Simulated radiocarbon cycle revisited by considering the bipolar seesaw and benthic ^{14}C data

Peter Köhler[1], Luke C. Skinner[2], Florian Adolphi[1]

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Benthic ^{14}C data

Applied model

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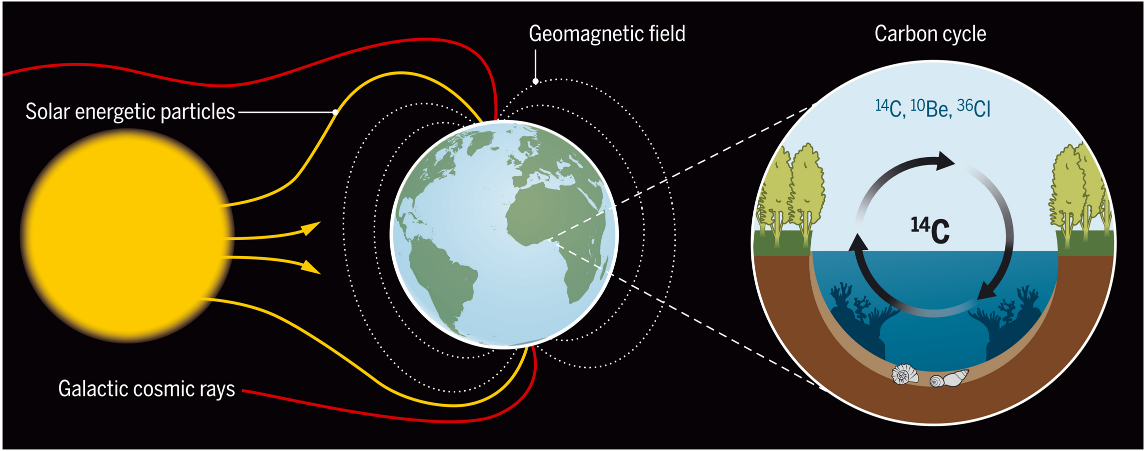
Radiocarbon cycle

Radiocarbon Cycle in a Nutshell

(Heaton et al., 2021)



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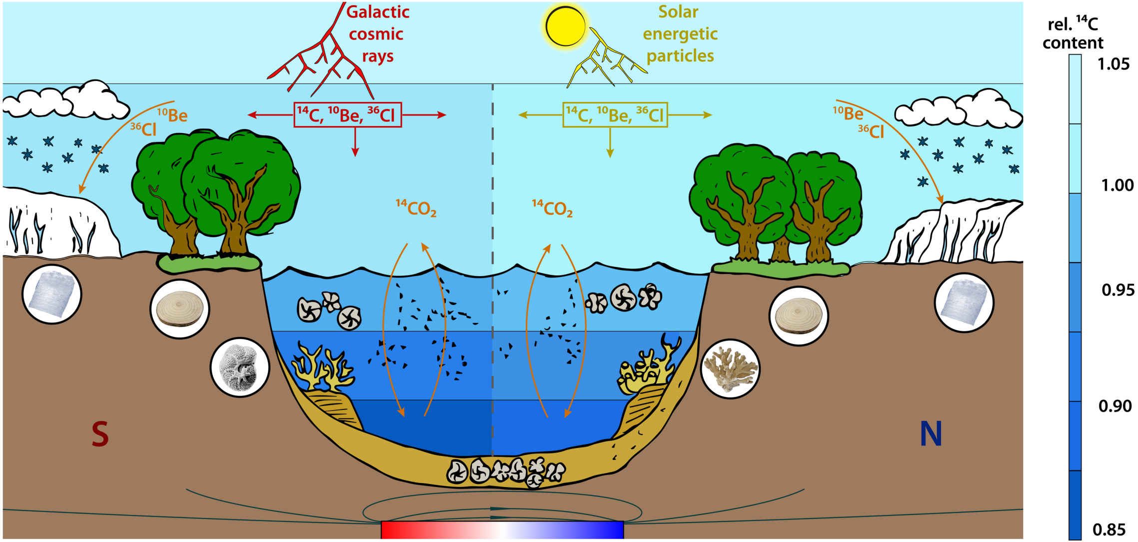
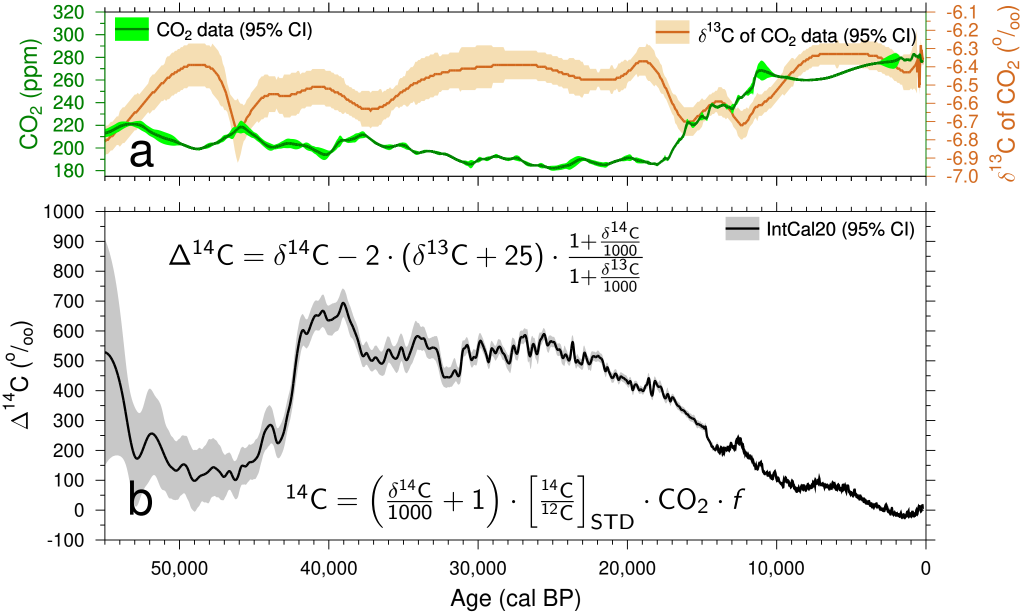


Carbon in the Atmosphere

(Köhler et al., 2022)



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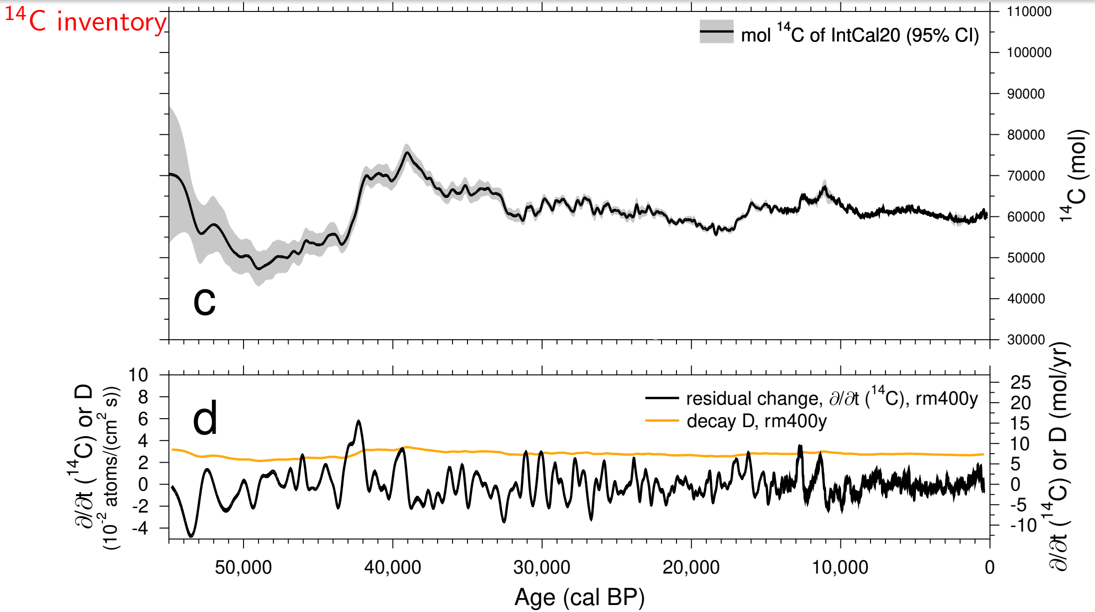

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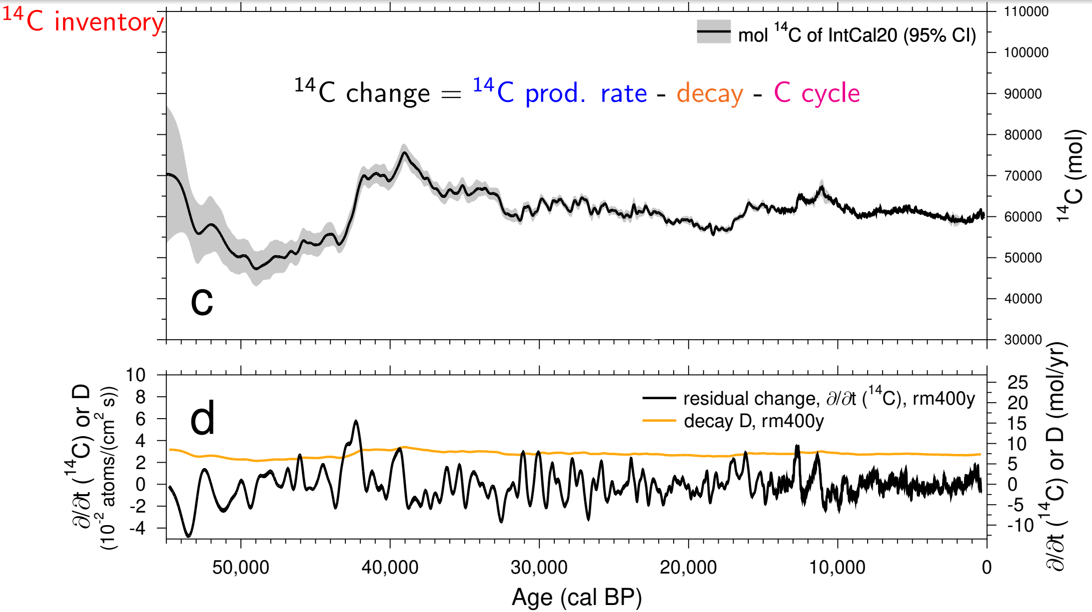

