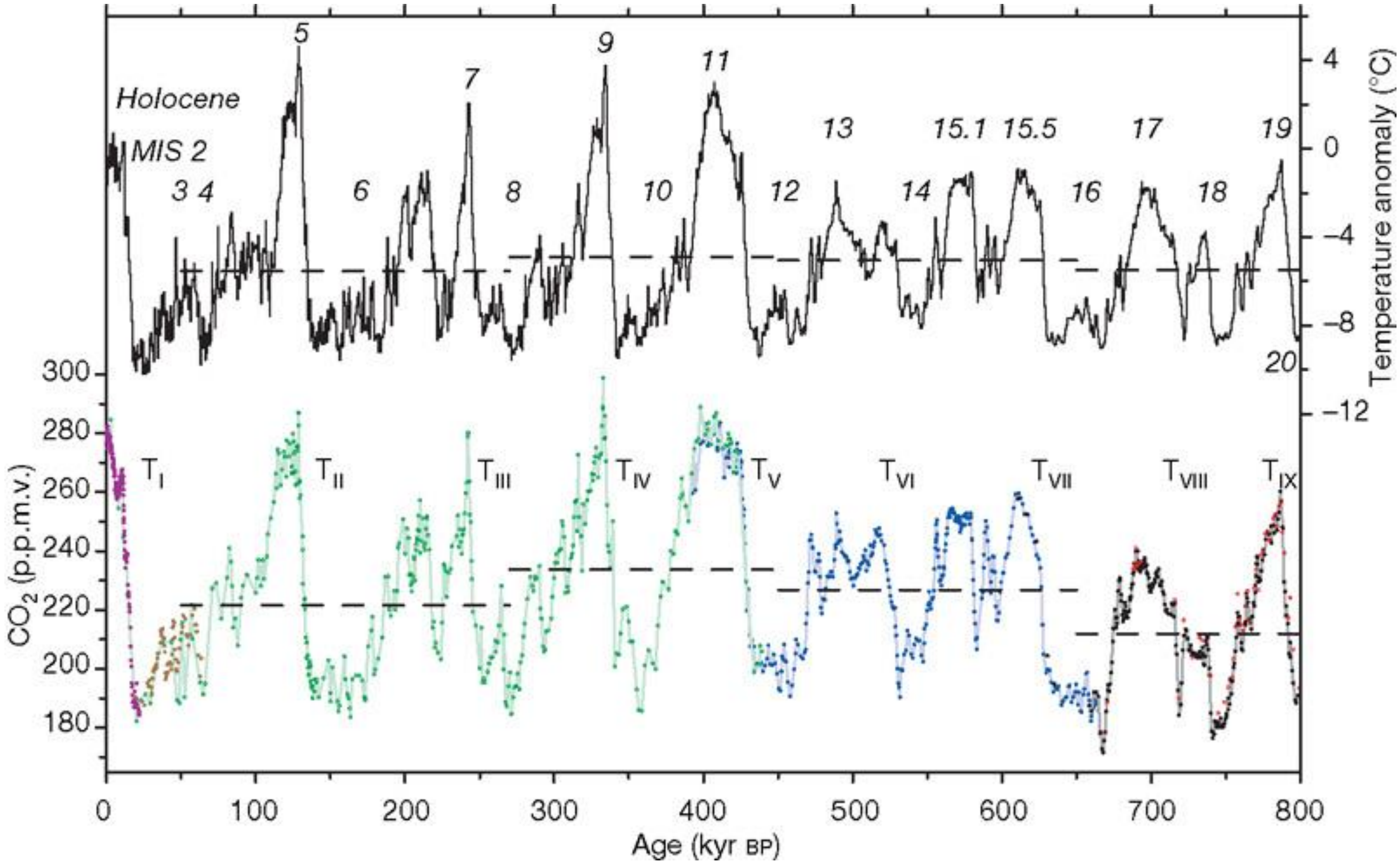
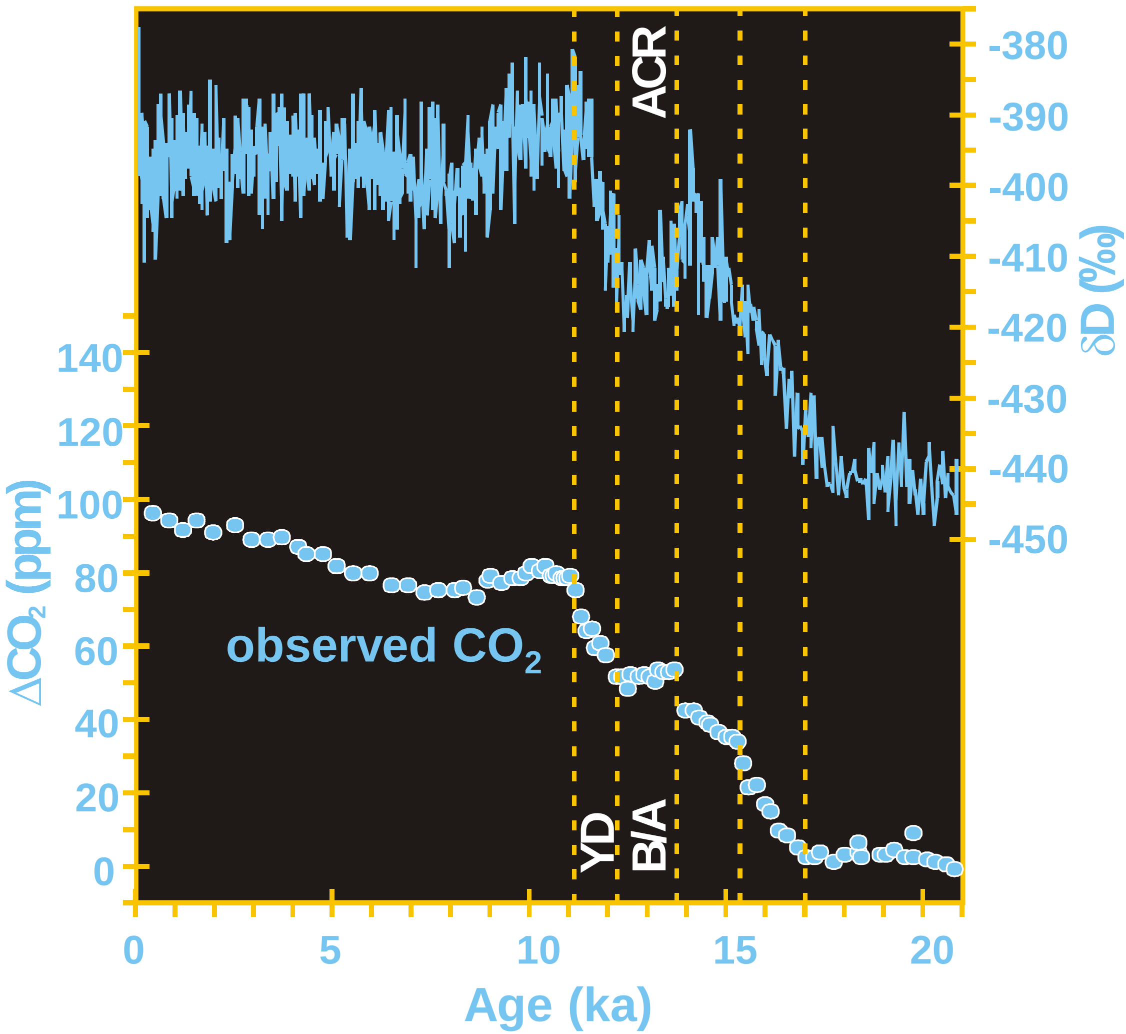
Dome C temperature (deuterium) and CO_2



