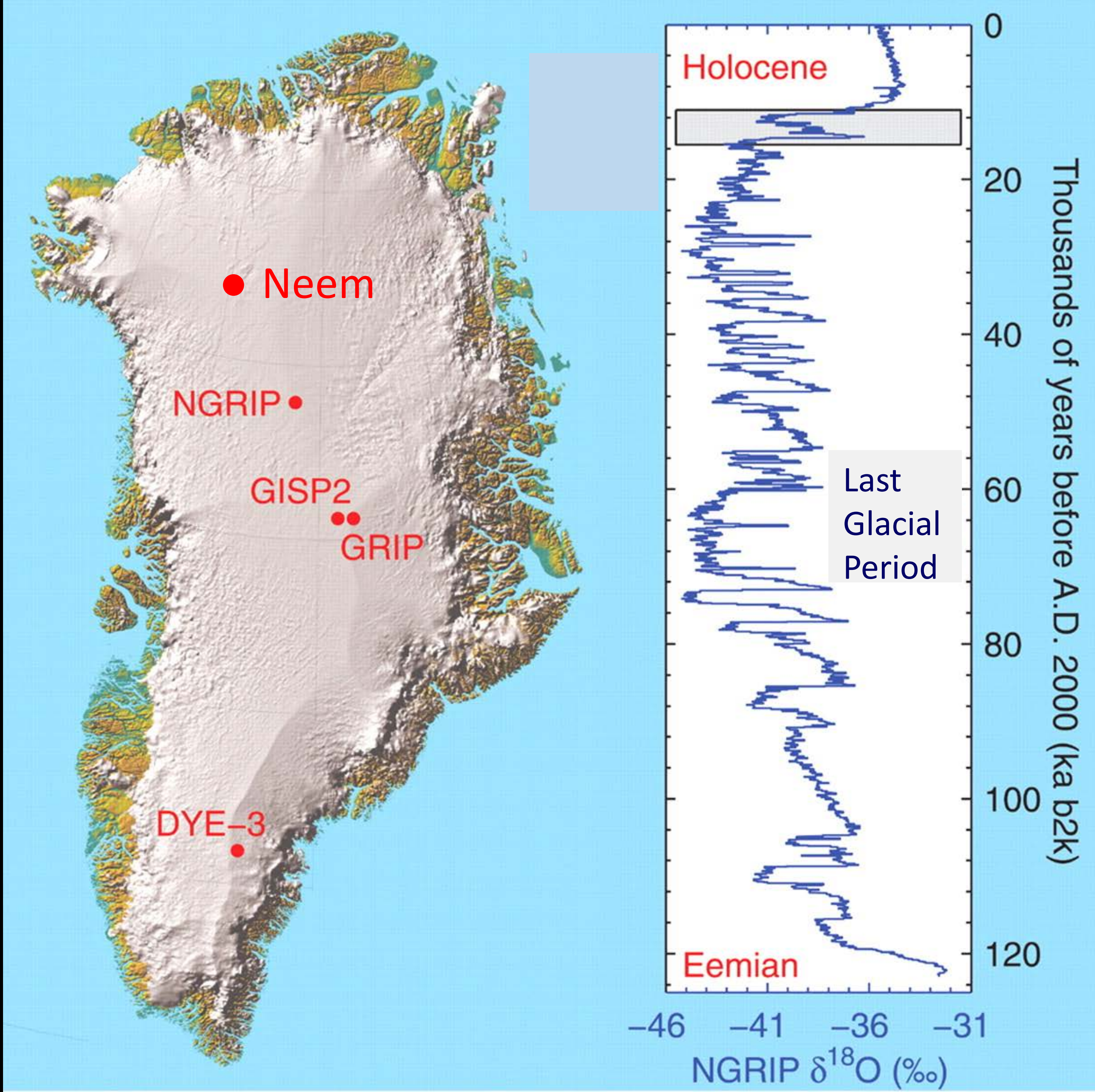
Modelling Isotope Tracers in the Laurentide Ice Sheet through the Last Glacial Cycle

Shawn Marshall, University of Calgary

Reasons to Model Ice Sheet Isotopes

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


Neem
NGRIP
GISP2
GRIP
DYE–3
Holocene
Last Glacial Period
Eemian
0
20
40
60
80
100
120
Thousands of years before A.D. 2000 (ka b2k)
–46
–41
–36
–31
NGRIP δ18O (‰)

Reasons to Model Ice Sheet Isotopes

Within Greenland and Antarctica, $\delta^{18}O$ and δD 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)

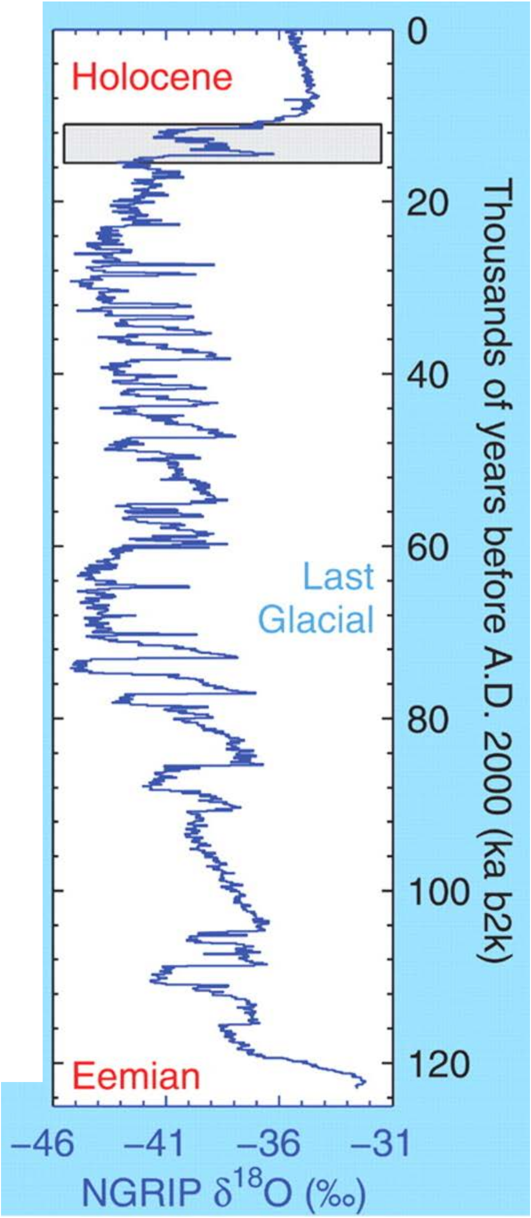
- Lagrangian tracer of ice origin and age (x,y,z)
  i.e. can query any part of the ice sheet for (x_0,y_0,z_0,t_0)
- Next you need estimates of $\delta^{18}O$ (and/or δD) of precipitation at (x_0,y_0,z_0,t_0), to map $\delta\ (x,y,z)$
- Typically in ice sheet models, $n_z \sim 20$, so e.g. $\Delta z \sim 150$ 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 ~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 $\delta(T)$:

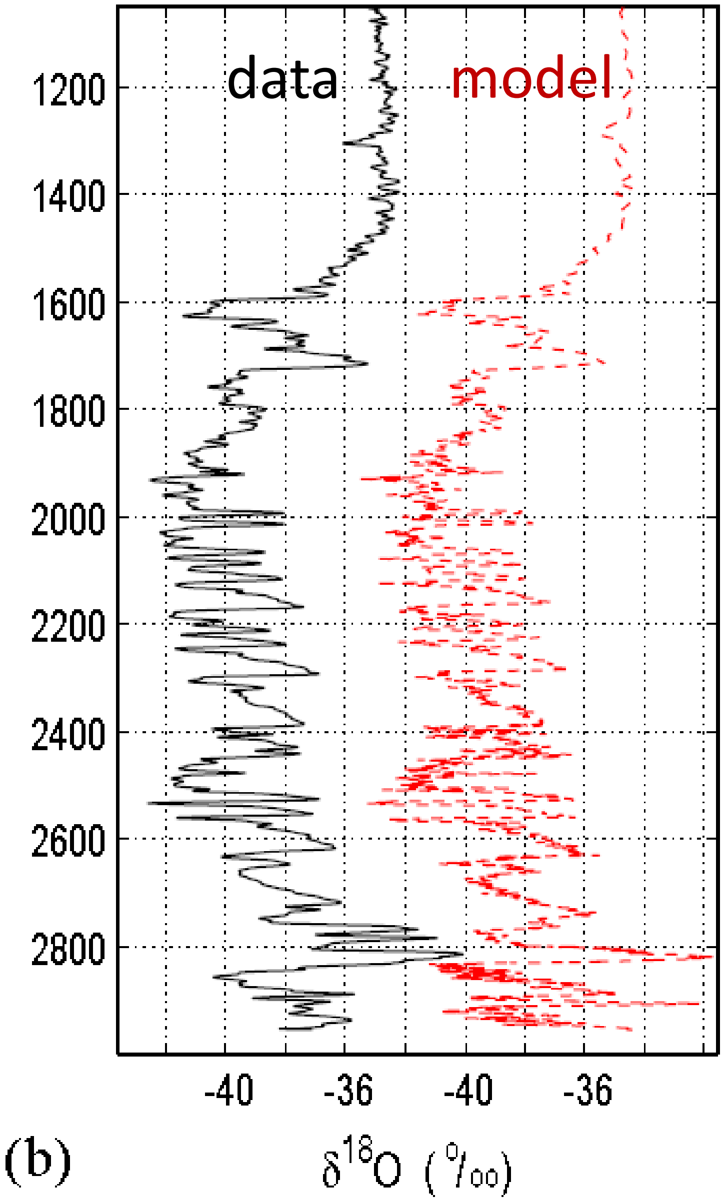
i.e. transfer function based on modern day