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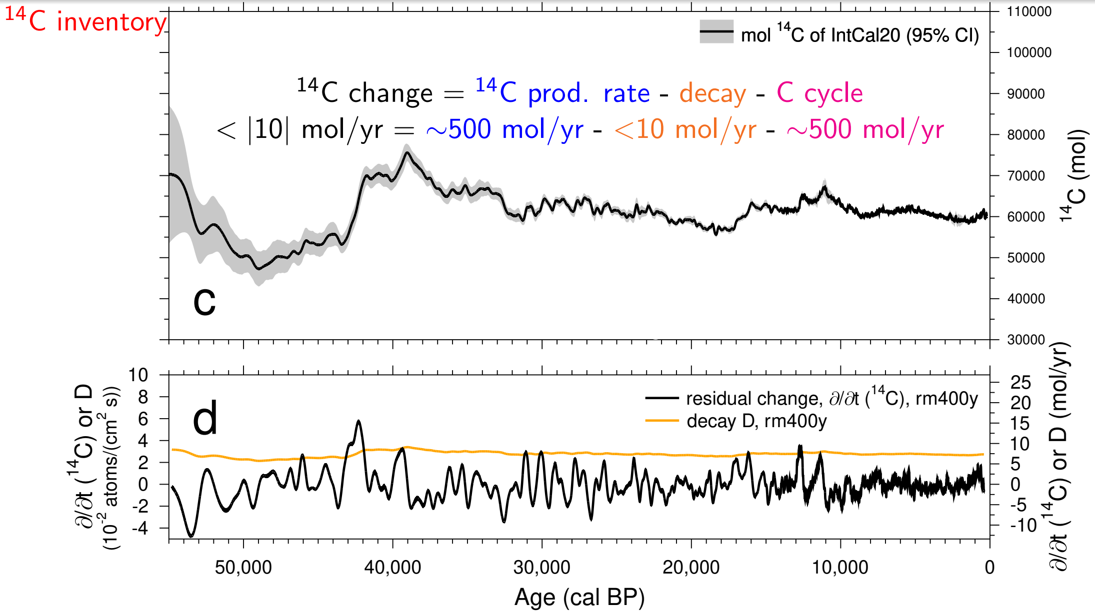
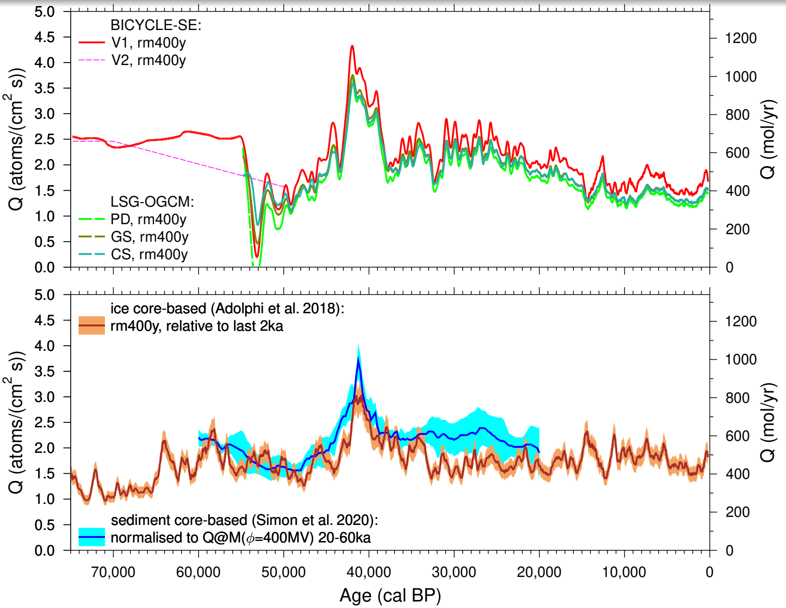


^{14}C Production Rate Q: C Cycle Models vs ^{10}Be Data (Köhler et al., 2022)



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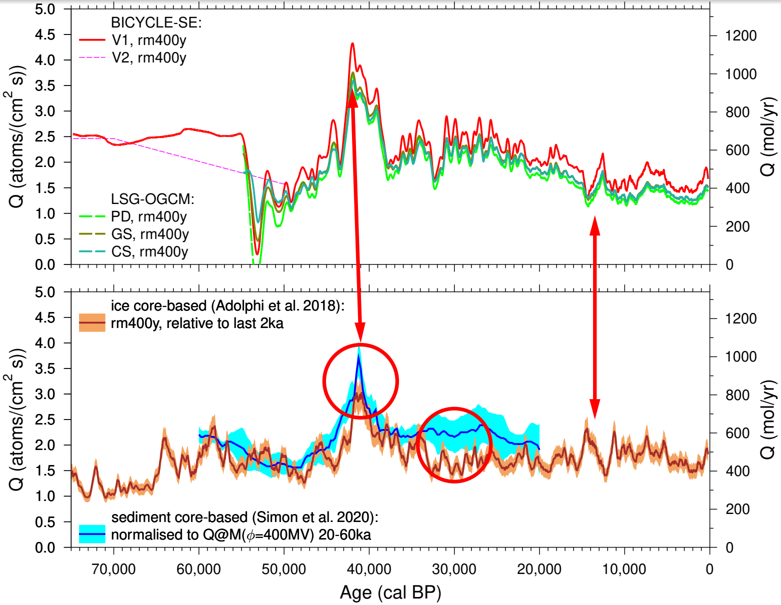

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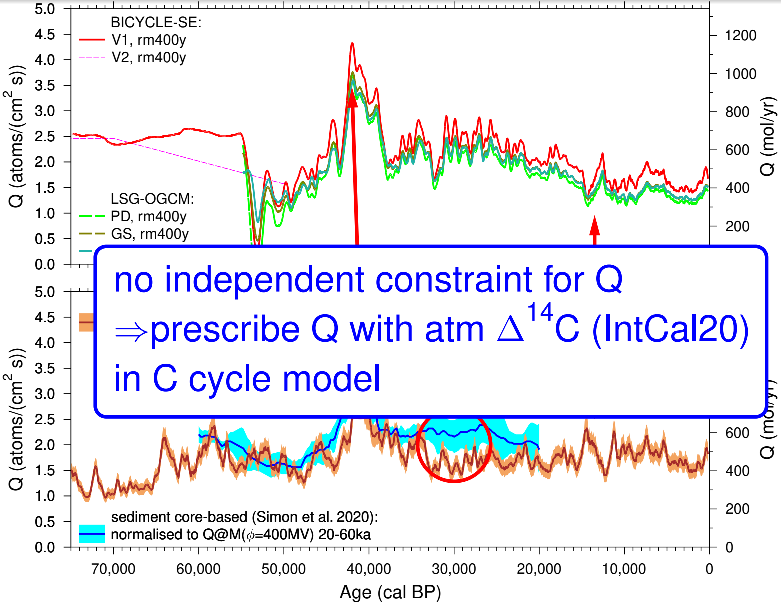


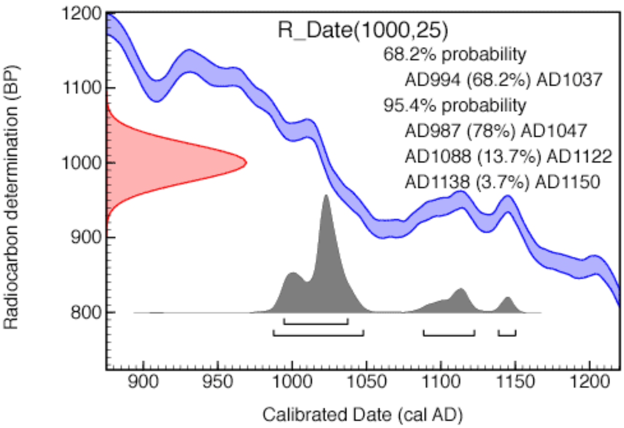
no independent constraint for Q
⇒prescribe Q with atm Δ^{14}C (IntCal20)
in C cycle model

Simulated radiocarbon cycle revisited

Radiocarbon calibration — Example from OxCal (https://c14.arch.ox.ac.uk/oxcal.html)

$R_i = -8033 \cdot ln(F^{14}C_i)$,
with R_i in 14C-yr

Example:
$F^{14}C_i = 0.88$ gives
$R_i = 1000$ 14C-yr BP



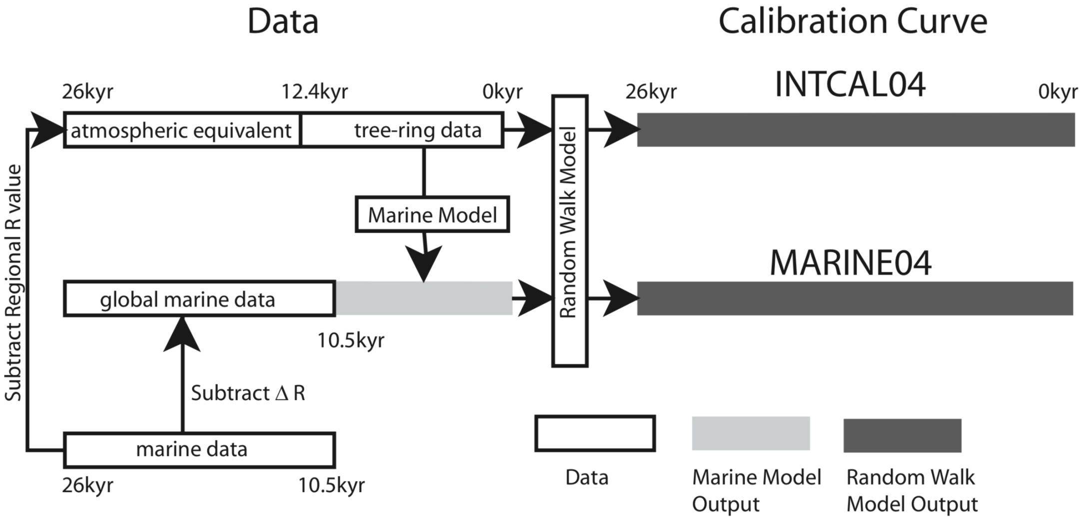
Calibration curve (14C-yr vs cal-yr) is a function of atmospheric $\Delta^{14}C$ which depends on

— ^{14}C production rate (upper atmosphere)

— C cycle (mainly air-sea gas exchange and ocean circulation)