Lüthi et al, Nature 453, 379-382(2008)

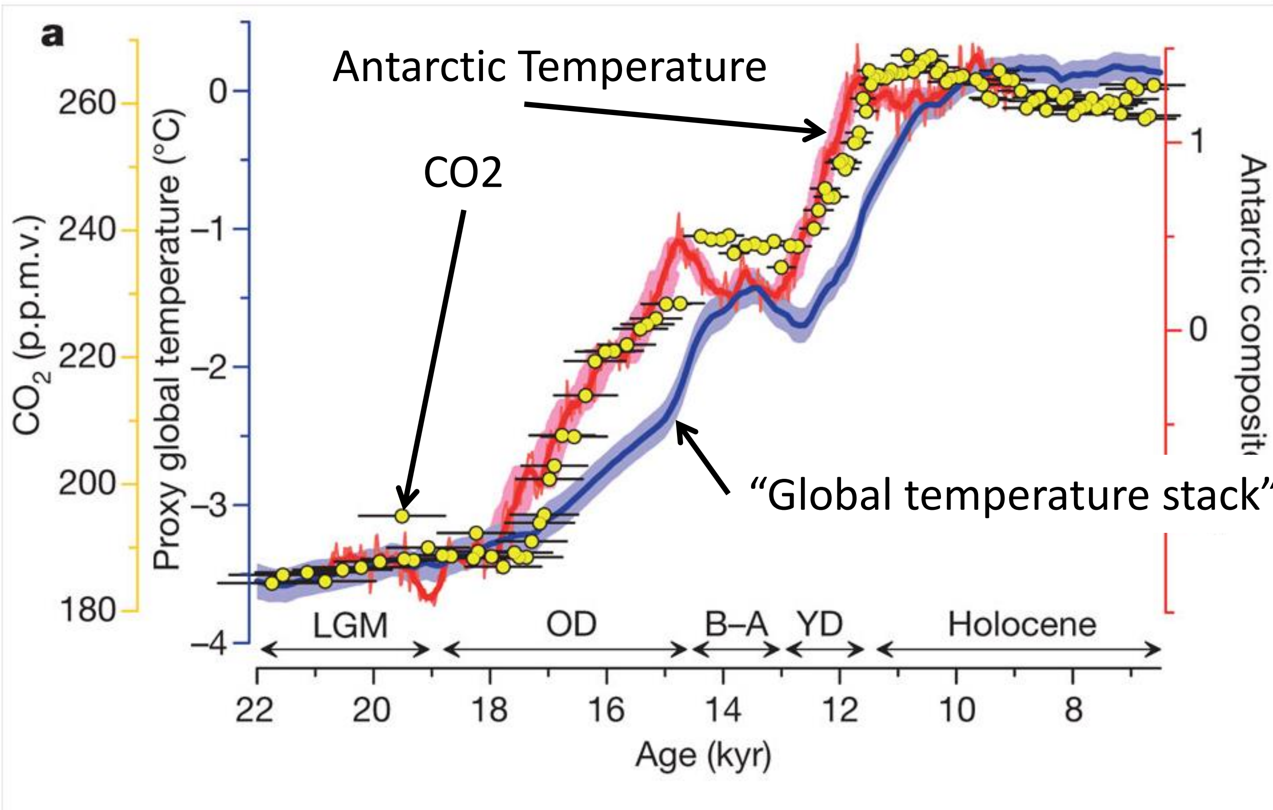
Glacial-interglacial CO_2 change

- 80ppm change occurs in 6000 years.
- Change is co-incident with increase in Antarctic temperature
  - Before global or northern hemisphere temperature increase.



data - Dome C δD; *Jouzel et al.* [2001]
Dome C CO_2; *Flückiger et al.* [2002], *Monnin et al.* [2001]

