Isotopes in the CESM

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NCAR Earth System Laboratory
Climate & Global Dynamics

NSF

U.S. DEPARTMENT OF ENERGY

A Collaborative Proposal: Development of an Isotope-Enabled CESM

Objective: To enhance the CESM with the capability of simulating key isotopes and geotracers, including $\delta^{18}O$, δD, Pa/Th, $\delta^{14}C$, and $\delta^{13}C$, to allow for better comparisons with observations

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CICE
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POP2
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S. Peacock
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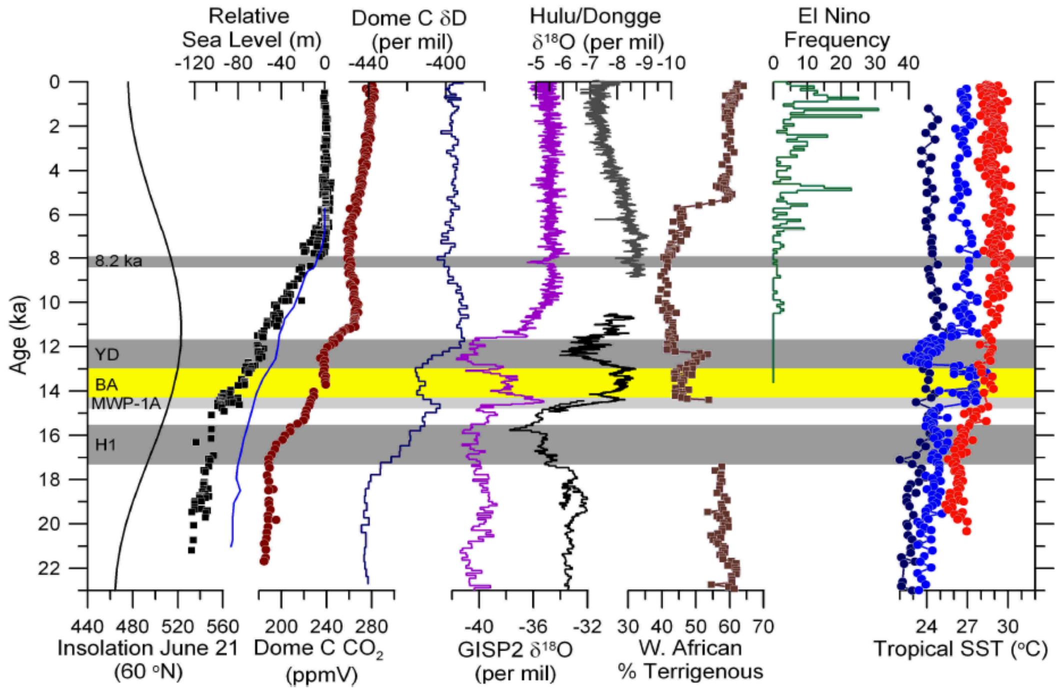
Why are isotopes useful?



- **Climate proxies:**
- ($\delta^{18}O$, δD, Pa/Th, $\delta^{13}C$, etc.) are used to infer climate change signals like ΔT, Δprecip, and ocean circulation changes

→ Comparisons of isotope data with simulated isotopes are more direct than comparisons with inferred climate

Notation: Use of Delta Values

- Measured isotope abundances are expressed as delta (δ) values, calculated as a deviation relative to a known standard.

  $\delta(‰) = (R_{sample}/R_{standard} - 1) \times 1000$

  where R is the measured isotopic ratio relative to the most abundant isotope (e.g., $R={}^{13}C/{}^{12}C$ or $R={}^{18}O/{}^{16}O$).

- Negative δ → depleted relative to the standard
- Postive δ → enriched relative to the standard

What is Fractionation?

Fractionation refers to the small differences in isotopic ratio that arise as a result of different behavior during a chemical or physical(thermodynamic) process.

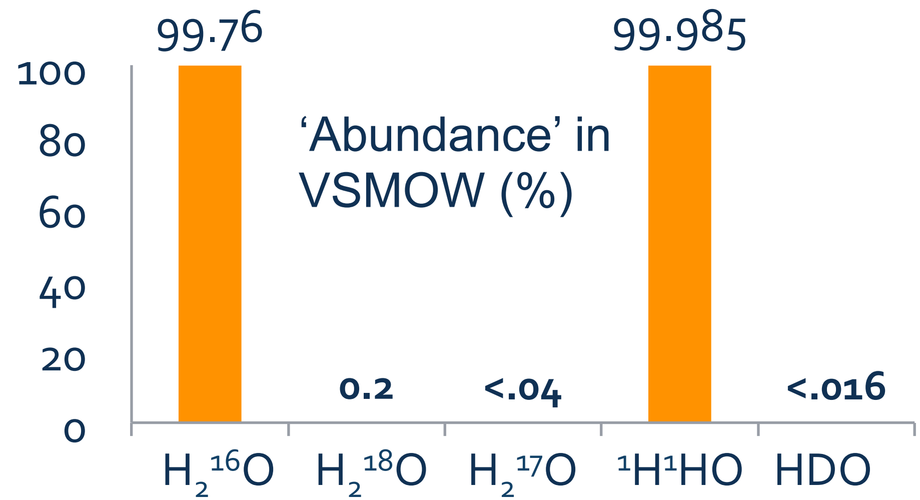
<u>Occurs during</u>:

- isotopic exchange reactions in which the isotopes are redistributed among different molecules containing that element (photosynthesis, formation of calcite)
- physical processes like evaporation/condensation, melting/crystallization, adsorption/desorption, diffusion

Water Isotopes

Stable Water 'Isotopes' 101

TRACERS:
$H_2{}^{16}O$
$H_2{}^{18}O$
H^2HO (HDO)
$H_2{}^{17}O$ (not currently included)



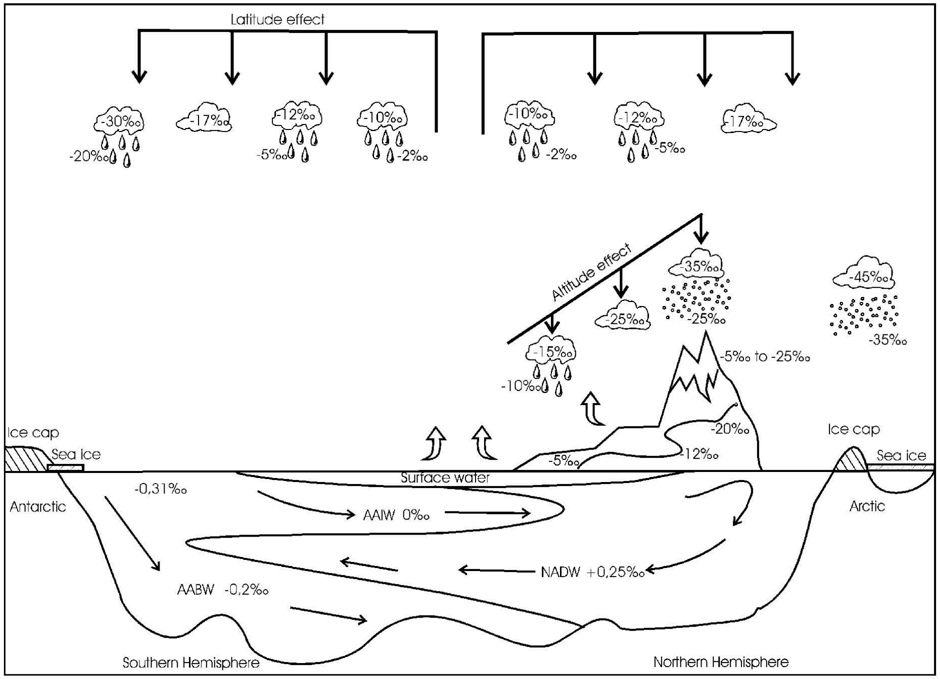
Range in found in Nature:
$-50^{o}/_{oo} < \delta^{18}O <$ to $10^{o}/_{oo}$ terrestrial
$-10^{o}/_{oo} < \delta^{18}O <$ to $3^{o}/_{oo}$ seawater

VSMOW = Vienna Standard Mean Ocean Water, an International standard

How is past climate change inferred from isotopic water signals in paleo ‘archives’?

+ 1. Temperature Effect

$\delta^{18}Op$ is positively correlated with Mean Annual temperature at mid- and high latitudes.



$\delta^{18}Op$ depends on:

1)Temperature of ocean source
2)Rain-out history during transport (climate, distance)
3)Mixture of different air masses
4)Post-condensation effects
5)Local Temperature

From Paul et al. 1999

How is past climate change inferred from isotopic water signals in 'archives'?

$\delta^{18}O$ in Snow vs. Temp.

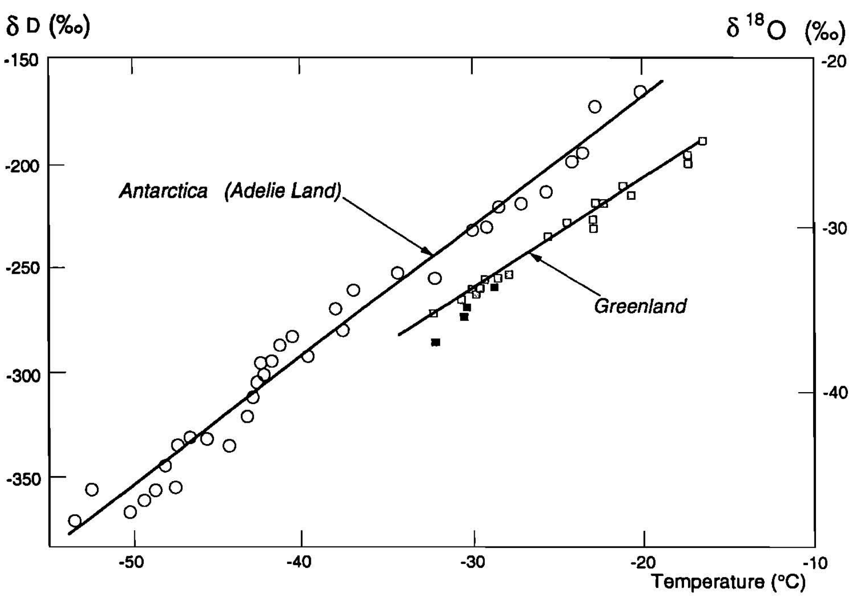


Figure 1. Isotope content of snow versus local surface temperature (annual average). Antarctic data (δD, left scale) are from *Lorius and Merlivat* [1977], and Greenland data ($\delta^{18}O$, right scale) are from *Johnsen et al.* [1989].