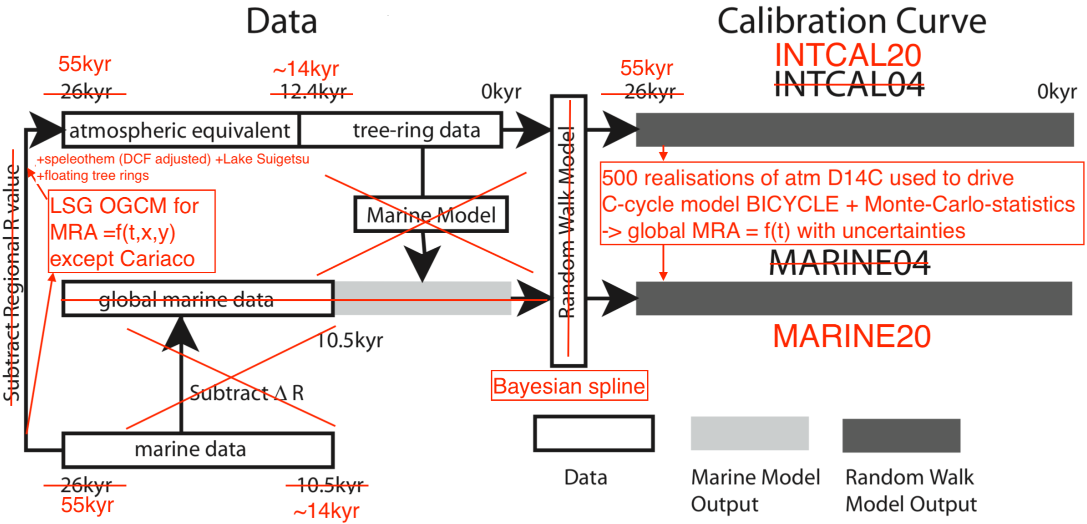
Setup for Calibration Curve IntCal04/09/13

(Reimer et al., 2004)



Revised Setup for Calibration Curve IntCal20

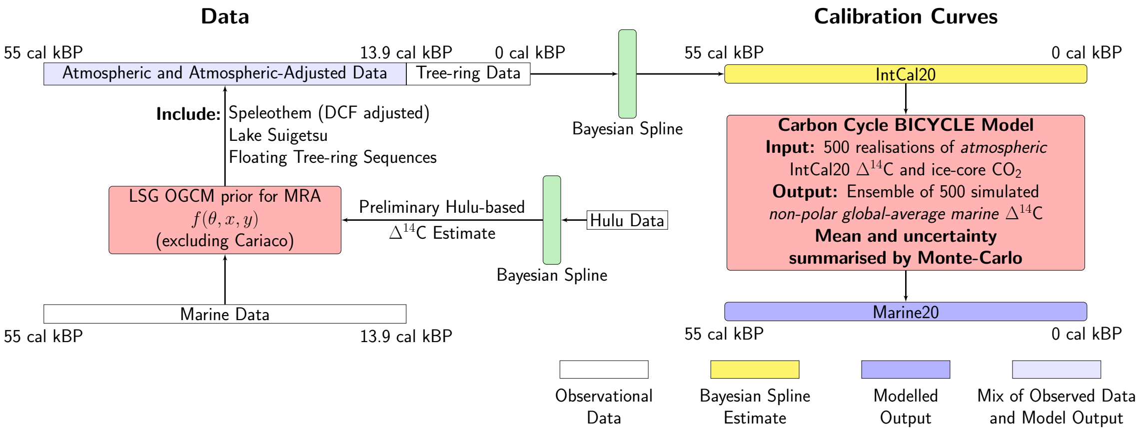
(Reimer et al., 2004)



LSG, BICYCLE = $f(CO_2$, atm $\Delta^{14}C)$

Revised Setup for Calibration Curve IntCal20

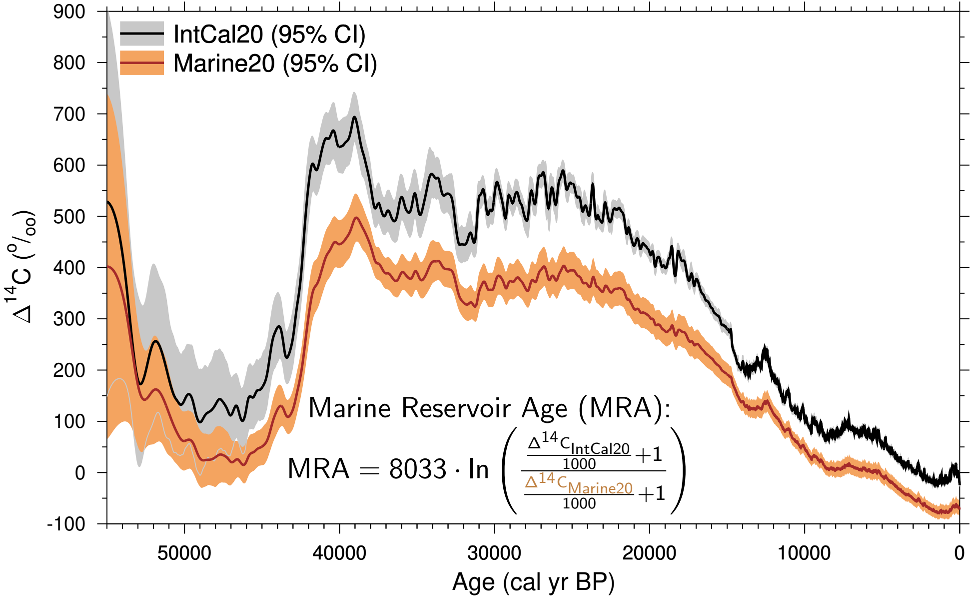
(Heaton et al., 2020)



C cycle models LSG-OGCM and BICYCLE have been used in IntCal20 and Marine20

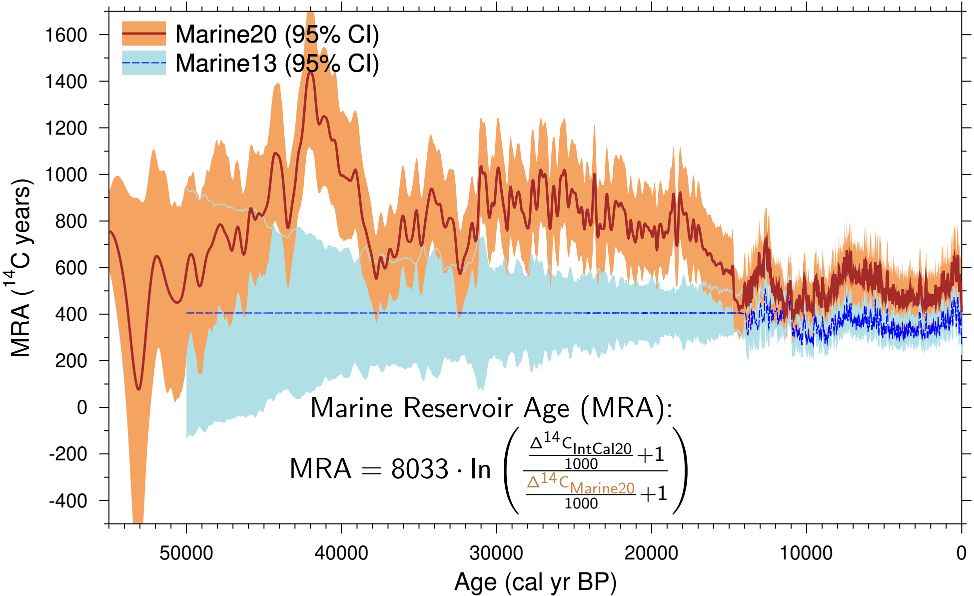
Calibration Curve IntCal20 and Marine20

(Heaton et al., 2020)



Calibration Curve IntCal20 and Marine20

(Heaton et al., 2020)



Calibration Curve IntCal20 and Marine20

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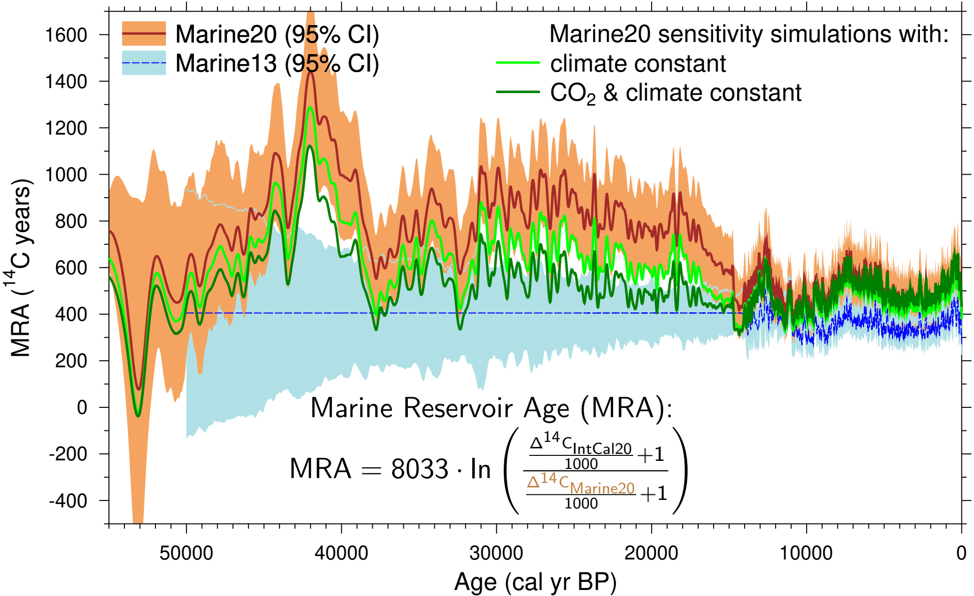

Model largely based on 18 years old paper...

