Explicit isotope modeling with CESM and ECHAM/MPI-OM

Alexandra Jahn (CESM) and Martin Werner (ECHAM/MPI-OM)

Explicit isotope modeling with CESM

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With contributions from the CESM Isotope Development team: B. Otto-Bliesner[1], E. Brady[1], Z. Liu[2], D. Noone[4], K. Lindsay[1], M. Vertenstein[1], D. Bailey[1], F. Joos[3], A. Bozbiyik[3], A. Gettelman[1], S. Gu[2], C. Koven[5], E. Kluzek[1], J. Nusbaumer[4,7], B. Riley[5], J. Tang[5], P. Thornton[6], X. Wen[2], T. Wong[4], J. Zhang[2], J. Zhu[2]

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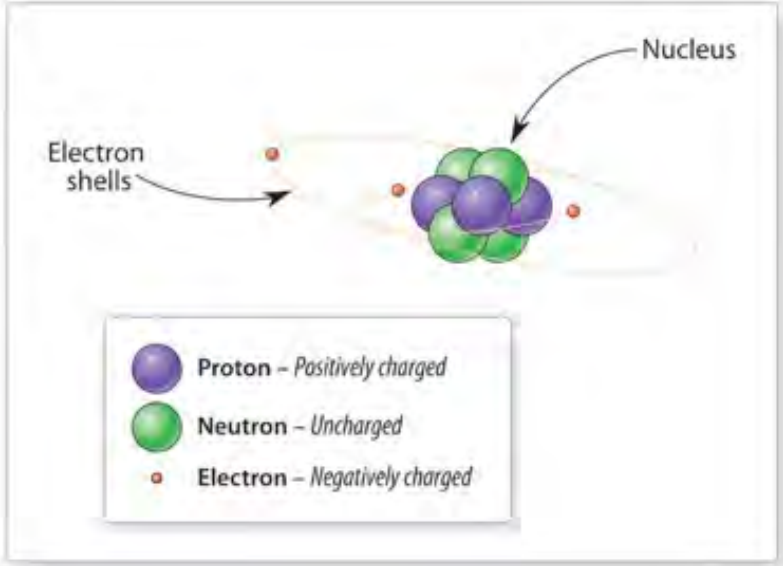
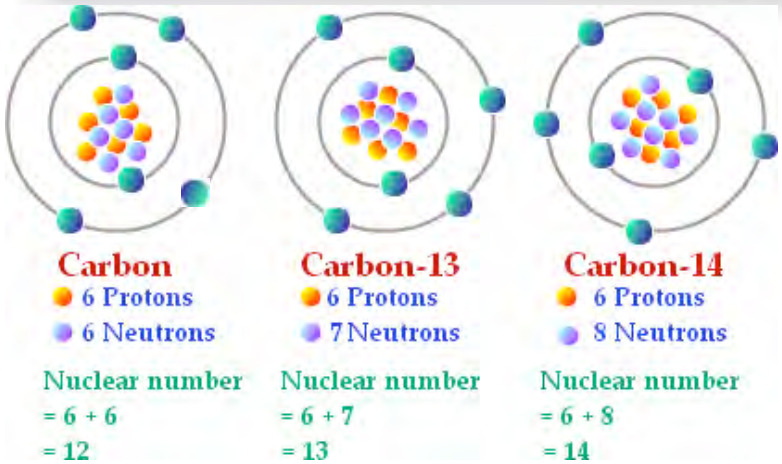
What are isotopes?

- Isotopes are variants of an element with additional neutrons → these lead to small differences in the physical properties of the element

- Unstable isotopes break down by radioactive decay at a constant rate

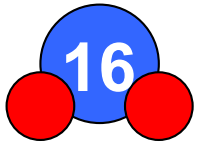




Fractionation

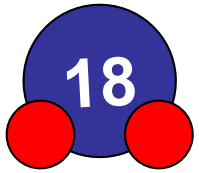
- The small differences in the physical properties of each isotope affect how isotopes are partioned between different parts of the climate system → this is called "fractionation"
- Due to fractionation, isotopes can be used to measure environmental changes
  - Oxygen and hydrogen isotopes help us reconstruct temperature, ice volume, precipitation pathways
  - Carbon isotopes help us infer changes in the ocean circulation and in the biological productivity, as well as use radiocarbon as "clock"

Isotope Delta Notation



$H_2{}^{16}O$

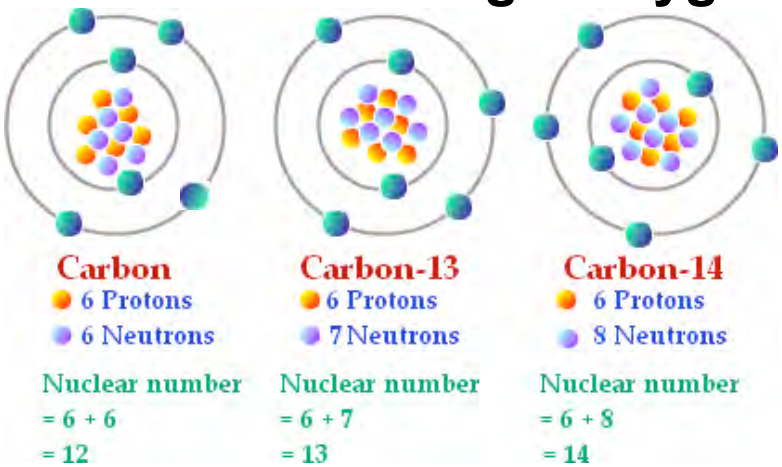
Light Oxygen



$H_2{}^{18}O$

Heavy Oxygen (0.2% of all oxygen, 11% heavier than light oxygen)

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) * 1000\ ‰$$



98.89% 1.11% <0.01%

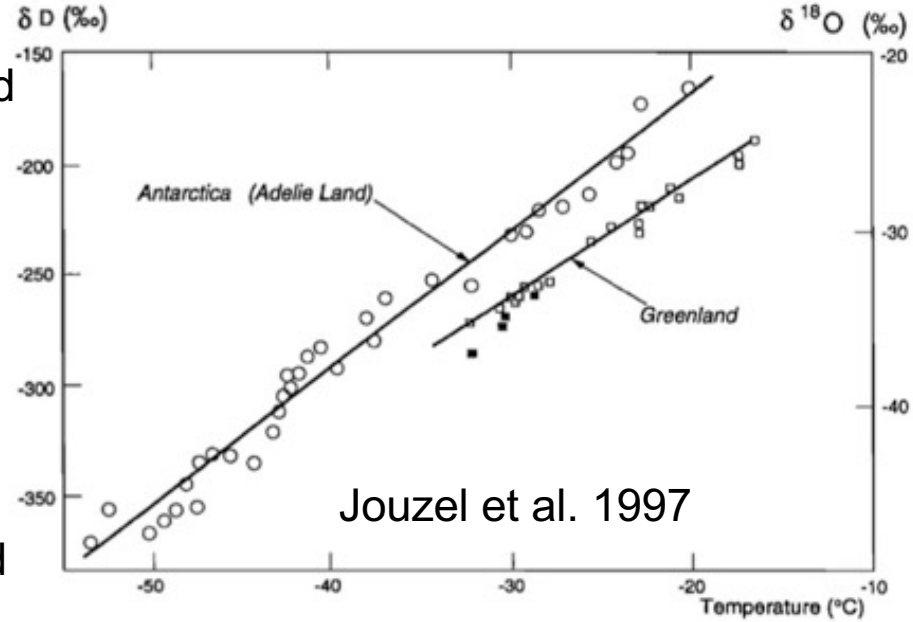
$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample}}{\left(\frac{^{13}C}{^{12}C}\right)_{standard}} - 1 \right) * 1000\ ‰$$