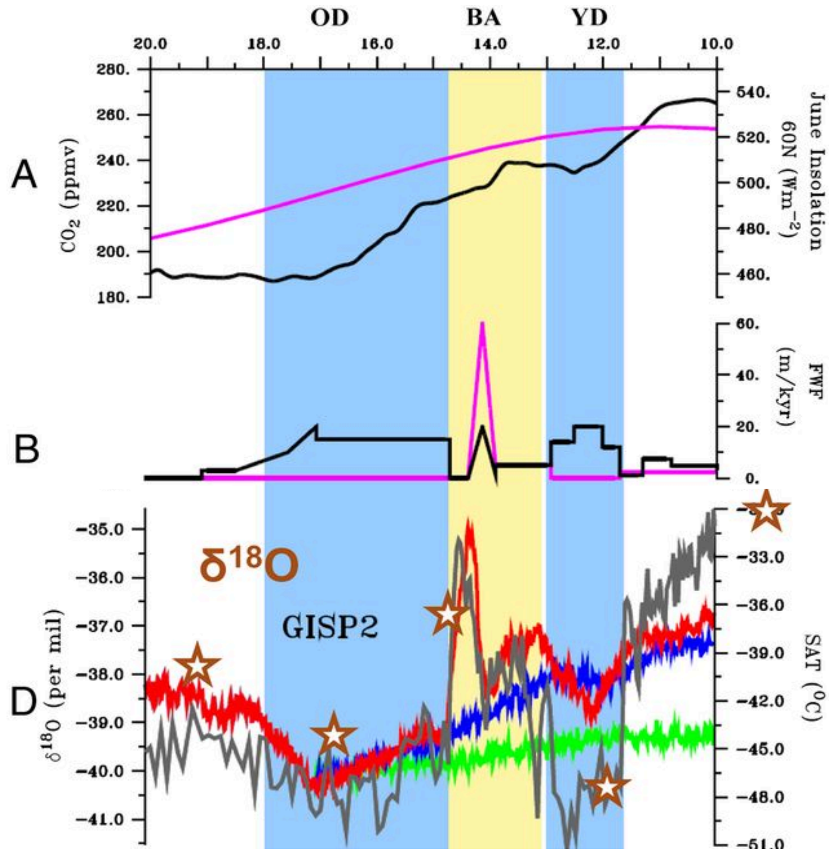
From Jouzel et al. 1997

Paleo-thermometer:
$\Delta(\delta^{18}O) \sim 0.7[^{o}/_{oo}/K]\ \Delta T$
Spatial relationship – Observed to hold seasonally and interannually

Use over long time periods?
(Cuffey and Clow, 1997)
Alternate relationship based on fitting $\delta^{18}O$ record to Bore-hole Temperature record:
$\Delta(\delta^{18}O) \sim 0.33[^{o}/_{oo}/K]\ \Delta T$

Slope may change with time
Due to complexity of underlying processes!

CCSM3 T31_gx3, Transient Simulation of the Last Deglaciation



Liu Z et al. PNAS 2012;109:11101-11104

*δ^{18}Op ~ w/offset for bias

Forcing:

60°N June Insolation(Orbital)

Atm CO2 concentration

(+Ice Sheet orography)

Meltwater input

NH

SH

Proxy Comparison

☆ δ^{18}Op* over Greenland From IsoCAM3 'slices'

Greenland SAT CCSM3-Full

CO2+IS, Orbital+IS

δ^{18}O GISP2 Record

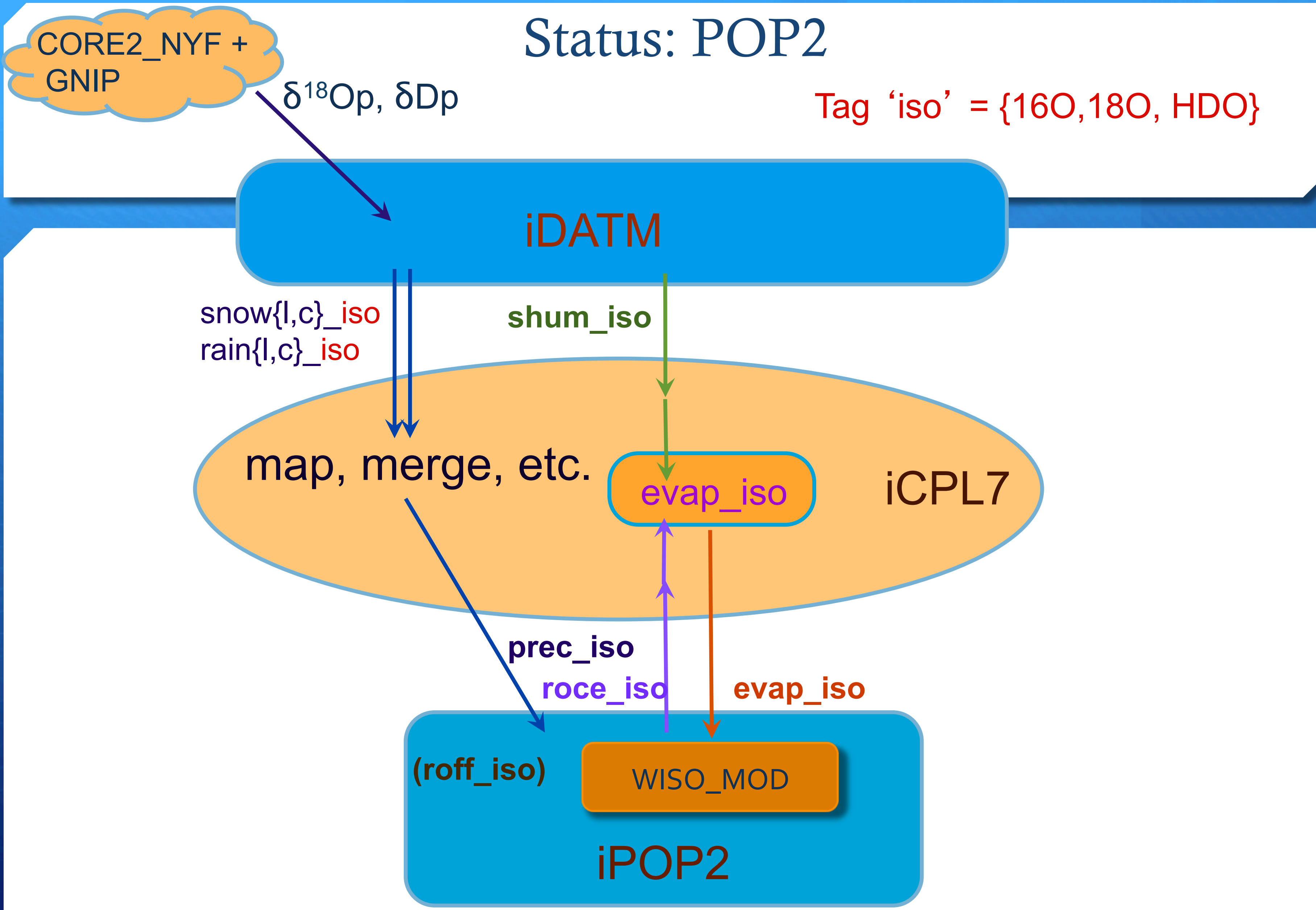
CCSM3 suggests weaker YD cooling

Isocam3 agrees with icecore data

Project goal: Include isotopic water tracers in all aspects of the CESM hydrologic cycle.

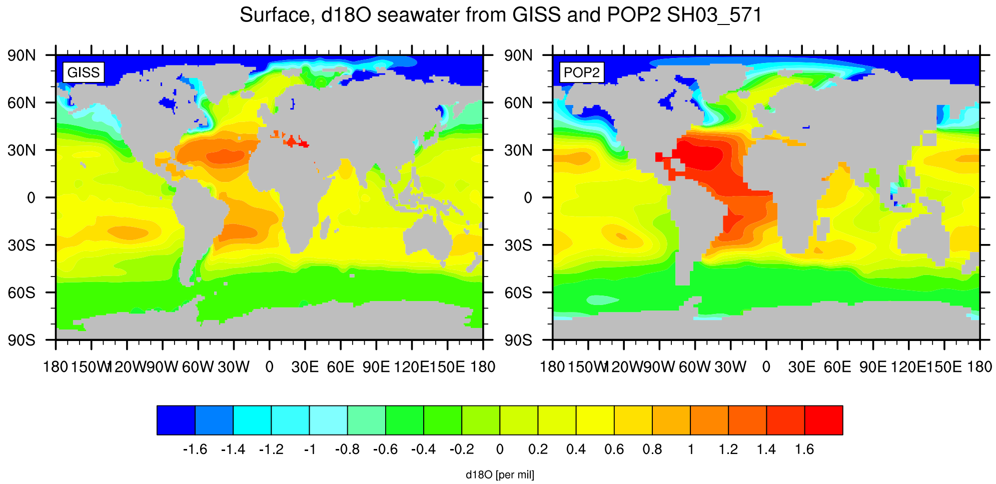
- Allow more direct Data-Model comparisons for model assessment
- Investigate the link between climate variations and isotope tracer responses in order to help interpret paleoclimate records
- To better elucidate the processes underlying changes in the hydrologic cycle induced by climate change

