Benthic foraminifer δ^{13}C: useful but ambiguous

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acclimate
Elucidating the Causes and Effects of Atlantic
Circulation Changes through Model-Data Integration

Outline

1. Oceanic carbon $\delta^{13}C$ in the modern ocean
   - Controls on $\delta^{13}C$ of oceanic carbon
   - Interpretation of oceanic $\delta^{13}C$ in terms of circulation

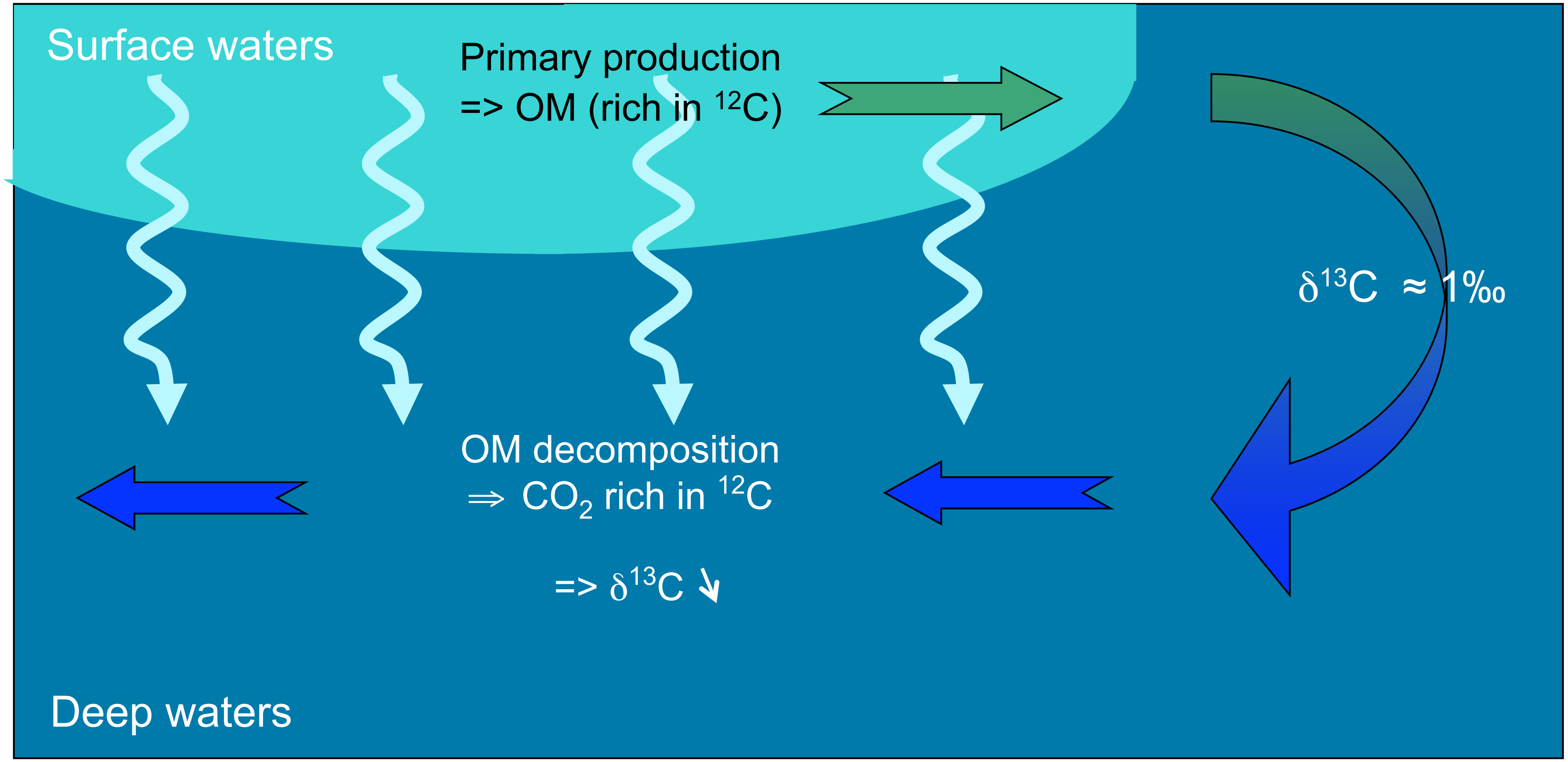
2. DIC $\delta^{13}C$ paleo-reconstructions
   - [Duplessy et al., 1984] + update
   - Remaining sources of uncertainties

3. Modelling studies
   - A few words on benthic $\delta^{13}C$ simulations
   - Simultaneous simulation of benthic $\delta^{13}C$, $\Delta^{14}C$ and sedimentary Pa/Th

4. Conclusions

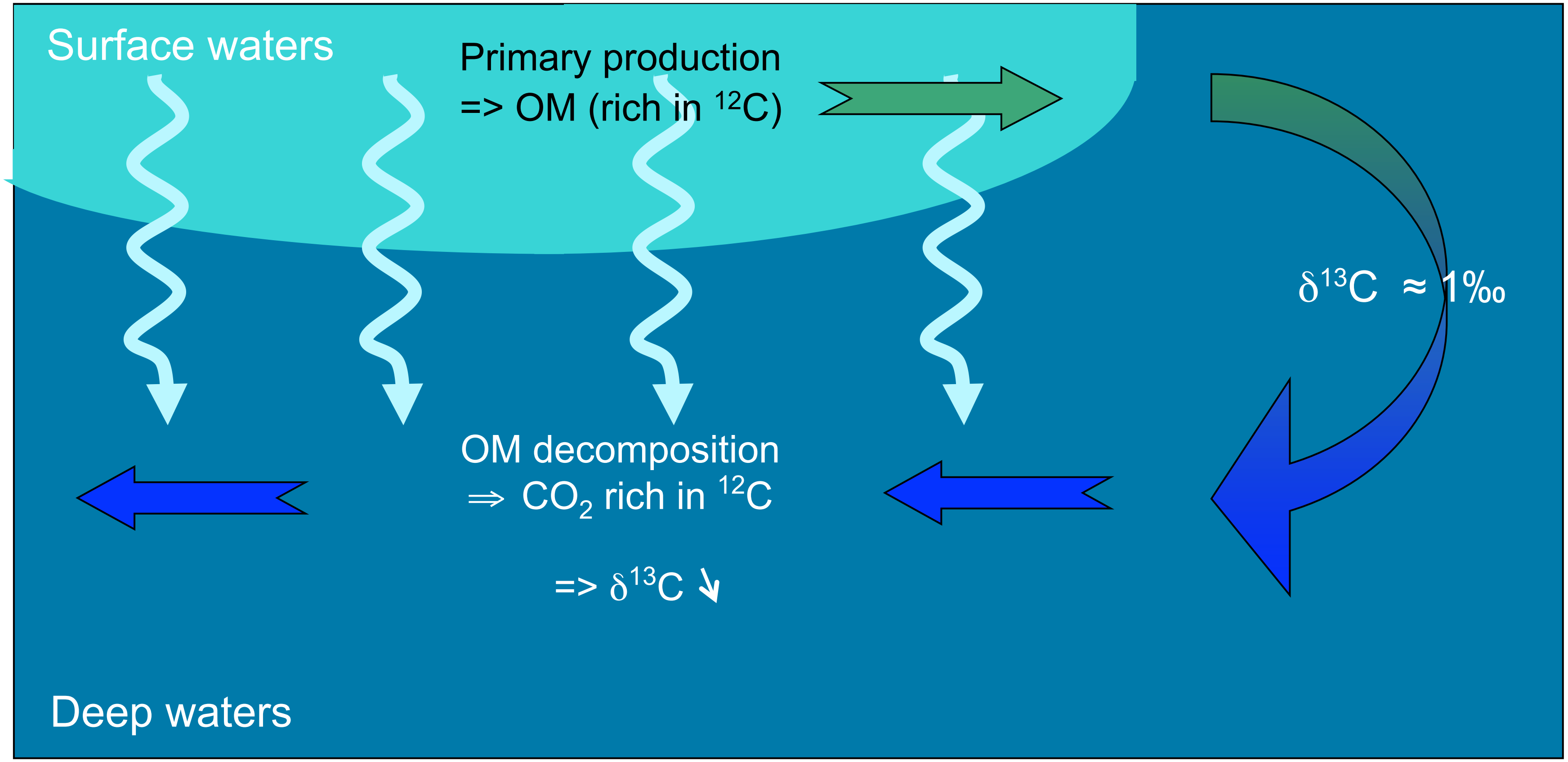
1. DIC $\delta^{13}C$ in the modern ocean (1)