Temperature Effect for $\delta^{18}O$ in Precipitation

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

Less depleted

More depleted



Colder

Warmer

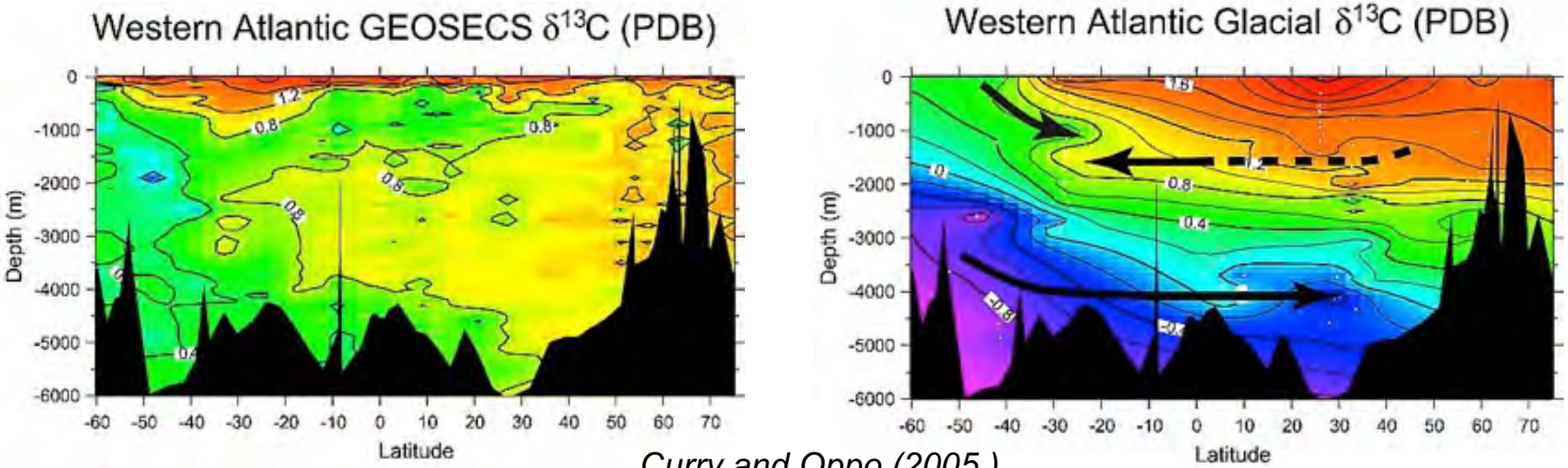
"Paleo-Thermometer"

$\Delta(\delta^{18}O) \sim 0.7[^{o}/_{oo}/K]\ \Delta T$

Spatial relationship – Observed to hold temporally over seasons and interannually in ice cores.

But can the modern relationship be used to reconstruct high-latitude temperature change over the long time periods of Glacial-Interglacial change?

Isotopes as ocean circulation tracers

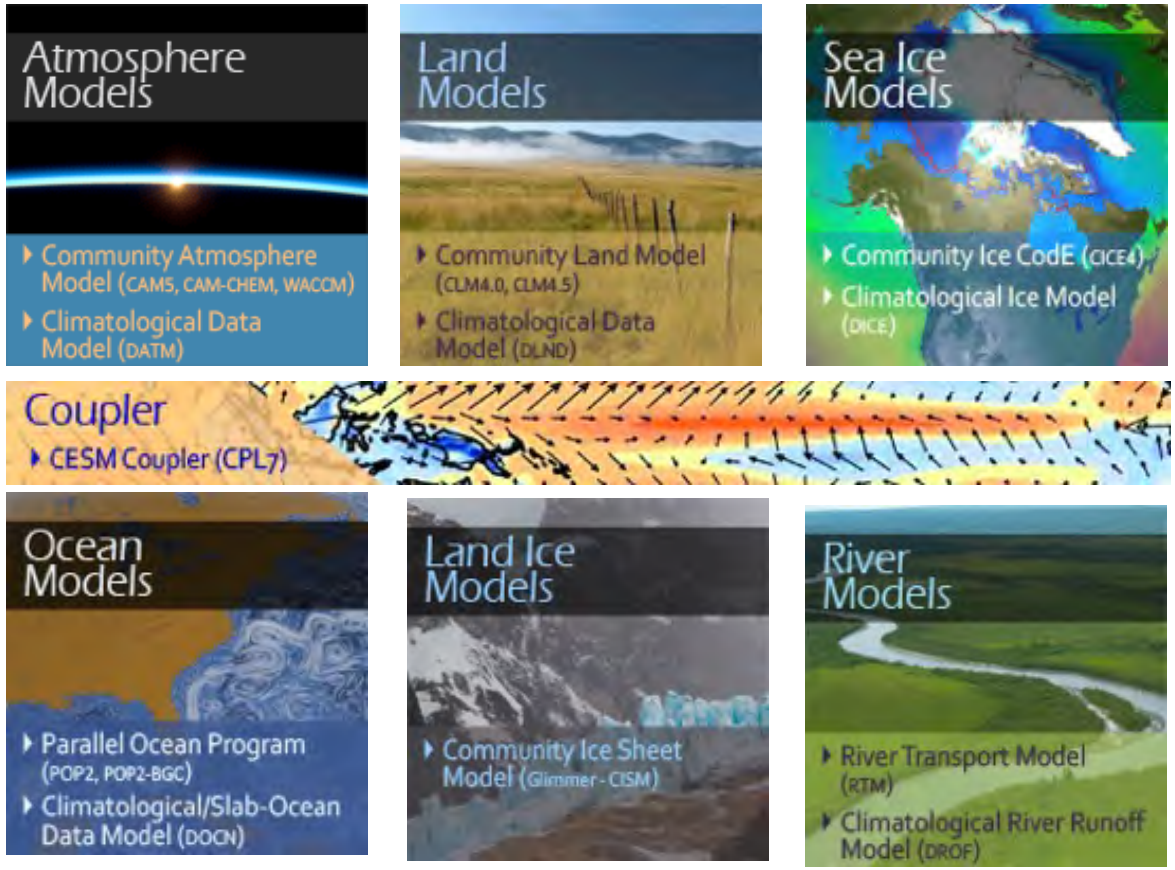


Curry and Oppo (2005)

- $\delta^{13}C$, Neodymium, and Pa/Ta are used as water mass tracers to infer past ocean circulation changes
- $\Delta^{14}C$ is used as ocean reservoir age tracer

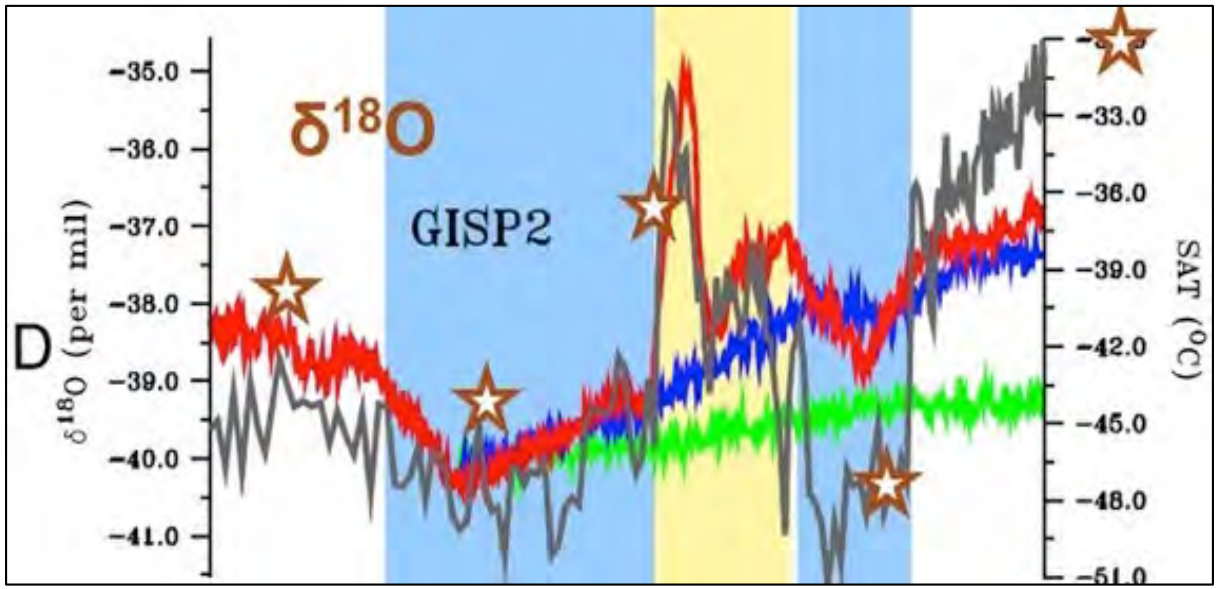
What is the CESM?

