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

Shawn Marshall, University of Calgary
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)
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. \(\Delta z \sim 150\) 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 \textasciitilde 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

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

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 $T(z)$

$\delta^{18}O$ (%) vs depth (m)

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

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.

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.

*Nature News, 2013*
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
Modern modelled $\delta^{18}$O (T,z, $\theta$)

$\delta^{18}$O (precipitation) present day

-45  -40  -35  -30  -25  -20  -15  -10
Precipitation $\delta^{18}O$ in Canada

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

Mean monthly $\delta^{18}O$ (‰)

$N = 1986$

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

- $t = 80$ ka
- $t = 60$ ka
- $t = 21$ ka
- $t = 13$ ka
Mean $\delta^{18}O$ of the North American ice sheets ($\%_o$)
Ice sheet $\delta^{18}O$ (‰)

Marine $\Delta\delta^{18}O$ (‰)
Ice sheet $\delta^{18}O$ (‰)

Marine $\Delta \delta^{18}O$ (‰)

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

**SUBGLACIAL LIS CONCRETIONS AT CANTLEY**
(over Grenvillian Precambrian marbles)

Age of concretions: 22.2 ± 1.3 ka (TSD/U-Th)

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

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

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)
Modeling vapor transport and isotope fractionation
Q. What was the $\delta^{18}O$ of Laurentide Ice Sheet runoff?

Collaboration with Claude Hillaire-Marcel, Anne de Vernal, Garry Clarke & Andy Bush
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…

Appr. -16‰

- *L. Erie ostracods*, Fritz et al., 1975