(Köhler et al., 2006)

Geochemistry Geophysics Geosystems G3

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A model-based interpretation of low-frequency changes in the carbon cycle during the last 120,000 years and its implications for the reconstruction of atmospheric $\Delta^{14}C$

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Raimund Muscheler

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Hubertus Fischer

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Model largely based on 18 years old paper... (Köhler et al., 2006)

Main shortcomings:

– no solid Earth fluxes

– missing bipolar seesaw

Geochemistry Geophysics Geosystems G³
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Bipolar seesaw

Bipolar Seesaw

(Köhler et al., 2022)

a: atmospheric $\Delta^{14}C$

b: Greenland (NGRIP) $\delta^{18}O$

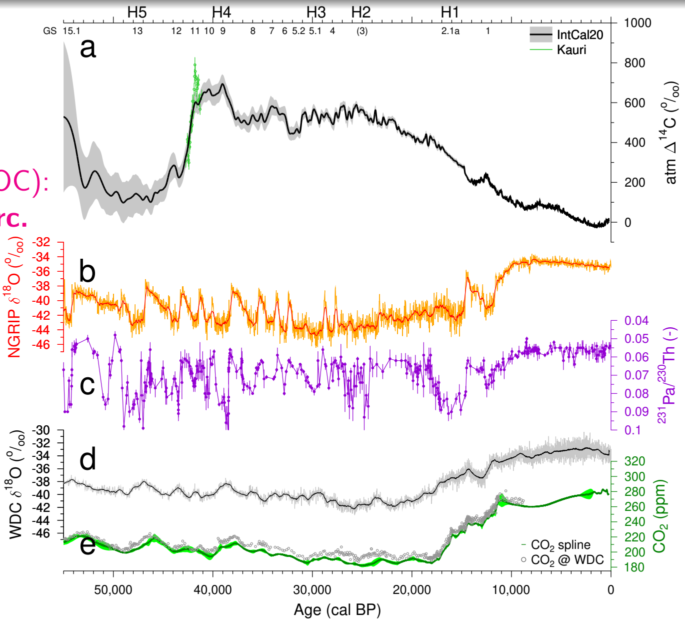
c: $^{231}Pa/^{230}Th$ @ Bermuda Rise (AMOC):

Atlantic Meridional Overturning Circ. is reduced during each stadials

$\Longrightarrow$

d: Antarctic (WDC) $\delta^{18}O$

e: atmospheric CO_2



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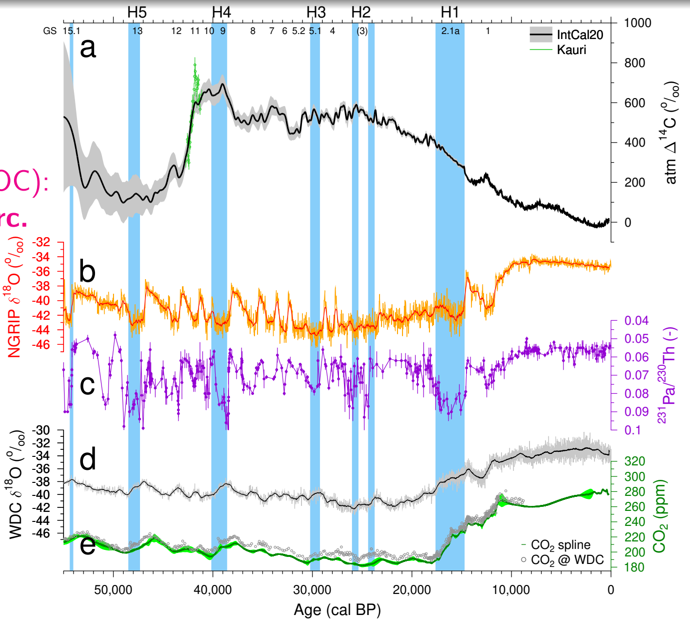
with H event

⟹



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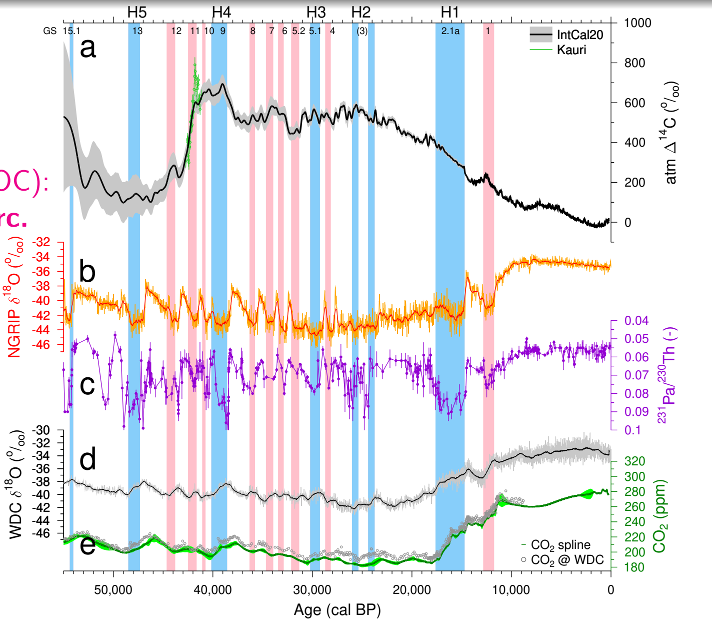

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c: $^{231}Pa/^{230}Th$ @ Bermuda Rise (AMOC):

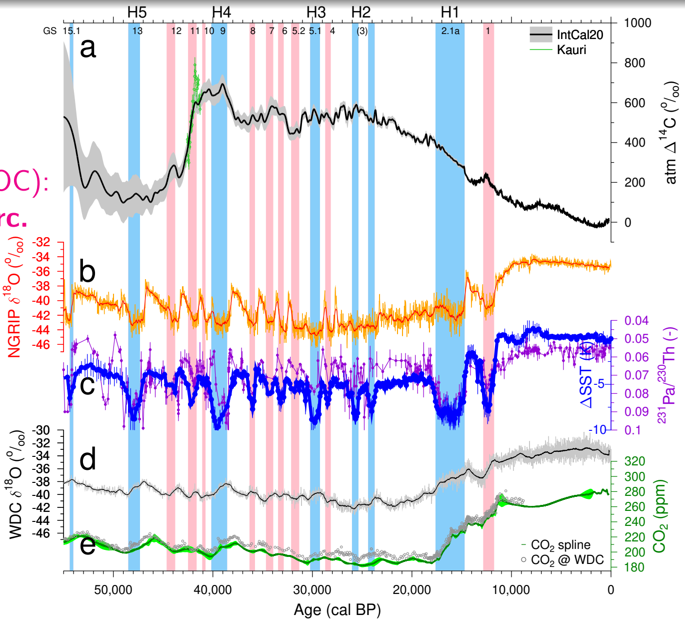
Atlantic Meridional Overturning Circ. is reduced during each stadials

with H event and without H event

c: Alternative AMOC proxy: Iberian Margin SST (Davtian & Bard, 2023) ⟹

d: Antarctic (WDC) $\delta^{18}O$

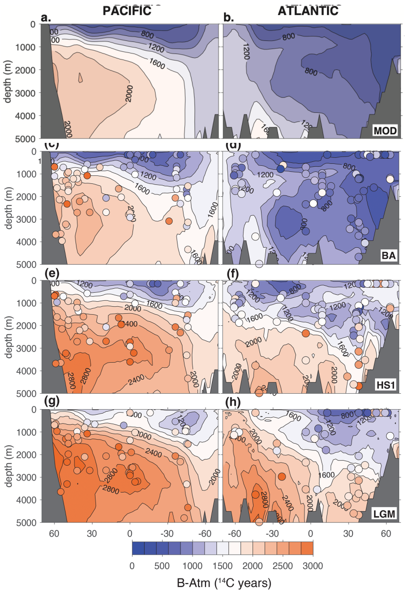
e: atmospheric CO_2



Benthic ^{14}C data

Marine Reservoir Age (MRA) of the deep ocean

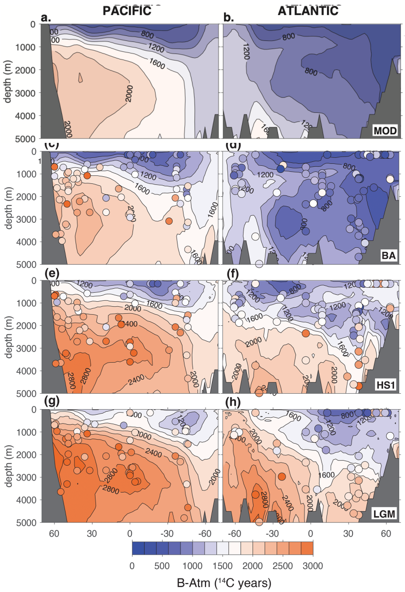
(Skinner et al., 2023)



$\Longleftarrow$

Data on ^{14}C age

Marine Reservoir Age (MRA) of the deep ocean (Skinner et al., 2023; Heaton et al., 2021)



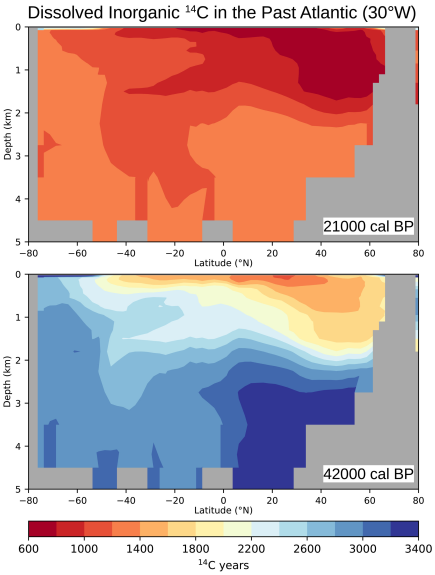
⇐

Data on ^{14}C age

⇒

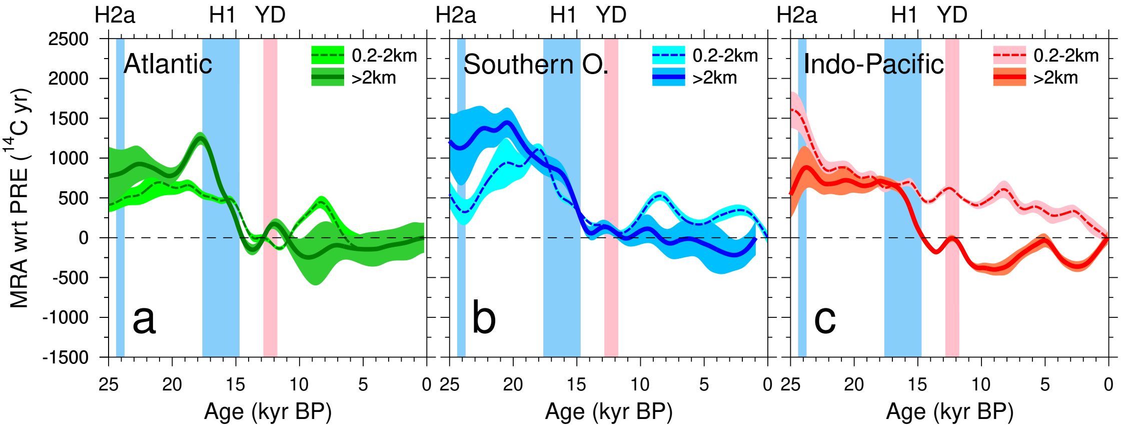
same ocean circ.
only different
atm Δ^{14}C & CO_2

Change in ^{14}C age
is NOT only
caused by
ocean circulation!