Status: POP2


CORE2_NYF + GNIP
δ18Op, δDp
Tag ‘iso’ = {16O,18O, HDO}
iDATM
snow{l,c}_iso
rain{l,c}_iso
shum_iso
map, merge, etc.
evap_iso
iCPL7
prec_iso
roce_iso
evap_iso
(roff_iso)
WISO_MOD
iPOP2

POP2 results for δ^{18}Ow

Surface δ18Ow



NASA-GISS
Global Seawater ^{18}O Database
(Legrande and Schmidt, 2006)

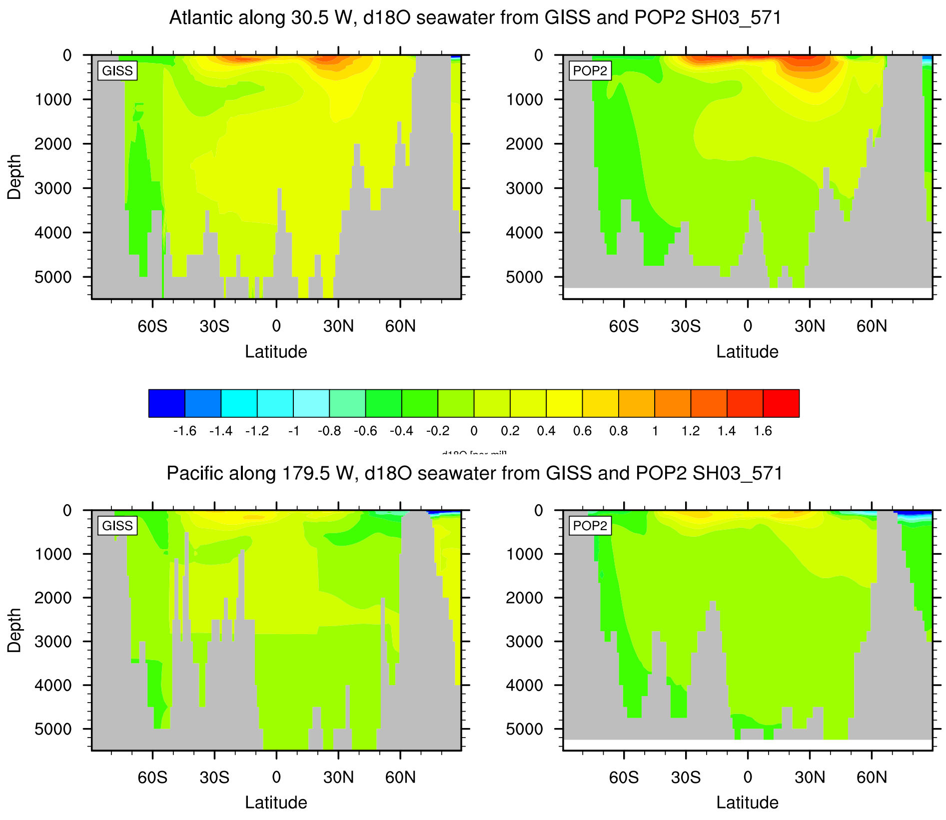
Year 570

570 year spin-up; POP2
CORE2 NYF
(Large and Yeager, 2009)
(T62, repeat monthly mean)

gx3v7 POP2 grid

Biases:
Tropical Atlantic too enriched
(assumptions about shum_18O?)
S. Ocean too depleted

POP2 results for δ18Ow



570 year spin-up; POP2
CORE2 NYF
(Large and Yeager, 2009)
(T62, repeat monthly mean)

gx3v7 POP2 grid

Biases:
Too depleted in SH and Deep Ocean
>Iso-Evaporation bias
Too depleted deep N. Atl:
>Weak AMOC

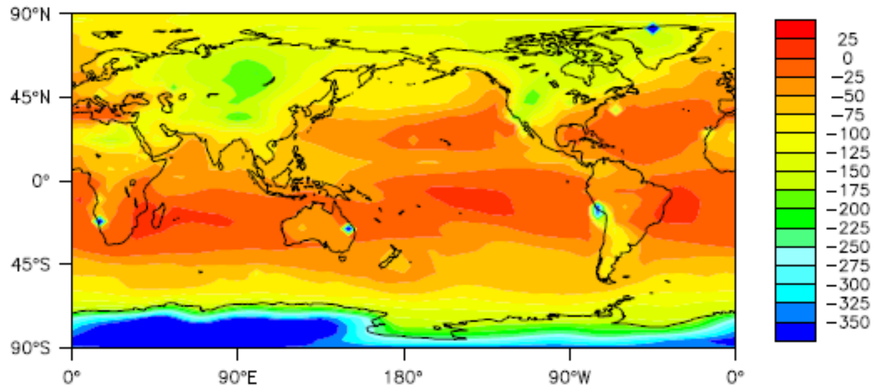
NASA-GISS
Global Seawater 18O Database
(Legrande and Schmidt, 2006)

Year 570

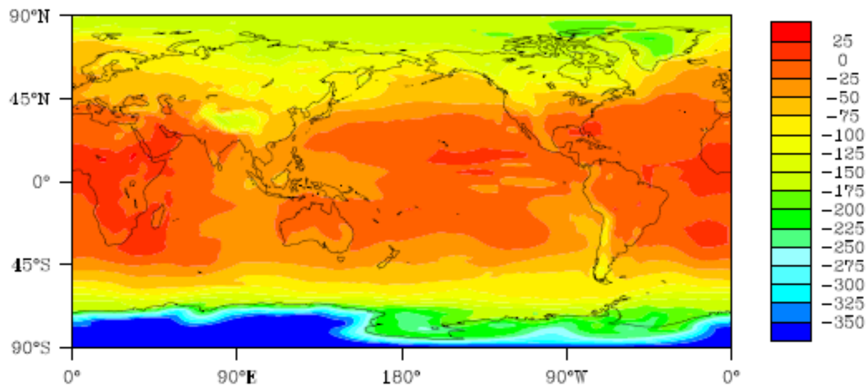
CAM5 Update: δD Precipitation - JJA

Courtesy of
J. Nusbaumer,
Univ. of CO

CAM5



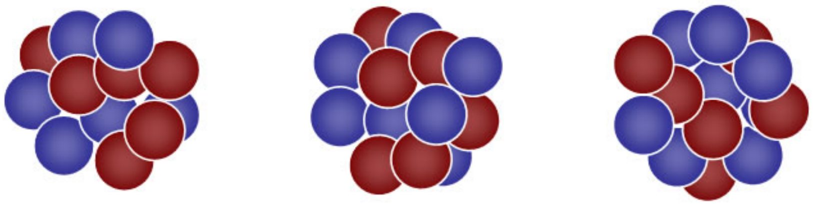
GNIP



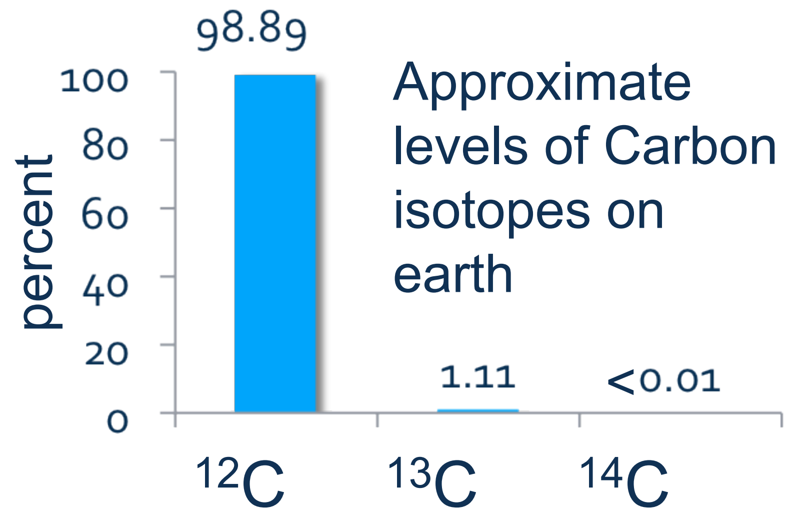
The model has a few locations where the precipitation values are too negative, particularly over land, again indicating the need for an isotopic land model and rain re-evaporation.

Carbon Isotopes

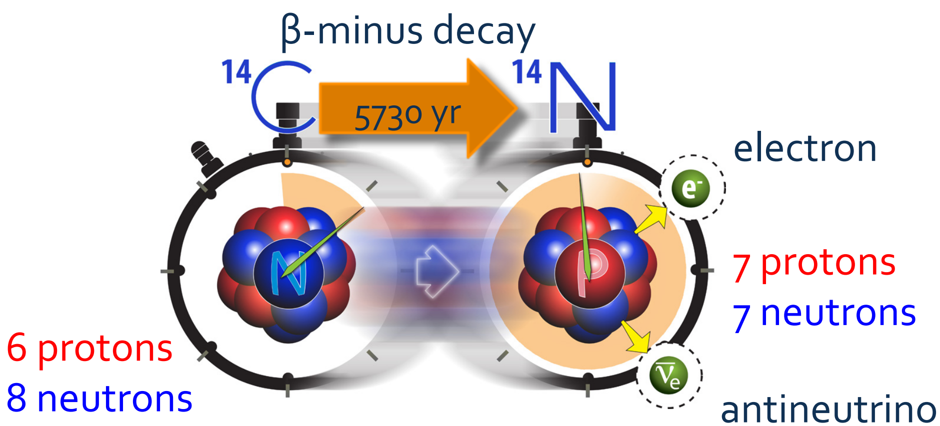
Carbon Isotopes 101



^{12}C	^{13}C	^{14}C
6 protons	6 protons	6 protons
6 neutrons	7 neutrons	8 neutrons
(stable)	(stable)	(radioactive)