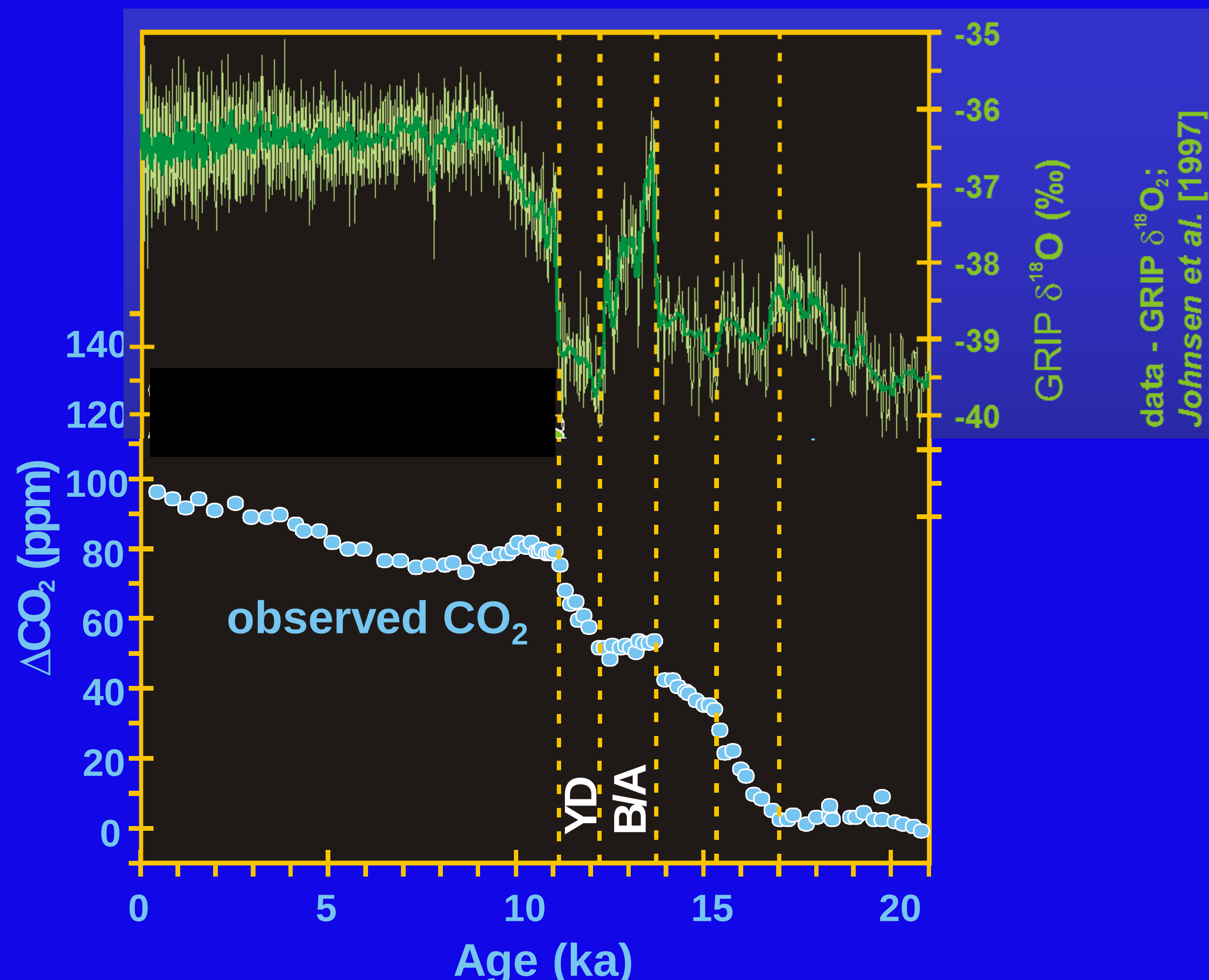
Comparison to global temperature



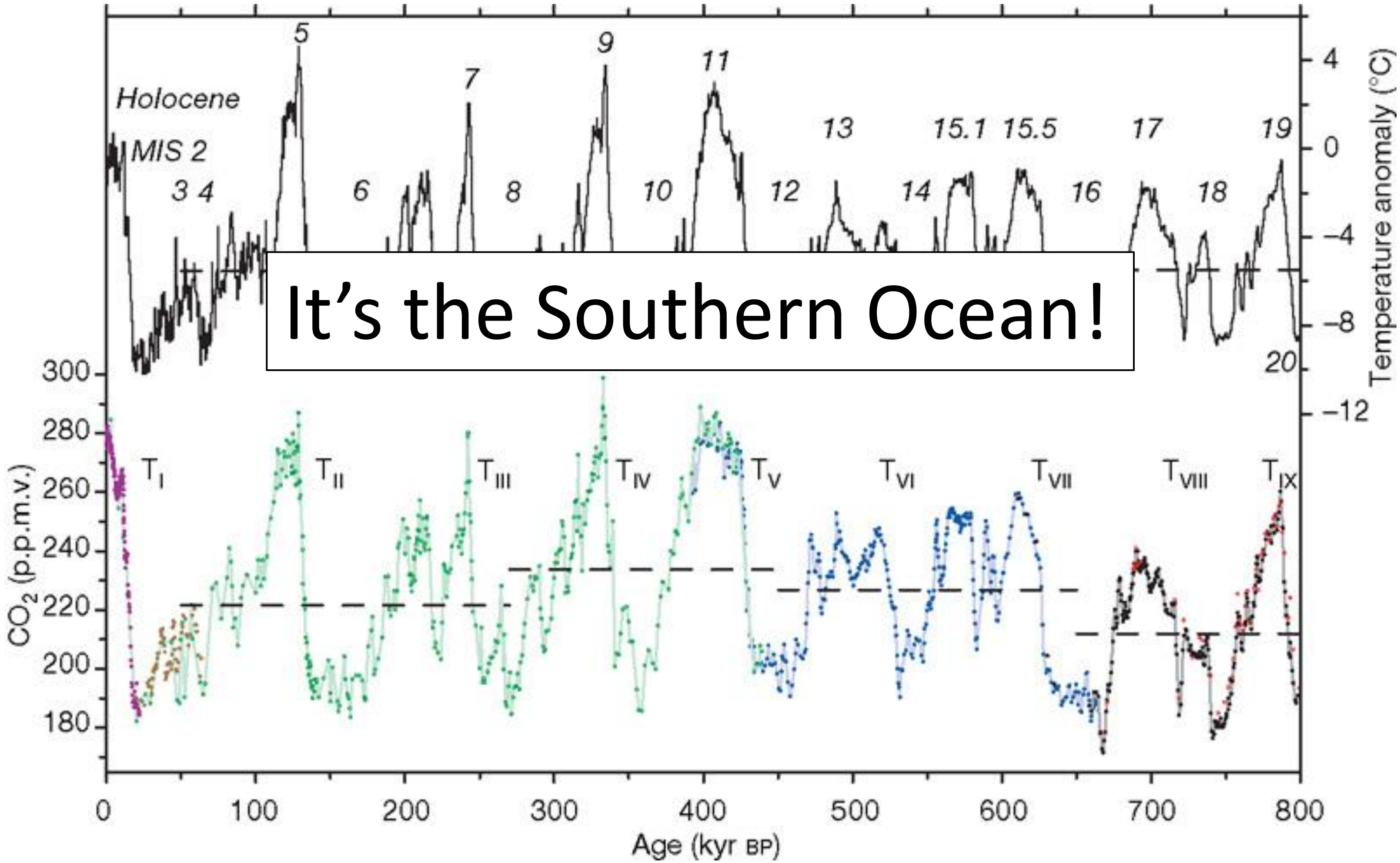
- Shakun et al, nature 484, 49-54 (2012)