CESM = Community Earth System Model



- Fully coupled climate model
- “Free running” – no assimilation of any data
- Resolution of 1 degree is standard
- For Paleo simulations, often 2 degree atmosphere is coupled to 1 degree ocean

CCSM3 TraCE, Transient Simulation of the Last Deglaciation



*δ18Op ~ w/offset for bias

Proxy Comparison

★ δ18Op* over Greenland From IsoCAM3 'slices'

Greenland SAT CCSM3-Full CO2+IS, Orbital+IS

δ18O GISP2 Record

- *CCSM3 suggests weaker YD cooling than reconstructed*
- *But, Iso-CAM3 agrees well with Δδ18Op*

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

Development of an Isotope-enabled CESM

*Bette Otto-Bliesner, Zhengyu Liu[2], and iCESM Team****

Isotopes included in CESM: Water isotopes, Carbon Isotopes, Neodymium isotopes, Pa/Th isotopes, Nitrogen isotopes^

****E. Brady, A. Jahn[7], D. Noone[4], K. Lindsay[1], M. Vertenstein[1], D. Bailey[1], F. Joos[3], A. Bozbiyik[3], A. Gettelman[1], S. Gu[2], C. Koven[5], E. Kluzek[1], J. Nusbaumer[4], B. Riley[5], J. Tang[5], P. Thornton[6], X. Wen[2], T. Wong[4], J. Zhang[2], J. Zhu[2]*
^ S. Yang and N. Gruber, ETH

1. National Center for Atmospheric Research, 2. University of Wisconsin, Madison, 3. University of Bern, 4. Oregon State University, 5. Lawrence Berkeley Laboratory, 6. Oak Ridge National Laboratory, 7. University of Colorado, Bould

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iCESM: Water Isotope and Carbon isotope tracers development

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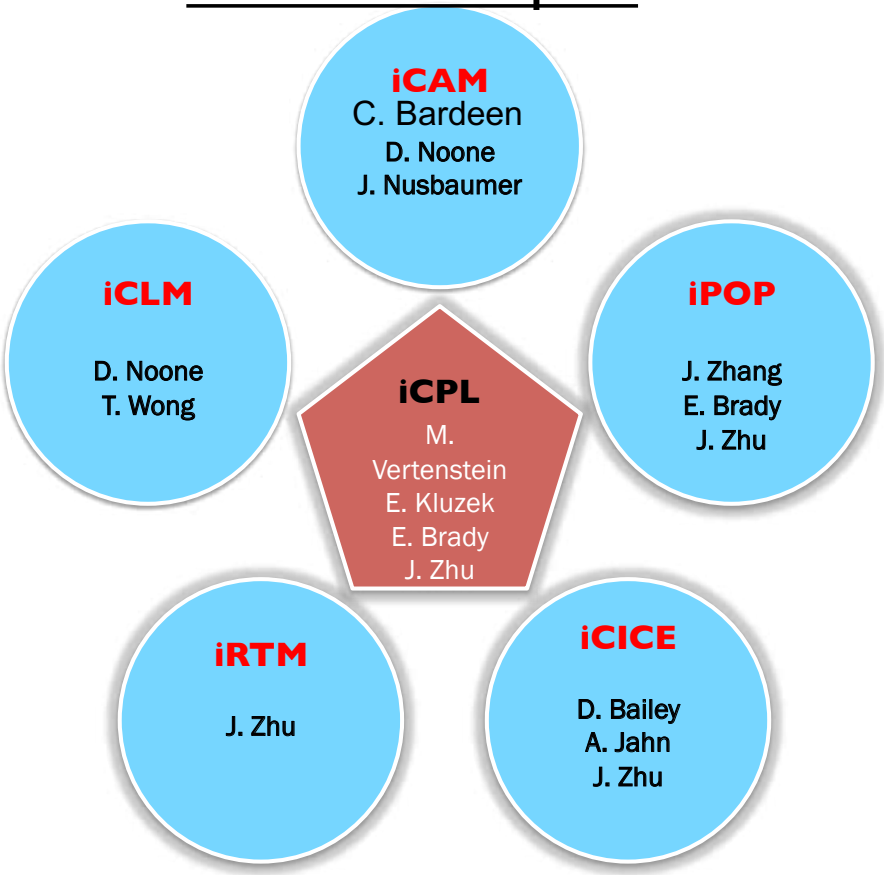
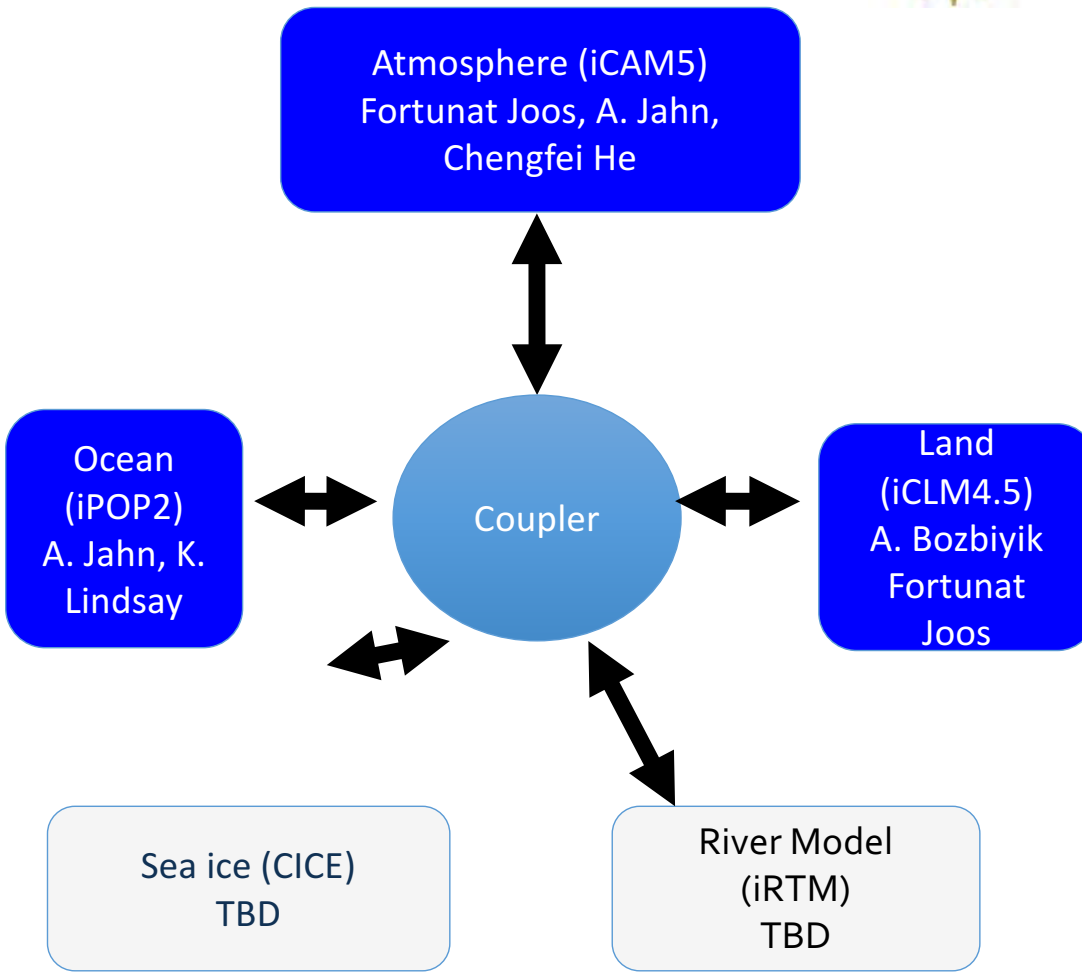
Water Isotopes



Done, to be part of CESM2

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

Carbon Isotopes



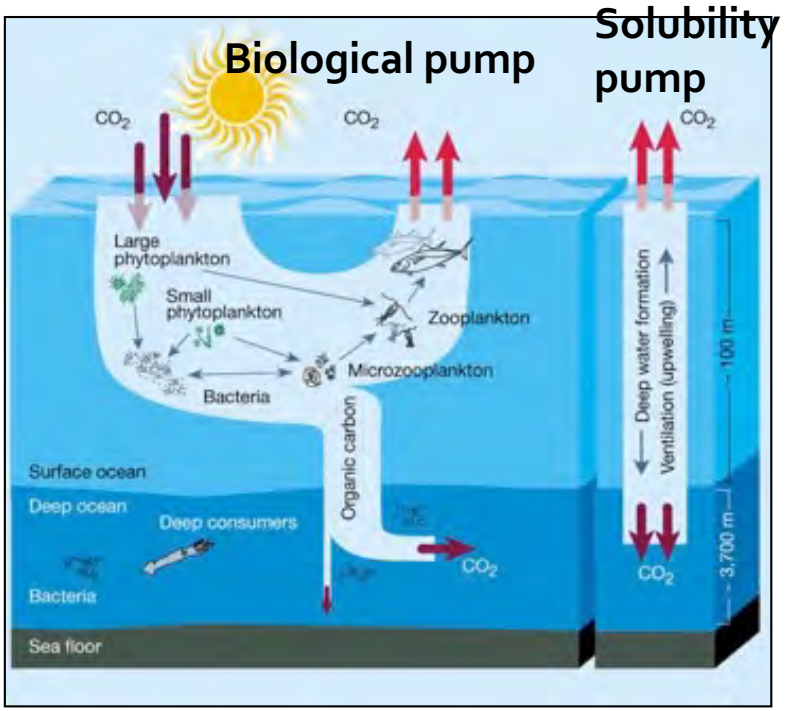
Atmosphere and coupling current under development