Approximate levels of Carbon isotopes on earth

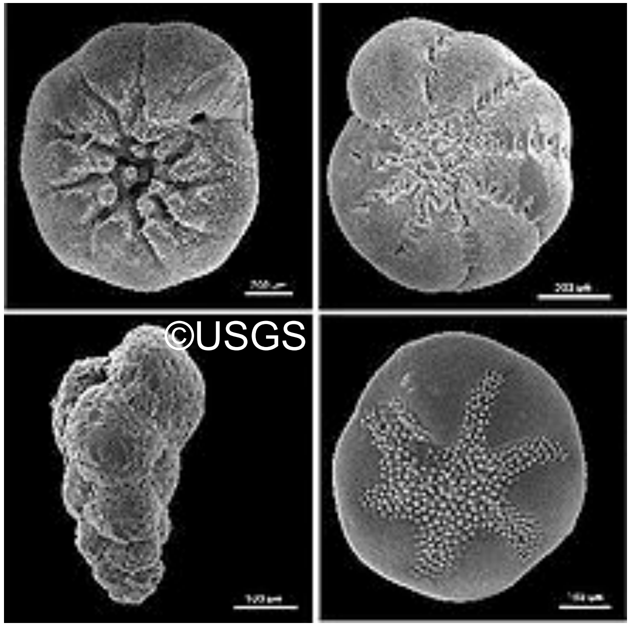


Stable isotopes (^{12}C, ^{13}C) allow the tracing of water masses due to (fractionation)

^{14}C acts as clock

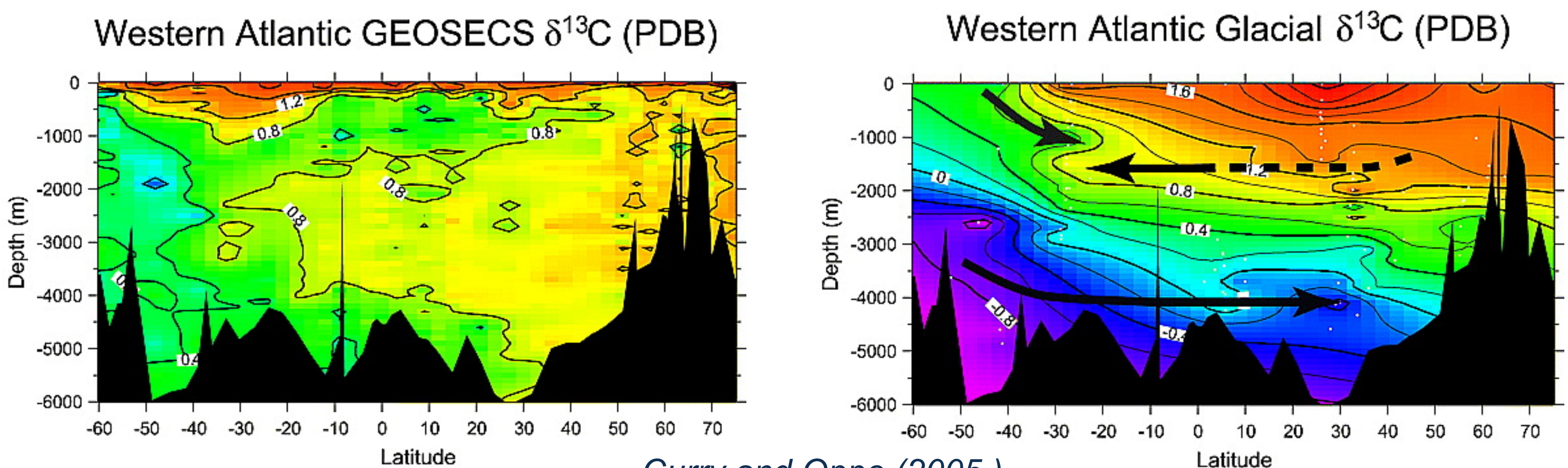
How is paleo carbon isotope data recorded?

- The ambient ocean $\delta^{13}C$ ($\Delta^{14}C$, and $\delta^{18}O$) is build into the $CaCO_3$ shells of benthic foraminiferans and in the $CaCO_3$ of corals
- Corals and fossilized benthic foraminiferans (from ocean cores) allow a reconstruction of paleo oceanic $\delta^{13}C$ and $\Delta^{14}C$ concentrations
- $\Delta^{14}C$ and other radioactive isotopes (e.g., ^{230}Th) allow the dating of these corals and benthic foraminiferans



Clockwise from top left: *Ammonia beccarii*, *Elphidium excavatum clavatum*, *Buccella frigida*, and *Eggerella advena (©USGS)*

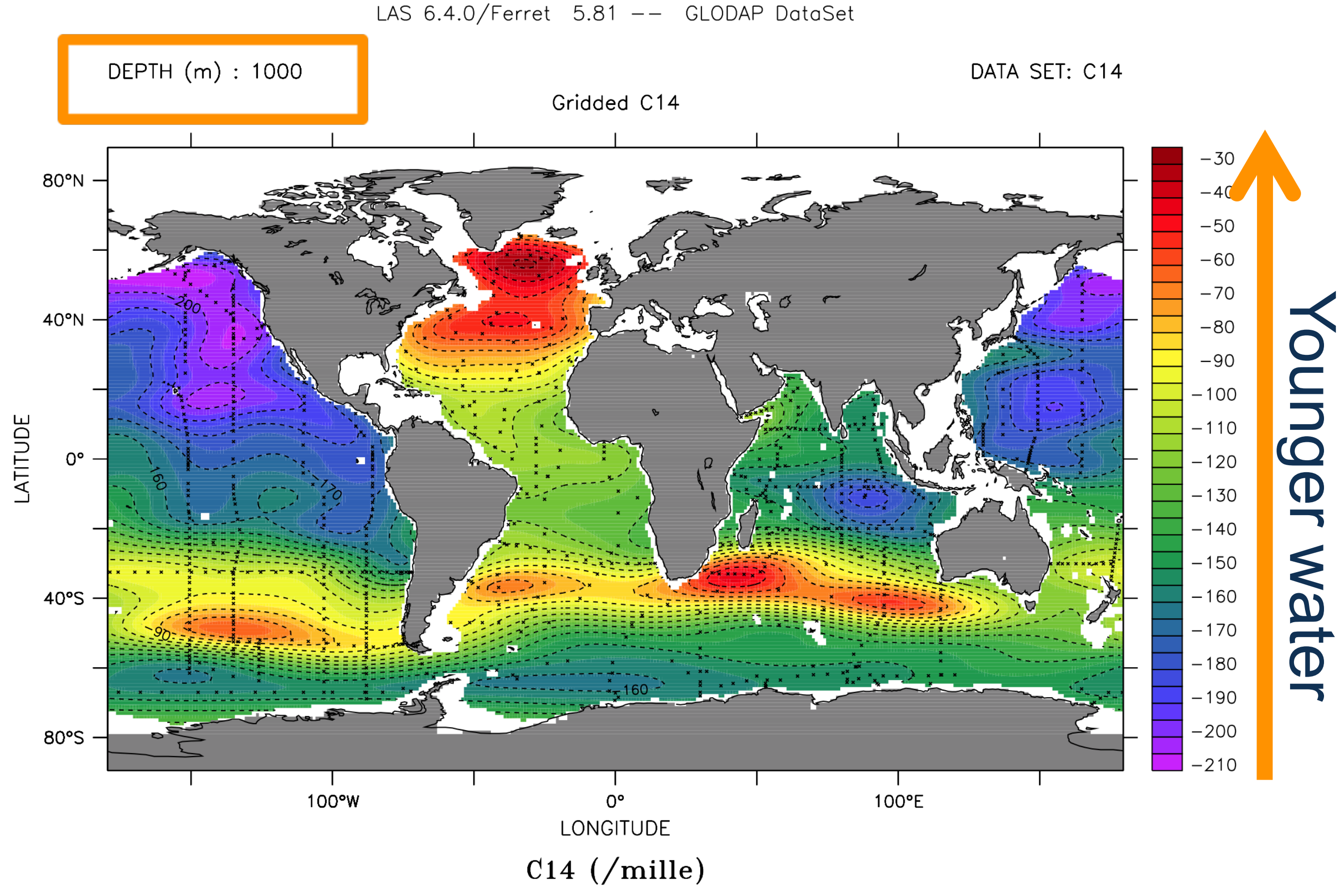
Examples of δ^{13}C as ocean tracer



Curry and Oppo (2005)