- Primary control: <u>biological: decomposition of ^{13}C-poor organic material</u> → spatial distribution of DIC $\delta^{13}C$ resembles that of nutrients (e.g. PO_4)

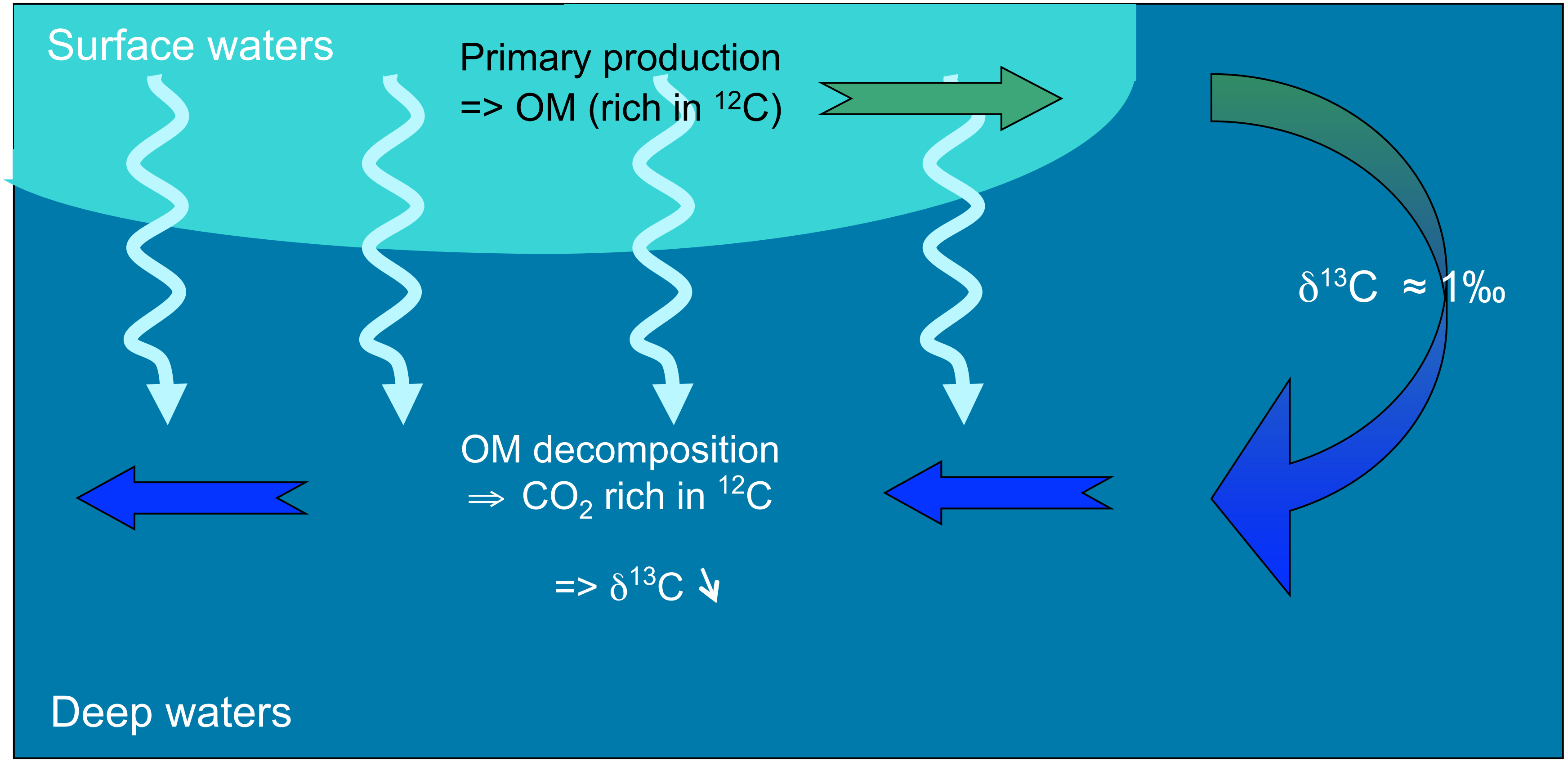


1. DIC $\delta^{13}C$ in the modern ocean (1)

- Primary control: biological: decomposition of ^{13}C-poor organic material → spatial distribution of DIC $\delta^{13}C$ resembles that of nutrients (e.g. PO_4)
- Secondary control: thermodynamic: C fractionation during air-sea exchange. Cold waters have higher $\delta^{13}C$ than warm waters at air-sea isotopic equil. But isotopic equil. rarely reached (~10 y for a 50 m deep mixed layer, i.e. 10 x longer then chemical equil.) → effect subdued: -0.8 to + 0.8‰



- Invasion and evasion of atm CO_2: atm CO_2 and $CO_{2(aq)}$ are isotopically light relative to total oceanic C → oceanic C depleted in ^{13}C in areas of CO_2 invasion, and enriched in ^{13}C in areas of CO_2 outgassing. Total range of this effect ~0.6‰.
- Other factors: kinetic effects, $CaCO_3$ dissolution.
  Less impact on oceanic $\delta^{13}C$ than biological and air-sea effects.