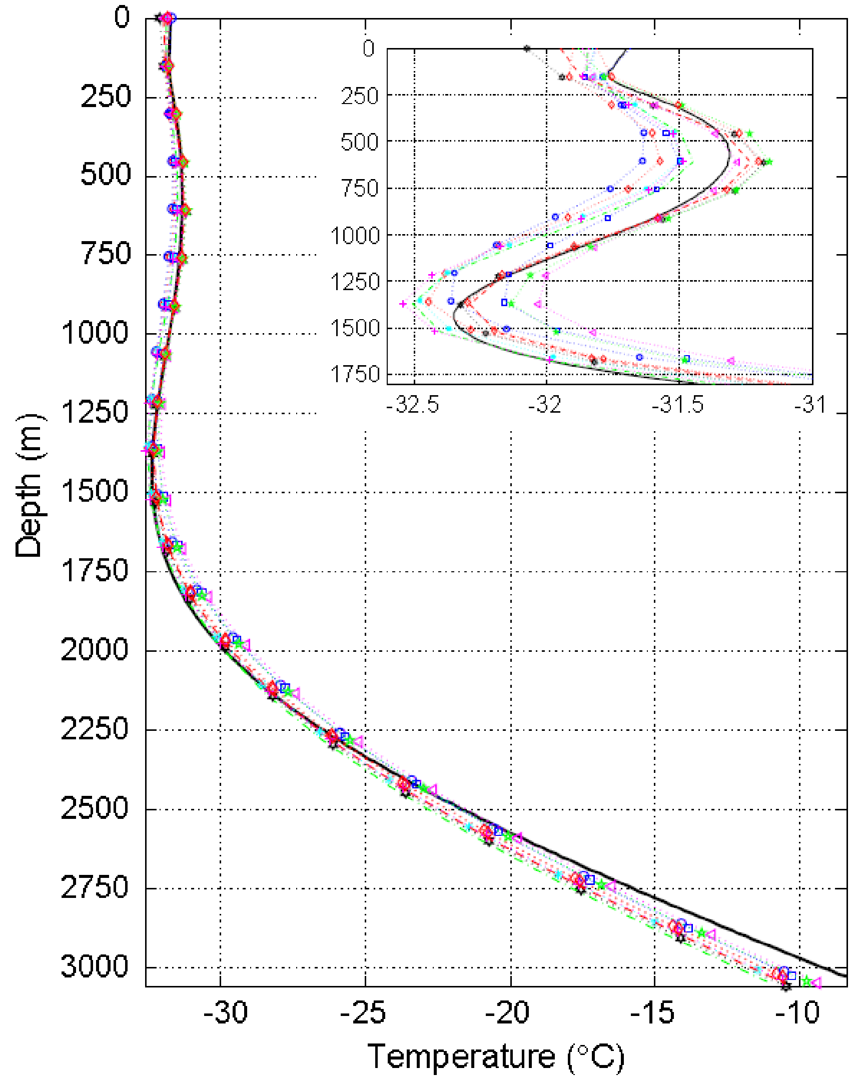
$$\delta_{18m} = 0.69_5 t_a - 13.6\,‰$$

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 $T(z)$





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 δ-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 δ-*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

Journal of Glaciology, Vol. 55, No. 194, 2009

Isotope thermometry in melt-affected ice cores

T. Moran,[1] S. J. Marshall,[1] and M. J. Sharp[2]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, F02010, doi:10.1029/2010JF001738, 2011

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

CLIMATOLOGY

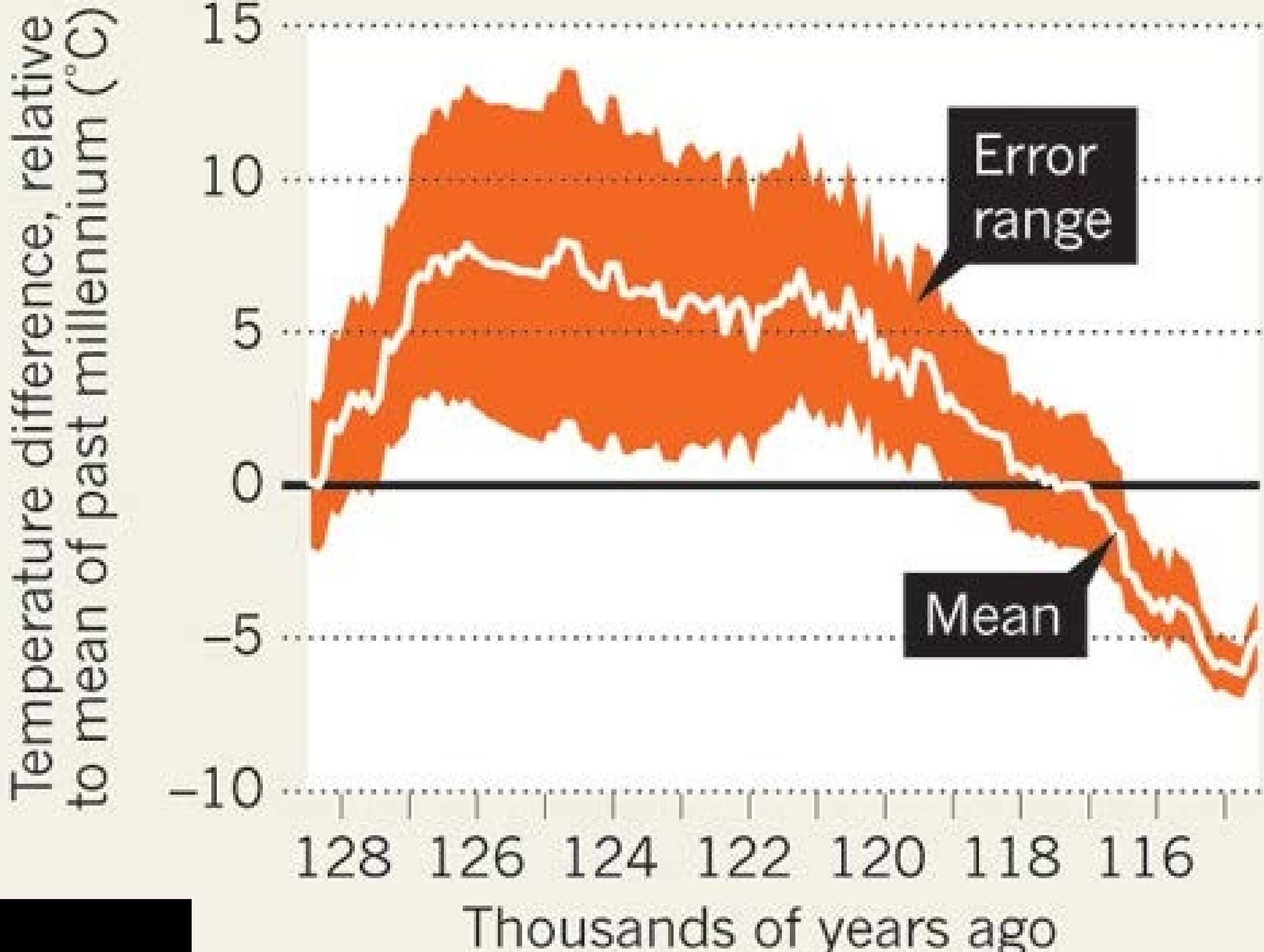
Greenland defied ancient warming

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.



Nature News, 2013

Passive Tracers in Ice Sheet Models

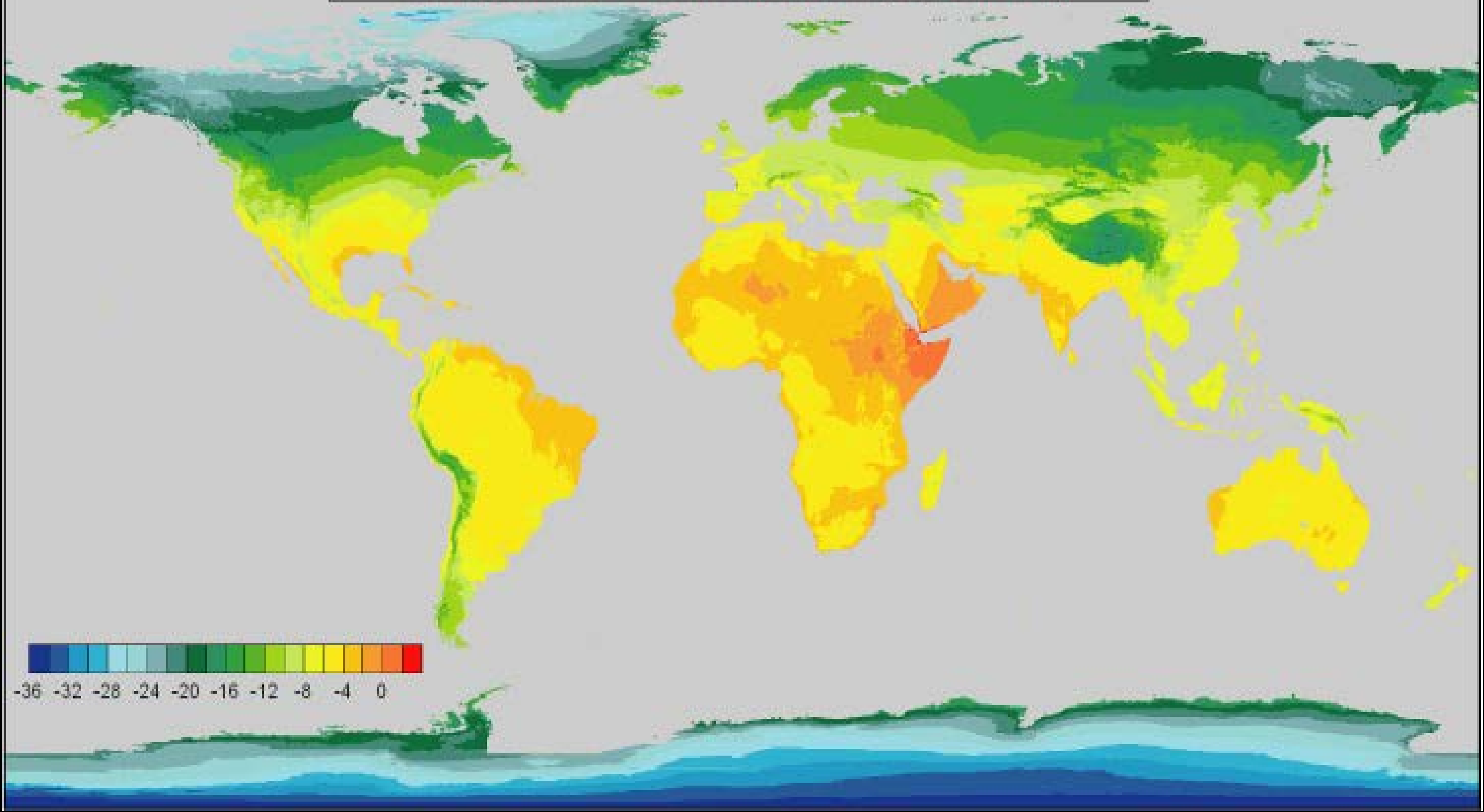
Application to the Laurentide Ice Sheet:

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

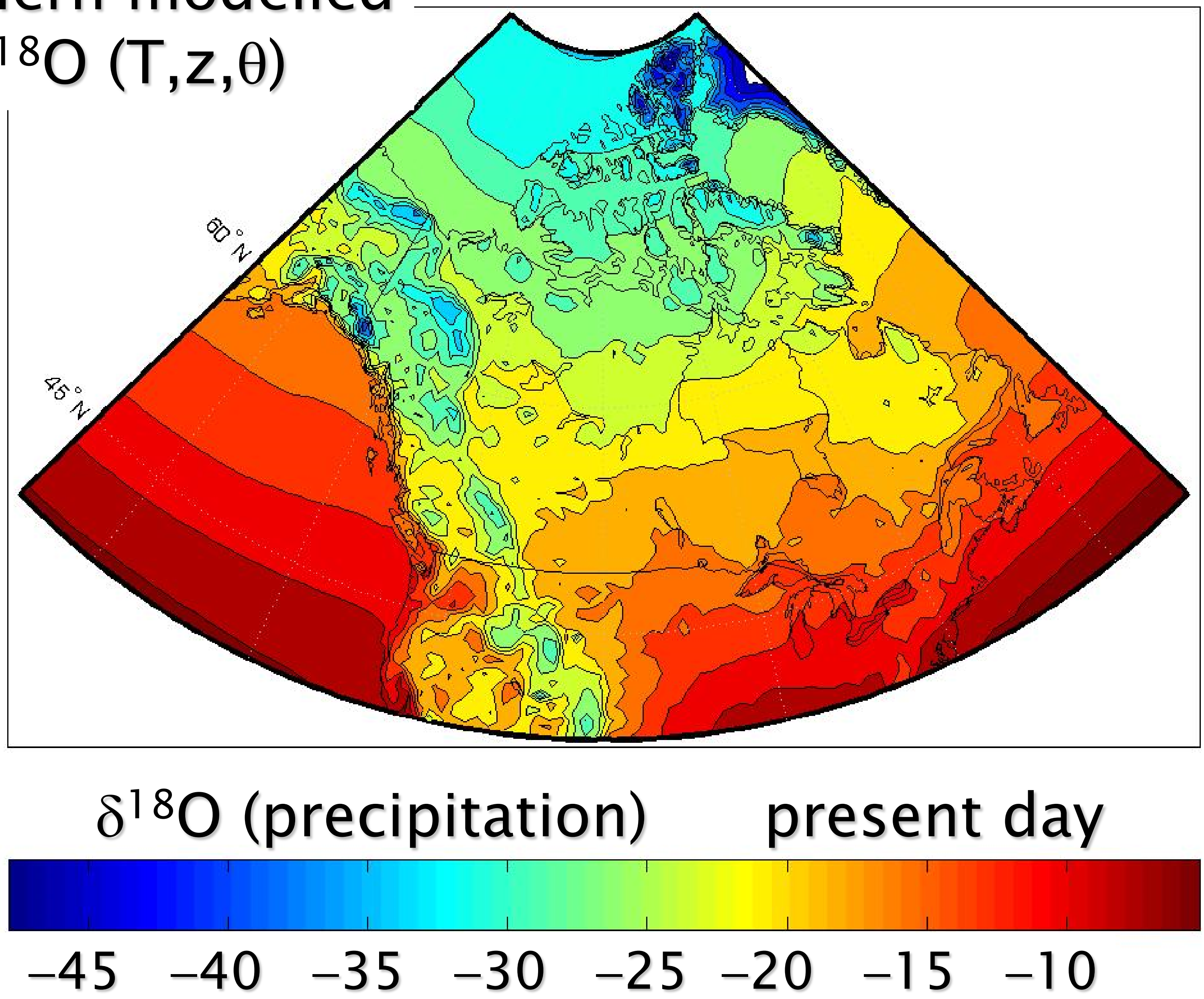
Options:

- transfer function based on modern day
- independent isotopic model, e.g. Rayleigh
- isotope-enabled GCM

Interpolated δ18O of Precipitation (‰, V-SMOW)

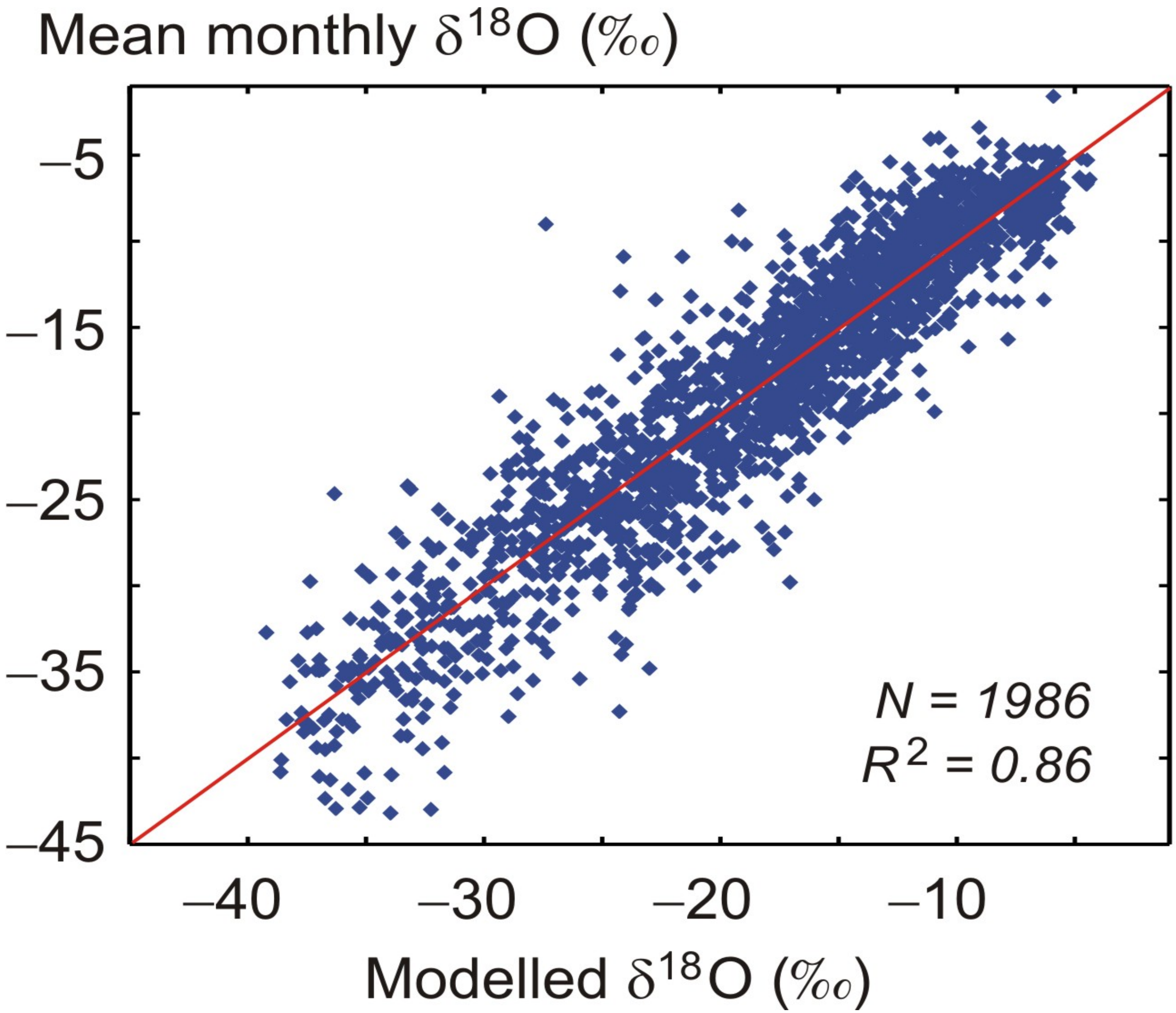


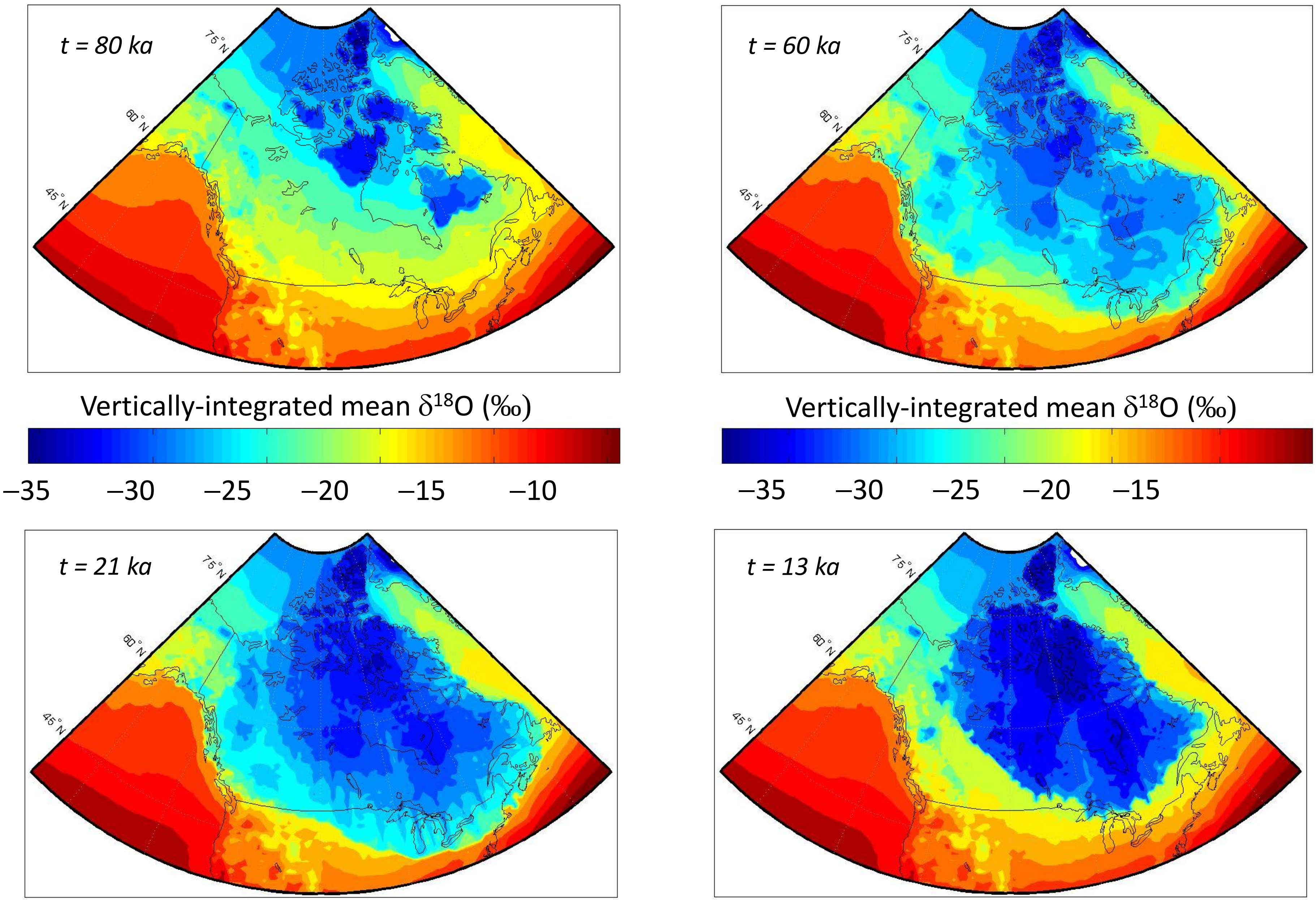
Modern modelled $\delta^{18}O$ (T,z,θ)