Marine Reservoir Age (MRA) of the deep ocean

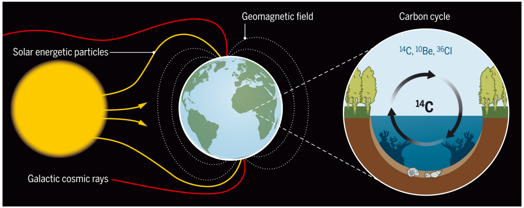
(based on Skinner et al., 2023)

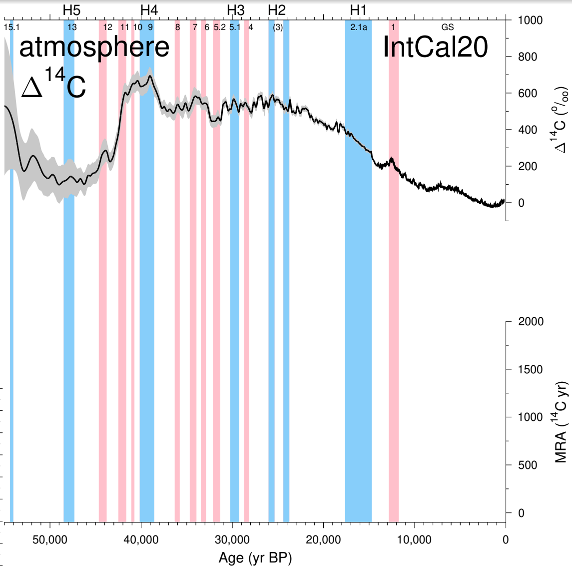


$$\mathrm{MRA} = 8033 \cdot \ln\left(\frac{\frac{\Delta^{14}C_{\mathrm{IntCal20}}}{1000}+1}{\frac{\Delta^{14}C_{\mathrm{sample}}}{1000}+1}\right)$$

Summary of Approach

(Heaton et al., 2020, 2021, Reimer et al. 2020, Skinner et al., 2023)





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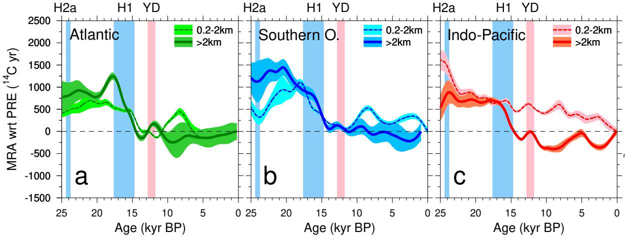
deep ocean



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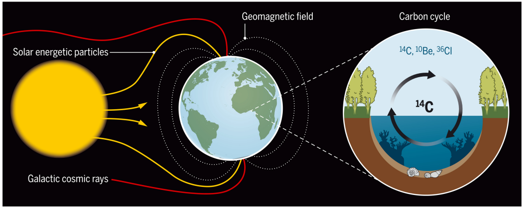

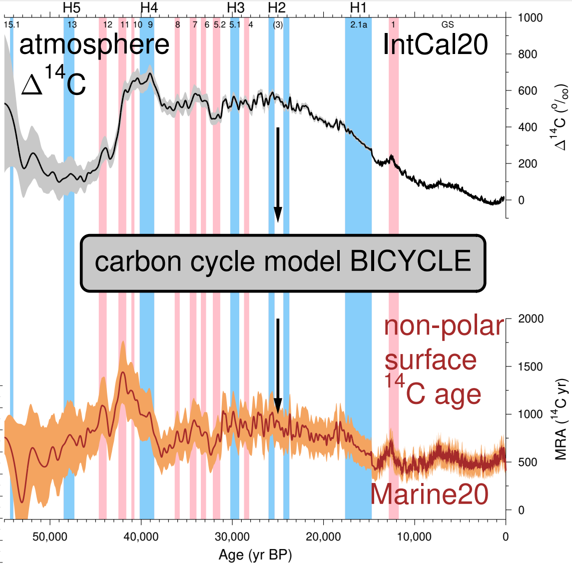

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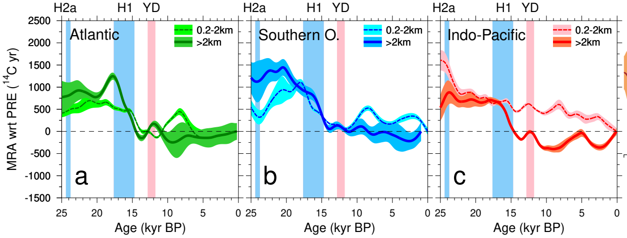
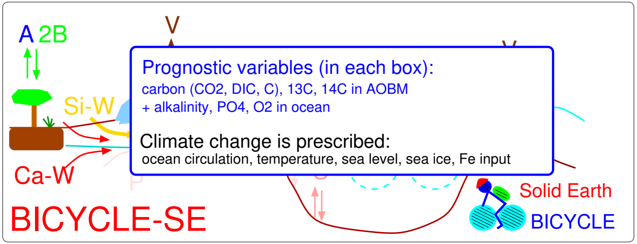
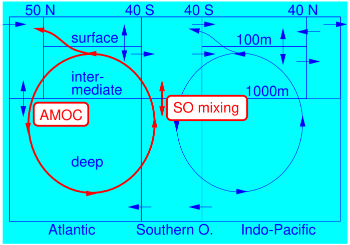


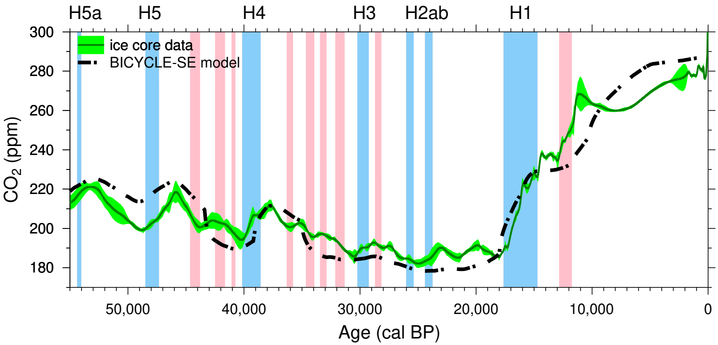
Applied model — BICYCLE-SE

What is in the BICYCLE-SE model?

(Köhler et al., 2020, 2022, 2024)







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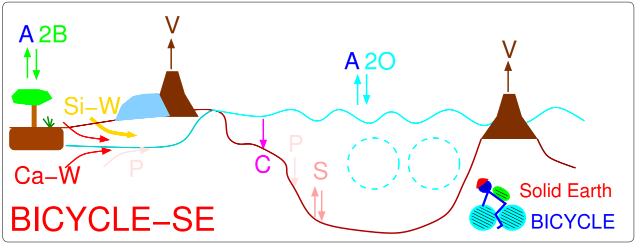
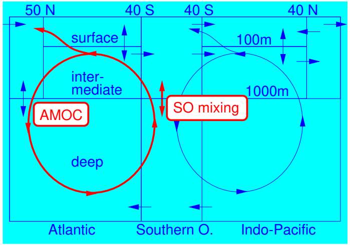
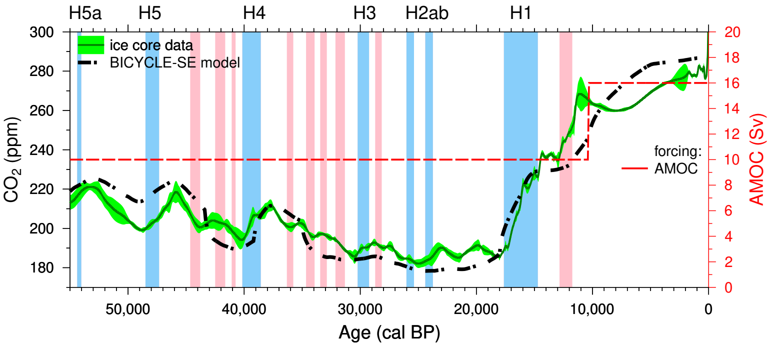
(Köhler et al., 2020, 2022, 2024)



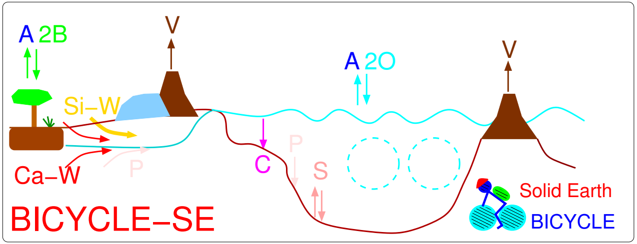


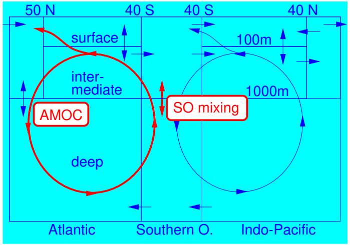


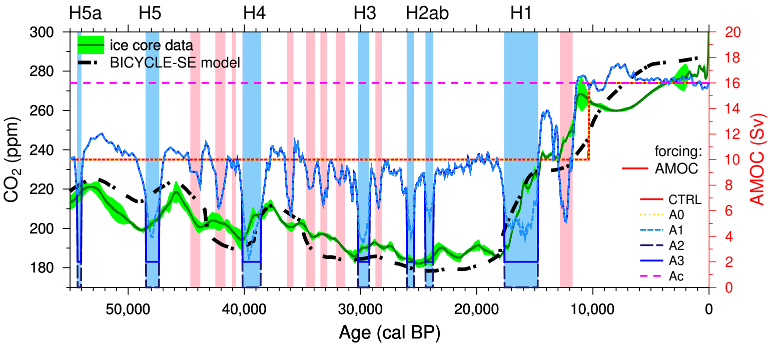
How important are abrupt AMOC changes for the ^{14}C cycle?