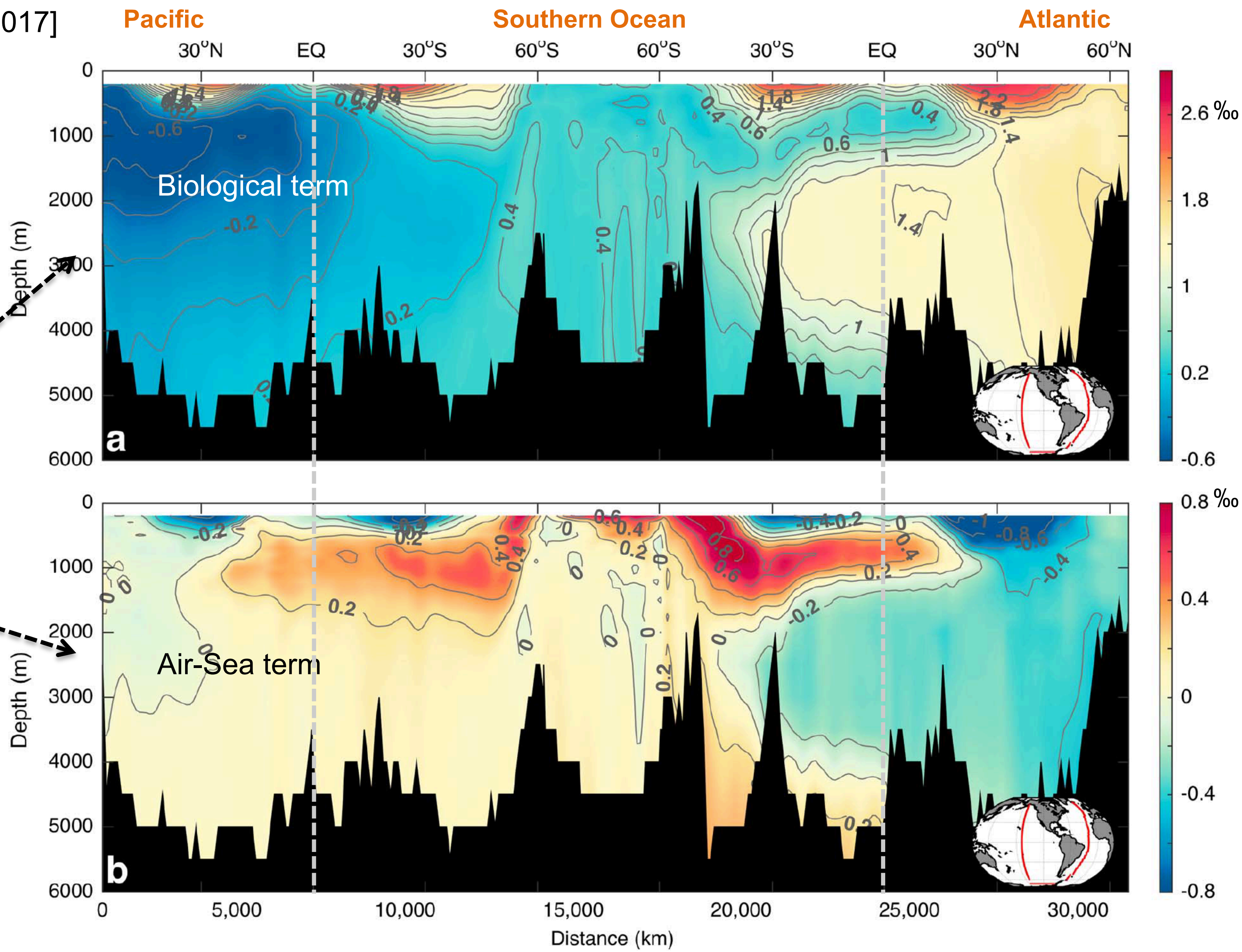
1. DIC δ13C in the modern ocean (3)

[Eide et al., *GBC* 2017]

Computation of the preindustrial ocean δ13C (correction for the Suess effect) divided into:

- Biological term $= 2.8 - 1.1 \times PO_4$ [Broecker & Maier-Reimer, 1992; Lynch-Stieglitz et al., 1995]

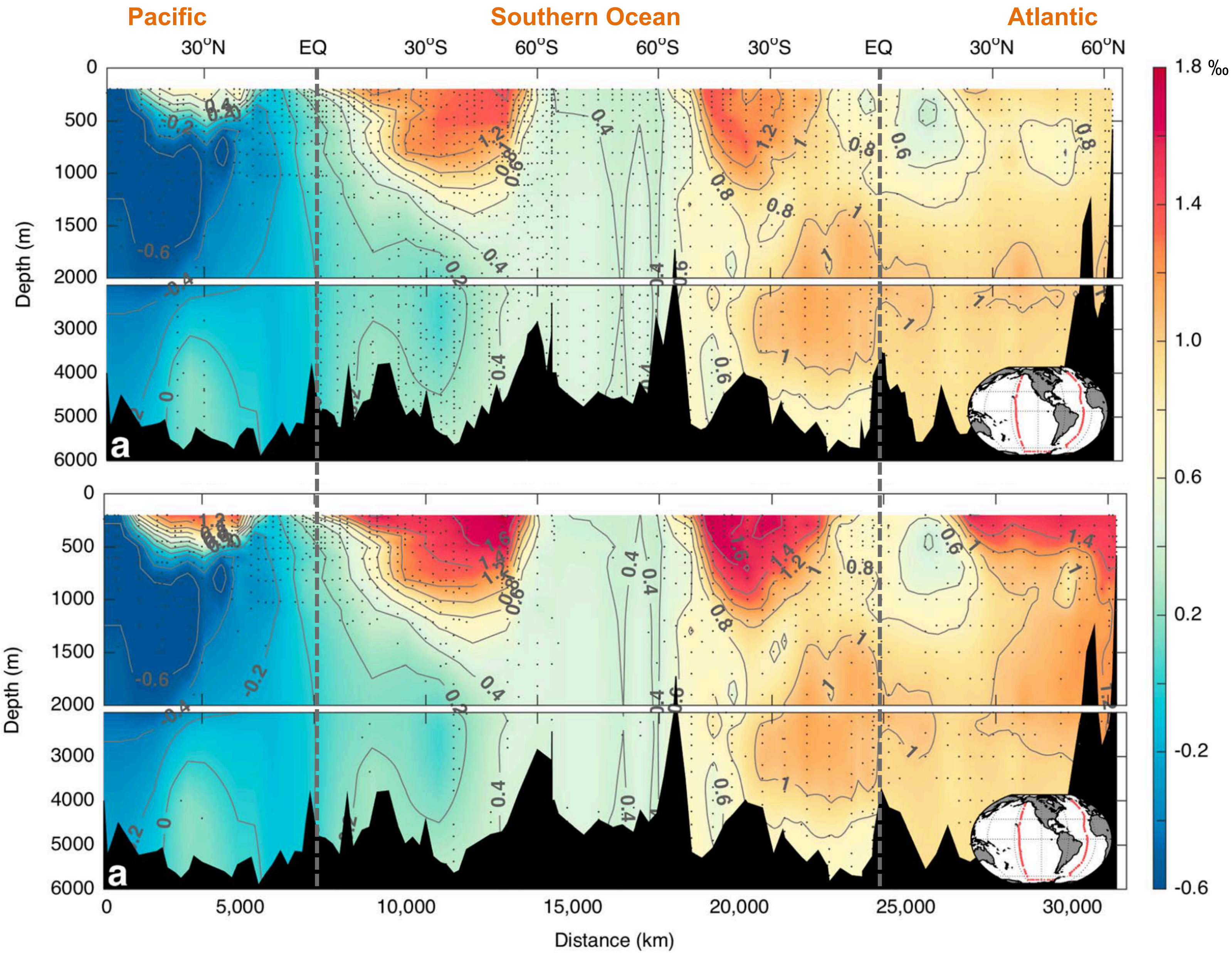
- Air-Sea term $= \delta^{13}C - \delta^{13}C_{BIO}$



1. DIC $\delta^{13}C$ in the modern ocean (4)

Modern ocean $\delta^{13}C$: GLODAP

Reconstructed preindustrial ocean $\delta^{13}C$ (corrected for the Suess effect) [Eide et al., *GBC* 2017]