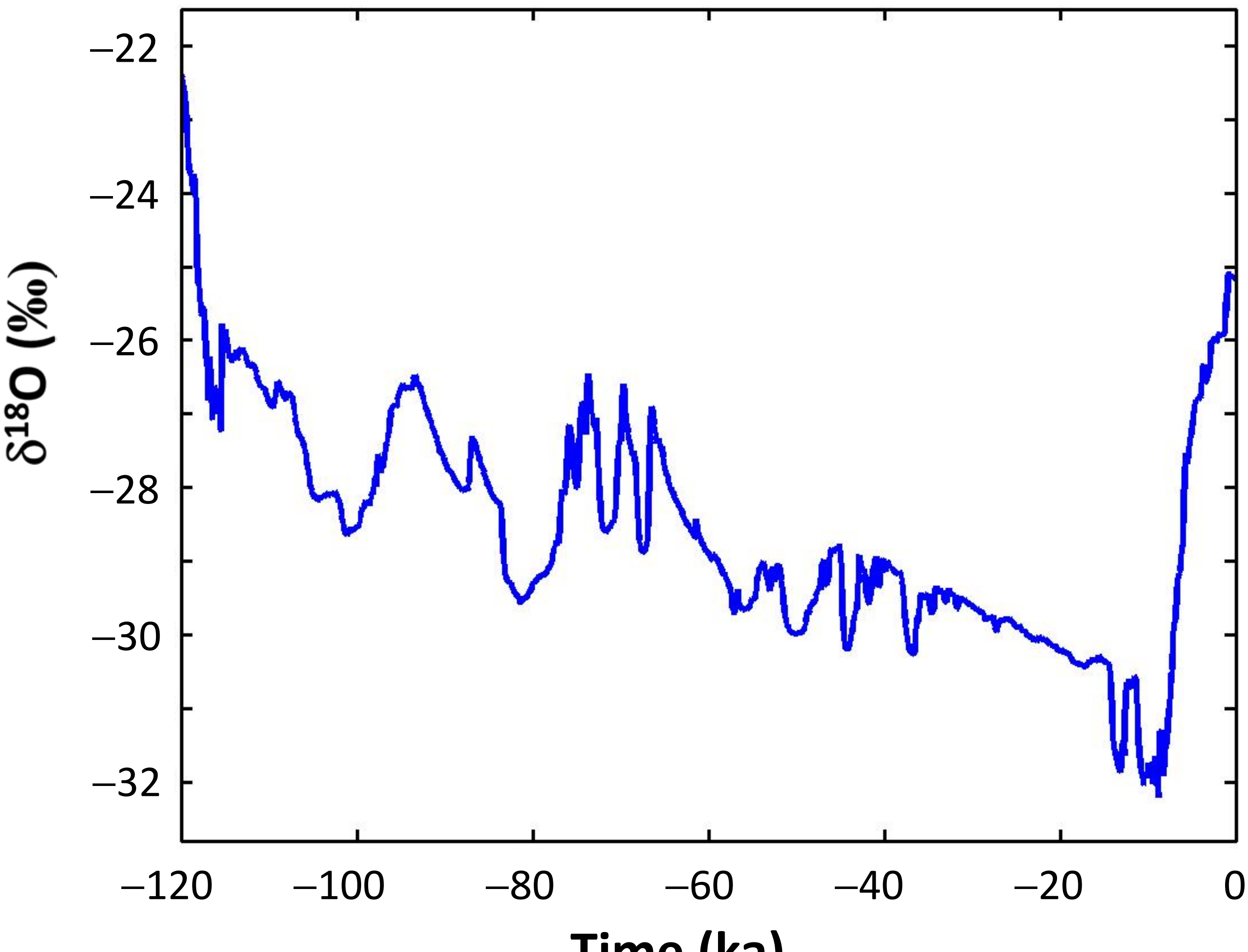
Precipitation $\delta^{18}O$ in Canada

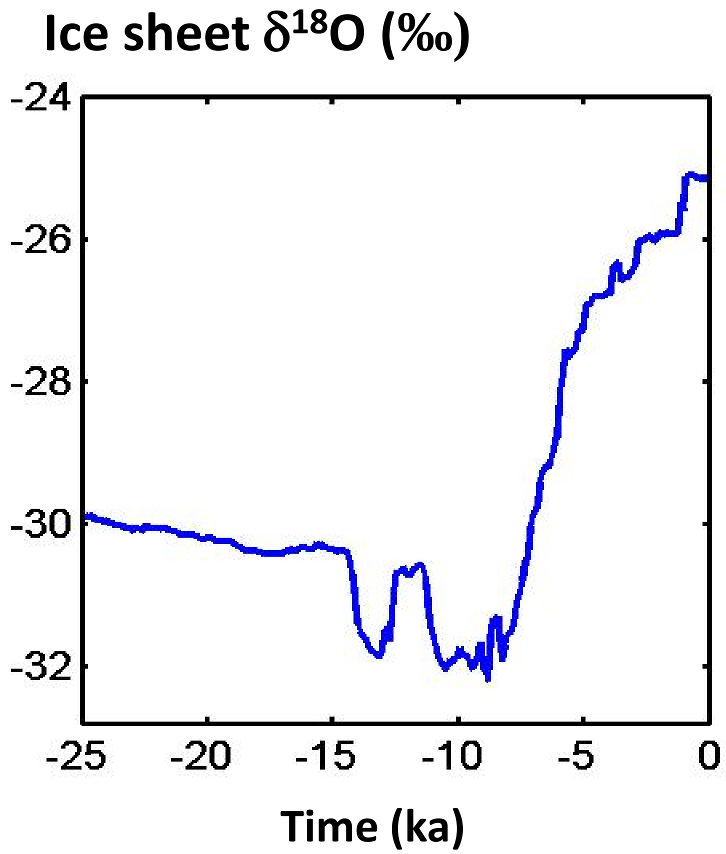
Observed vs. modelled: $\delta^{18}O$ (T, θ, z)