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

University of Colorado Boulder

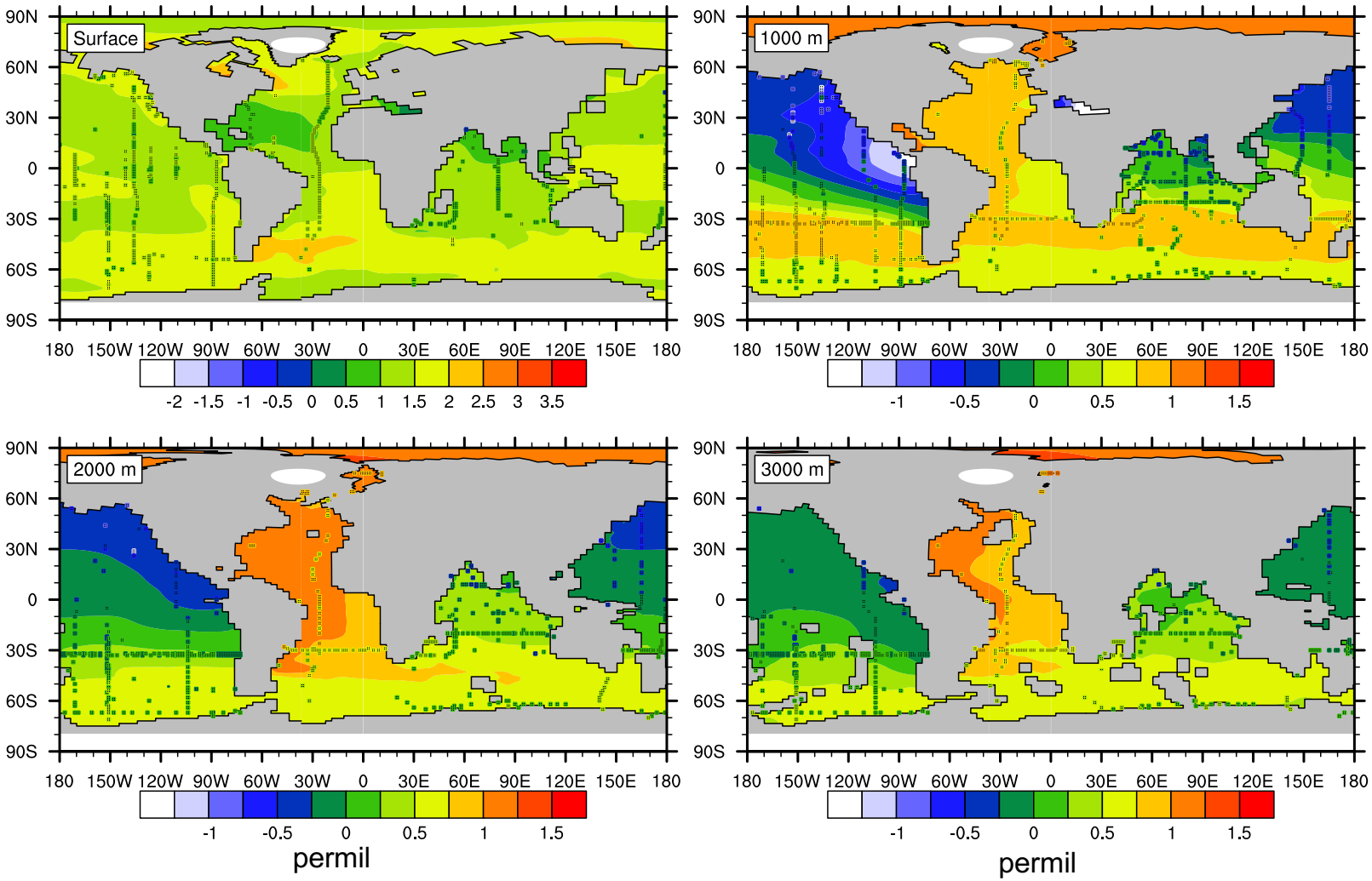
Implementation of Carbon isotopes in the ocean model of the CESM

- Abiotic Radiocarbon: can be run independently of the ecosystem model, no fracitioantion
- Biotic ^{13}C and ^{14}C:
  - Carbon isotopes in all 7 carbon pools currently in the ecosystem model (DIC, DOC, small phytoplankton, diatoms, diazotrophs, zooplankton, $CaCO_3$)
  - Accounts for fractionation effects during gas exchange (equilibrium and kinetic, following Zhang et al. (1995)), photosynthesis (Rau et al., 1989), and CaCO3 formation



Jahn et al., 2015, GMD

Surface simulations of $\delta^{13}C$ (1990s) compared to Cruise data compiled by Schmittner et al. (2014)



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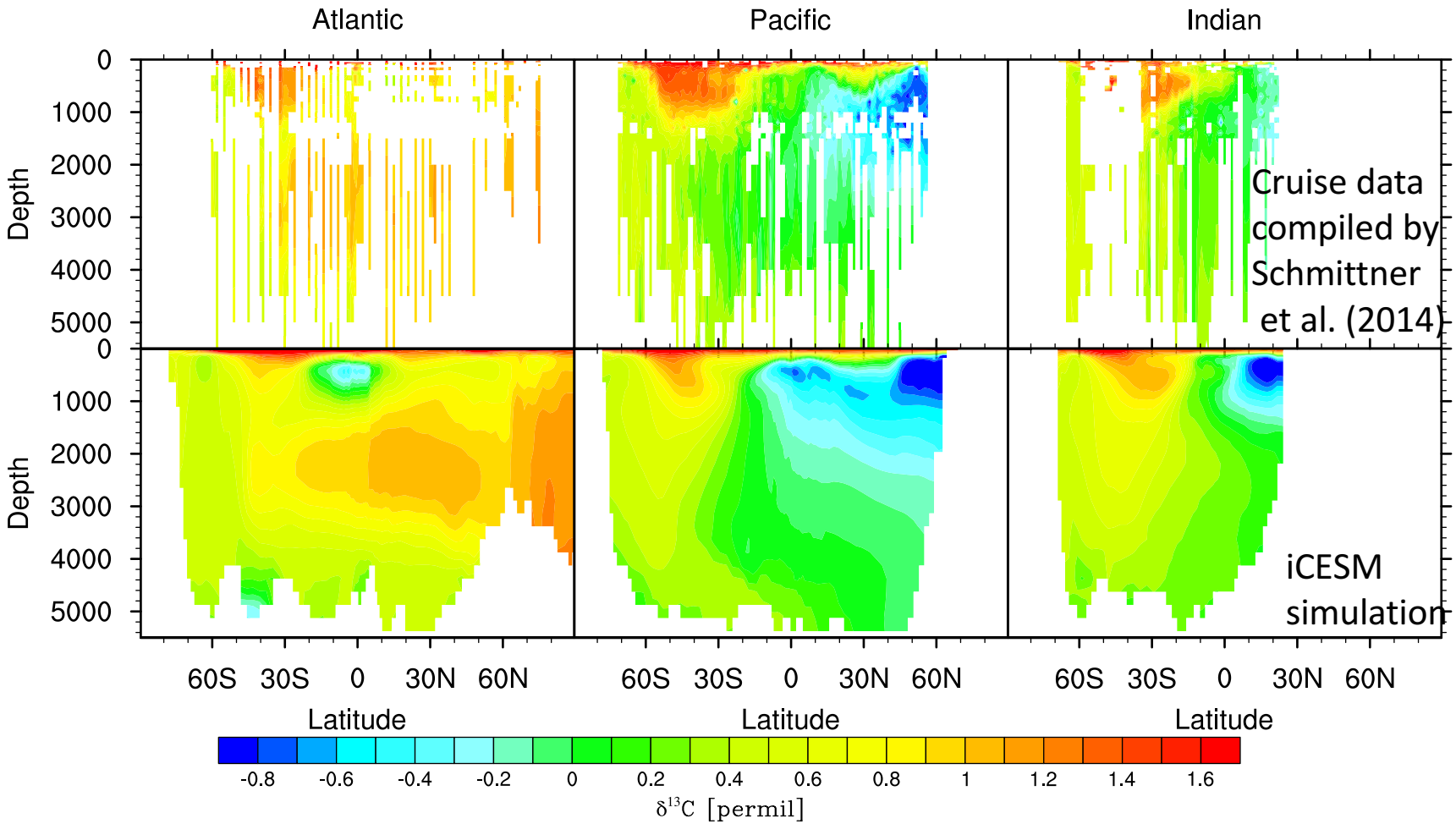
Jahn et al. (2015), GMD