Interpretation of oceanic $\delta^{13}C$ in terms of circulation

- DIC $\delta^{13}C$ is **not a conservative tracer**
- $\delta^{13}C_{as} = \delta^{13}C - (2.8 - 1.1 \times PO_4)$ can be assumed to be conservative but difficult to reconstruct in the past

Interpretation of oceanic $\delta^{13}C$ in terms of circulation

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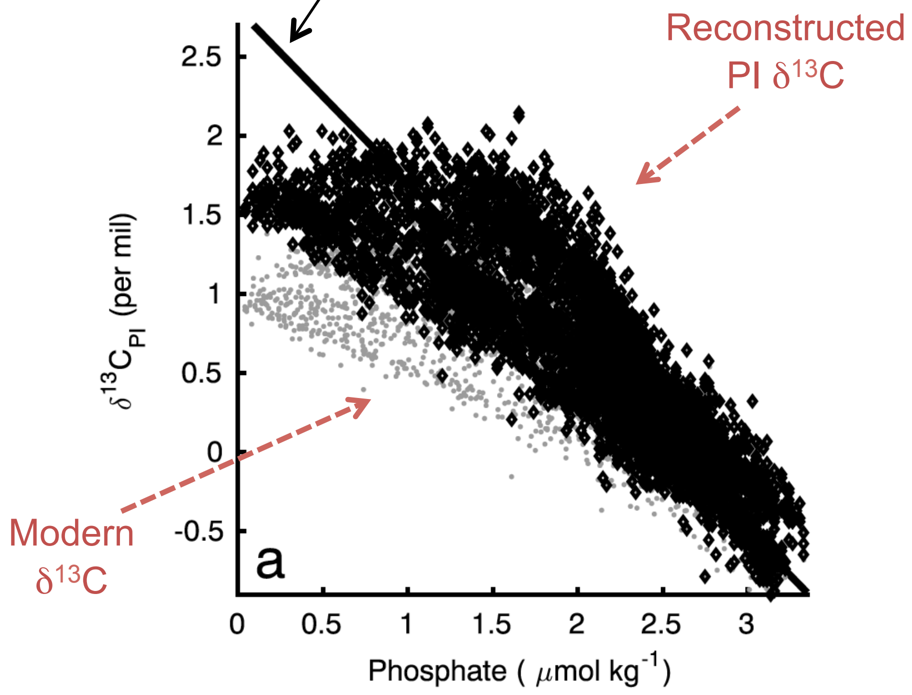
DIC $\delta^{13}C$ ~ nutrient proxy

-1.1‰/µmol kg^{-1} line describing biological control on ocean $\delta^{13}C$



- correcting for the Suess effect → closer to the expected slope
- a large spread remains, due to air-sea exchanges

Interpretation of oceanic δ^{13}C in terms of circulation

- DIC δ^{13}C is not a conservative tracer
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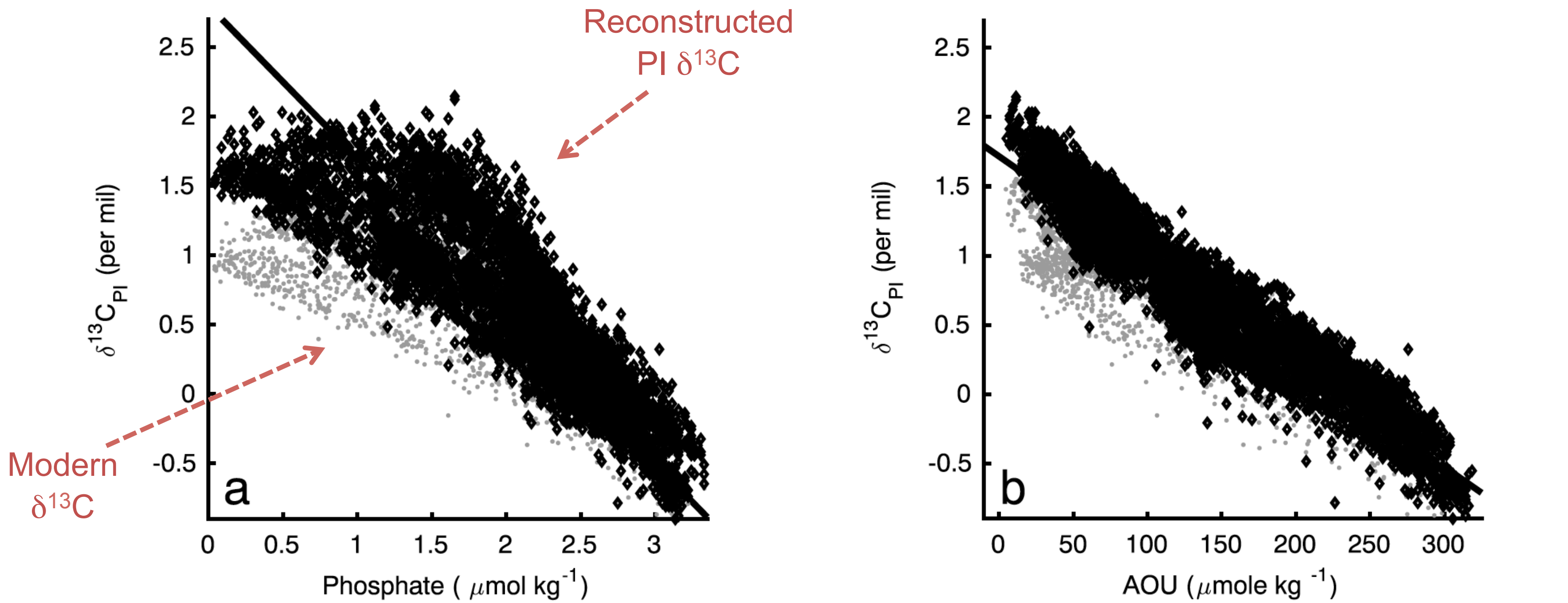
DIC δ^{13}C ~ nutrient proxy

DIC δ^{13}C: a ventilation proxy

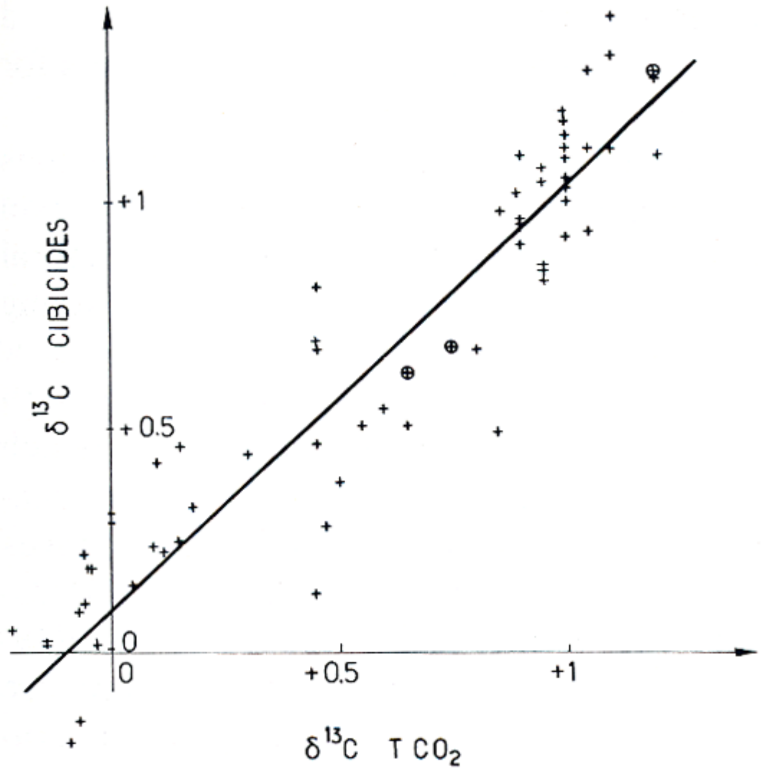
Better correlation with AOU: both δ^{13}C and AOU are reset when waters are ventilated