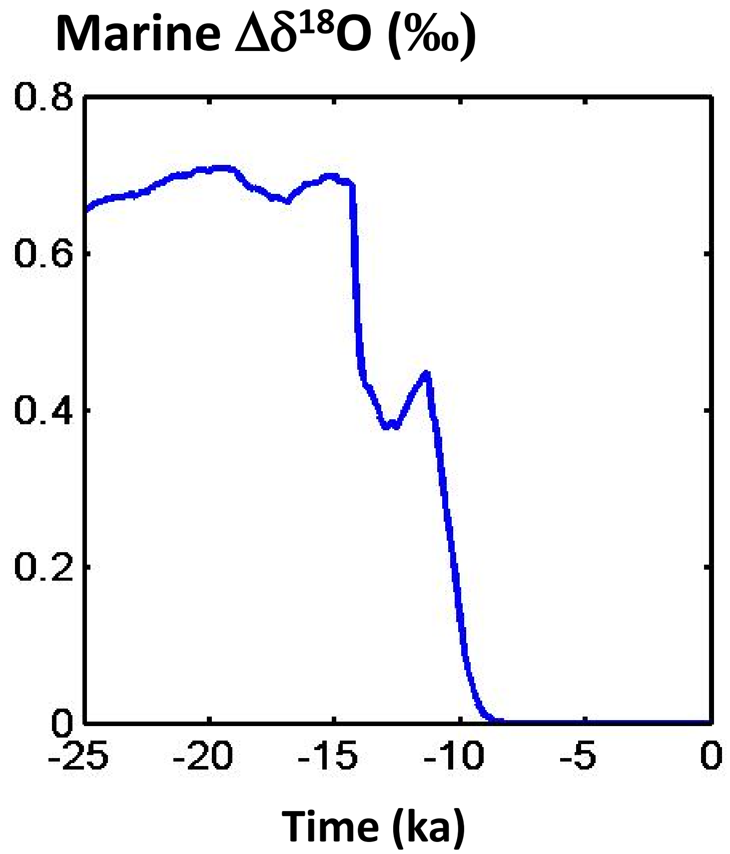


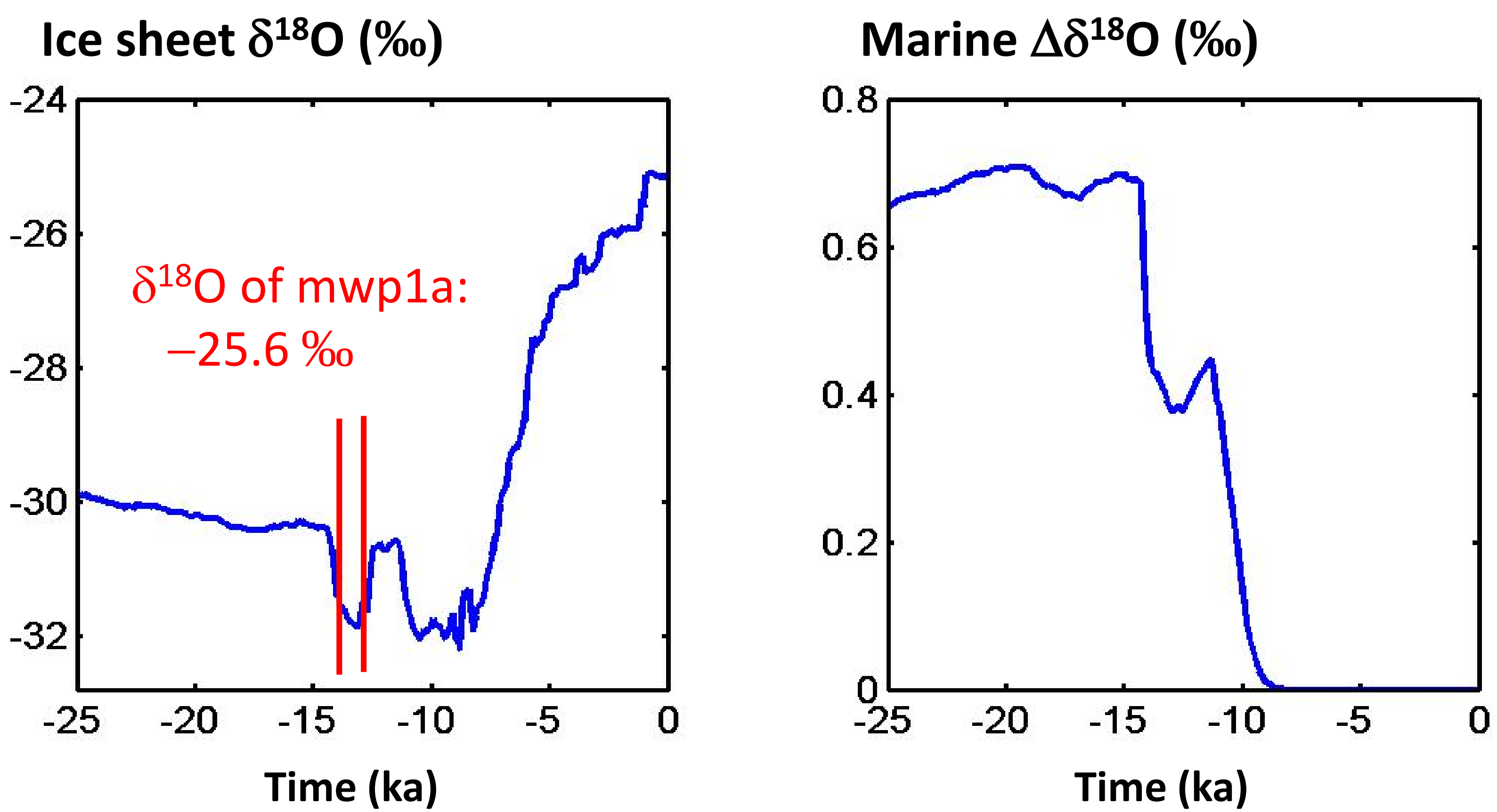

t = 80 ka
t = 60 ka
t = 21 ka
t = 13 ka
75°N
60°N
45°N
Vertically-integrated mean δ18O (‰)
−35 −30 −25 −20 −15 −10
Vertically-integrated mean δ18O (‰)
−35 −30 −25 −20 −15

Mean δ18O of the North American ice sheets (‰)




Ice sheet δ18O (‰)
-24
-26
-28
-30
-32
-25
-20
-15
-10
-5
0
Time (ka)


Marine Δδ18O (‰)
0.8
0.6
0.4
0.2
0
-25
-20
-15
-10
-5
0
Time (ka)



Ice sheet δ18O (‰)
-24
-26
-28
-30
-32
δ18O of mwp1a:
−25.6 ‰
-25
-20
-15
-10
-5
0
Time (ka)
Marine Δδ18O (‰)
0.8
0.6
0.4
0.2
0
-25
-20
-15
-10
-5
0
Time (ka)

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)

$\delta^{18}O_{calcite} \sim -25‰$

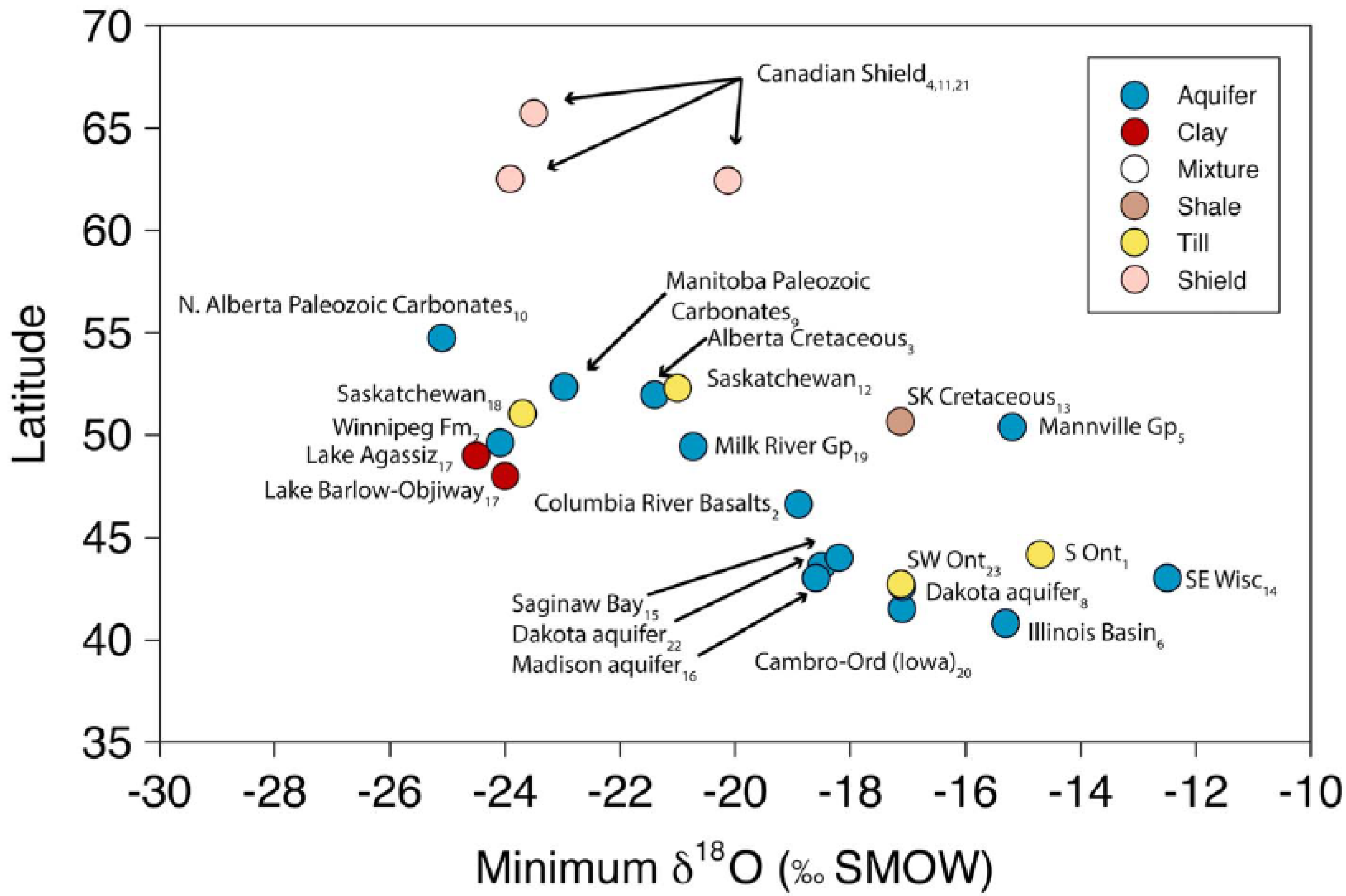
with T ~ 0°C, $\delta^{18}O_{water} \sim -30‰$