Comparison with Greenland record

- CO_2 changes before northern hemisphere deglaciation



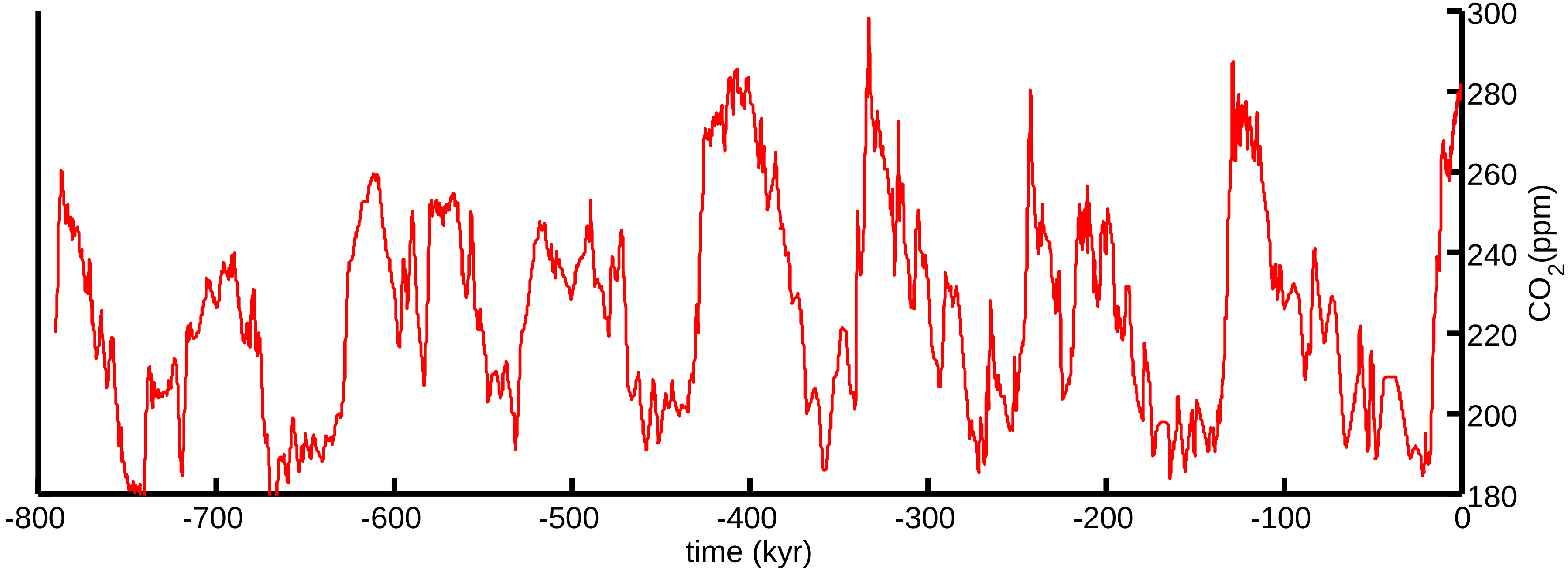
Dome C temperature (deuterium) and CO_2



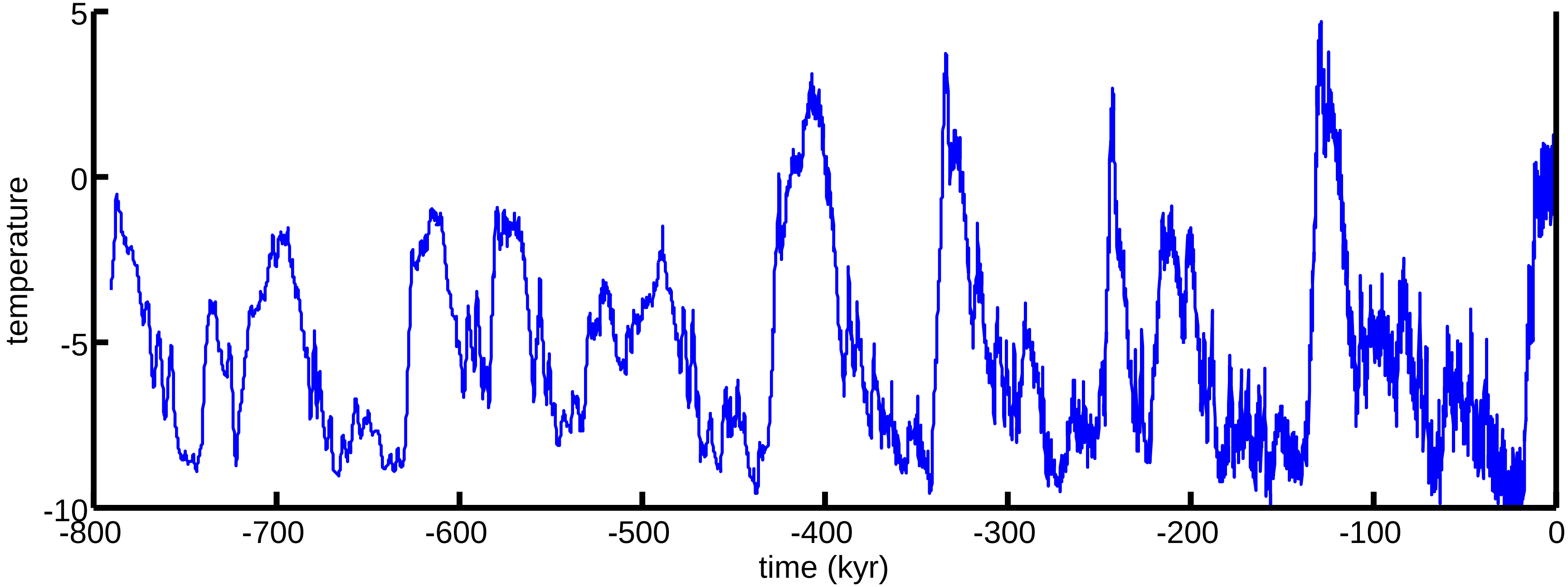
It's the Southern Ocean!

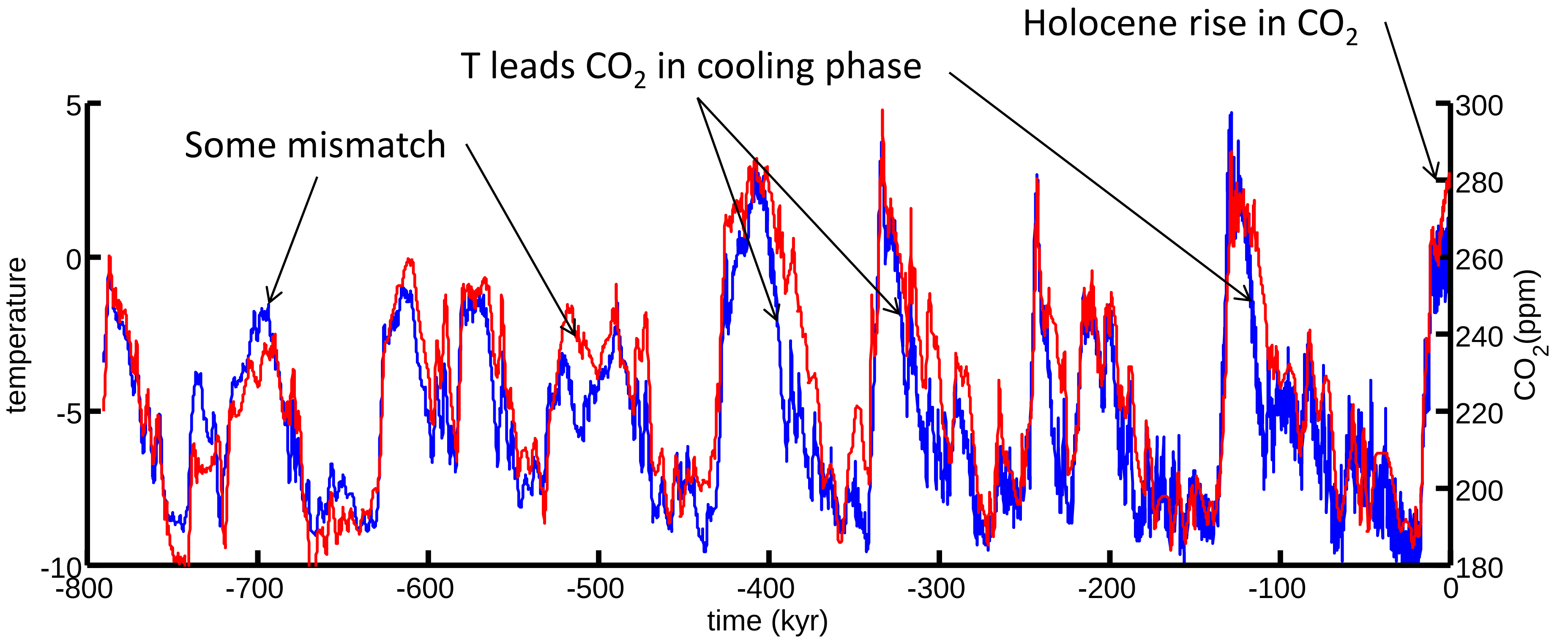
Lüthi et al, Nature 453, 379-382(2008)