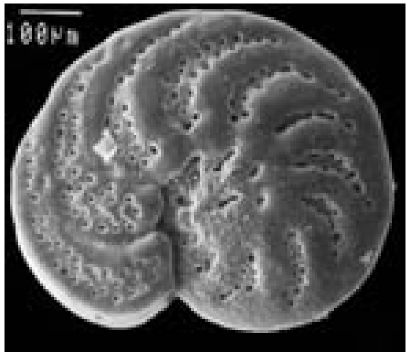
QUATERNARY RESEARCH 21, 225–243 (1984)

^{13}C Record of Benthic Foraminifera in the Last Interglacial Ocean: Implications for the Carbon Cycle and the Global Deep Water Circulation

JEAN-CLAUDE DUPLESSY,* NICHOLAS J. SHACKLETON,† ROBLEY K. MATTHEWS,‡ WARREN PRELL,‡ WILLIAM F. RUDDIMAN,§ MICHÈLE CARALP,|| AND CHRIS H. HENDY*,[1]



$$\boxed{\delta^{13}C_{Cibicides} = 0.954\ \delta^{13}C_{TCO_2} + 0.096}\quad (n = 67)$$



Cibicides wuellerstorfi

2. DIC δ13C paleo-reconstructions (2)

"Changes in the vertical structure of the North Atlantic Ocean between glacial and modern times"

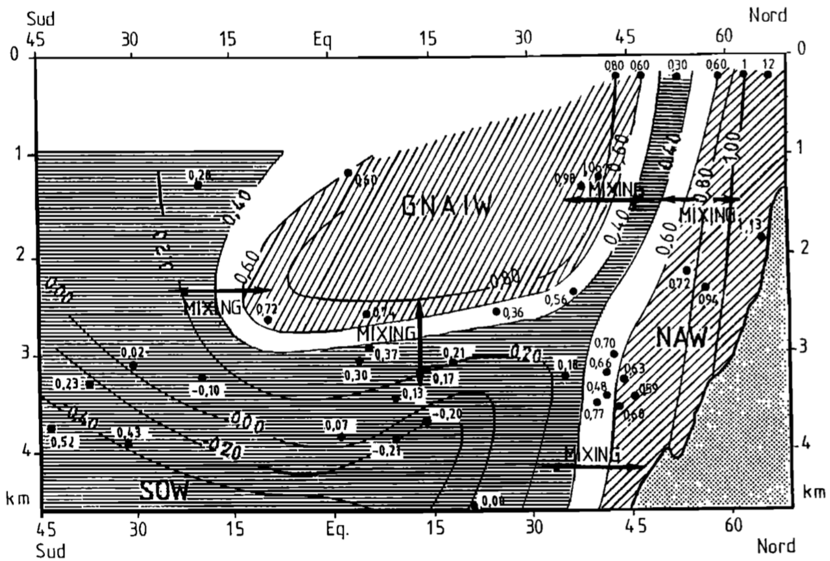
Quaternary Science Reviews, Vol. 11, pp. 401–413, 1992.

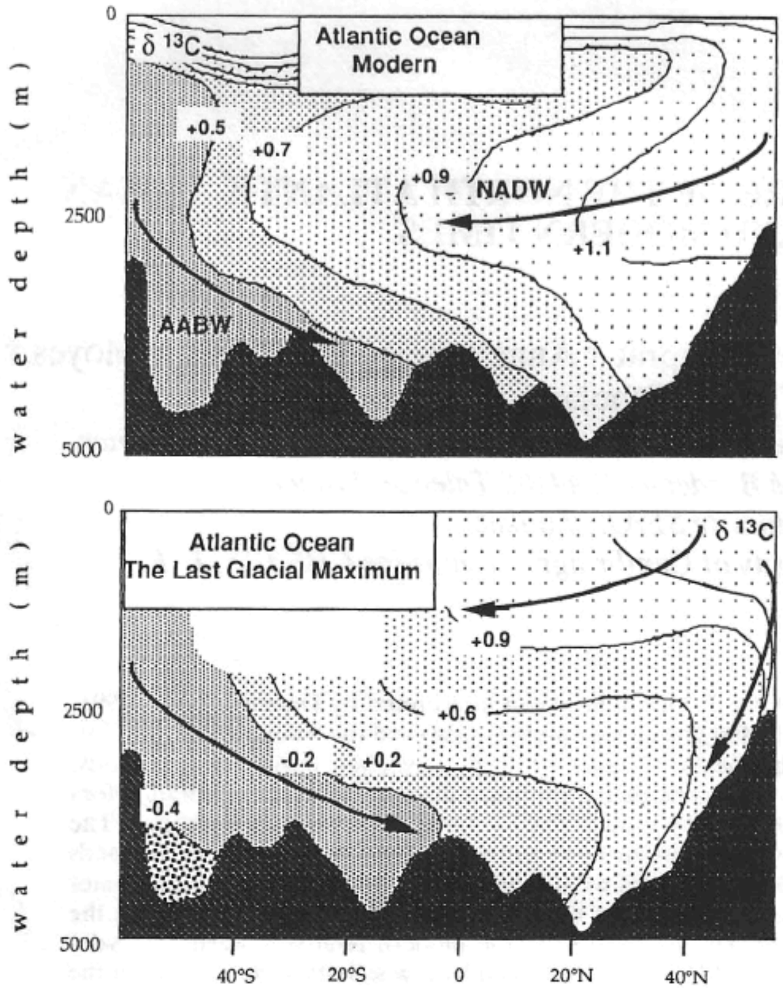
Laurent D. Labeyrie,* Jean-Claude Duplessy,* Josette Duprat,† Anne Juillet-Lecl
Elizabeth Michel,* Nejib Kallel*‡ and Nicholas J. Shackleton§

"Deep water source variations [...] and their impact on the global deepwater circulation"