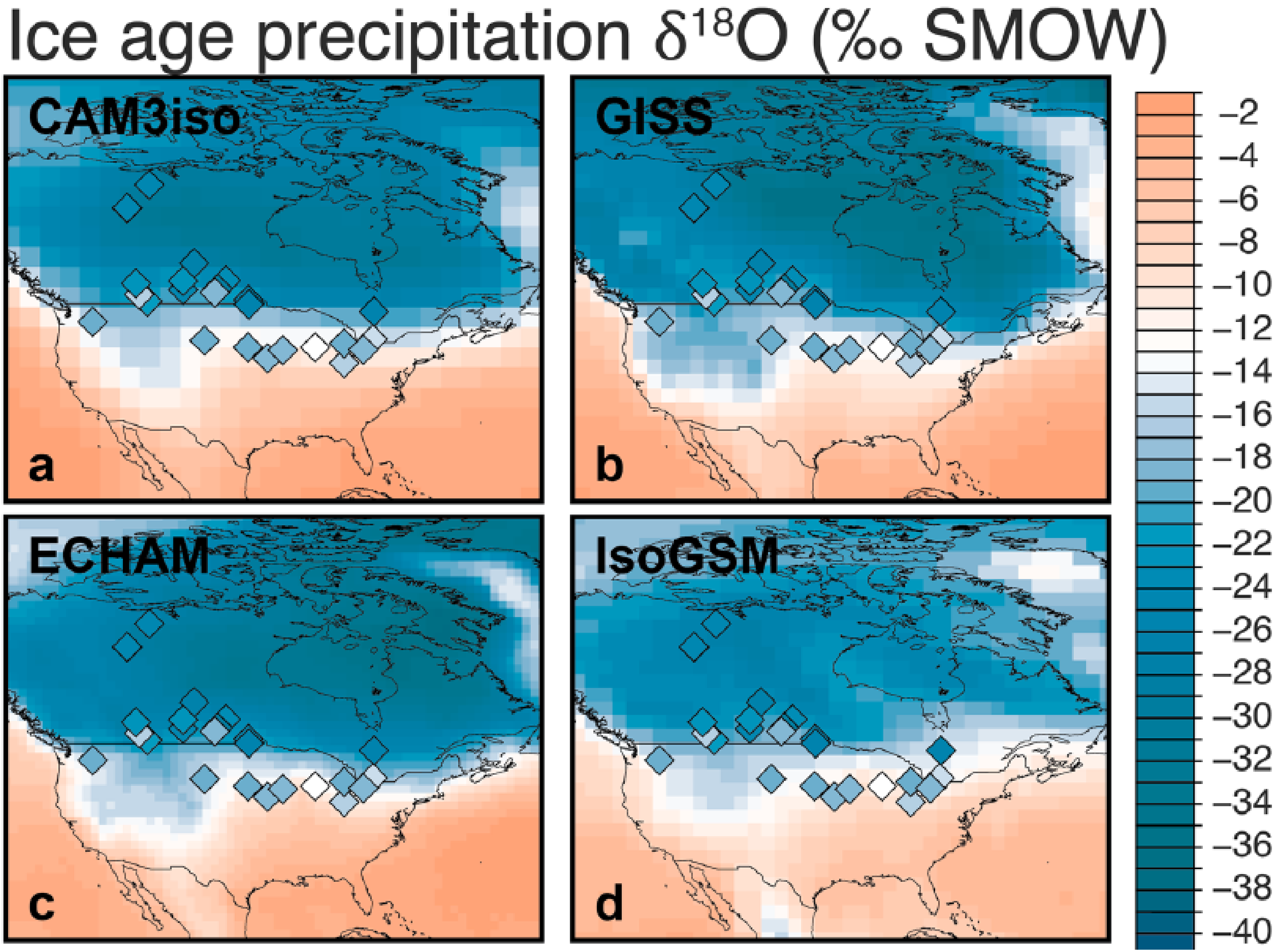
Hillaire-Marcel et al, CJES, 1979
Hillaire-Marcel & Causse, QR, 1989

AGU Geophysical Research Letters 10.1002/2015GL064106

The isotopic composition of the Laurentide Ice Sheet and fossil groundwater

Grant Ferguson[1] and Scott Jasechko[2]




Ice age precipitation δ18O (‰ SMOW)
CAM3iso
a
GISS
b
ECHAM
c
IsoGSM
d
−2
−4
−6
−8
−10
−12
−14
−16
−18
−20
−22
−24
−26
−28
−30
−32
−34
−36
−38
−40

Summary and Preliminary Conclusions

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

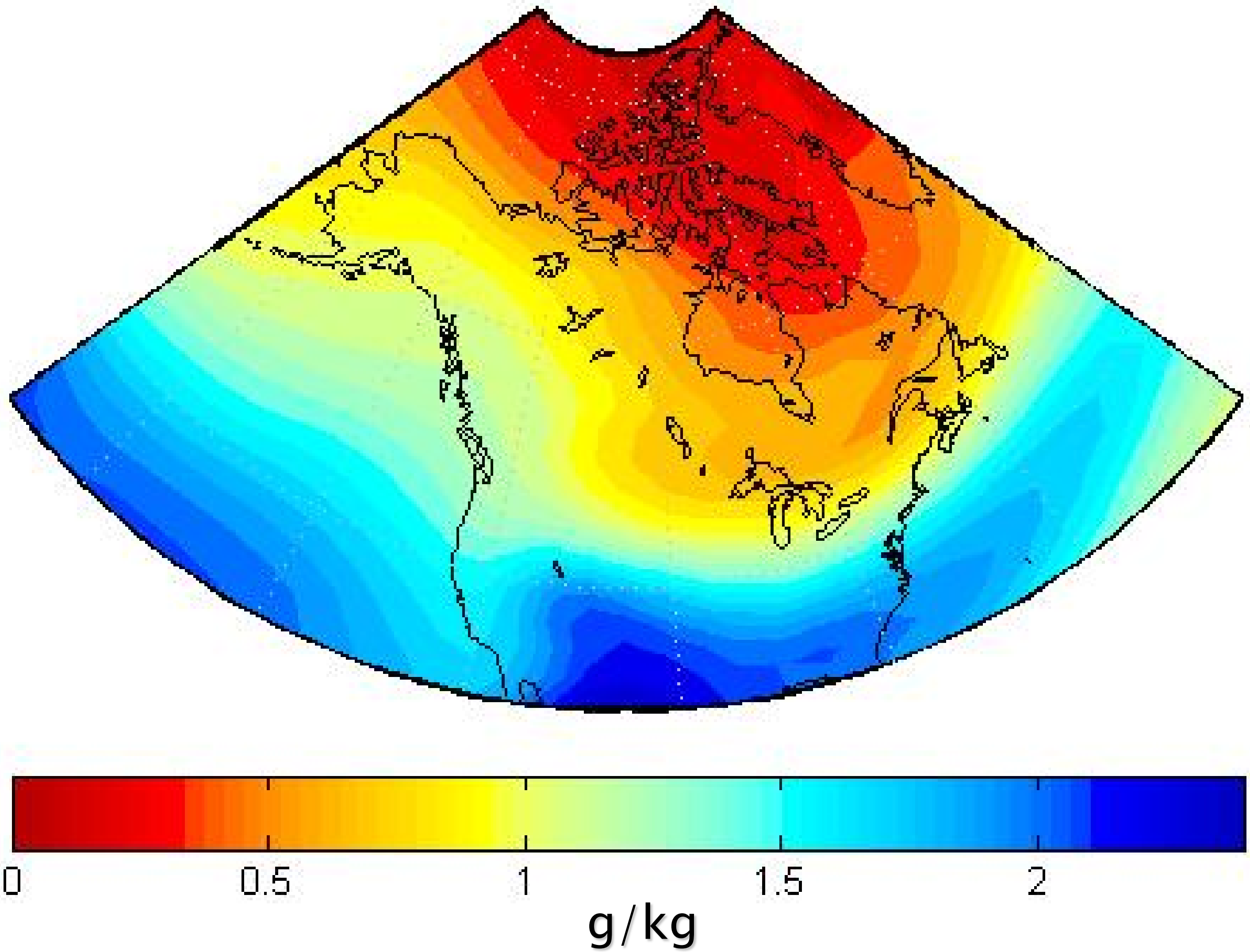
Maybe need to think about $\Delta\delta$ for this, depending on atmospheric model biases.

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

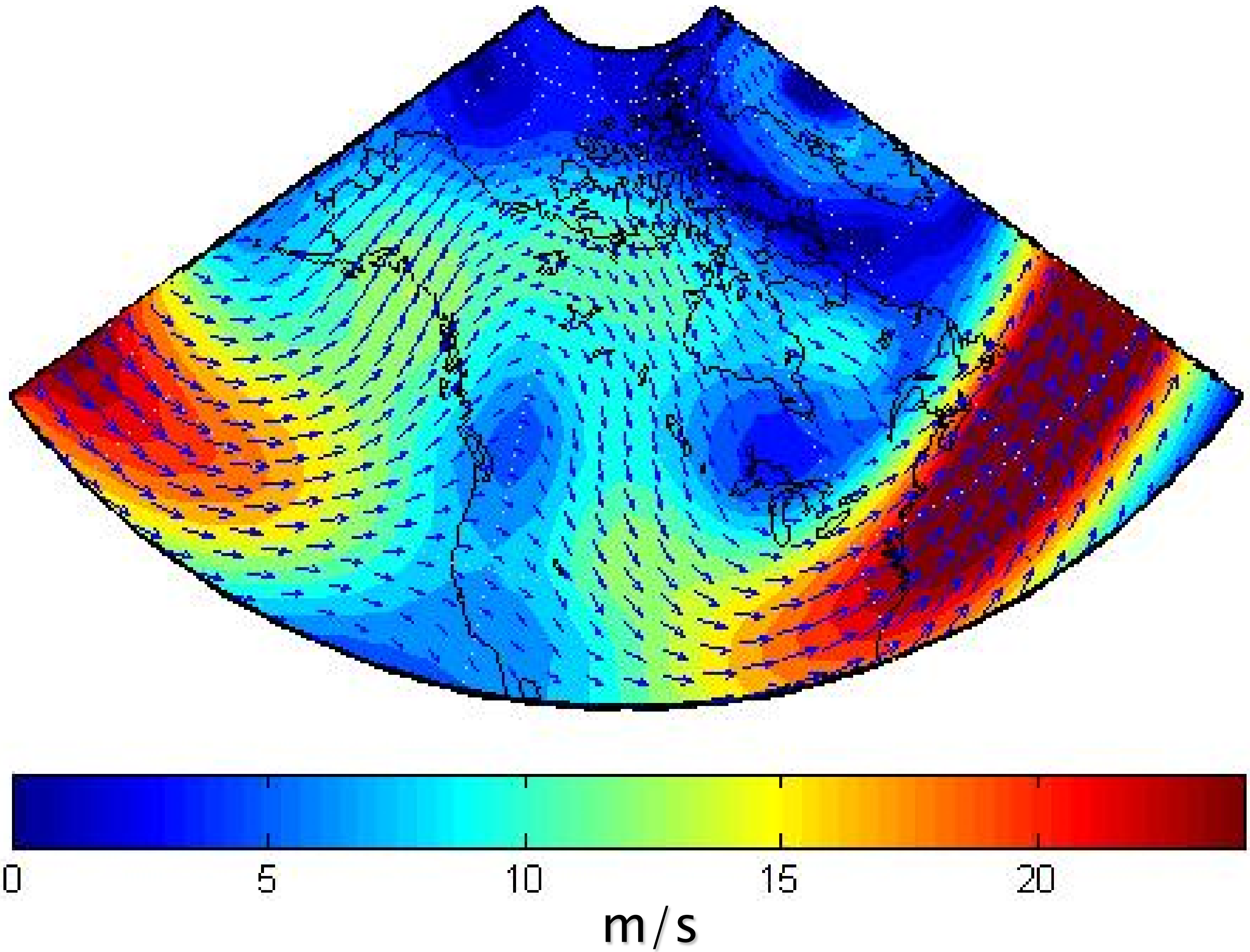
One option is to map $\delta(T)$ or $\delta(z,\theta,T)$ relationships for different ice sheet geometries, from snapshots