Cross sections of oceanic $\delta^{13}C$ (1990s)



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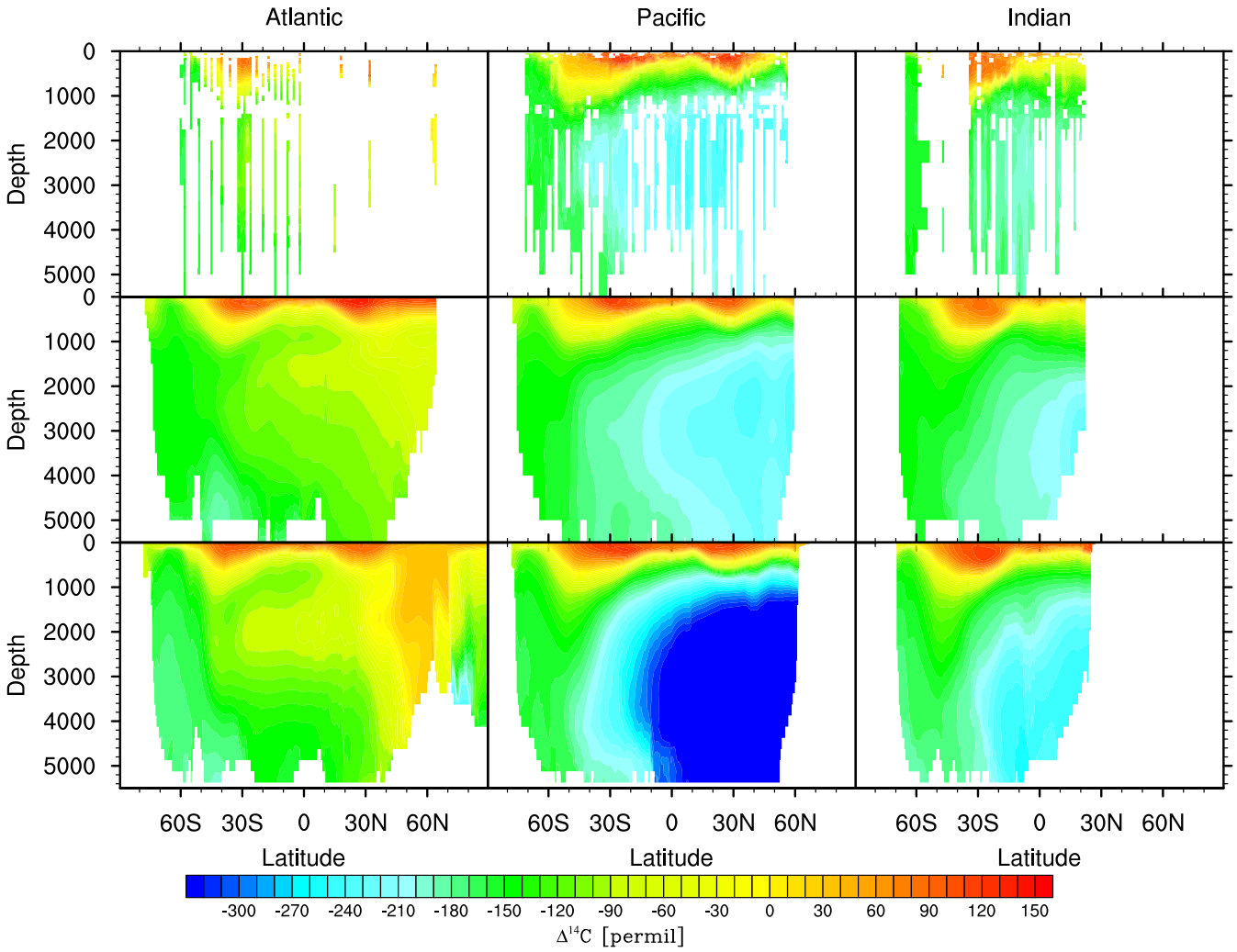
Jahn et al. (2015), GMD

Cross sections of Radiocarbon



Cruise data compiled by Schmittner et al. (2014)

GLODAP (Key et al., 2004)

Abiotic Radiocarbon Simulation with iCESM (Last Millennium ensemble)

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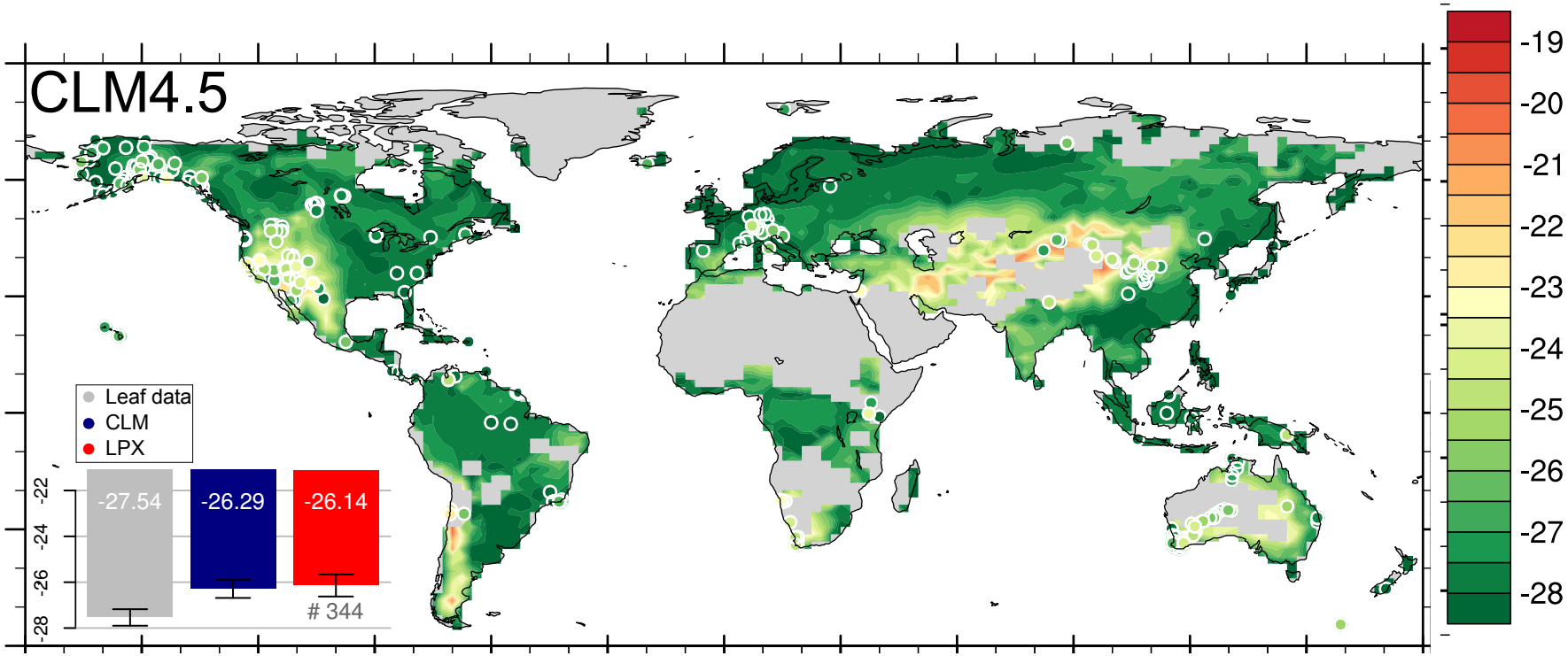
Jahn et al. (2015), GMD

Carbon isotopes in the land model of the CESM



δ13C as measured on leaves of C3 trees (colored circles; Cornwell et al., 2016) and as simulated by iCLM4.5