What is in the BICYCLE-SE model?

(Köhler et al., 2020, 2022, 2024)





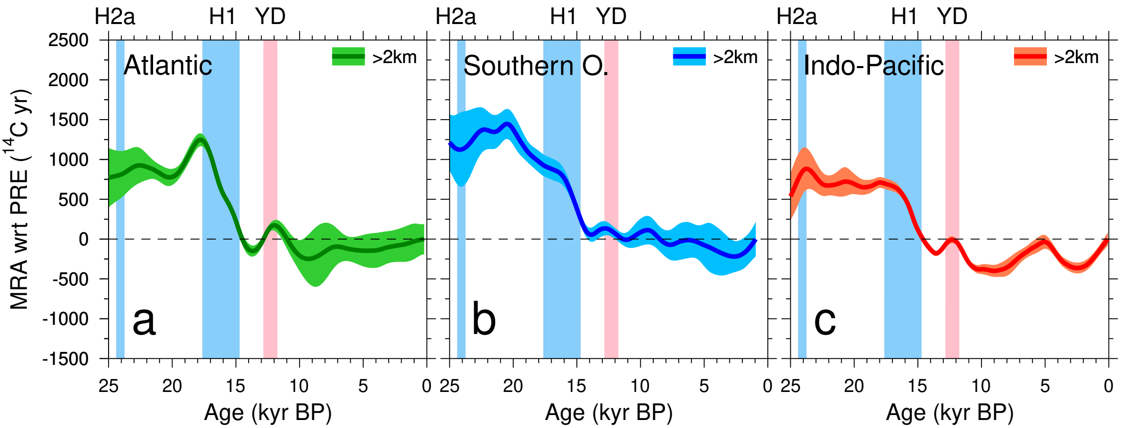


Using Iberian Margin SST (Davtian & Bard, 2023) to prescribe AMOC

Results

Deep ocean ^{14}C
Surface ocean ^{14}C
Atmospheric ^{14}C
Atmospheric CO_2

Deep Ocean ^{14}C Age (in model: >1 km)



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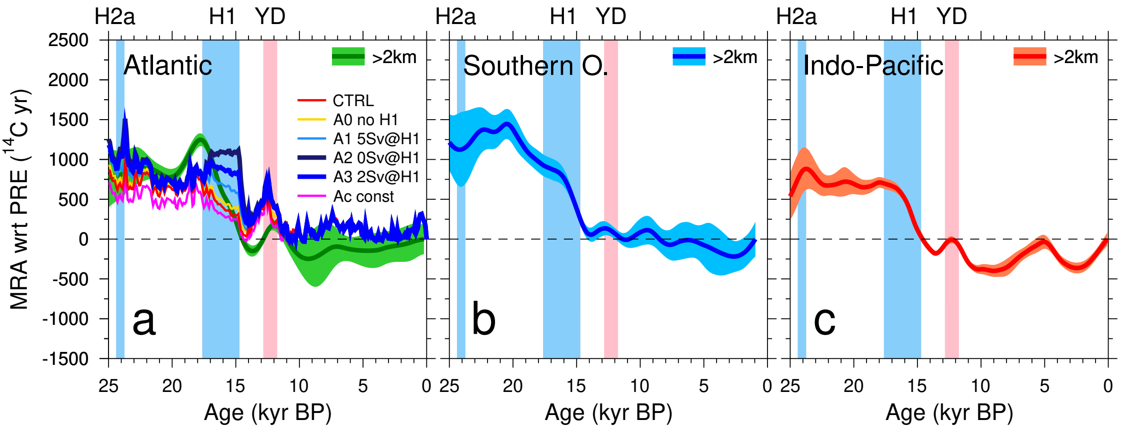
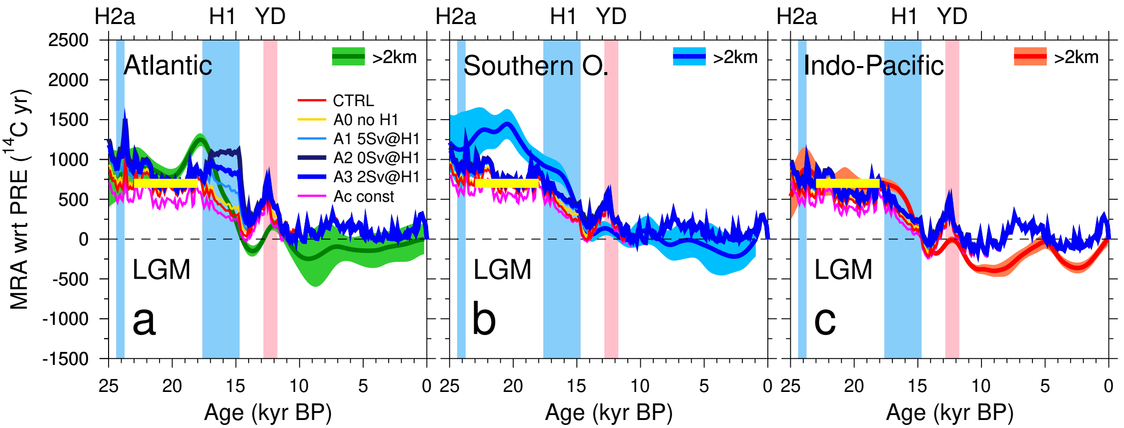


#1: AMOC of 0-2 Sv @ Heinrich 1 event agrees best with deep Atlantic data

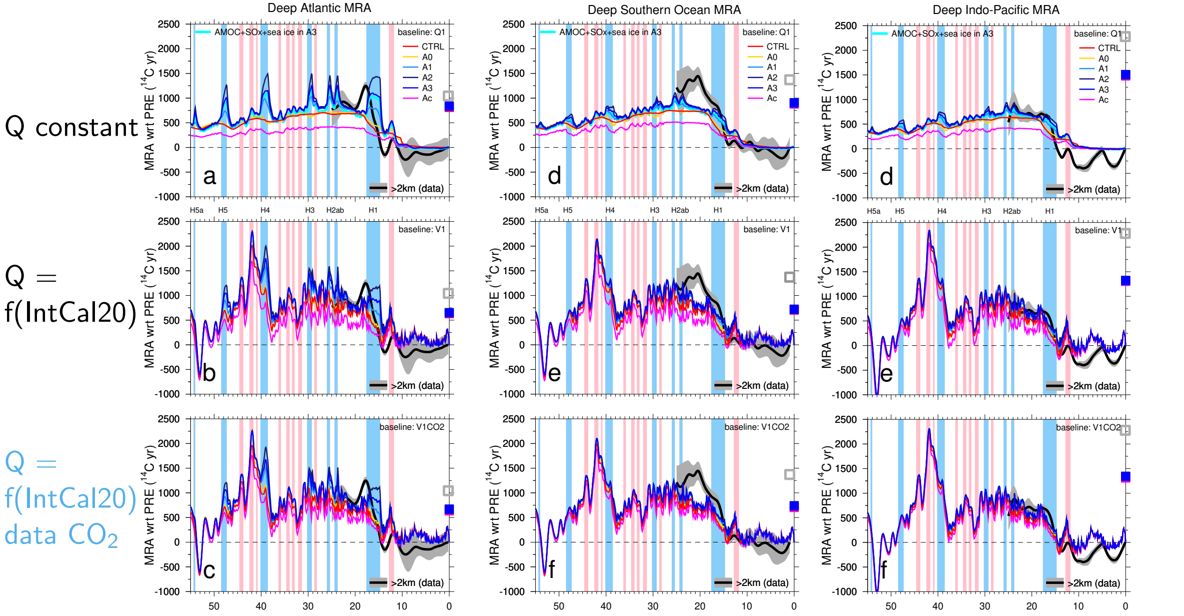
Deep Ocean ^{14}C Age (in model: >1 km)



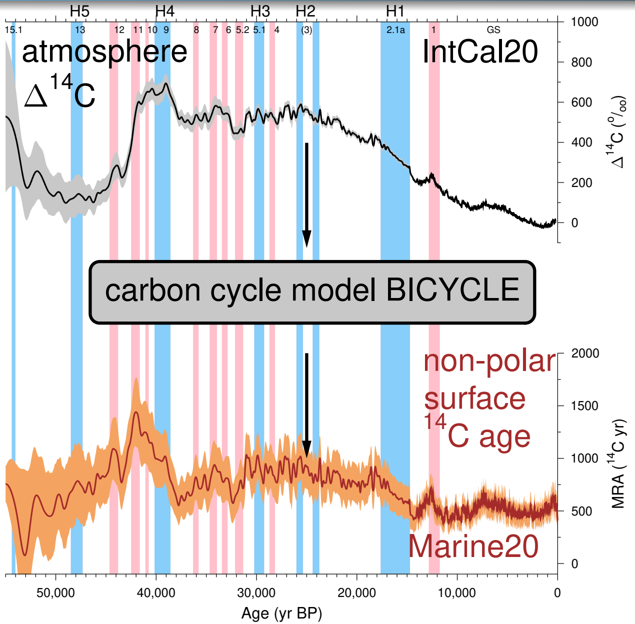
#1: Heinrich 1 event: AMOC of 0-2 Sv agrees with deep Atlantic data (scenario A3)

#2: The deep LGM ocean is ~700 ^{14}C yr "older" than at preindustrial

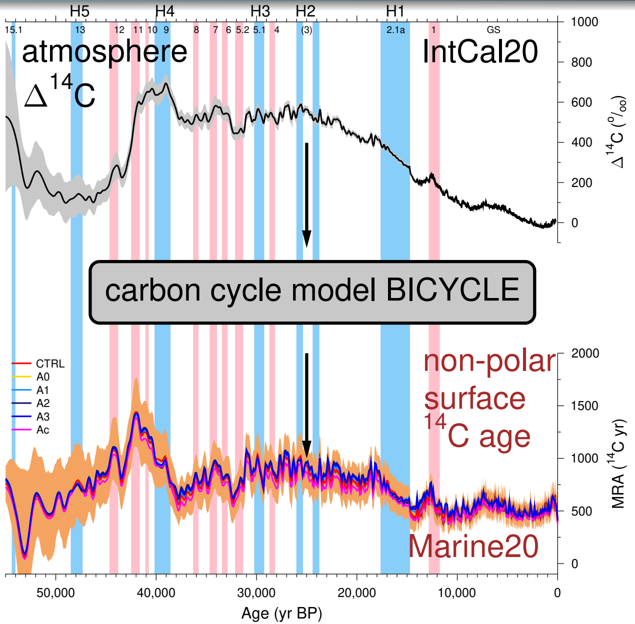
Deep Ocean ^{14}C Age (in model: >1 km)