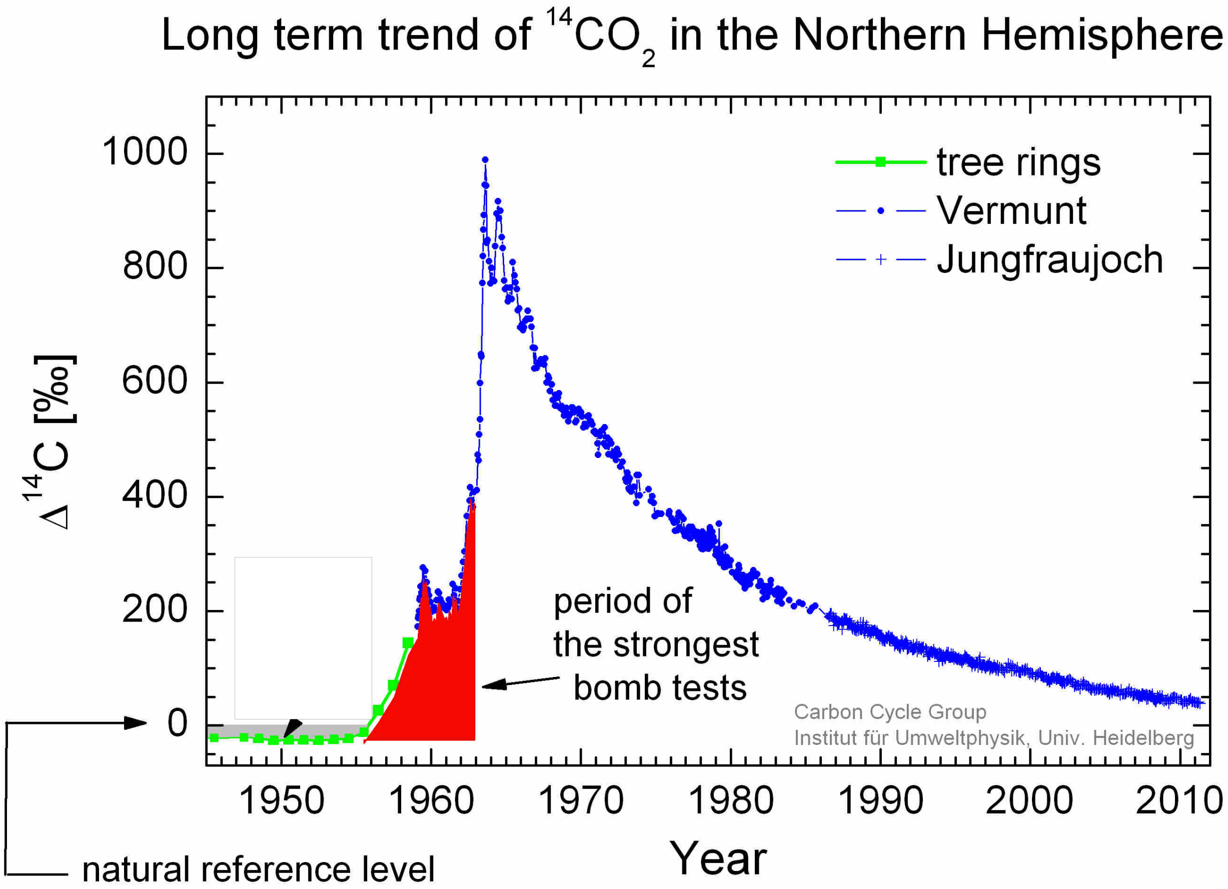
- δ^{13}C is used to infer paleo ocean water masses (e.g., NADW)
- δ^{13}C can be used as tracers of carbon cycle processes → e.g., used to diagnose the oceanic uptake of anthropogenic CO_2

$\Delta^{14}C$ as ocean tracer for ventilation



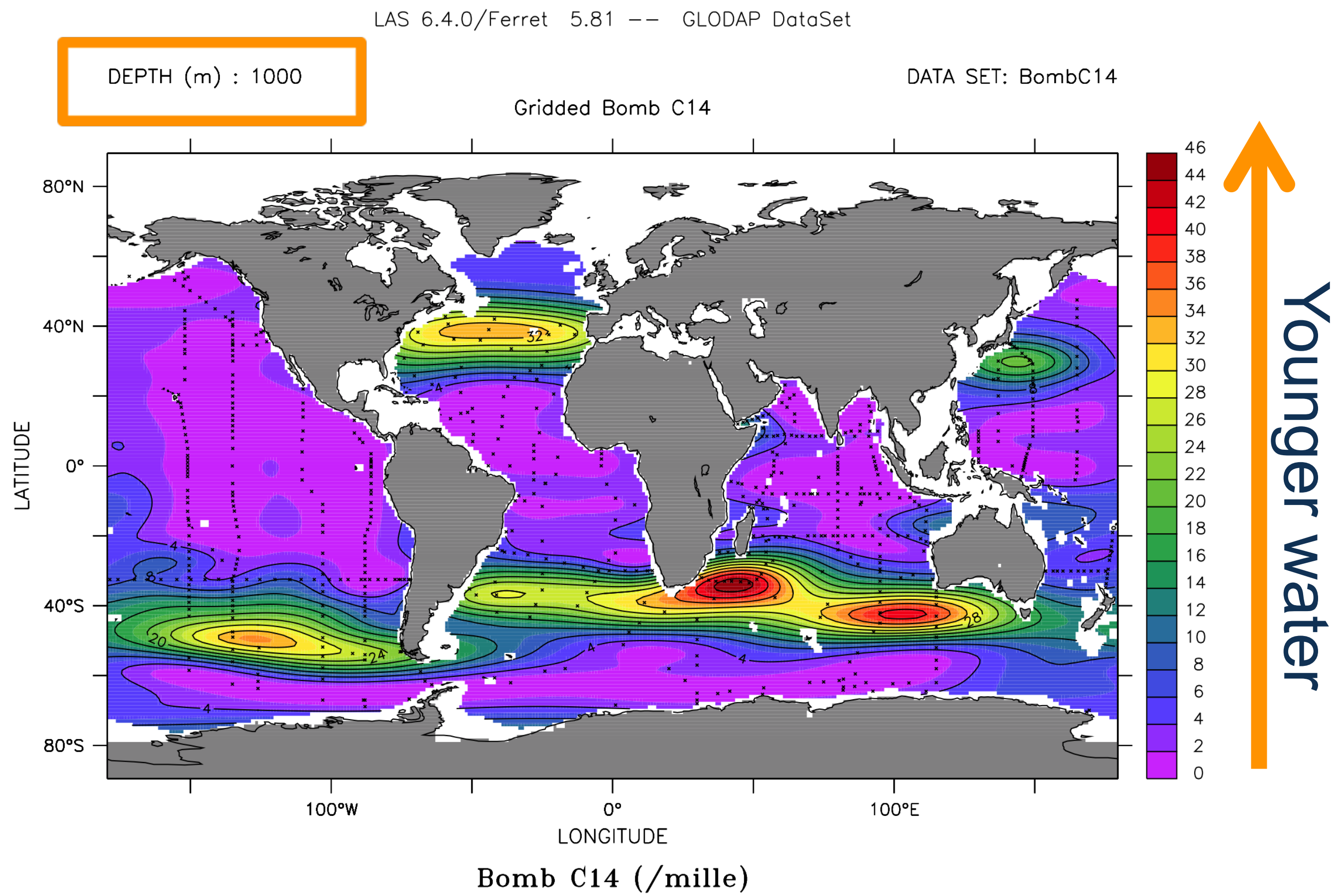
Source: GLODAP, http://cdiac3.ornl.gov/las/servlets/dataset?catitem=97

Atmospheric $\Delta^{14}C$ measurements



Source: http://www.iup.uni-heidelberg.de/institut/forschung/groups/kk/en/14CO2_html

Bomb $\Delta^{14}C$ as ocean tracer

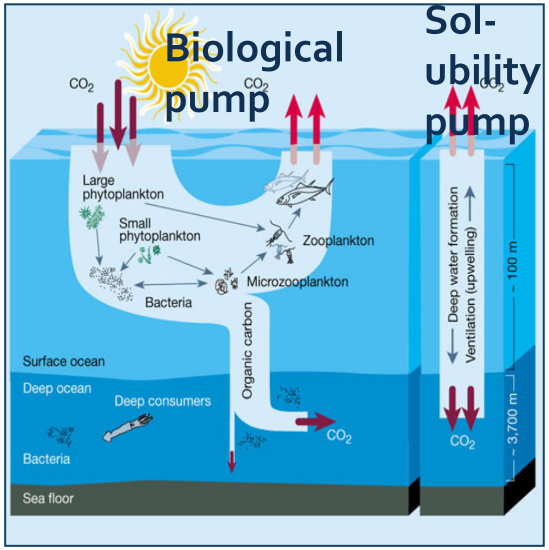


Source: GLODAP, http://cdiac3.ornl.gov/las/servlets/dataset?catitem=97

Implementation of Carbon isotopes in POP2 (as additional passive tracers)

- **Two different implementations:**
  - Abiotic Radiocarbon (2 additional tracers): can be run independently of the ecosystem model, ocean-model cost increase is a factor of 1.2 compared to the normal ocean model
  - Biotic ^{13}C and ^{14}C (14 additional tracers): Carbon isotopes in all seven carbon pools currently in the ecosystem. Cost increase is by a factor of 4 compared to ocean only model.

  ^{13}C code was based on code from ETH *(Xavier Giraud & Nicholas Gruber, ETH)* developed for POP1



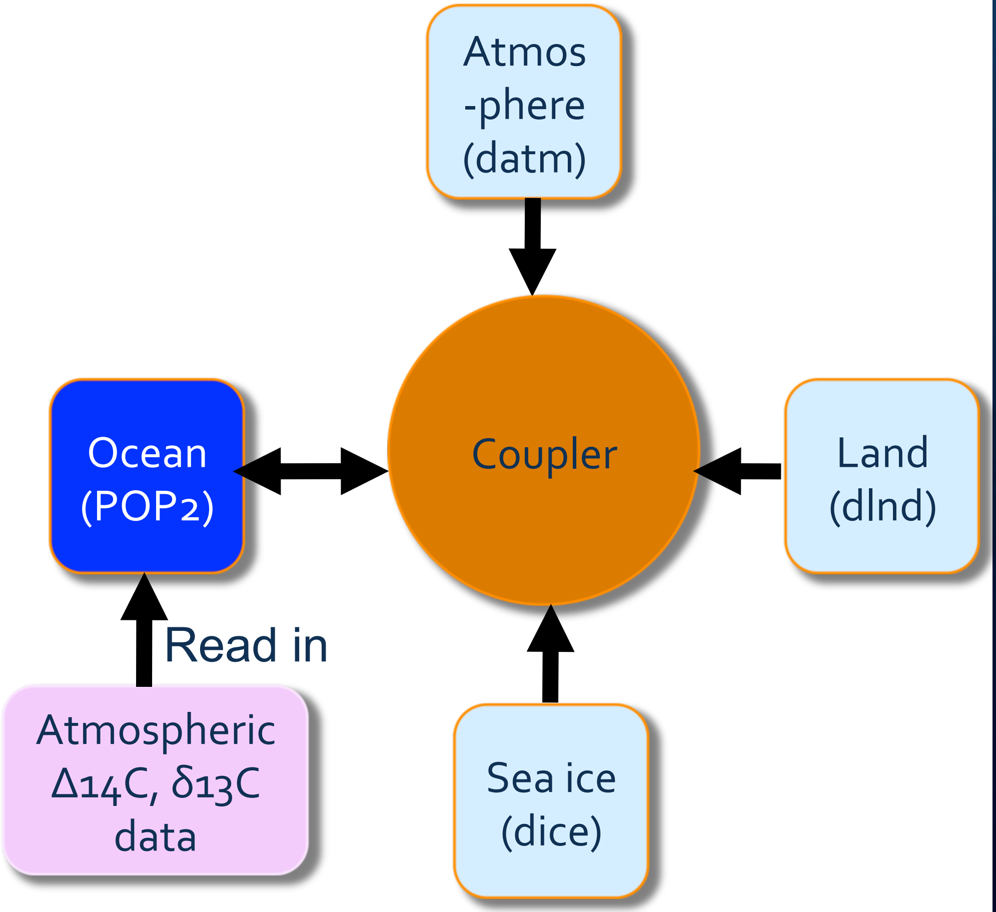
- **Status update:**
  - Abiotic Radiocarbon and biotic ^{13}C and ^{14}C are implemented, tested, and spun-up in the 3° cesm1.0.5 model and are ported to cesm1.2