PALEOCEANOGRAPHY, VOL. 3, NO. 3, PAGES 343-360, JUNE 1988

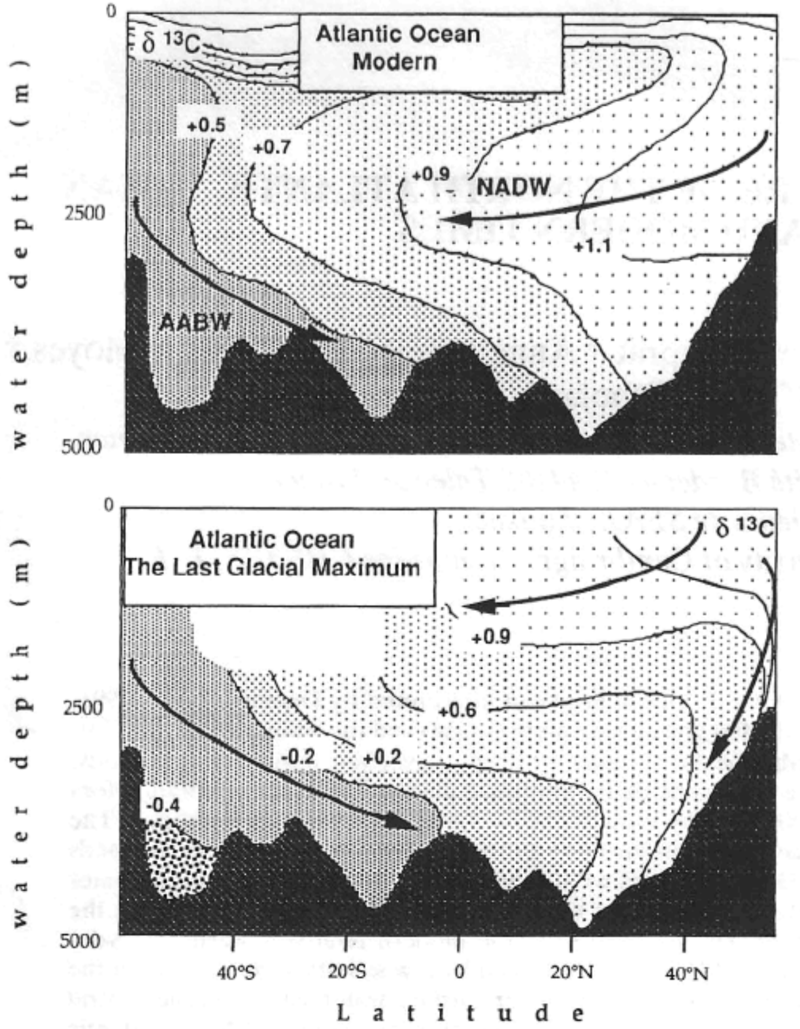
J. C. Duplessy,[1] N. J. Shackleton,[2]
R. G. Fairbanks,[3] L. Labeyrie,[1] D. Oppo,[3]
and N. Kallel [1]





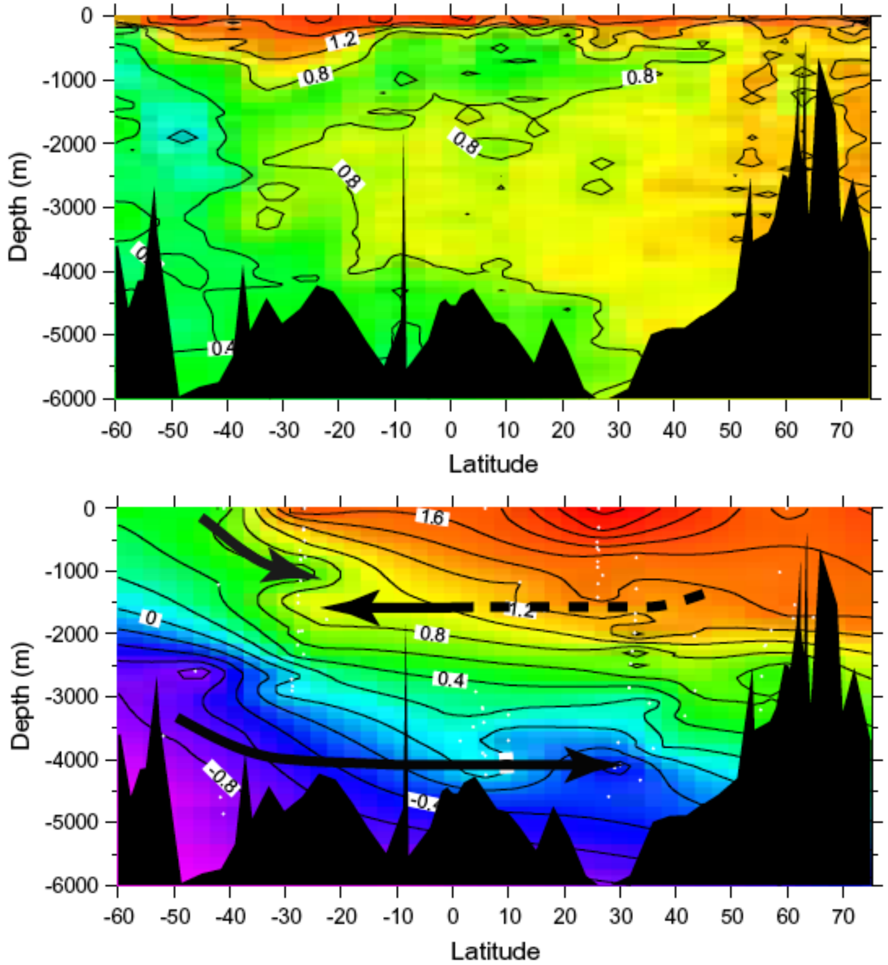
2. DIC δ13C paleo-reconstructions (3)

[Labeyrie et al., *Quat. Sci. Res.* 1992]



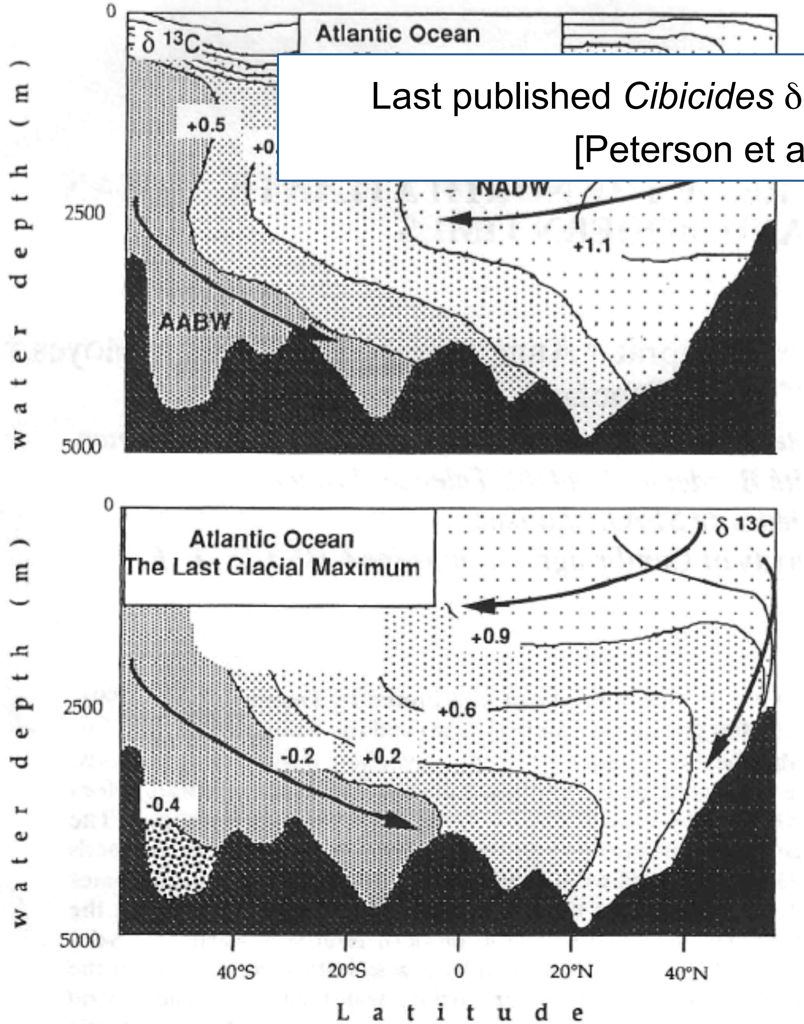
[Curry and Oppo, *Paleocean.* 2005]