Ice core CO_2

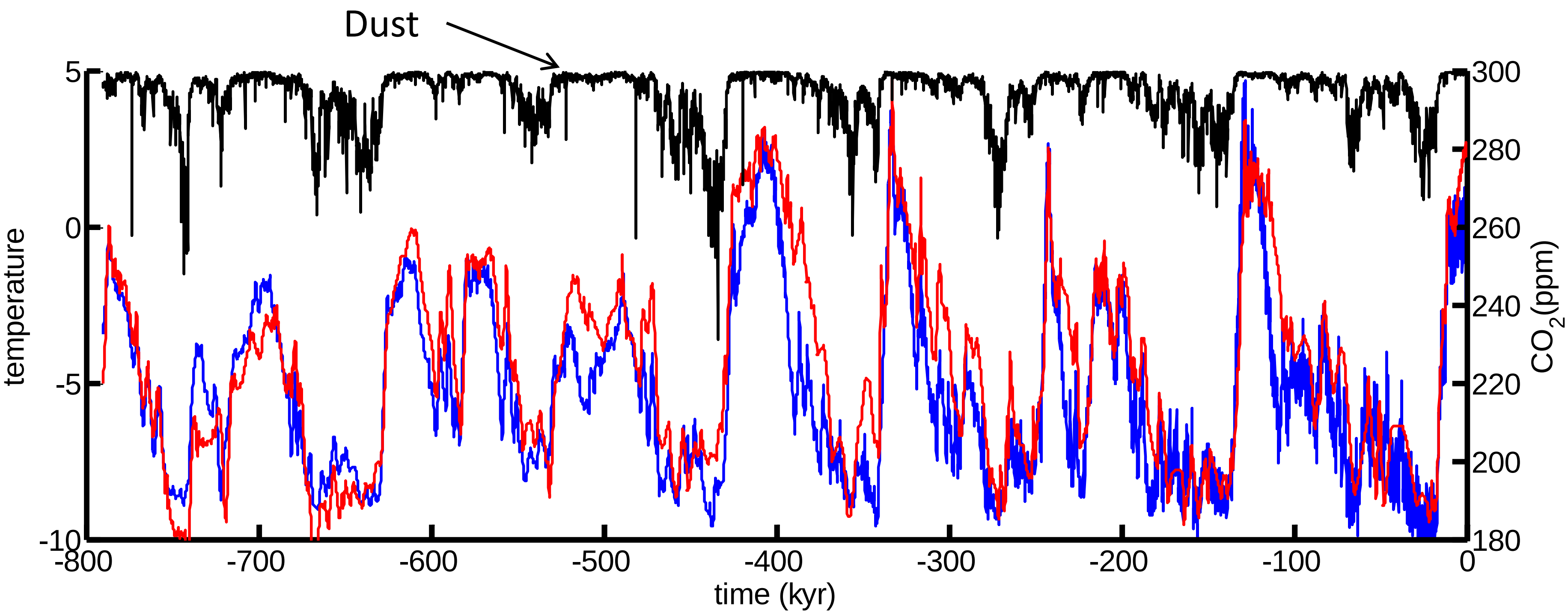

300
280
260
240
220
200
180
CO2(ppm)
-800
-700
-600
-500
-400
-300
-200
-100
0
time (kyr)

Ice core δD





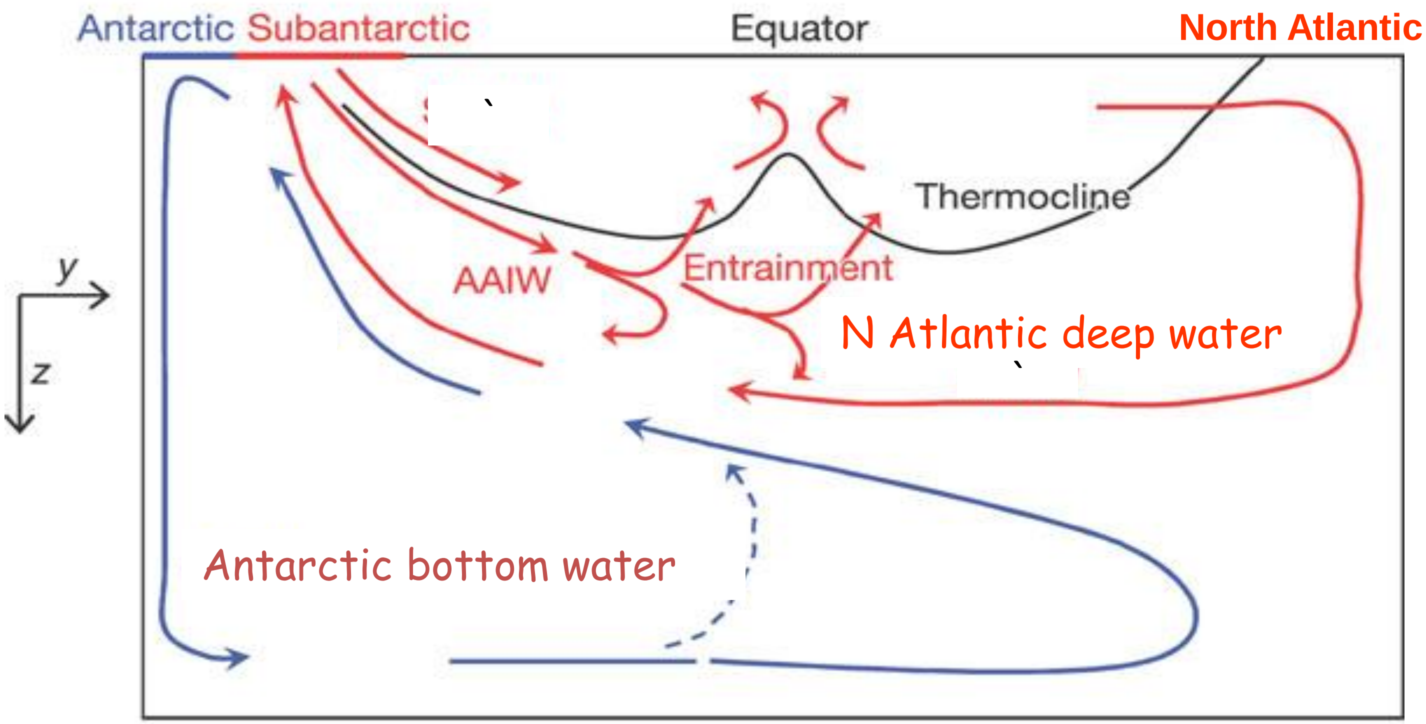
Holocene rise in CO_2
T leads CO_2 in cooling phase
Some mismatch
temperature
5
0
-5
-10
CO_2(ppm)
300
280
260
240
220
200
180
-800
-700
-600
-500
-400
-300
-200
-100
0
time (kyr)



Dust
temperature
5
0
-5
-10
300
280
260
240
220
200
180
CO_2(ppm)
-800
-700
-600
-500
-400
-300
-200
-100
0
time (kyr)

Why is the Southern Ocean so important for atmospheric CO_2?