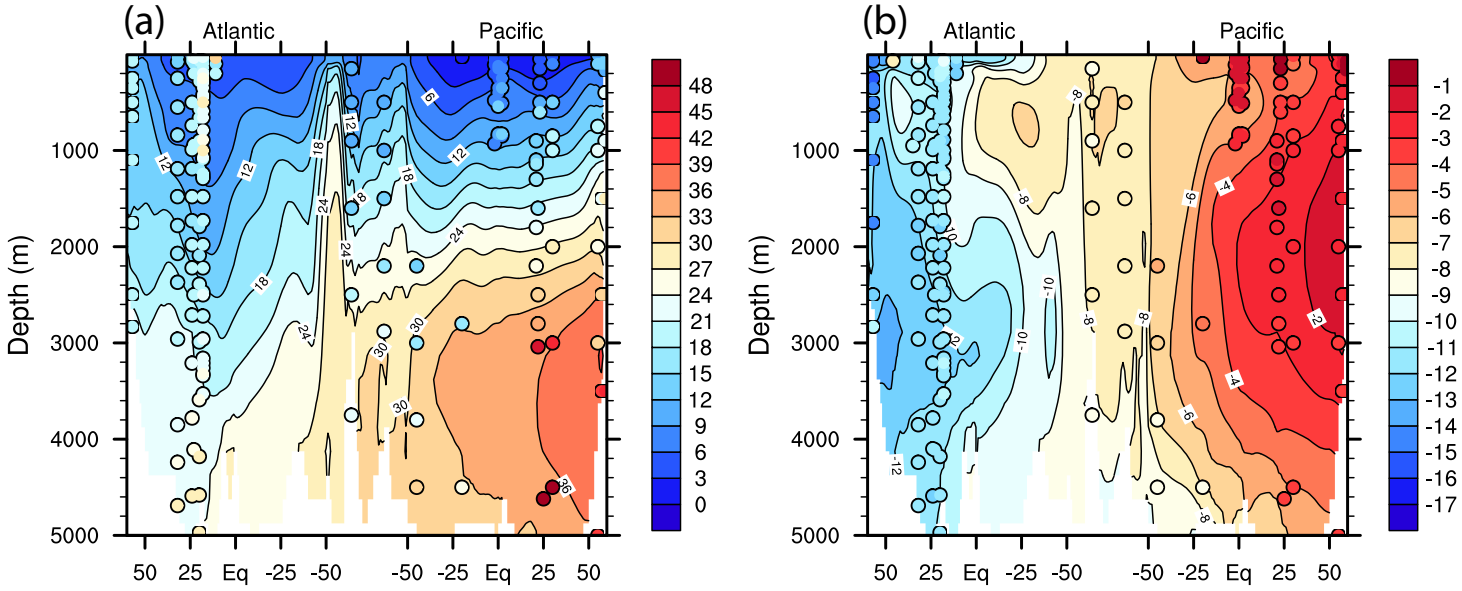
Keller et al., 2017

Ongoing: Carbon isotopes in the atmosphere

- $^{14}CO_2$ and $^{13}CO_2$ will be carried in the atmosphere as tracers in addition to the current CO_2 tracer
- No fractionation in atmosphere
- Exchange with the ocean and land through the coupler
- For ^{14}C we need an atmospheric production term

C. Fei, Z. Liu, A. Jahn, E. Brady, F. Joos

Neodymium isotopes in iCESM ocean

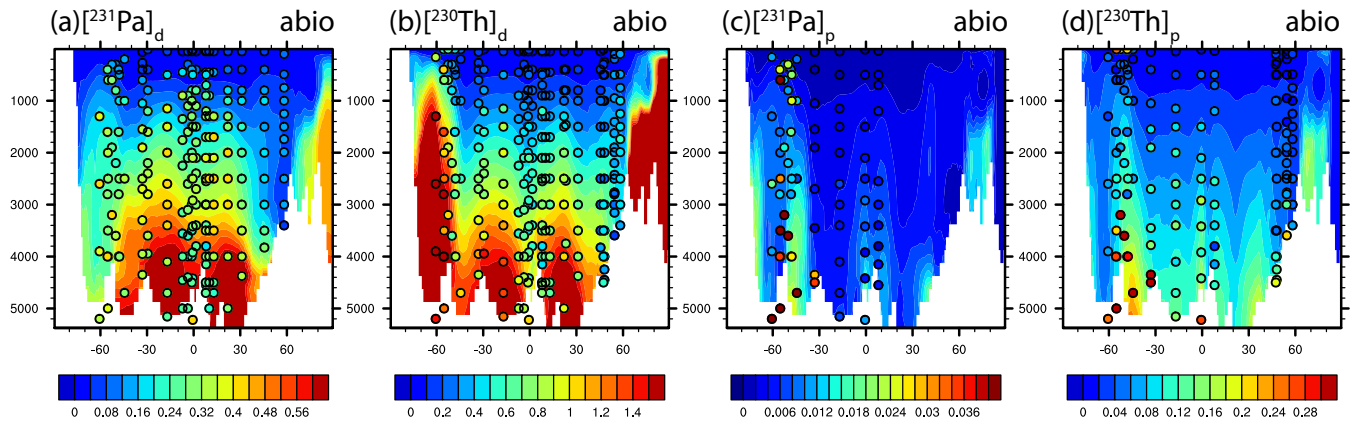


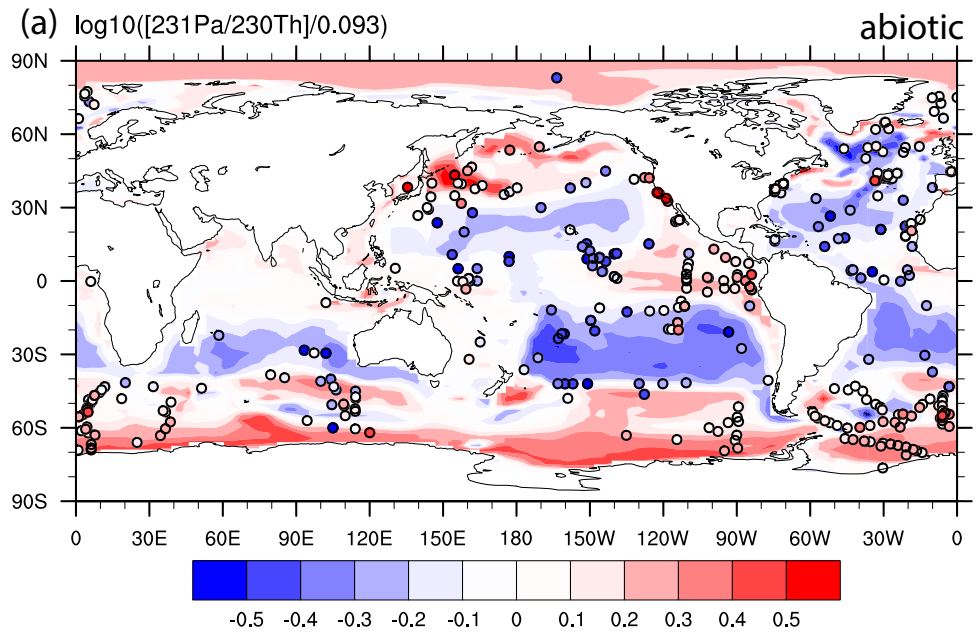
Both abiotic and biotic versions

Figure 5. Vertical sections of $[Nd]_d$ (a) and ε_{Nd} (b) along the track (indicated in Fig.2 (a)) from the North Atlantic to the North Pacific in CTRL. Color contours are model results and observations are attached as filled cycles using the same color map.