West Atlantic



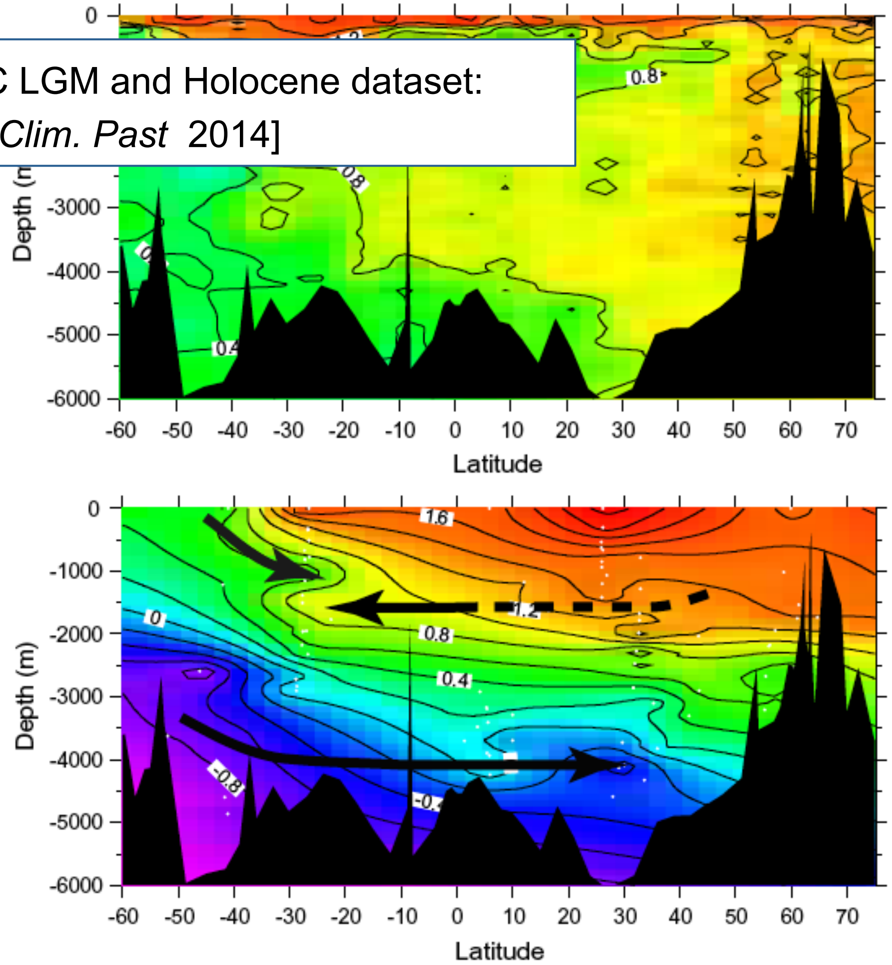
2. DIC δ¹³C paleo-reconstructions (3)

[Labeyrie et al., *Quat. Sci. Res.* 1992]



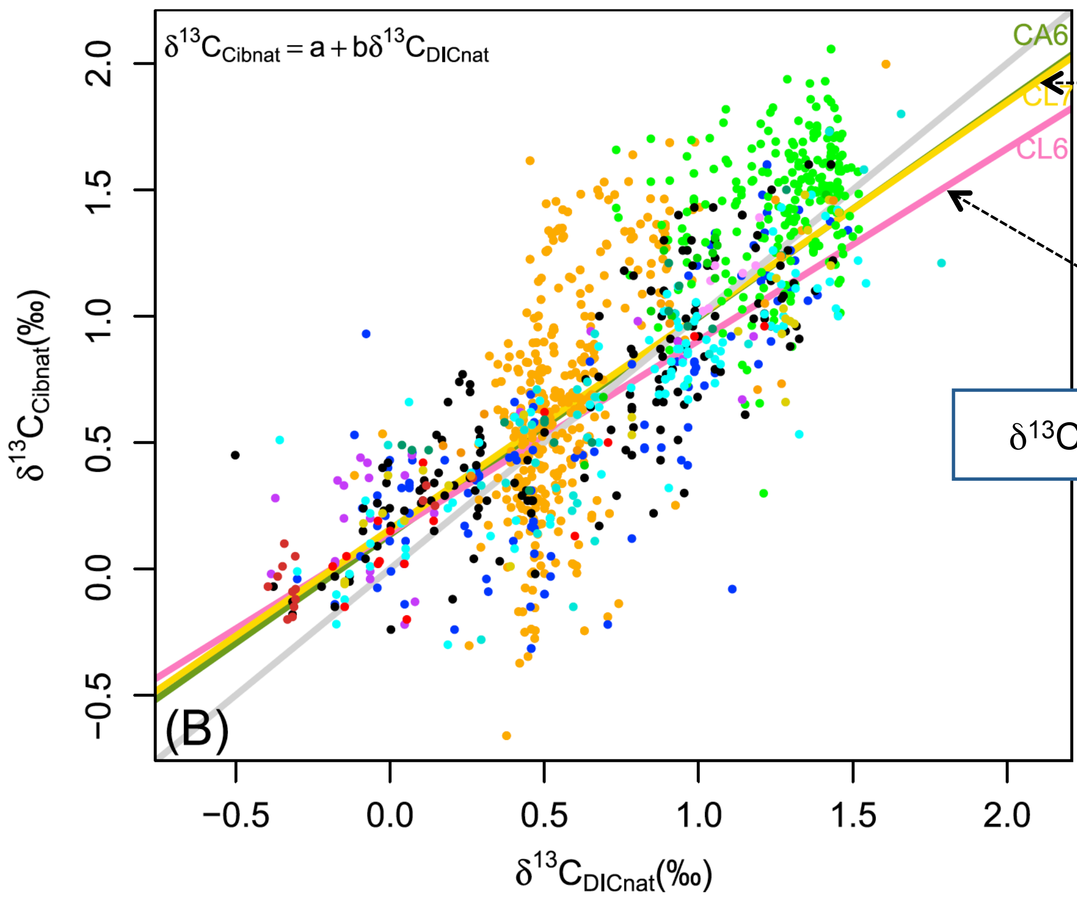
[Curry and Oppo, *Paleocean.* 2005]

West Atlantic



Last published *Cibicides* δ¹³C LGM and Holocene dataset:
[Peterson et al., *Clim. Past* 2014]