- The deep sea is where most of the carbon in the ocean-atmosphere system is stored.
- Only in the cold surface oceans can water rapidly move from the surface to the interior.
- The Southern Ocean is where most deep water upwells, and also the formation zone for AAIW and AABW.

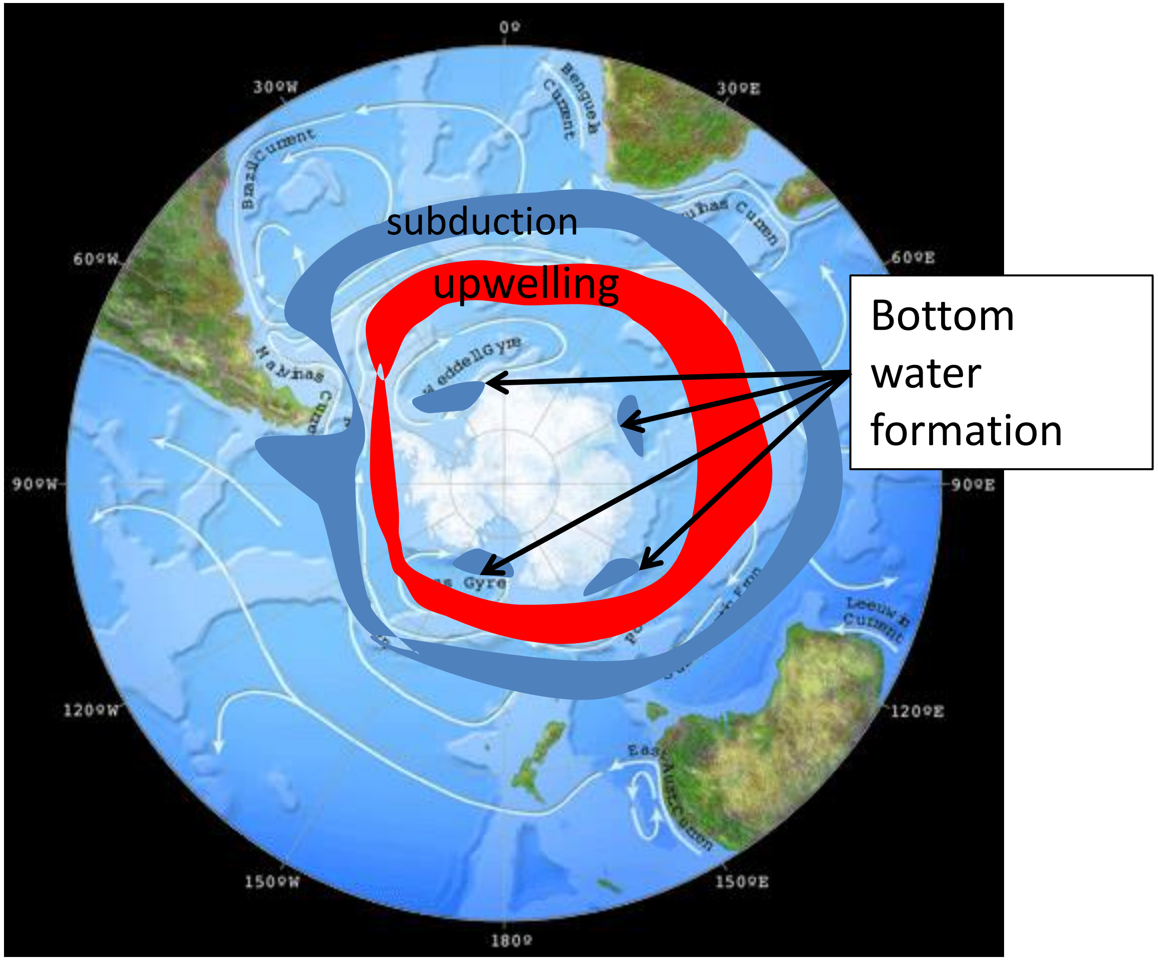


Ito, Follows and preformed nutrient

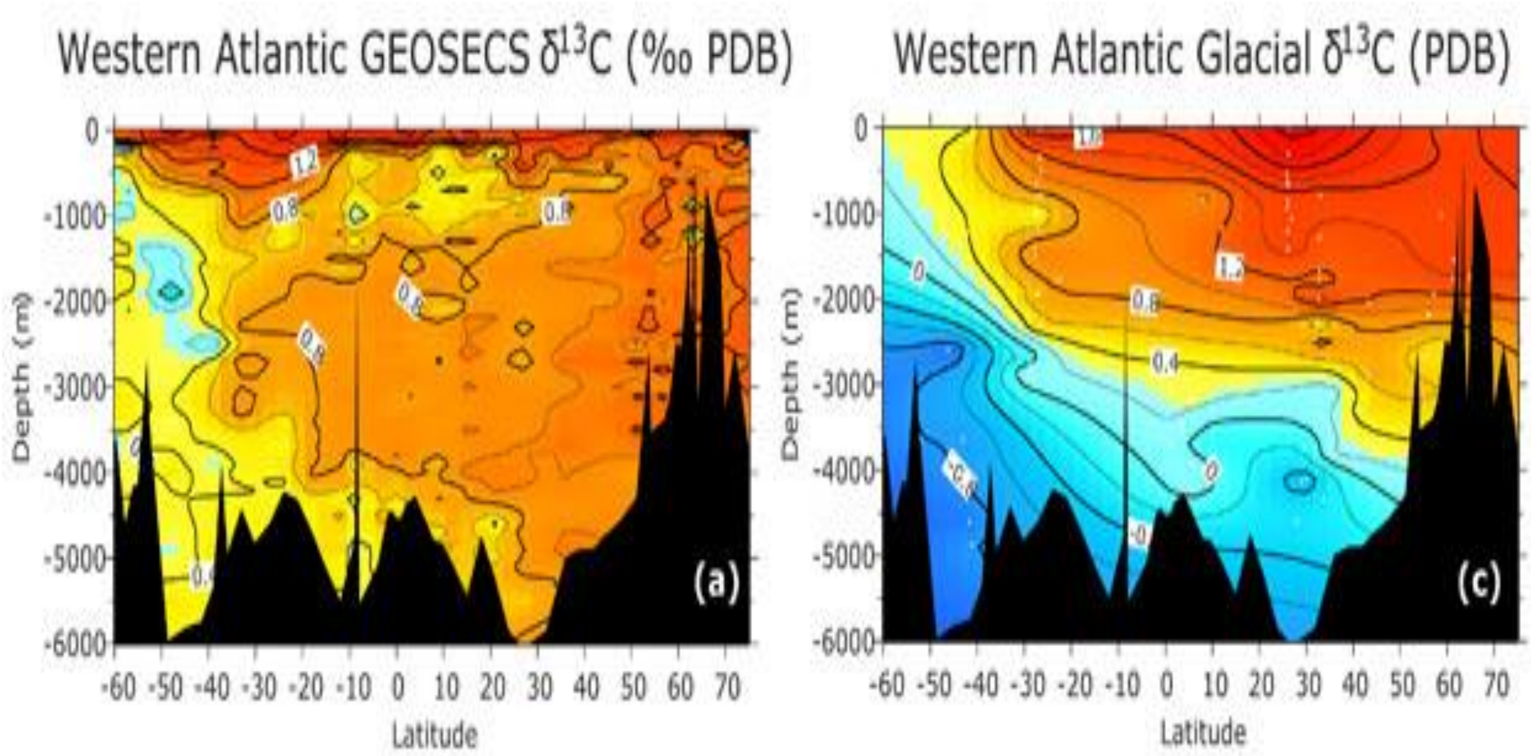
T. Ito and M. J. Follows, "Preformed phosphate, soft tissue pump and atmospheric CO_2
J. Mar. Res, 63, 813–839, 2005

