Modelling Isotope Tracers in the Laurentide Ice Sheet through the Last Glacial Cycle

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Reasons to Model Ice Sheet Isotopes

Within Greenland and Antarctica, $\delta^{18}O$ and $\delta D$ offer additional internal ice sheet constraints for models of ice sheet and climate history (i.e. via ice cores)
Last Glacial Period

Neem

NGRIP

GISP2

GRIP

DYE-3

Holocene

Last Glacial Period

NGRIP $\delta^{18}O$ (%)
Reasons to Model Ice Sheet Isotopes

Within Greenland and Antarctica, $\delta^{18}$O and $\delta$D offer additional internal ice sheet constraints for models of ice sheet and climate history (i.e. via ice cores).

At LGM, oceans were enriched by ca. 1‰ in $^{18}$O; $\delta^{18}$O of the ice sheets needs to be done to equate this to ice sheet volume at LGM.

- This is usually assumed to be $-30$‰.
- The evolution of ice sheet $\delta^{18}$O (t) is even more interesting, and offers potential constraints.
Passive Tracers in Ice Sheet Models

Following Clarke & L’homme (2002, 2005)

- Lagrangian tracer of ice origin and age \((x,y,z)\)
  i.e. can query any part of the ice sheet for \((x_0,y_0,z_0,t_0)\)

- Next you need estimates of \(\delta^{18}O\) (and/or \(\delta D\)) of precipitation at \((x_0,y_0,z_0,t_0)\), to map \(\delta (x,y,z)\)

- Typically in ice sheet models, \(n_z \sim 20\), so e.g. \(\Delta z \sim 150 \text{ m}\), too coarse for a synthetic ice core. Hence it is necessary to interpolate \(\delta(z)\).

- Finally, diffuse the interpolated \(\delta(z)\) profile.
Passive Tracers in Ice Sheet Models

Application to Greenland:

Precipitation $\delta^{18}O$ is somewhat constrained, since we know $\delta(x_0,y_0,z_0,t_0)$ at ice core sites.

Actually we only really know $\delta(t_0)$. The spatial origin of ice at a given depth in an ice core is unknown. One can assume it is the same as modern, or one can use an ice sheet model to refine estimates of $(x_0,y_0,z_0)$.
Passive Tracers in Ice Sheet Models

Application to Greenland

Another option is to rely on Dansgaard for estimates of $\delta(x_0,y_0,z_0,t_0)$ – really this means $\delta(T)$:

i.e. transfer function based on modern day

$$\delta_{18m} = 0.695t_a - 13.6\%$$

This assumes stationarity and assumes that we can model past temperatures $T(x_0,y_0,z_0,t_0)$ with some confidence (climate model or ice core based).
Example for Greenland

GRIP ice core $\delta^{18}O$ and $T(z)$

(b) $\delta^{18}O$ (‰)

Depth (m)

Temperature (°C)

N. Lhomme et al. / Quaternary Science Reviews 24 (2005) 173 194
Some questions and limitations

There is circularity here, in the modeling of Greenland ice cores based on Greenland ice cores. We need more spatial information for precipitation $\delta^{18}O$ and changes in seasonality of precipitation, moisture pathways, etc. through the glaciation – i.e., not just the modern $\delta-T$ relation.
Some questions and limitations

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Post-depositional melt effects on $\delta^{18}$O?

The effects of meltwater percolation on the seasonal isotopic signals in an Arctic snowpack

Tara MORAN, Shawn MARSHALL


Isotope thermometry in melt-affected ice cores

T. Moran, S. J. Marshall, and M. J. Sharp

Isotopes in this ice core reveal how glaciers responded to climate change more than 100,000 years ago.

**CLIMATOLOGY**

**Greenland defied ancient warming**

But Antarctic glaciers may be more vulnerable than thought.
WARM SPELL
The Eemian interglacial period (130,000–115,000 years ago) began with a burst of climate warming—but this caused only a modest shrinkage of the ice sheet that covered Greenland at the time.

Passive Tracers in Ice Sheet Models

Application to the Laurentide Ice Sheet:

Here we really don’t know $\delta(x_0, y_0, z_0, t_0)$.

Options:
- transfer function based on modern day
- independent isotopic model, e.g. Rayleigh
- isotope-enabled GCM
Interpolated $\delta^{18}O$ of Precipitation (‰, V-SMOW)
Modern modelled $\delta^{18}O (T,z,\theta)$
Precipitation $\delta^{18}O$ in Canada

Observed vs. modelled: $\delta^{18}O (T, \theta, z)$

Mean monthly $\delta^{18}O$ (‰)

Modelled $\delta^{18}O$ (‰)

$N = 1986$

$R^2 = 0.86$
Vertically-integrated mean $\delta^{18}\text{O} \, (\%)$

$t = 80 \text{ ka}$

$t = 60 \text{ ka}$

$t = 21 \text{ ka}$

$t = 13 \text{ ka}$
Mean $\delta^{18}$O of the North American ice sheets (‰)
Ice sheet $\delta^{18}O$ (‰)

Marine $\Delta\delta^{18}O$ (‰)

$\delta^{18}O$ of mwp1a: $-25.6 \, \text{‰}$
Proxies documenting Laurentide $\delta^{18}O$ values?

SUBGLACIAL LIS CONCRETIONS AT CANTLEY
(over Grenvillian Precambrian marbles)

Age of concretions: $22.2 \pm 1.3$ ka
(TSD/U-Th)

$\delta^{18}O_{\text{calcite}} \sim -25\%$o

with $T \sim 0^\circ$C, $\delta^{18}O_{\text{water}} \sim -30\%$o

Hillaire-Marcel et al, CJES, 1979
Hillaire-Marcel & Causse, QR, 1989
The isotopic composition of the Laurentide Ice Sheet and fossil groundwater

Grant Ferguson¹ and Scott Jasechko²
Ice age precipitation $\delta^{18}O$ (% SMOW)

- CAM3iso
- GISS
- ECHAM
- IsoGSM
Summary and Preliminary Conclusions

Advances should be possible through isoCESM: complete the loop on the global hydrological and water isotope cycles.

Maybe need to think about $\Delta \delta$ for this, depending on atmospheric model biases.

Challenge: how to treat transient $\delta$ of precipitation over many kyr, or a glacial cycle?

One option is to map $\delta(T)$ or $\delta(z, \theta, T)$ relationships for different ice sheet geometries, from snapshots.
Questions
LGM 700-mb specific humidity
LGM wind field (winter)

m/s
Modeling vapor transport and isotope fractionation
Q. What was the $\delta^{18}O$ of Laurentide Ice Sheet runoff?
SE margin LIS meltwater…

Appr. -16‰

- *L. Erie ostracods, Fritz et al., 1975*
- *Glacial lake concretions, Hillaire-Marcel & Causse, 1989*
Mean modelled surface $\delta^{18}O$

North America

Laurentide

Drainage of Lake Agassiz-Ojibway
SE margin LIS meltwater…

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