Explicit isotope modeling with CESM and ECHAM/MPI-OM

Alexandra Jahn (CESM) and Martin Werner (ECHAM/MPI-OM)
Explicit isotope modeling with CESM

Alexandra Jahn
Depart. of Atmospheric and Oceanic Sciences
& Institute for Arctic and Alpine Research
University of Colorado at Boulder

With contributions from the CESM Isotope Development team: B. Otto-Bliesner¹, E. Brady¹, Z. Liu², D. Noone⁴, K. Lindsay¹, M. Vertenstein¹, D. Bailey¹, F. Joos³, A. Bozbiyik³, A. Gettelman¹, S. Gu², C. Koven⁵, E. Kluzek¹, J. Nusbaumer⁴,⁷, B. Riley⁵, J. Tang⁵, P. Thornton⁶, X. Wen², T. Wong⁴, J. Zhang², J. Zhu²

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, Boulder

Contact: Alexandra.Jahn@colorado.edu
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 partitioned 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  
(0.2% of all oxygen, 11% heavier than light oxygen)

H$_2^{18}$O  
Heavy Oxygen

$\delta^{18}O = \left( \frac{^{18}O_{sample}}{^{16}O_{standard}} - 1 \right) \times 1000 \%$

98.89%  1.11%  <0.01%

$\delta^{13}C = \left( \frac{^{13}C_{sample}}{^{12}C_{standard}} - 1 \right) \times 1000 \%$

Carbon  
6 Protons  
6 Neutrons  
Nuclear number = 6 + 6 = 12

Carbon-13  
6 Protons  
7 Neutrons  
Nuclear number = 6 + 7 = 13

Carbon-14  
6 Protons  
8 Neutrons  
Nuclear number = 6 + 8 = 14
Temperature Effect for $\delta^{18}$O in Precipitation

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

“Paleo-Thermometer”

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

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

- $\delta^{13}C$, 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

Curry and Oppo (2005)
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

Proxy Comparison
δ¹⁸Op* over Greenland
From IsoCAM3 ‘slices’
Greenland SAT CCSM3-Full
CO₂+IS, Orbital+IS
δ¹⁸O GISP2 Record

*δ¹⁸Op ~ w/offset for bias

- 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\textsuperscript{2}, and iCESM Team\textsuperscript{***}

Isotopes included in CESM: Water isotopes, Carbon Isotopes, Neodymium isotopes, Pa/Th isotopes, Nitrogen isotopes\textsuperscript{^}\textsuperscript{^}

\textsuperscript{***}E. Brady, A. Jahn\textsuperscript{7}, D. Noone\textsuperscript{4}, K. Lindsay\textsuperscript{1}, M. Vertenstein\textsuperscript{1}, D. Bailey\textsuperscript{1}, F. Joos\textsuperscript{3}, A. Bozbiyik\textsuperscript{3}, A. Gettelman\textsuperscript{1}, S. Gu\textsuperscript{2}, C. Koven\textsuperscript{5}, E. Kluzek\textsuperscript{1}, J. Nusbaumer\textsuperscript{4}, B. Riley\textsuperscript{5}, J. Tang\textsuperscript{5}, P. Thornton\textsuperscript{6}, X. Wen\textsuperscript{2}, T. Wong\textsuperscript{4}, J. Zhang\textsuperscript{2}, J. Zhu\textsuperscript{2}

\textsuperscript{^} S. Yang and N. Gruber, ETH
iCESM: Water Isotope and Carbon isotope tracers development

Water Isotopes

- iCAM
  - C. Bardeen
  - D. Noone
  - J. Nusbaumer

- iCLM
  - D. Noone
  - T. Wong

- iCPL
  - M. Vertenstein
  - E. Kluzek
  - E. Brady
  - J. Zhu

- iPOP
  - J. Zhang
  - E. Brady
  - J. Zhu

- iRTM
  - J. Zhu

- iCICE
  - D. Bailey
  - A. Jahn
  - J. Zhu

Carbon Isotopes

- Ocean (iPOP2)
  - A. Jahn
  - K. Lindsay

- Atmosphere (iCAM5)
  - Fortunat Joos
  - A. Jahn
  - Chengfei He

- Land (iCLM4.5)
  - A. Bozbiyik
  - Fortunat Joos

Coupler

Sea ice (CICE)
- TBD

River Model (iRTM)
- TBD

Done, to be part of CESM2

Atmosphere and coupling current under development
Implementation of Carbon isotopes in the ocean model of the CESM

- **Abiotic Radiocarbon**: can be run independently of the ecosystem model, no fractionation
- **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 CaCO$_3$ formation

Jahn et al., 2015, GMD
Surface simulations of $\delta^{13}C$ (1990s) compared to Cruise data compiled by Schmittner et al. (2014)

Jahn et al. (2015), GMD
Cross sections of oceanic $\delta^{13}C$ (1990s)

Cruise data compiled by Schmittner et al. (2014)

Atlantic, Pacific, Indian

Depth

Cruise data compiled by Schmittner et al. (2014)

iCESM simulation

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)

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
Neodymium isotopes in iCESM ocean

Figure 5. Vertical sections of $[\text{Nd}]_d$ (a) and $\varepsilon_{\text{Nd}}$ (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
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.

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
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


• Several others currently under review (water isotopes in the ocean, first iTRACE publications)