Model set-up

+ All simulations were ocean-active-only simulations (C-Compset) in CESM1.0.5

+ Spin-up simulations are forced with constant pre-industrial CO_2 (278 ppm), Δ14C (0 permil), δ13C (-6.379 permil)

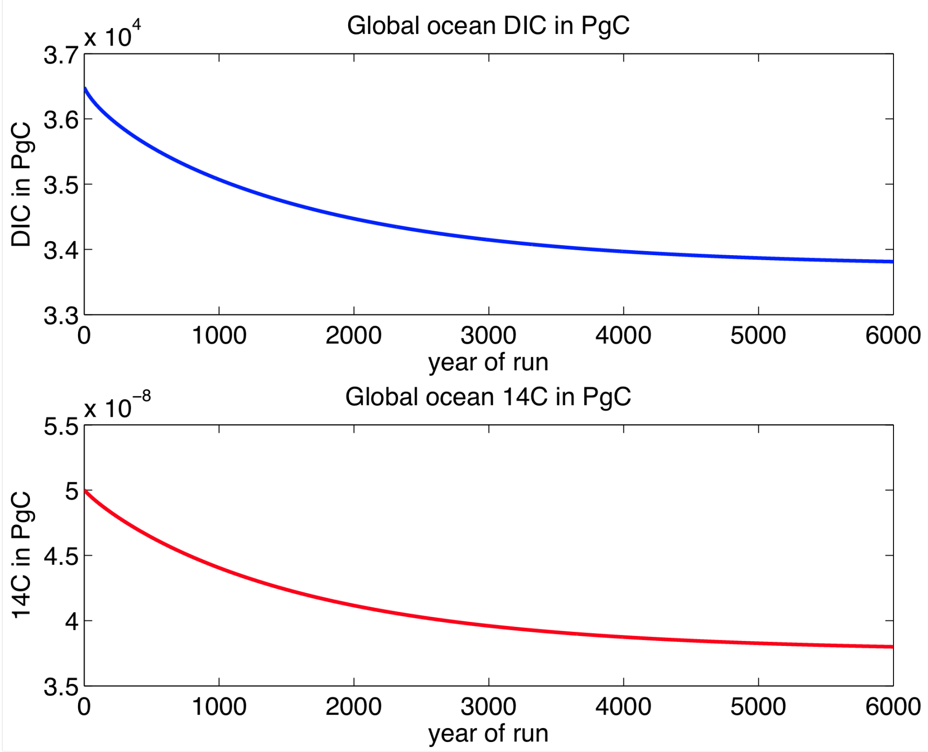
+ Simulations from 1765 to 2010 were forced with prescribed changing CO_2, Δ14C, δ13C but the same wind forcing as spin-up (CORE Normal year)



Model spin up

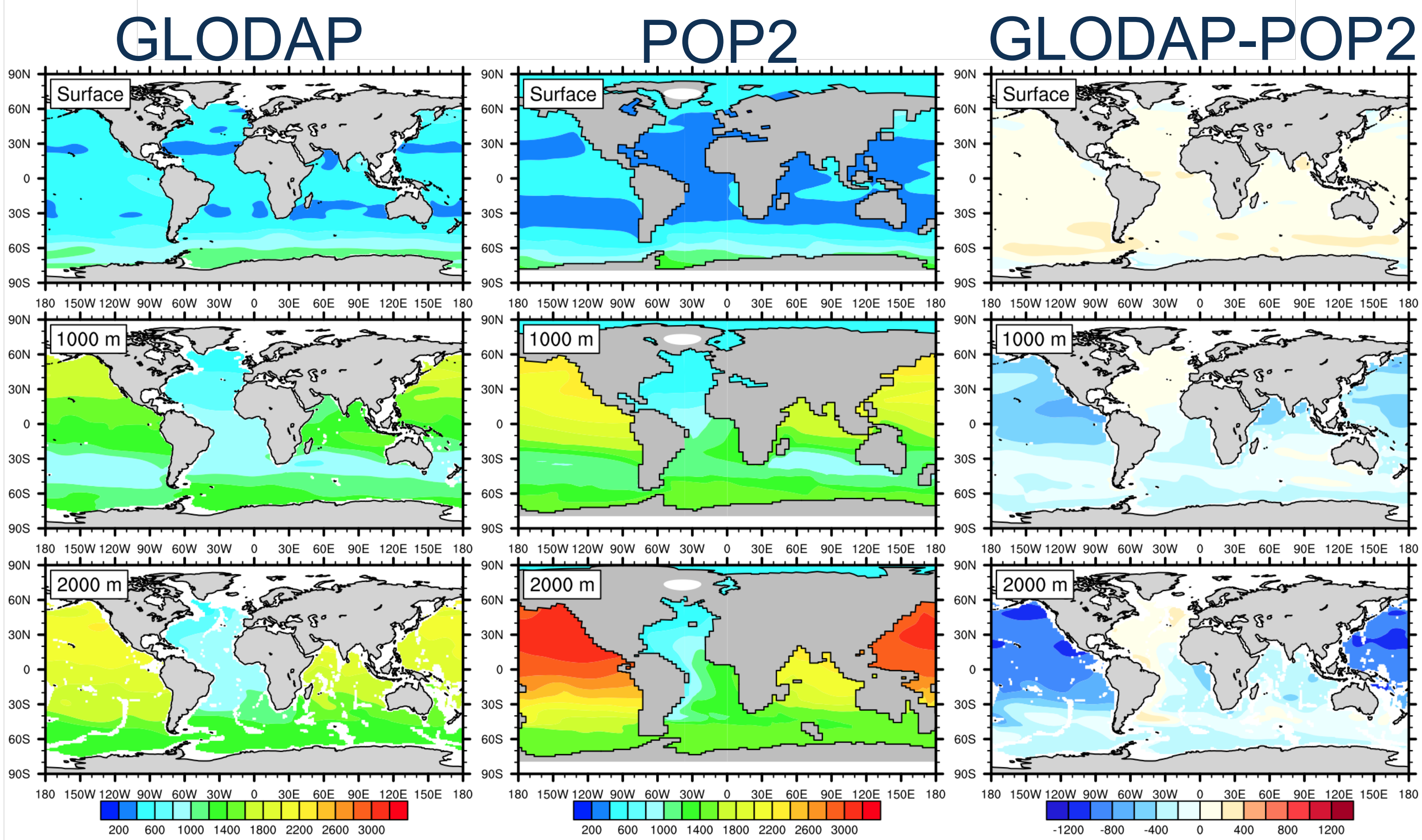
- Isotopes need a long spin-up. Approximately 5000-10,000 years.

→All simulations were performed in the ocean-active-only 3° POP2 model



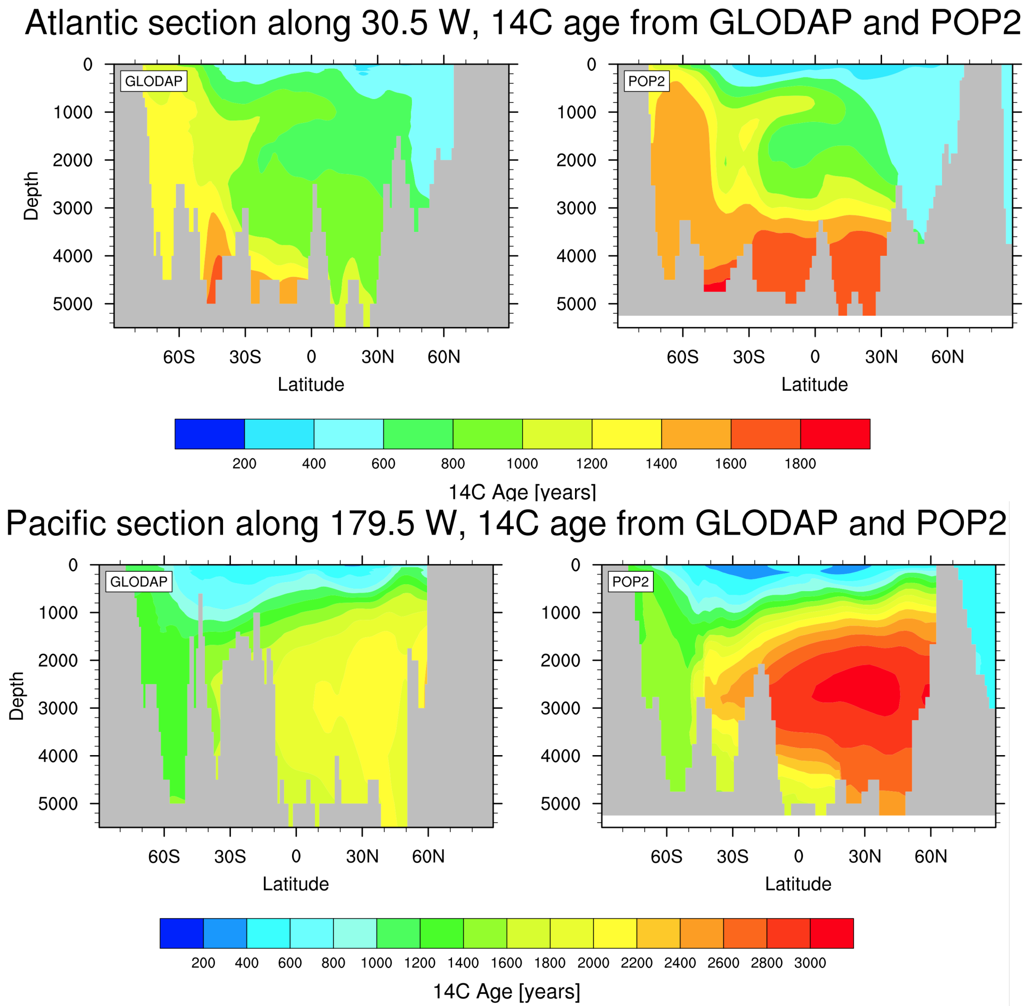
OCMIP2 definition of equilibrium:
-For DIC, the globally integrated air-sea flux should be less than 0.01 Pg C/yr: it is -0.0414 Pg C/yr (still needs some spin-up)
– For C-14, 98% of the ocean volume should have a drift of less than 0.001/year: it is 99.4%