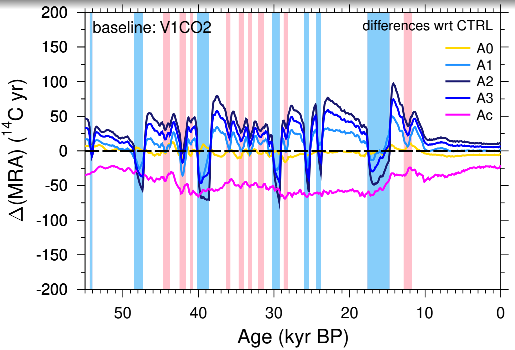


Surface Ocean Marine Reservoir Age



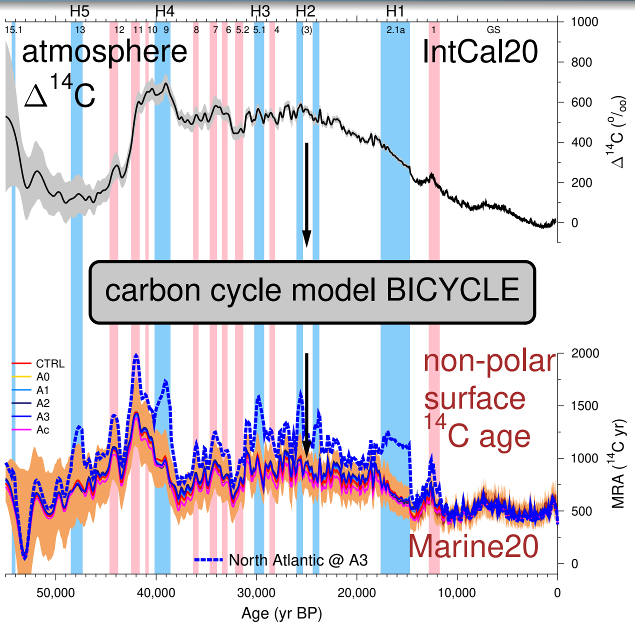
Surface Ocean Marine Reservoir Age

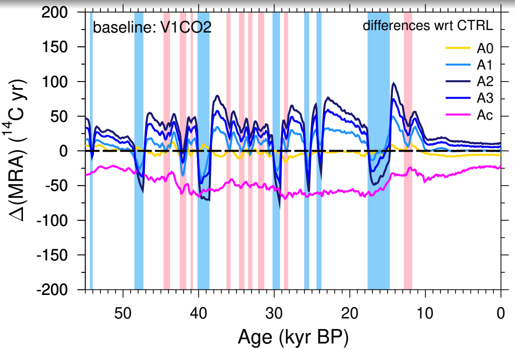




#3: ΔMRA for variable AMOC: <100 ^{14}C yr (non-polar surface)

Surface Ocean Marine Reservoir Age

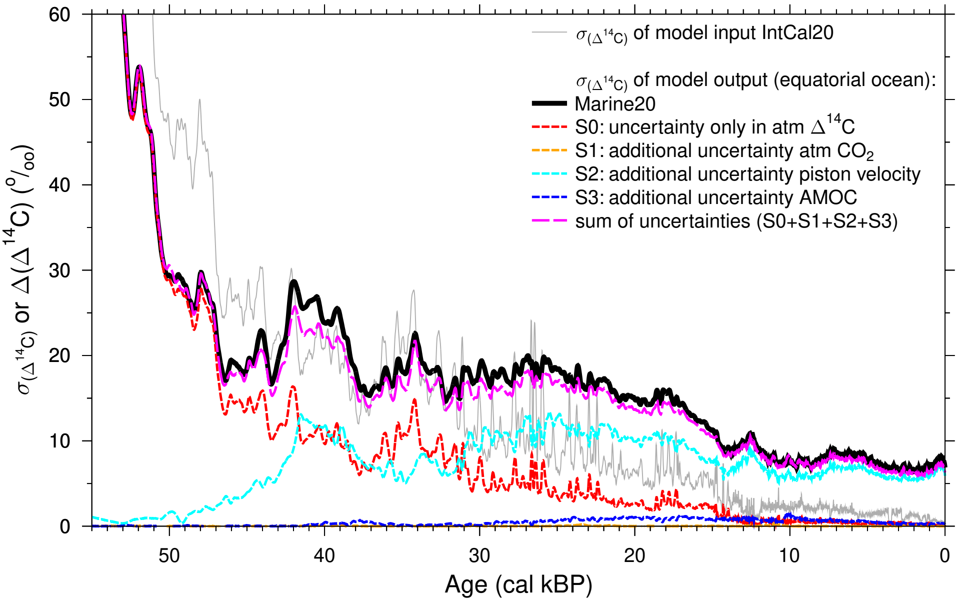




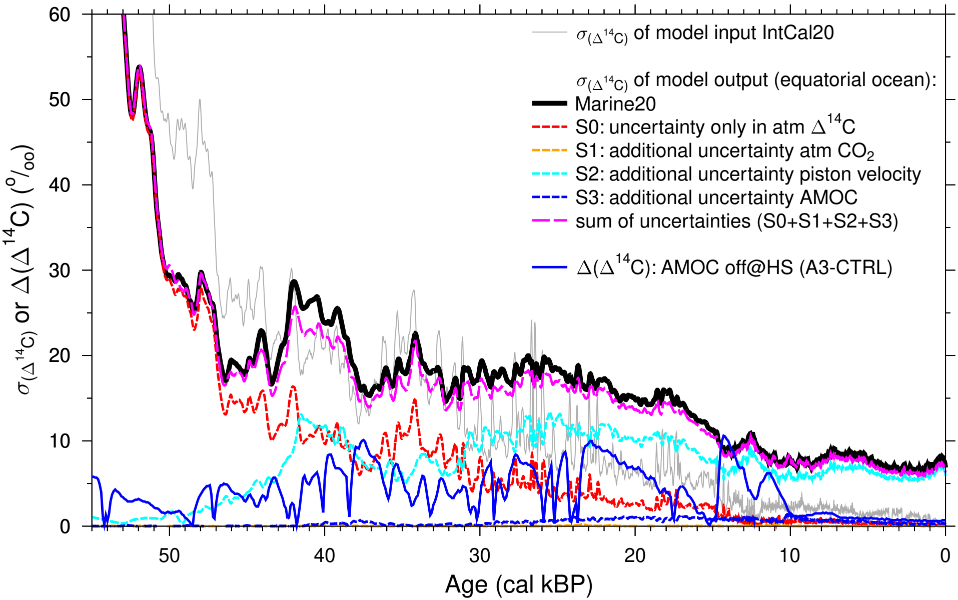
#3: ΔMRA for variable AMOC: <100 ^{14}C yr (non-polar surface)

North Atlantic: >1000 ^{14}C yr in H1 (∼ Stern & Lisiecki, 2013; Skinner et al., 2019)

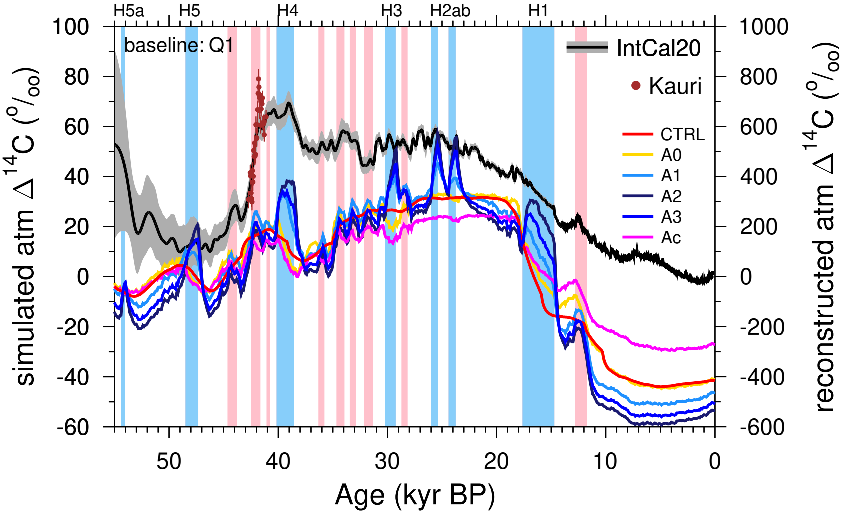
Errors in Marine20 (Surface Ocean Marine Reservoir Age) (Heaton et al., 2020)



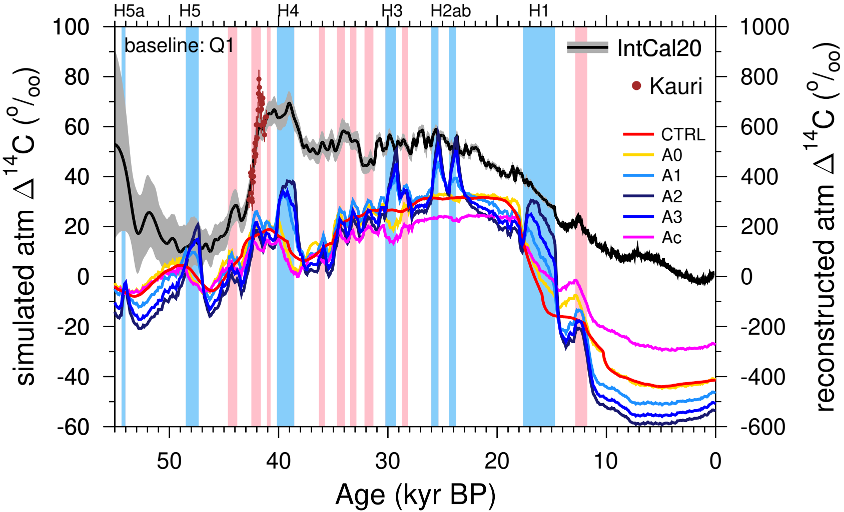
Errors in Marine20 (Surface Ocean Marine Reservoir Age) (Heaton et al., 2020)