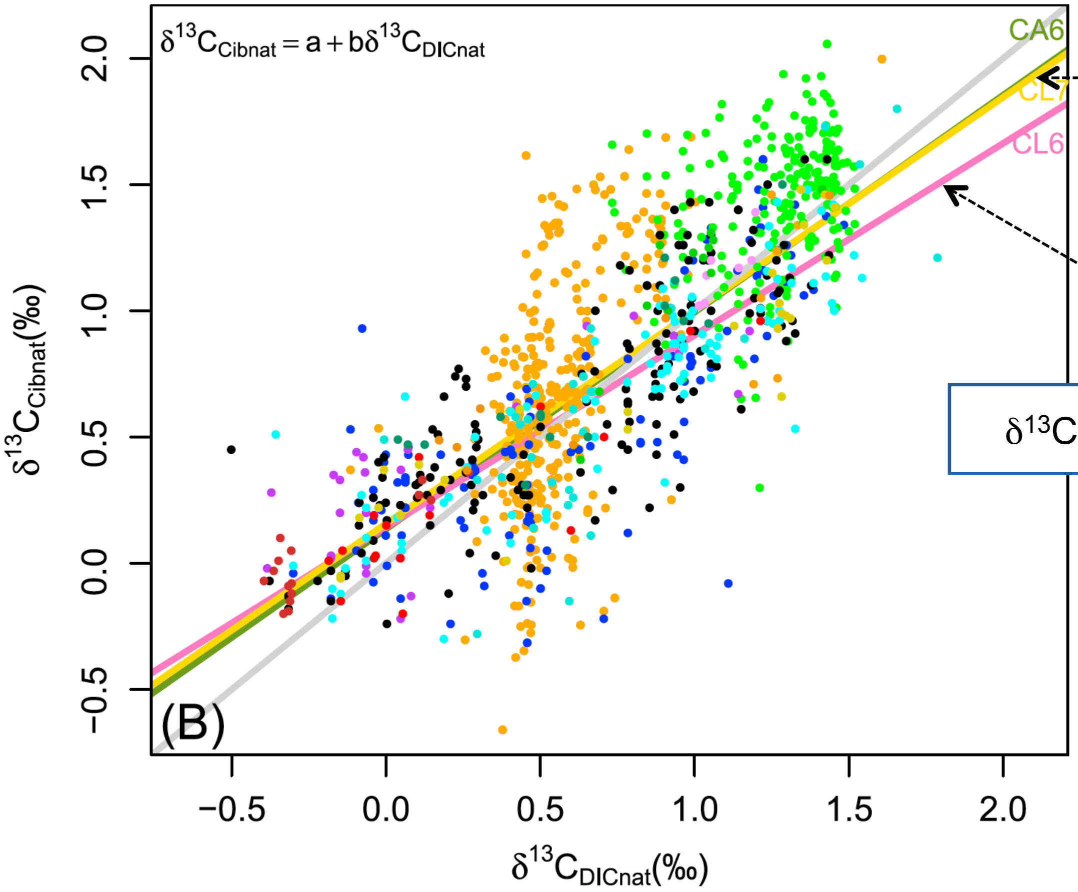
Updated calibration between *Cibicides* and modern DIC δ^{13}C [Schmittner et al., *Paleocean.* 2017]



$$\delta^{13}C_{Cib} = 0.76\ (\pm\ 0.02)\ \delta^{13}C_{DIC} + 0.14\ (\pm\ 0.02)$$

- multiple regression analyses assuming $\delta^{13}C_{Cib}/\delta^{13}C_{DIC}$ slope = 1
  → secondary factors: $CO_3^{=}$ and depth
- $CO_3^{=}$ effect on $\delta^{13}C_{Cib}$ is smaller than in cultures on planktonics
- practically no change in water depth for downcore records.

Updated calibration between *Cibicides* and modern DIC $\delta^{13}C$ [Schmittner et al., *Paleocean.* 2017]



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- $CO_3^=$ effect on $\delta^{13}C_{Cib}$ is smaller than in cultures on planktonics
- practically no change in water depth for downcore records.

→ Most conclusions from previous studies using a one-to-one relationship remain robust

Remaining sources of uncertainties

- Benthic foraminifer species identification, ecology [Mackensen et al., 1993; Gottschalk et al., 2016]

- Dating uncertainties → difficult to establish consistently dated *Cibicides* $\delta^{13}C$ time series from different cores, although necessary
  - to constrain transient climate runs
  - to extract *Cibicides* $\delta^{13}C$ time slices

- Bioturbation in low sedimentation rate cores

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Current effort within the ACCLIMATE project (focused on the Atlantic Ocean)

Selected cores:

- Sedimentation rate > 5 cm/ky
- ^{14}C dating in mid- and low-latitudes (40°S - 40°N); at higher latitudes: alignment of SST to air temperature records from polar ice cores

→ complex picture of the different Heinrich stadials

3. Modelling studies (1)

What has been done in terms of (forward) $\delta^{13}C$ modelling in paleoclimate ?

- Mostly with models of intermediate complexity (CLIMBER-2, LOVECLIM, Uvic, Bern-3D, iLOVECLIM…) + a few GCMs (IPSL, MIROC… but probably more in the future)

- Many studies have focused on the LGM, some have looked at the Holocene, last deglaciation or last G-IG cycle

- Some models (more in the future) simulate other proxies to have additional and usually complementary constraints, e.g. $\Delta^{14}C$, $\delta^{15}N$, Pa/Th, ε_{Nd} in the ocean, atmospheric CO_2 and its $\delta^{13}C$.

1) LGM studies

Most models indicate a reduced and/or shoaled northern-sourced deep waters, more complicated in the Southern Ocean where more work needs to be done and more data would help to better constrain processes

- [Brovkin et al., *Paleocean.* 2007] (CLIMBER-2) : shoaling of the THC
- [Tagliabue et al., *Clim. Past* 2009] (IPSL + PISCES): reduced ventilation
- [Bouttes et al., *GRL* 2011] (CLIMBER-2): stronger stratification in the Southern Ocean
- [Hesse et al., 2011] (HAMOCC2s): shoaled and weak NADW, strong AABW transport
- [Chikamoto et al., *Clim. Past* 2012] (MIROC): increased NADW formation- or - increased AABW with weaker NADW
- [Schmittner and Lund, CP, 2015] (UVic) : reduced AMOC
- [Menviel et al., *Paleocean.* 2017] (LOVECLIM): weak and shallow NADW, reduced AABW transport
- [Muglia et al., *EPSL* 2018] (Uvic, with $\delta^{13}C$ and $\delta^{15}N$): weak and shallow AMOC

3. Modelling studies (2)

2) Deglaciation

- [Menviel et al., QSR, 2011]
- [Tschumi et al., *Clim. Past* 2011] (BERN-3D)
- [Bouttes et al., *Clim. Past* 2012]
- [Menviel et al., *Nat. Comm.* 2018]

3) Holocene and some other interglacials

- [Joos et al., *GBC* 2004] (BERN CC)
- [Menviel and Joos, *Paleocean.* 2012] (Bern3D)

Recent work has focused more on $\delta^{13}C$ of atm. CO_2

- [Kleinen et al., *Clim. Past* 2016]
- [Brovkin et al., *QSR* 2016]

4) Glacial-Interglacial cycle

- [Menviel et al., *QSR* 2012]
- [Brovkin et al., *Clim. Past* 2012]

4. Conclusions

Open questions:

- Difficult interpretation of decreases in benthic $\delta^{13}C$ during certain stadials (HS1 only?!). Lack of data of DIC $\delta^{13}C$ in brine waters + $\delta^{13}C$ of live benthics. Necessary to monitor DIC $\delta^{13}C$ over the entire seasonal cycle, several years in a row. Ongoing efforts by E. Michel.

- if not already done, evaluate how the $\delta^{13}C$ of DIC versus AOU and nutrients relationships vary for different climatic and ocean circulation conditions

Perspectives:

- Multiproxy modelling

- Inversion of multiproxy time series