Results from abiotic Radiocarbon: ^{14}C age



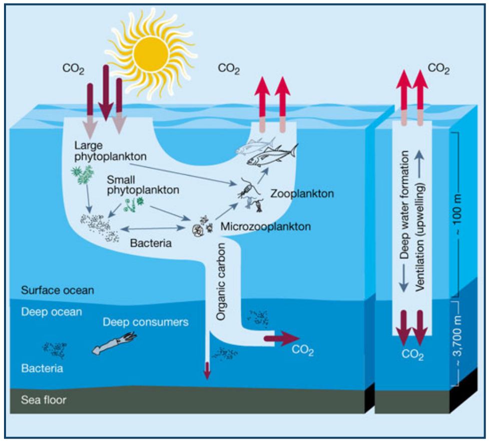
$$C^{14}\ \text{age} = -8033 \ln(1 + \Delta^{14}C/1000)$$

Results from abiotic Radiocarbon: ^{14}C age



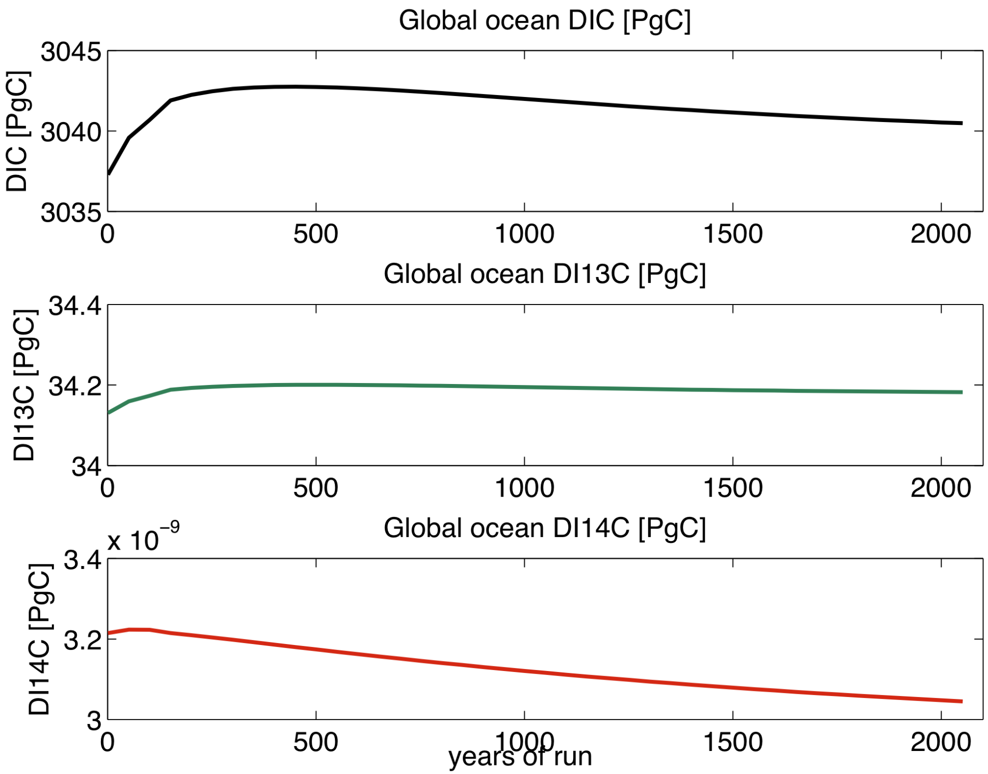
Adding the biological pump

- Currently there are 7 carbon pools in the ecosystem model (DIC, DOC, small phytoplancton, diatoms, diazotrophs, zooplankton, $CaCO_3$)
- Each Carbon isotope adds 7 tracers
  - Currently the ecosystem model has 24 tracers
  - The 14 additional carbon isotopes increases the ocean-model computation cost by:
    - a factor of 1.4 compared to just running the ecosystem model,
    - a factor of 4 compared to just running the ocean-only model without the ecosystem



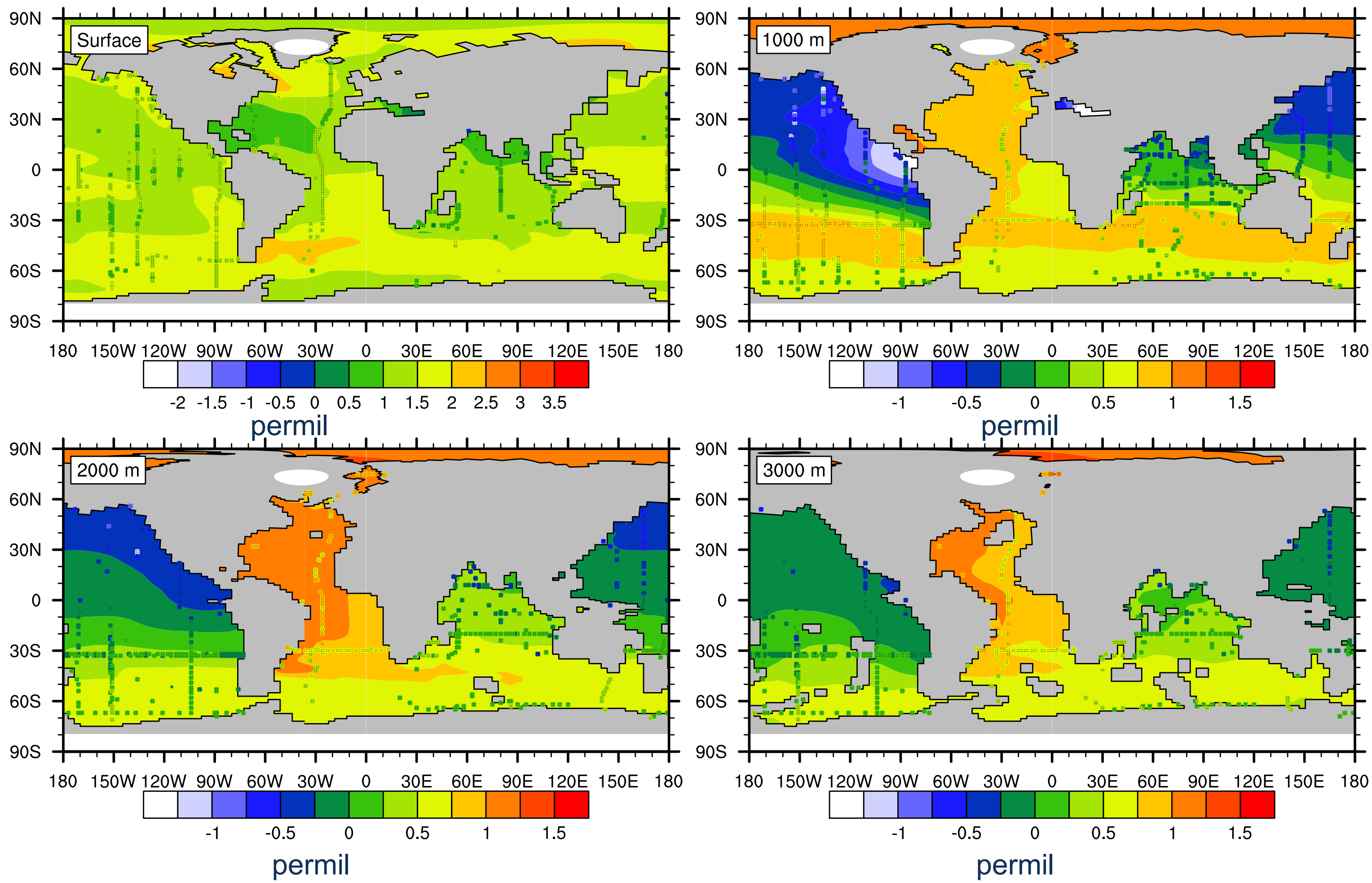
"Complete"
=
Include both biological effects and solubility effects