Questions

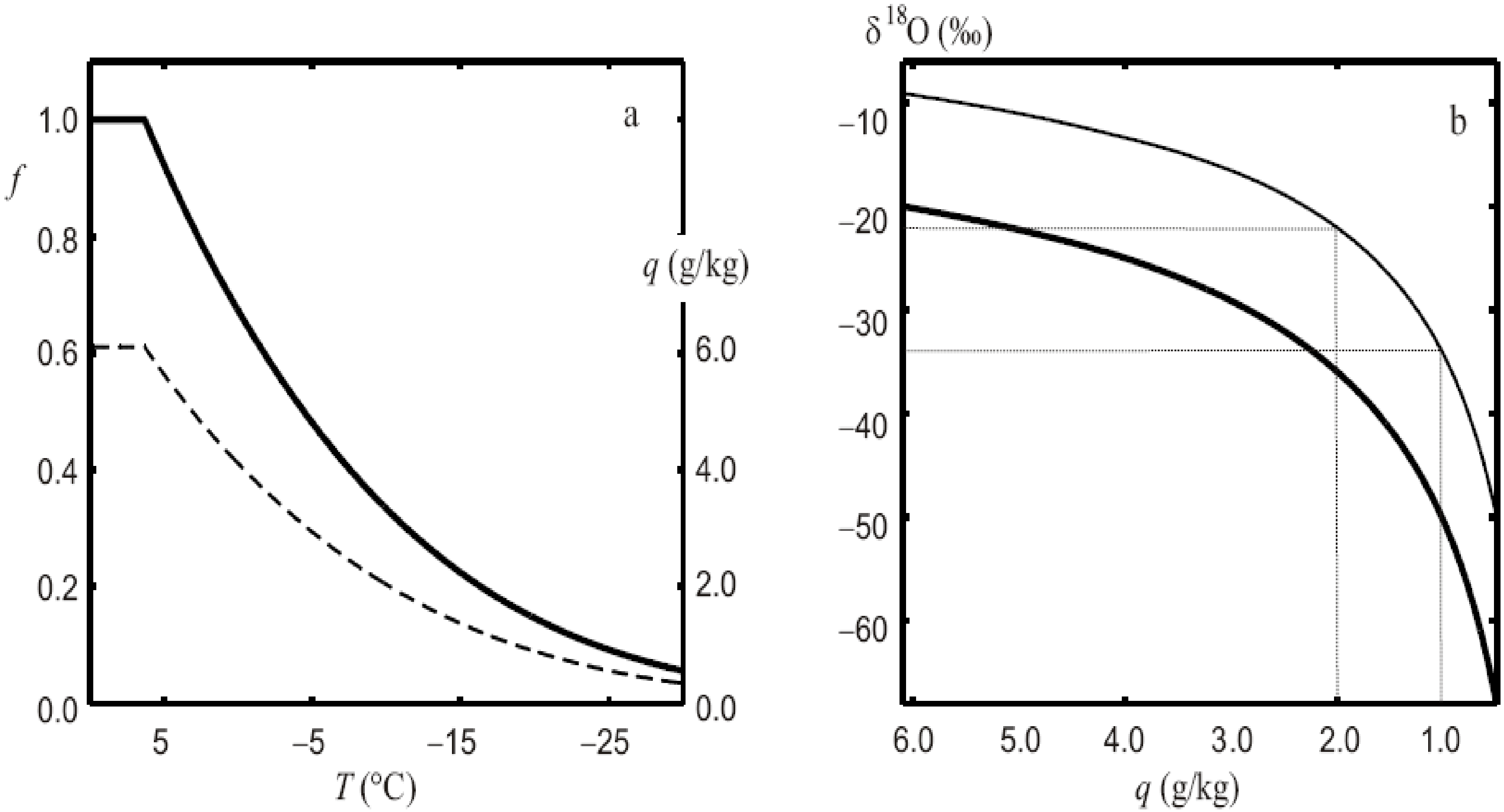
LGM 700-mb specific humidity

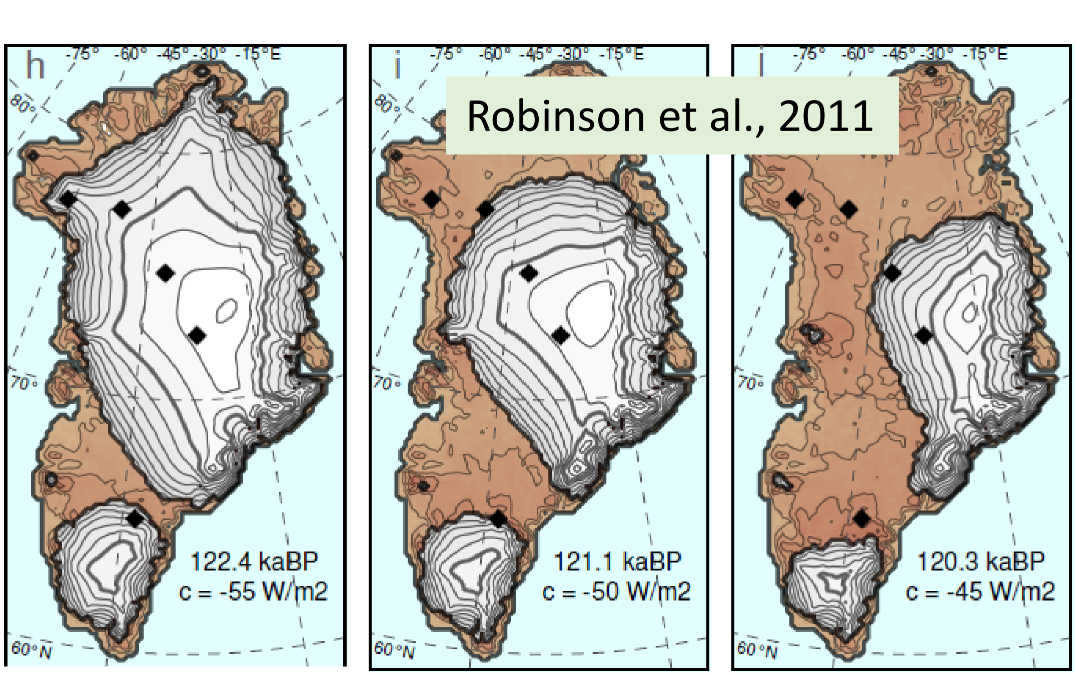


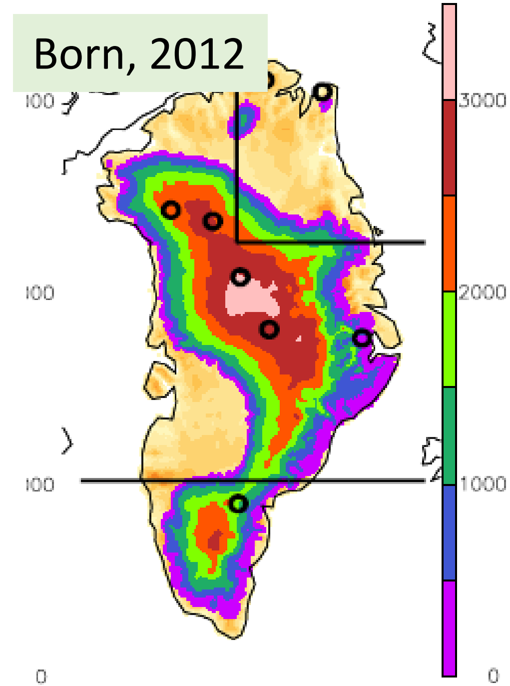
LGM wind field (winter)

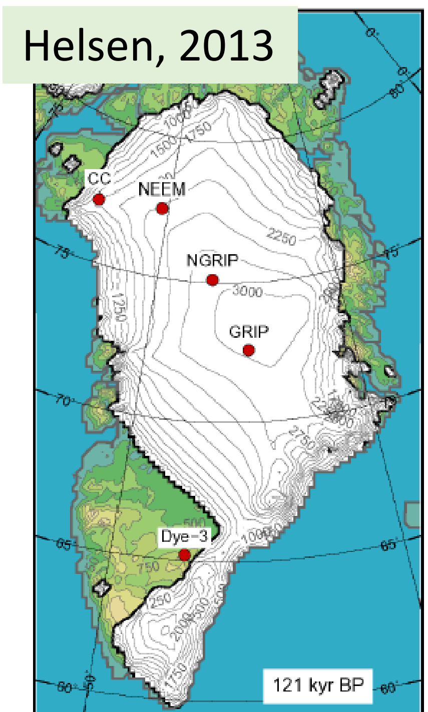


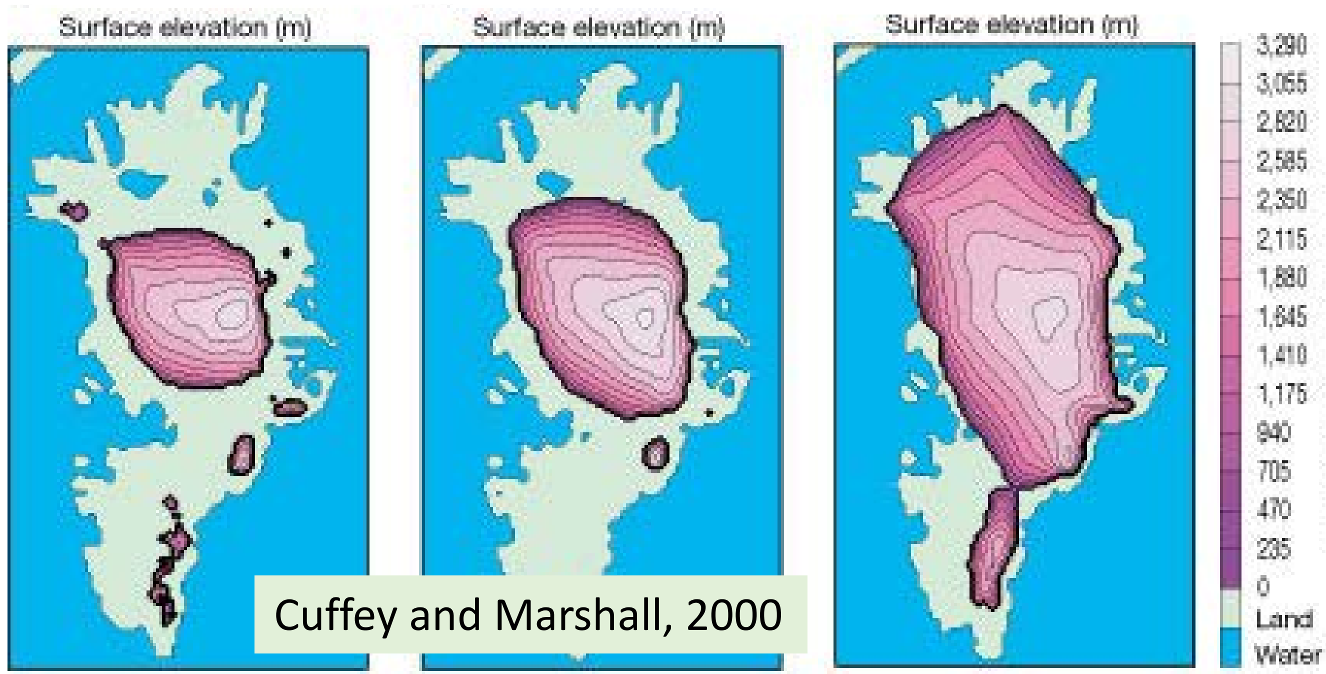
Modeling vapor transport and isotope fractionation