- Subject to very general assumptions, the *pre-formed* nutrient content of the deep ocean controls the natural atmospheric CO_2 concentration. Higher pre-formed nutrient = higher CO_2.
  - The assumptions include: constant Redfield ratios, constant ocean+atmosphere inventory of carbon and total nutrient.
- The present-day ocean is relatively inefficient at sequestering CO_2.
- Pre-formed nutrient is high in the present ocean, and most of it comes from the Southern Ocean

Proximity of upwelling and downwelling zones

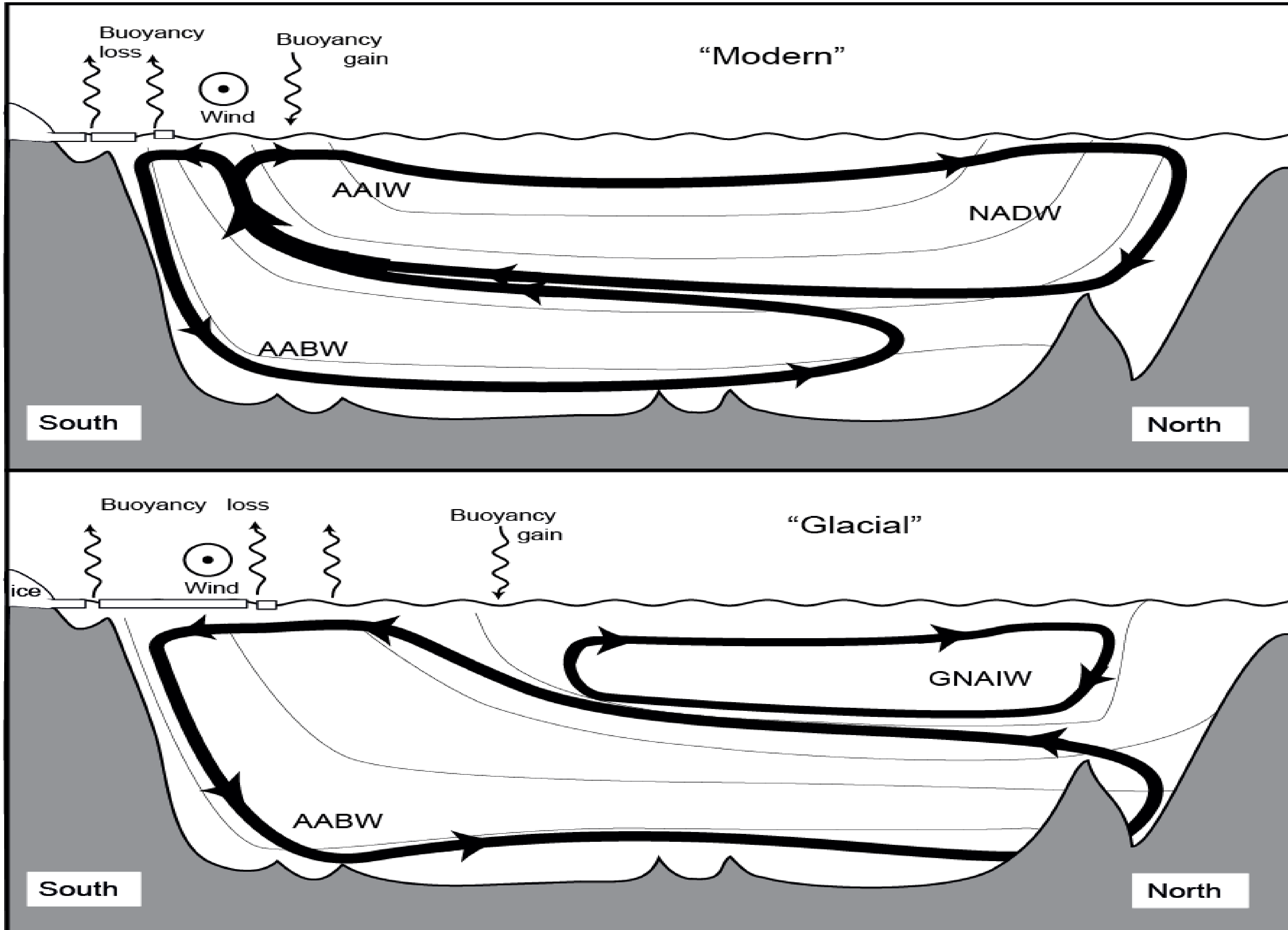


How did MOC in glacial time differ from the modern day?



- Proxies suggest a lesser volume of North Atlantic-derived subsurface water ("GNAIW") and greater volume of Antarctic-derived bottom water

(Curry and Oppo, 2005)

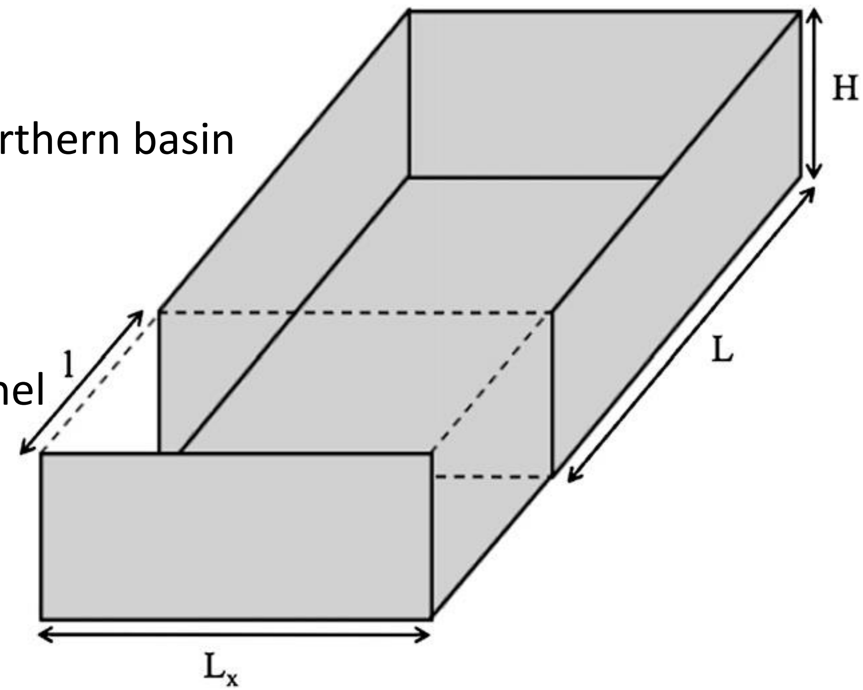

Buoyancy loss
Buoyancy gain
Wind
"Modern"
AAIW
NADW
AABW
South
North
Buoyancy loss
Buoyancy gain
Wind
"Glacial"
ice
GNAIW
AABW
South
North