Gu et al., 2017a, GMDD

Pa/Th isotopes in iCESM ocean

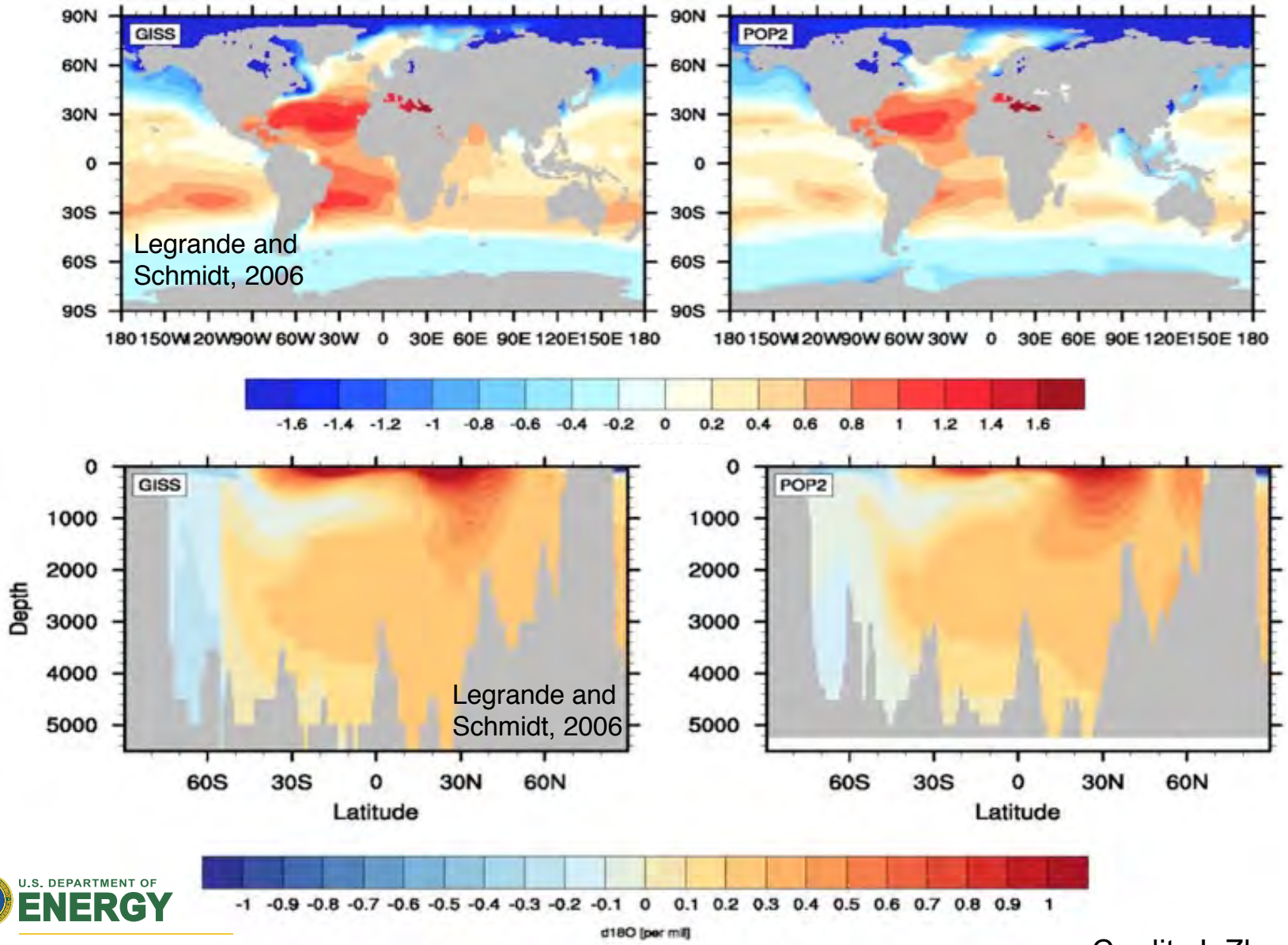




Both abiotic and biotic versions

Gu et al., 2017b, GMDD

Coupled iCESM water isotopes: ocean results



Credit: J. Zhang

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Coupled iCESM water isotopes: atmosphere results

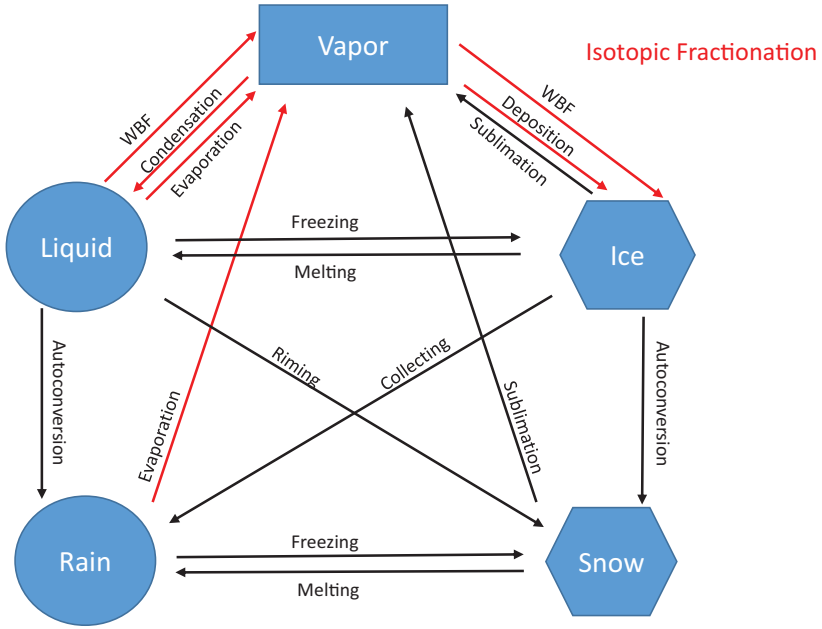


Figure 1. Depiction of microphysical processes accounted for in CAM5. The blue shapes represent all of the physical states of water and water isotopologues allowed in the cloud physics schemes. The arrows indicate physical processes that convert between the different states of water, with the red arrows being processes that produce isotopic fractionation.

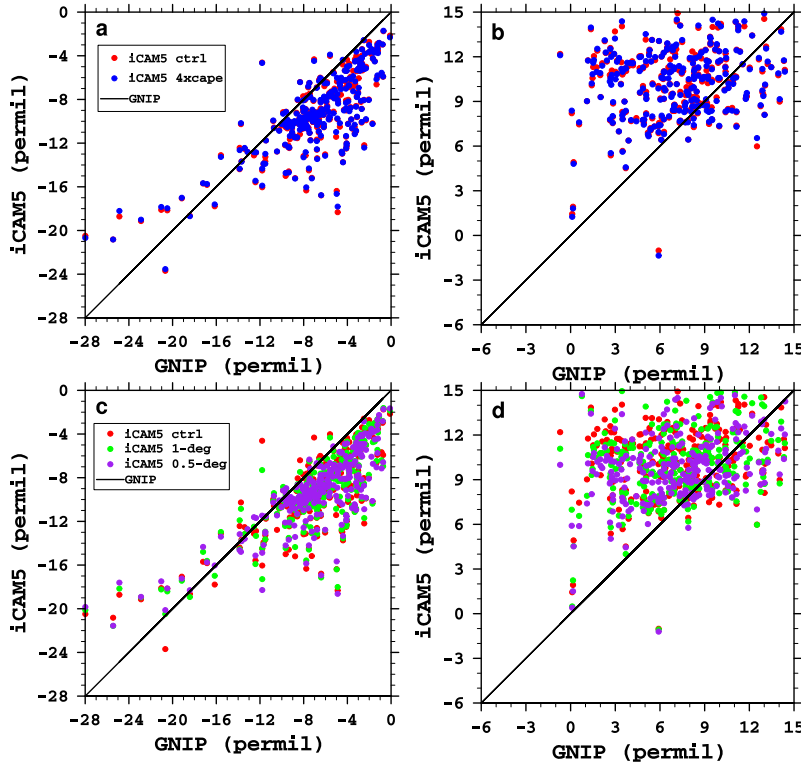


Figure 5. (a and c) A scatter plot comparing the annual average GNIP values for $\delta_{18}O$ in precipitation and (c and d) *d*-excess in precipitation (c and d) against the colocated annual averaged values as simulated by iCAM5. The red circles are for the iCAM5 control (2 × 2) run, the blue circles are for the iCAM5 run with the increased deep convective CAPE trigger (4xcape), the green circles are for the iCAM5 1 × 1 run, and the purple circles are for the iCAM5 0.5 × 0.5 run. The black diagonal line represents an exact fit between the observations and model values.