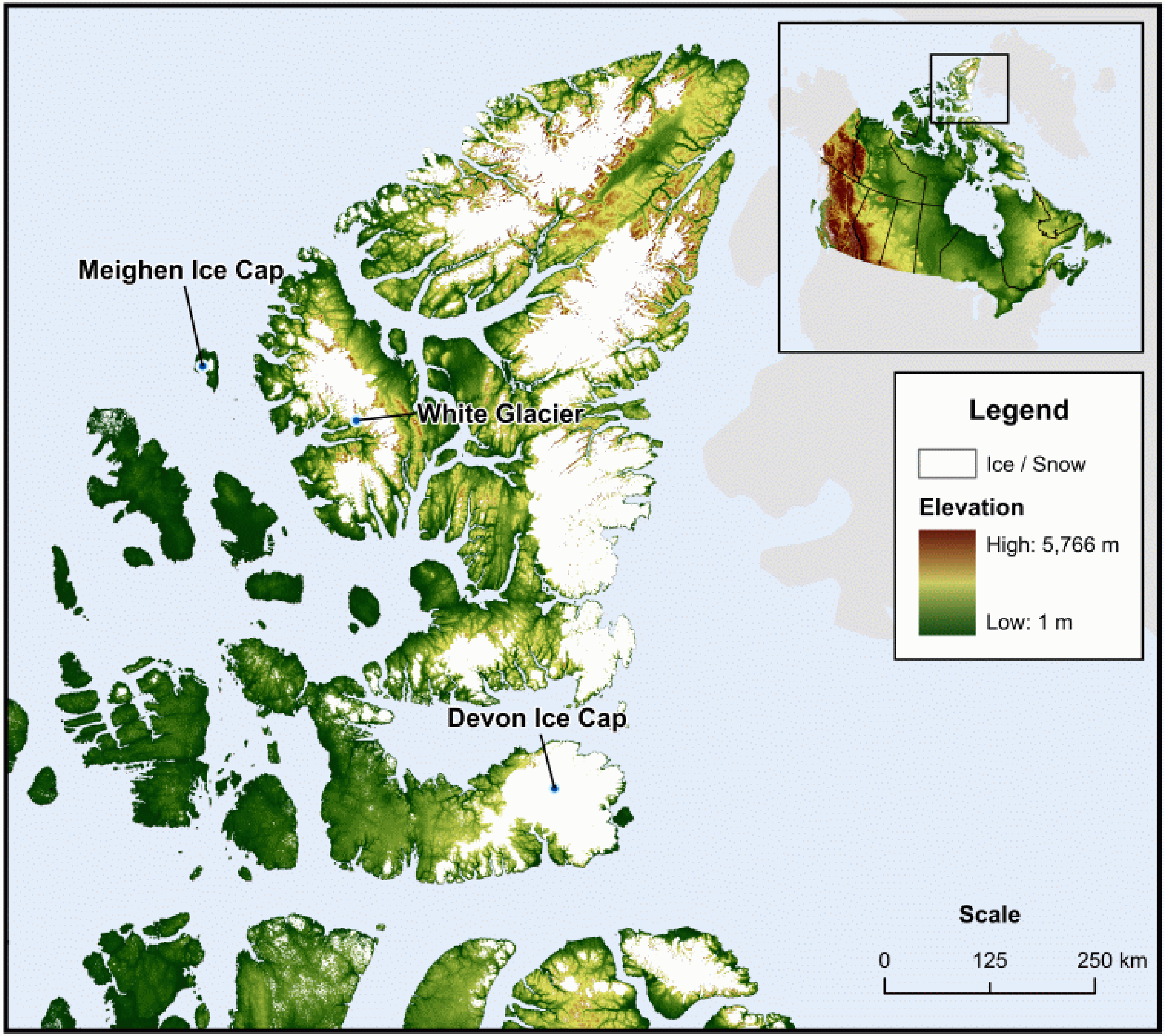



Robinson et al., 2011
h
i
j
-75° -60° -45° -30° -15°E
80°
70°
60°N
122.4 kaBP
c = -55 W/m2
121.1 kaBP
c = -50 W/m2
120.3 kaBP
c = -45 W/m2


Born, 2012
3000
2000
1000
0


Helsen, 2013
CC
NEEM
NGRIP
GRIP
Dye-3
2250
3000
121 kyr BP


Surface elevation (m)
Surface elevation (m)
Surface elevation (m)
3,290
3,055
2,820
2,585
2,350
2,115
1,880
1,645
1,410
1,175
940
705
470
235
0
Land
Water
Cuffey and Marshall, 2000


Meighen Ice Cap
White Glacier
Devon Ice Cap
Legend
Ice / Snow
Elevation
High: 5,766 m
Low: 1 m
Scale
0
125
250 km

Q. What was the $\delta^{18}O$ of Laurentide Ice Sheet runoff ?

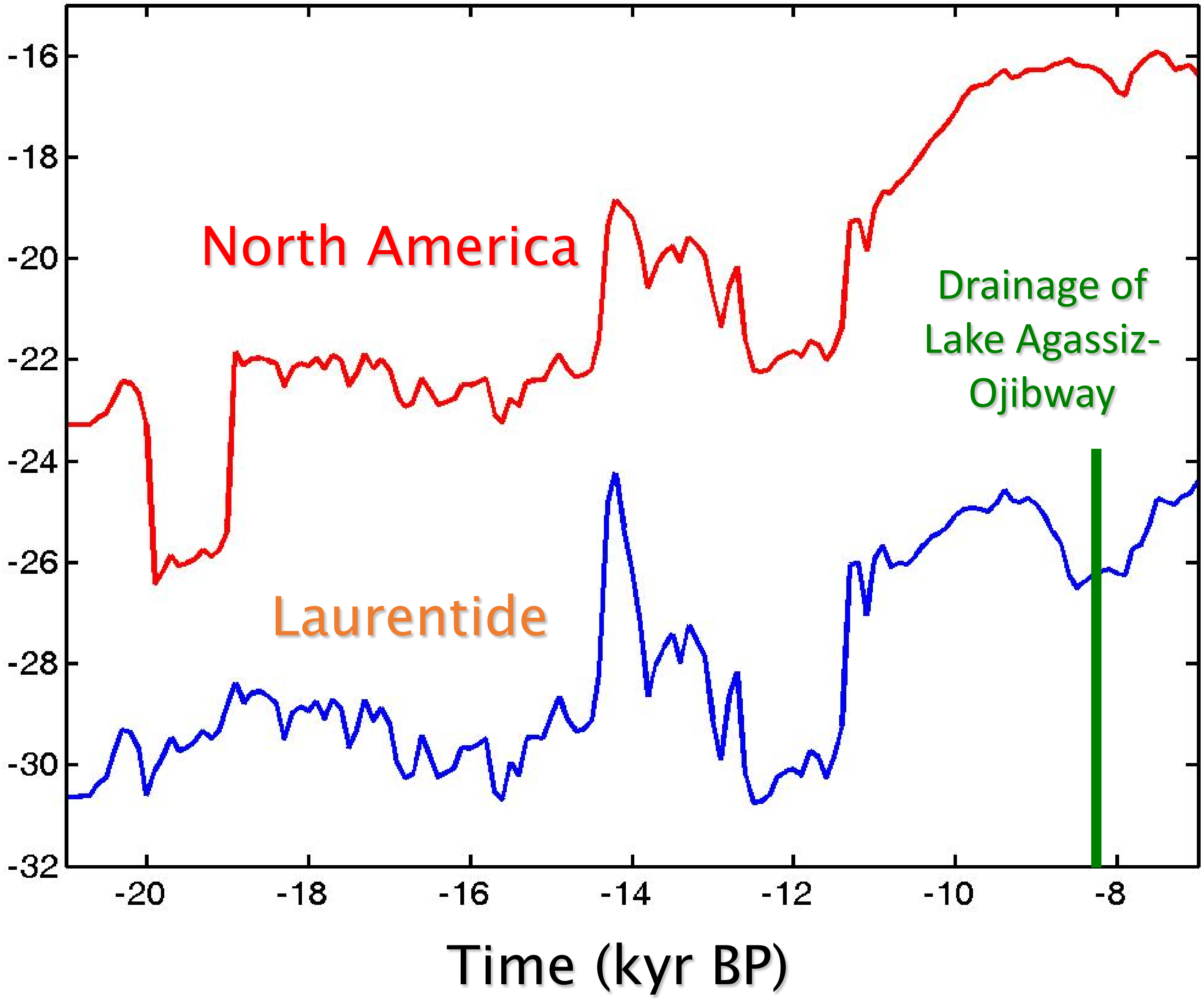
Collaboration with Claude Hillaire-Marcel, Anne de Vernal, Garry Clarke & Andy Bush

SE margin LIS meltwater…

Appr. -16‰

- *L. Erie ostracods, Fritz et al., 1975*
- *Glacial lake concretions, Hillaire-Marcel & Causse, 1989*

Mean modelled surface $\delta^{18}O$



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