“SAMBUCA”

- “Semi-Analytical Model” of Lower and Upper Cells”

Rectangular northern basin

Open, circumpolar channel



Nikurashin and Vallis, JPO, 2011, 2012

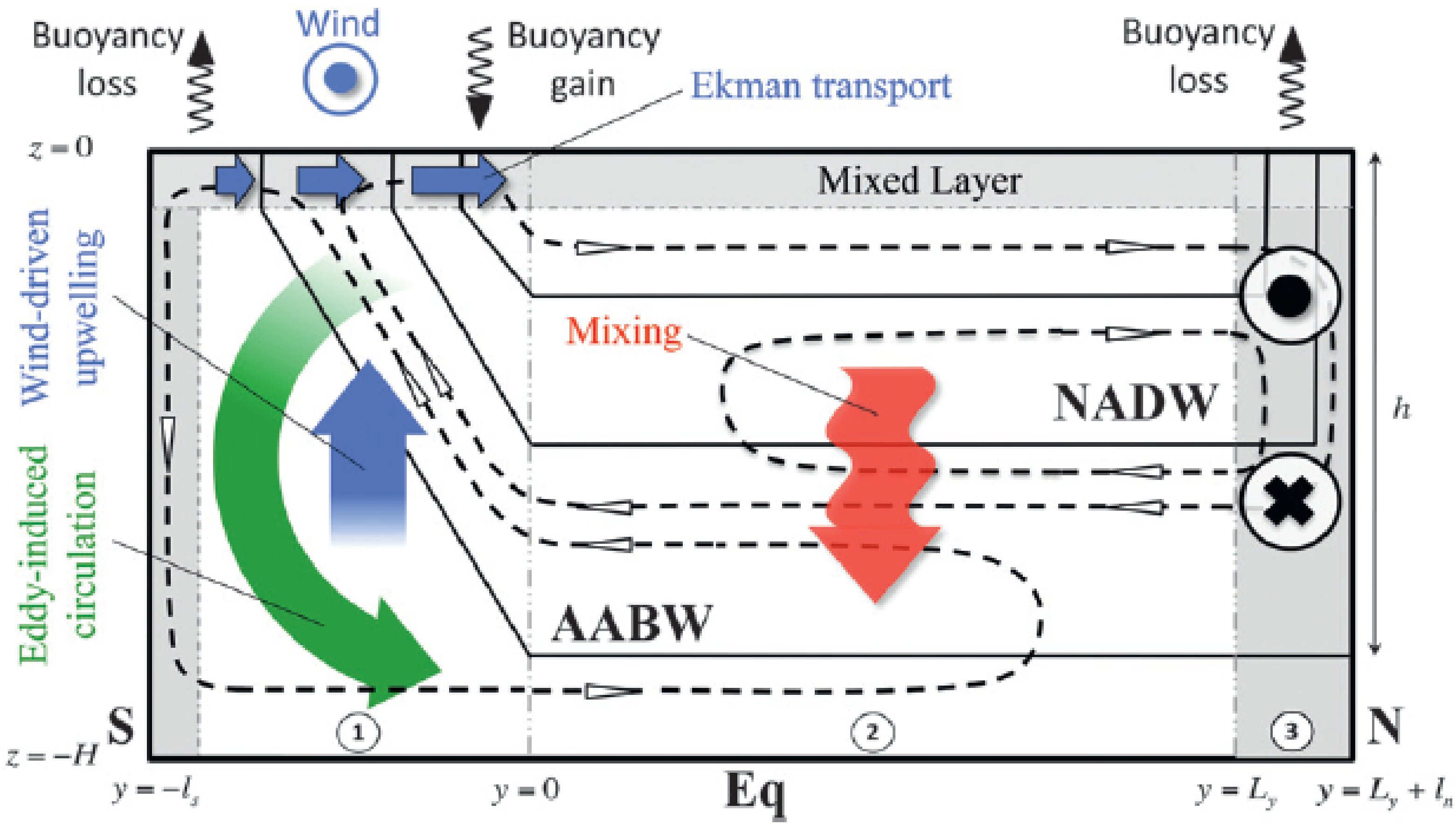


FIG. 8. Schematic of the MOC. Thin solid black lines are the isopycnals, thicker dashed black lines with arrows are the overturning streamlines of the residual circulation, dashed vertical lines are the boundaries between adjacent regions, shaded gray areas are the convective regions at high latitudes and the surface mixed layer, and the red arrow represents downward diffusive flux due to mixing uniform throughout the ocean. Labels 1, 2, and 3 (in circles) correspond to the circumpolar channel, ocean basin, and isopycnal outcrop regions considered in the theory.

Southern channel: Residual mean circulation

- 2-D, zonal average description
- Eulerian mean circulation is the Ekman transport. $\overline{\psi} = -\frac{\tau}{\rho_0 f}$,
- Eddy flux is parameterized, e.g. $\psi^* = -K_e \frac{\partial_y b}{\partial_z b}$
- Residual circulation is the sum of the two.
- Solve this simultaneously with continuity of buoyancy

Northern basin

- Isopycnals are flat except in north where convection can occur.
- Northern region: may convect. strength of upper cell is diagnosed by applying thermal wind equation to meridional buoyancy gradient, to find zonal velocities
- Overturning circulation matched to southern overturning at boundary between basin and channel.

Biogeochemistry

- Phosphate is consumed in the surface layer by biology, with a time constant of 1 year (appropriate to the Southern Ocean)
- Carbon, alkalinity consumed in Redfield ratios with phosphate.
- Remineralized at depth in Redfield ratio
- Oxygen is tracked and slows respiration if it is depleted below 100 μmol kg^{-1}.

- Results --- current in review!

Conclusions

- The Southern Ocean is key to natural glacial-interglacial variation in atmospheric CO_2
- Dynamical model based on residual mean overturning theory and simple carbon cycle gives a good match to atmospheric CO_2.
- It suggests a substantial role was played by the changed buoyancy forcing in the Southern Ocean, leading to
  - Slower upwelling, displaced to the north, therefore
  - Longer residence time at surface between upwelling and sinking to the lower cell, therefore,
  - Lower pre-formed nutrient, therefore
  - Lower atmospheric CO_2.
- Hypothesis of a direct relationship between buoyancy forcing and atmospheric CO_2 -- a straightforward rationale for why Antarctic temperature and CO_2 are so closely linked in the ice core record.