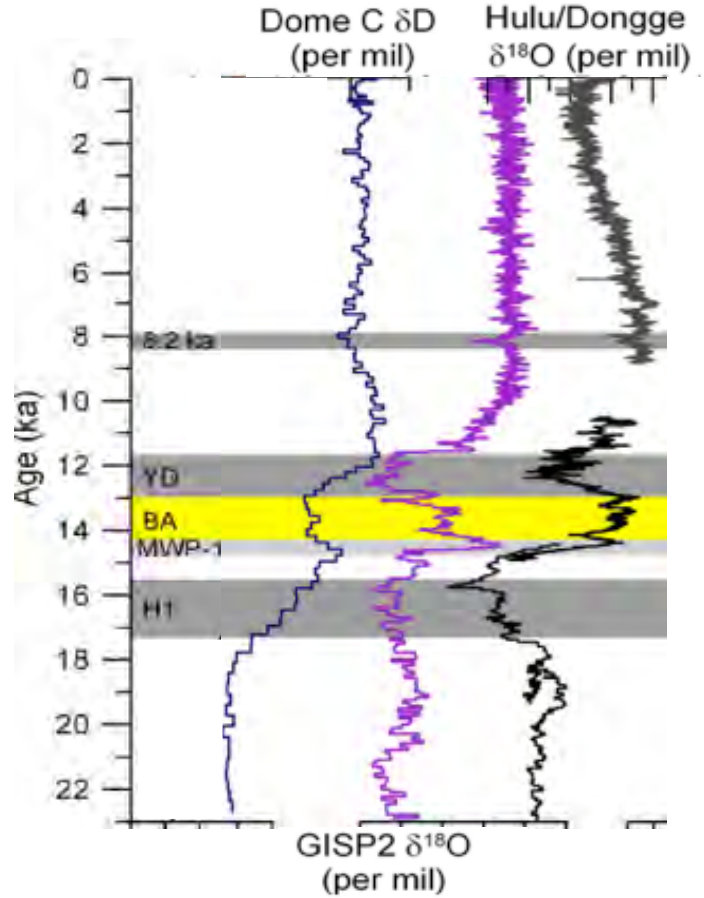
Nusbaumer et al., 2017

Water isotopes in the land model: Wong et al., 2017

Paleo Application of iCESM: iTraCE simulations for the last deglaciation

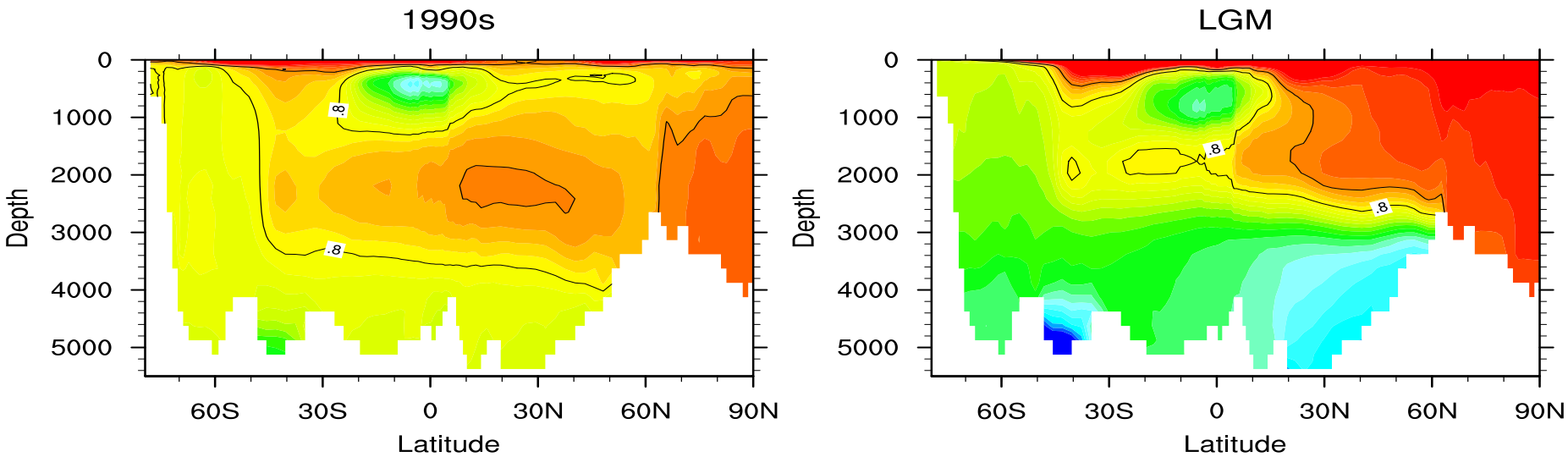
- iTraCE will allow us to evaluate the skill of CESM, stability through time of the interpretations of the proxies, and the mechanisms associated with abrupt changes of the last 21,000 years

- Currently running these, first papers in prep. (Gu et al., 2017, Zhu et al. 2017)

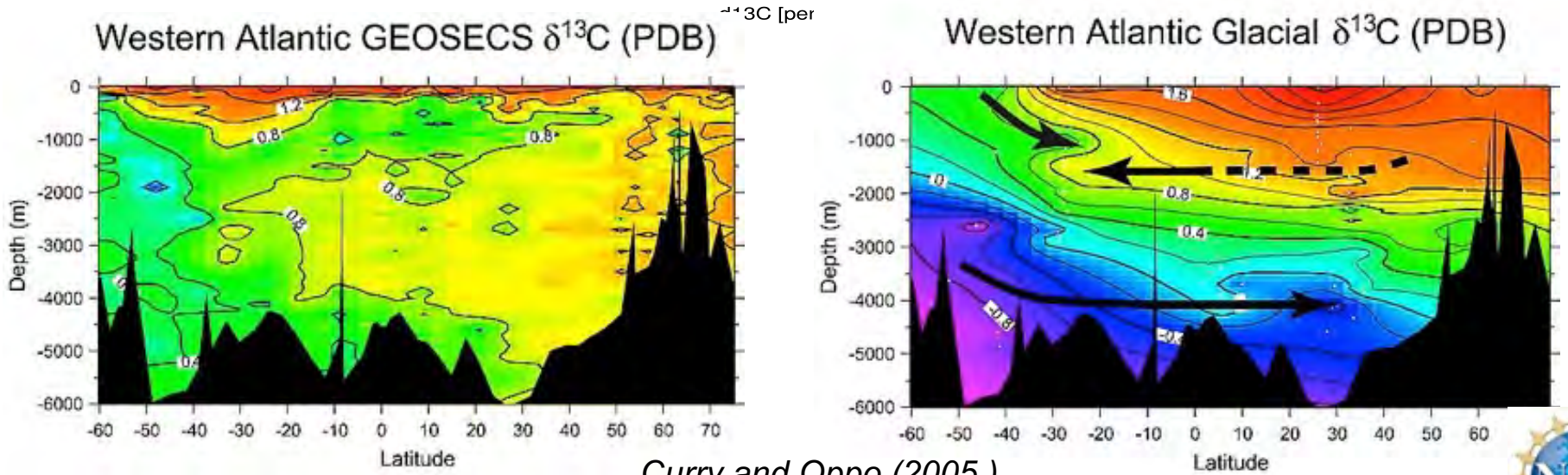


Water isotope iTraCE: Funded by NSF-P2C2: PIs: B. Otto-Bliesner (NCAR), Z. Liu (U. Wisc.), P. Clark (OSU)
Carbon Isotope O-iTraCE: Funded by NSF-P2C2: PIs: A. Jahn (CU) and Z. Liu (U. Wisc.)

First preliminary $\delta^{13}C$ results for the LGM from C-iTRACE-O



See Aaron Schroeder's Poster for radiocarbon simulations for the LGM with iCESM



Curry and Oppo (2005)

Other Paleo Application of iCESM:

- Ocean Radiocarbon was included in one Last Millennium ensemble simulation *(Otto-Bliesner et al., 2016)*

- Water isotopes were included in another ensemble member of the Last Millennium ensemble simulation *(Stevenson et al., in prep.)*

- Water isotopes and probably ocean carbon isotopes will be included in PMIP simulations at NCAR (LGM, Pliocene) (Otto-Bliesner and Matt Long, NCAR)

iCESM papers

- Jahn, A., K. Lindsay, X. Giraud, N. Gruber, B. L. Otto-Bliesner, Z. Liu, and E. C. Brady (2015), Carbon isotopes in the ocean model of the Community Climate System Model (CESM), Geosci. Model Dev., Vol. 8, 2419–2434.
- Nusbaumer, J., T. E. Wong, C. Bardeen, and D. Noone (2017), Evaluating hydrological processes in the Community Atmosphere Model Version 5 (CAM5) using stable isotope ratios of water, J. Adv. Model. Earth Syst., 9, doi:10.1002/2016MS000839.
- Wong, T. E., J. Nusbaumer, and D. C. Noone (2017), Evaluation of modeled land-atmosphere exchanges with a comprehensive water isotope fractionation scheme in version 4 of the Community Land Model, J. Adv. Model. Earth Syst., 9, doi:10.1002/ 2016MS000842.
- Gu, S., Z. Liu, A. Jahn, J. Rempfer, J. Zhang, F. Joos (2017), Neodymium isotopes in the ocean model of the Community Earth System Model (CESM1.3), under review at Geophys. Model Develop. Discussions, doi:10.5194/gmd-2017-40
- Keller, K. M., Lienert, S., Bozbiyik, A., Stocker, T. F., Churakova (Sidorova), O. V., Frank, D. C., Klesse, S., Koven, C. D., Leuenberger, M., Riley, W. J., Saurer, M., Siegwolf, R., Weigt, R. B., and Joos, F.: 20th century changes in carbon isotopes and water-use efficiency: tree-ring-based evaluation of the CLM4.5 and LPX-Bern models, Biogeosciences, 14, 2641-2673, doi:10.5194/bg-14-2641-2017, 2017.
- Gu, S. and Liu, Z.: ^{231}Pa and ^{230}Th in the ocean model of the Community Earth System Model (CESM1.3), Geosci. Model Dev. Discuss., doi:10.5194/gmd-2017-82, in review, 2017.
- Several others currently under review (water isotopes in the ocean, first iTRACE publications)