Spin up



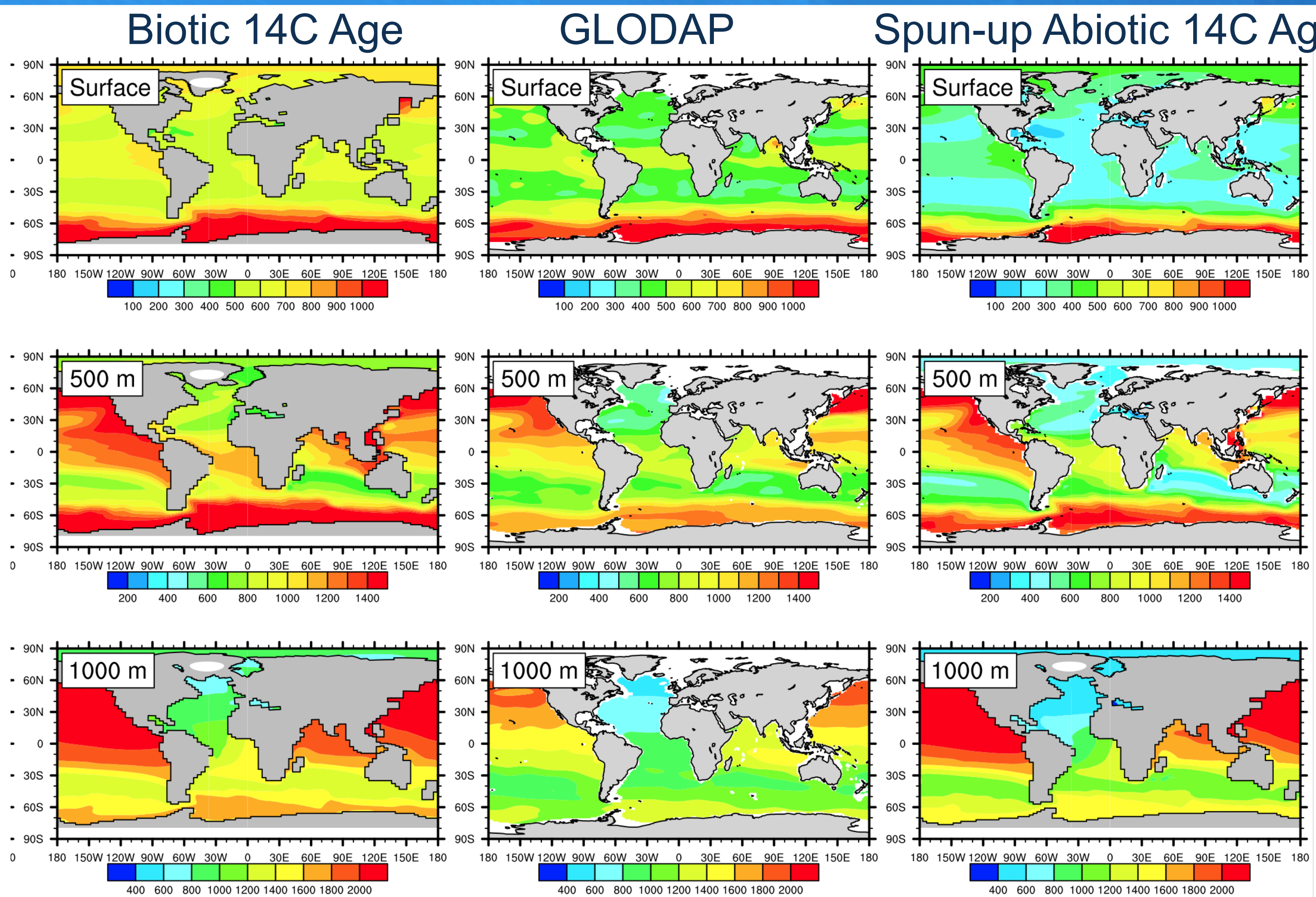
-The globally integrated air-sea CO^2 flux is -0.0106 Pg C/yr
– For DI14C/DI13C, 98.5/99.8% of the ocean volume has a drift of less than 0.001 permil/year

Preliminary results from the biotic ^{13}C isotope simulation (1990s): $\delta^{13}C$



Model compared to the present-day $\delta^{13}C$ dataset complied by Schmittner et al (2013)

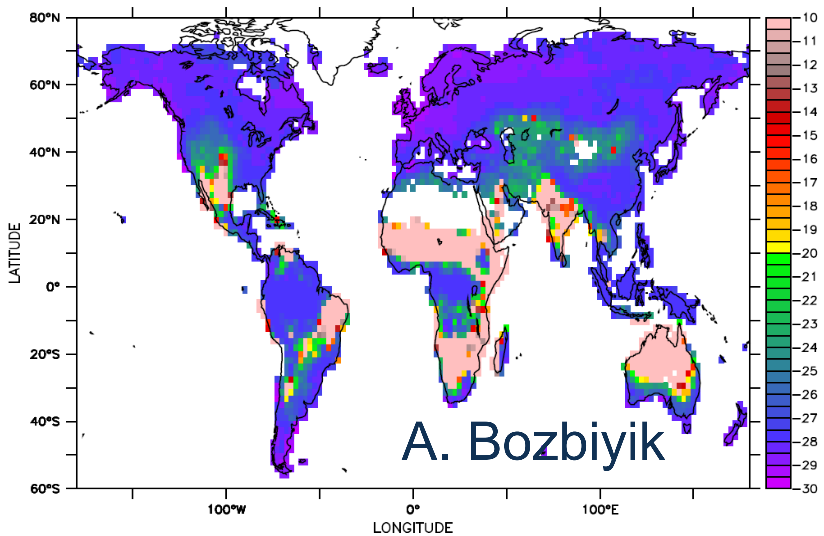
Preliminary results from the spin-up of biotic ^{14}C (year 1950, pre-bomb spike)



Update: Carbon isotopes in the land model (CLM4.5)

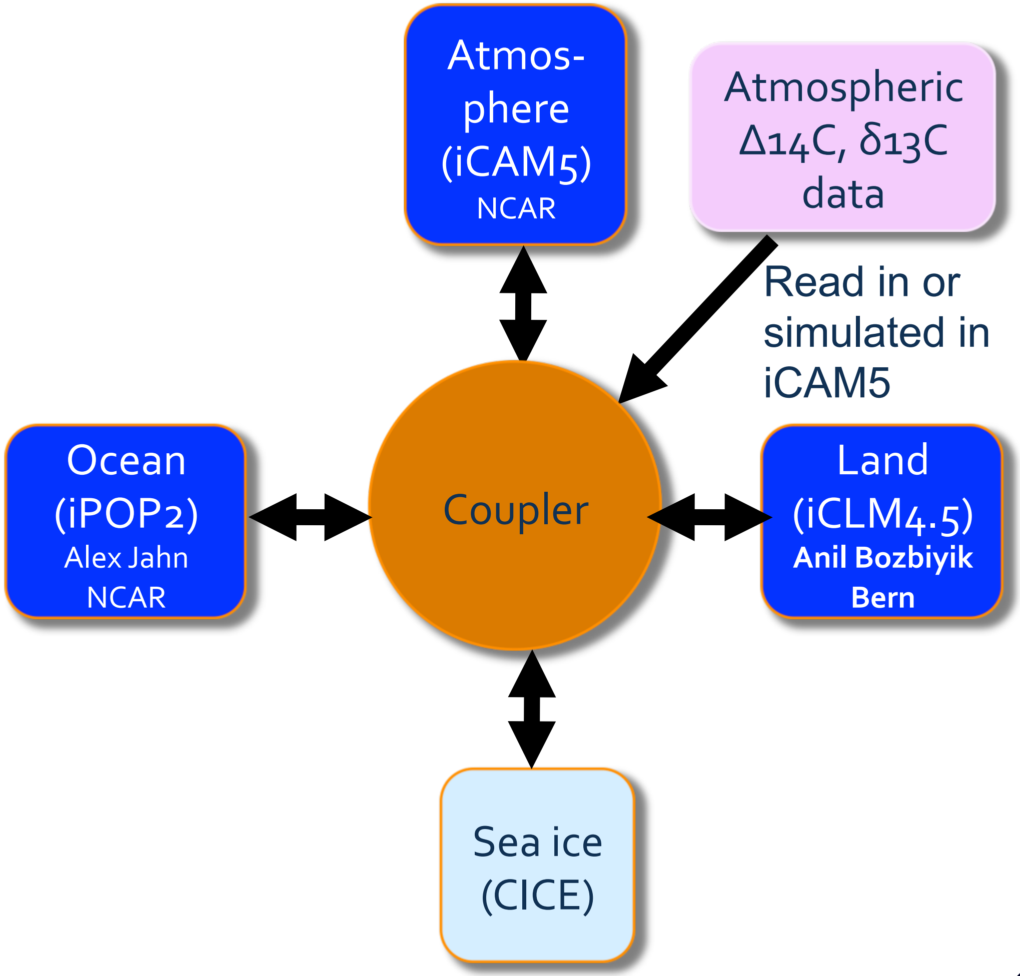
- ^{13}C and ^{14}C tracers have been added to the CLM4.5 land model as fully-prognostic variables
- The CLM4.5 has been spun-up in stand-alone mode for over 7000 years to equilibrium and more testing is under way
- **Developers:** A. Bozbiyik, J. Fortunat (University of Bern), W. Riley, C. Koven (LBNL), D. Lawrence (NCAR)

Global $\delta^{13}C$ of the Total Vegetation



Next steps for the Carbon isotope development in CESM

- Add ^{13}C and ^{14}C isotope tracers to the atmosphere
- Couple the carbon isotope enabled iCAM5, iCLM4.5, and iPOP2 for a coupled carbon isotope simulation
- Use a fast-spin up technique to get initial isotope conditions for 1 degree ocean model
- Release of functional carbon isotope code in May 2014 CESM1.3 release



Science applications of Carbon isotope work

- Include tracers in paleo simulations
  - Use the coupled carbon isotopes to investigate the Mystery Interval and the LGM
  - Compare simulations to observations, using the new tracers for more direct (but still not “apple to apple”) comparisons
  - Investigate how the physical climate parameters from the model (temperature, density, etc) relate to the simulated geochemical tracers

Other ongoing Isotope work

Other CESM isotope work we know about

- Nitrogen Isotopes in the ocean model
  - Simon Yang (ETH), N. Gruber (ETH)
- Neodymium
  - (University of Wisconsin)
- Pa/Th
  - (Alexandra Jahn, NCAR)
- Nitrogen isotopes in the land model
  - (?)

If you are working on adding isotopes to the model, please let us know!

Thanks!

Contact: brady@ucar.edu & ajahn@ucar.edu

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