Atmospheric $\Delta^{14}C$



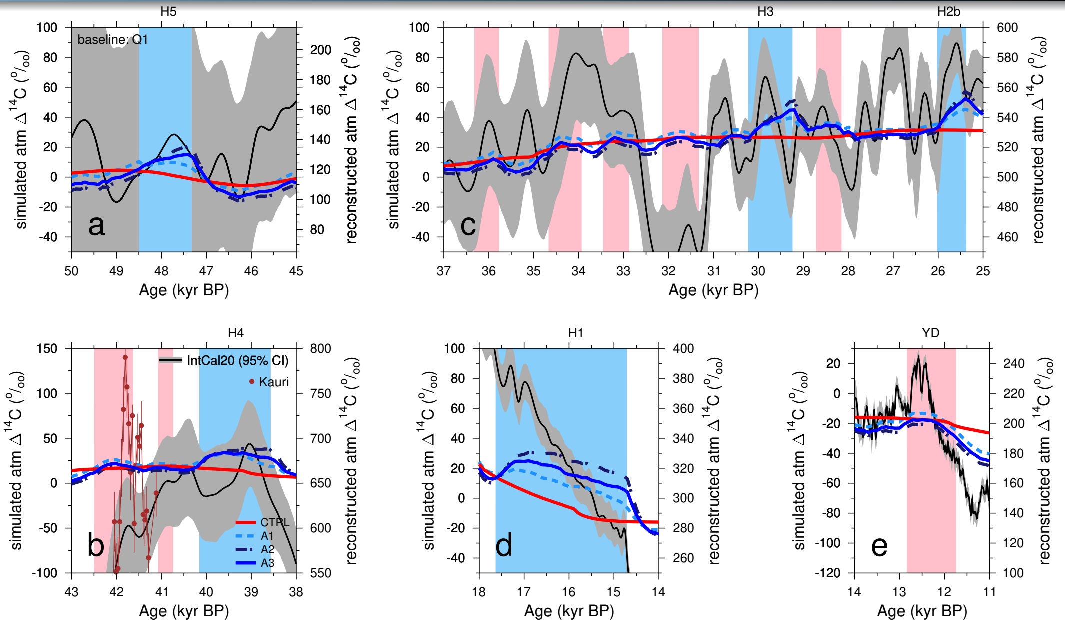
Atmospheric $\Delta^{14}C$



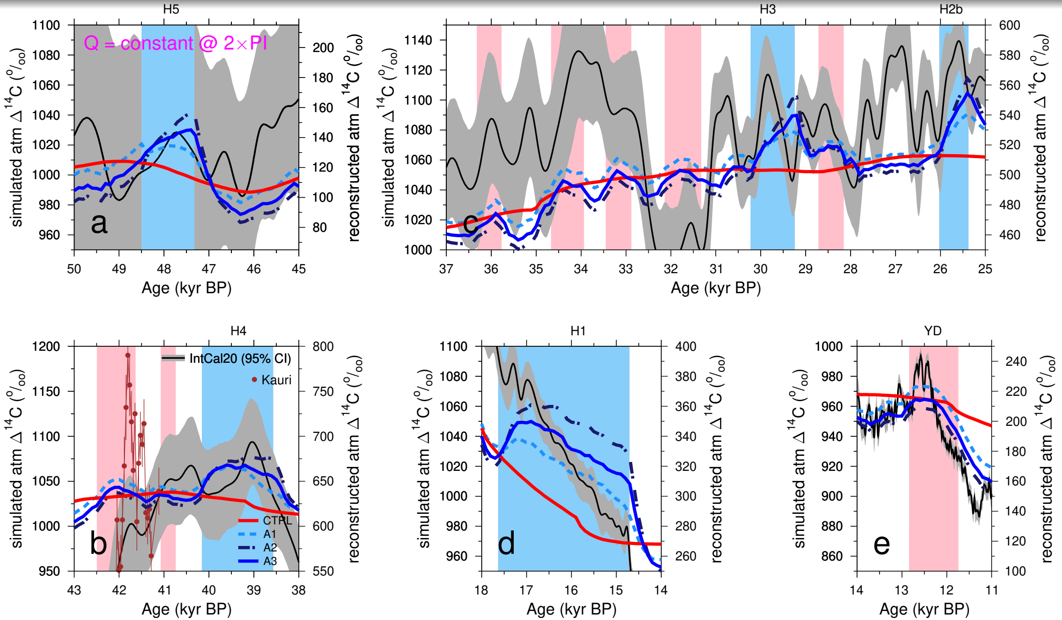
#4: Millennial-scale changes in atm $\Delta^{14}C$ of 10-30‰ related to AMOC reductions (Q constant)

(increases agreement with IntCal20, H1 is special, no non-HS vs HS difference in IntCal20)

Atmospheric $\Delta^{14}C$ ... in detail more difficult ...

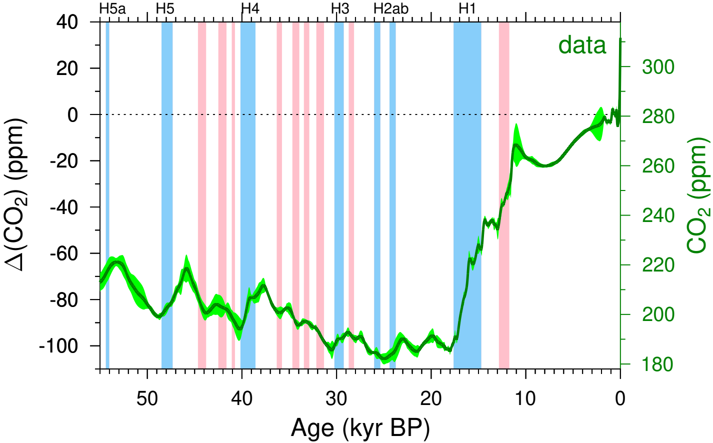


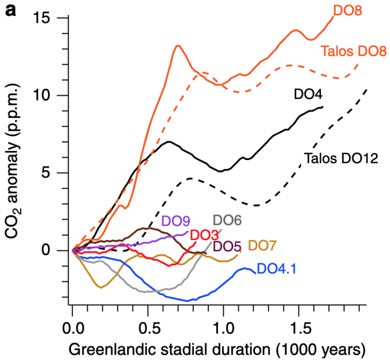
Atmospheric $\Delta^{14}C$ ... in detail more difficult ...



Atmospheric CO_2

(Ahn & Brook, 2014)





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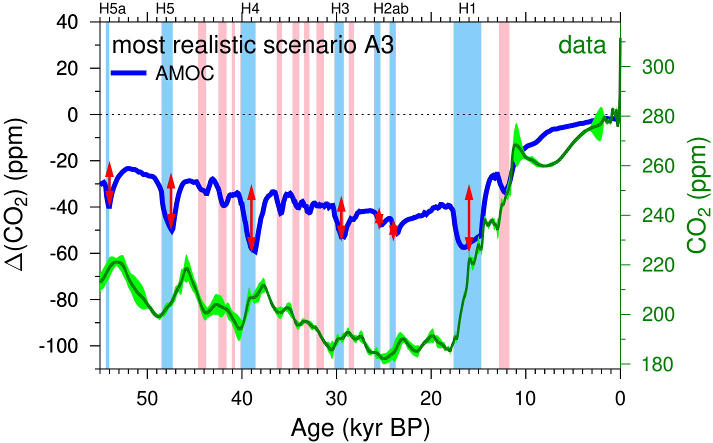
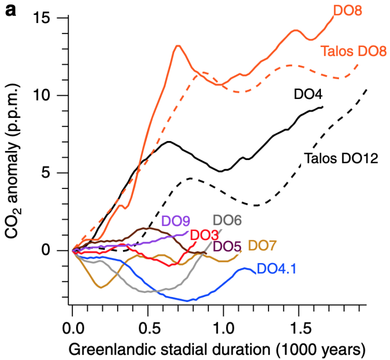


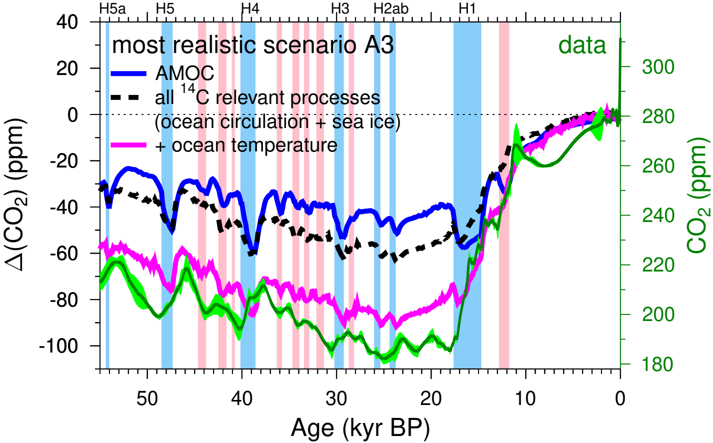


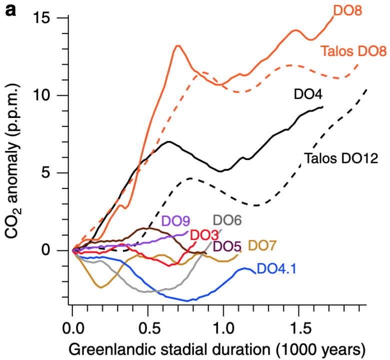
#5: CO_2 falls by 10-30 ppm during AMOC shutdown — opposite to ice core data

⇒ responsible process not connected to AMOC (proxies: SO physics and biology)

Atmospheric CO_2

(Ahn & Brook, 2014)





#5: CO_2 falls by 10-30 ppm during AMOC shutdown — opposite to ice core data
⇒ responsible process not connected to AMOC (proxies: SO physics and biology)

#6: Physical pump explains 85 ppm of glacial CO_2 drawdown
60 ppm from circulation + sea ice (^{14}C-related), 25 ppm from ocean cooling

Conclusions

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- #1: Massive AMOC reduction during Heinrich 1 event agrees best with benthic ^{14}C data
- #2: The deep LGM ocean is ~700 ^{14}C yr "older" than at preindustrial
- #3: Abrupt AMOC ⇒ offset in non-polar surface age (Marine20) by < 100 ^{14}C yr
- #4: Millennial-scale changes in atm $\Delta^{14}C$ (IntCal20) are related to AMOC reductions
- #5: AMOC shutdown during Heinrich stadials ⇒ fall of simulated CO_2 by 10-30 ppm
  ⇒ SO processes (or land carbon) responsible for ice core CO_2 rise in Heinrich stadials
- #6: Physical carbon pump explains 85 ppm of glacial CO_2 drawdown