The Last Great Retreat! What Happened to Antarctic Sea Ice 130 to 125,000 Years Ago?

Louise C. Sime (1), Max Holloway (1), Irene Malmierca (1), Robert Mulvaney (1), Paul J. Valdes (2), Joy S. Singarayer (3), and Julia C. Tindall (4)

(1) British Antarctic Survey, Cambridge, CB3 0ET, U.K., (2) School of Geographical Sciences, University of Bristol, University Road, Bristol, BS8 1SS, U.K., (3) Department of Meteorology, University of Reading, Reading, UK. (4) School of Earth and Environment, University of Leeds, Leeds, UK.

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An end-of-the-day detective story about Antarctic ice core data?

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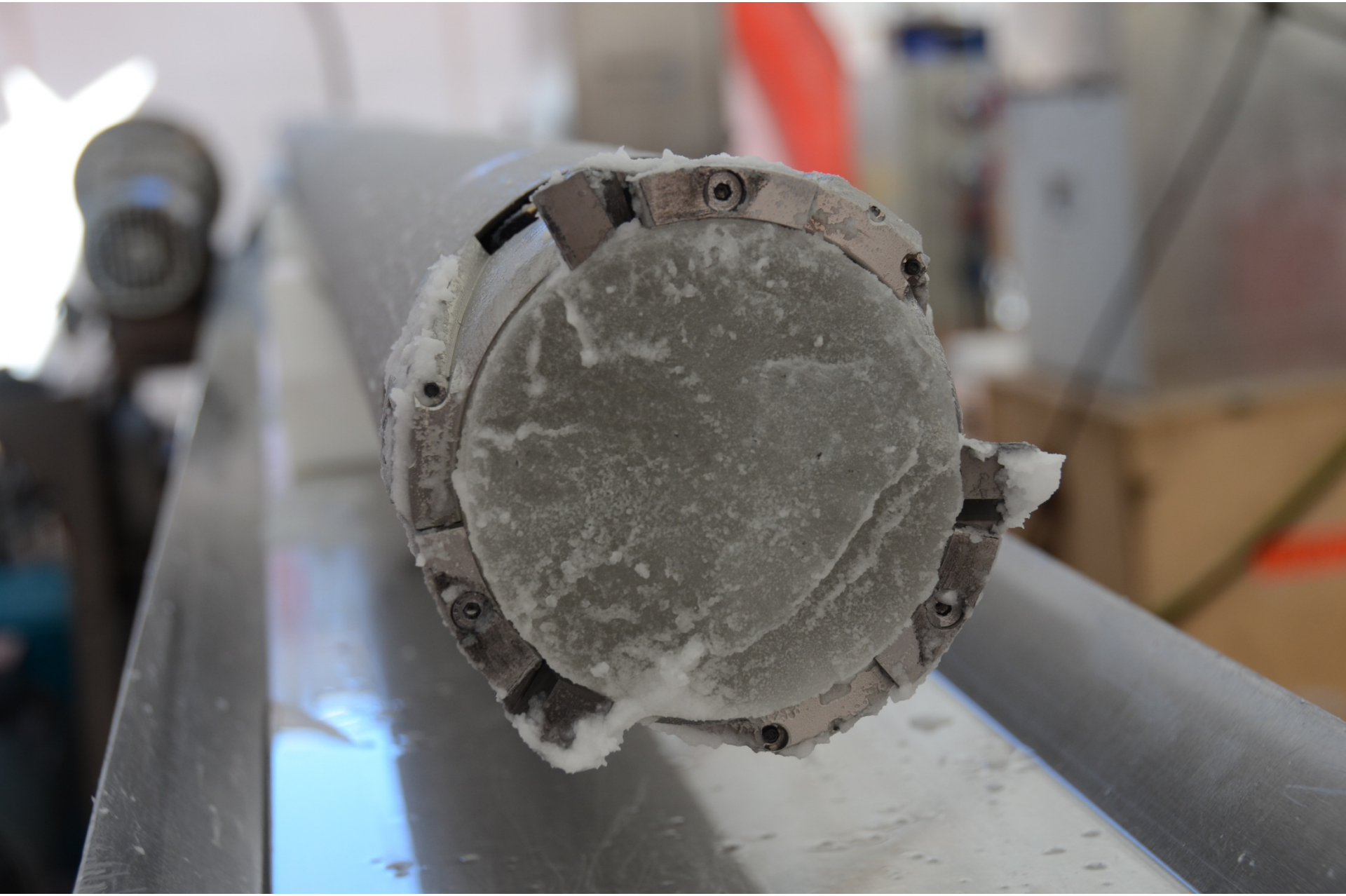
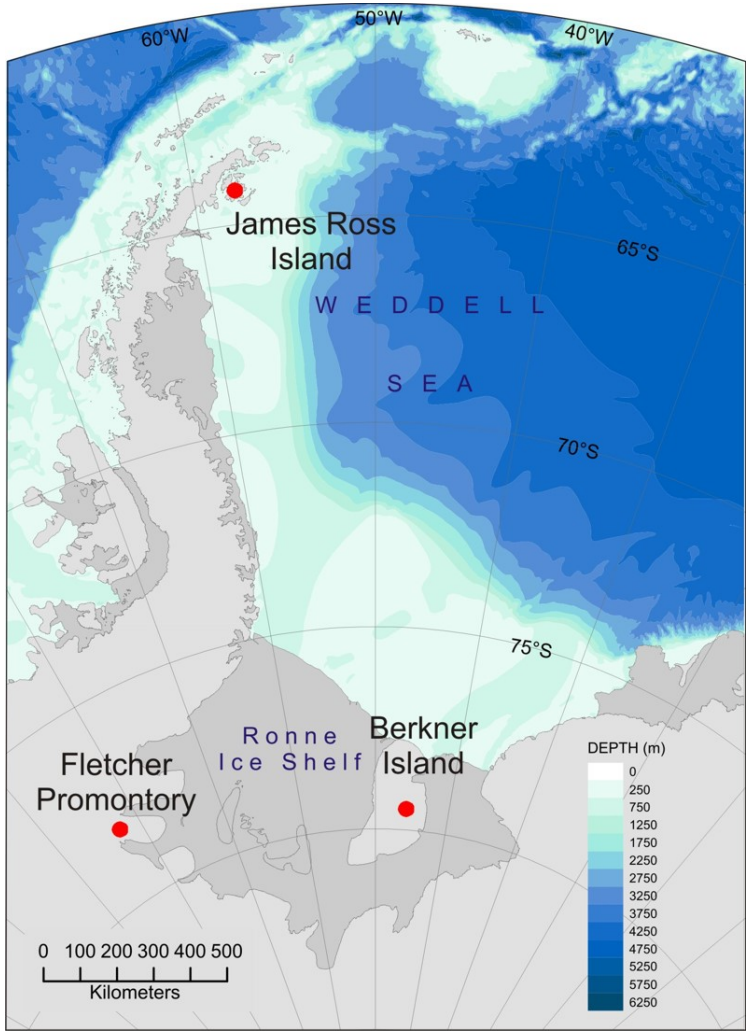
Outline:

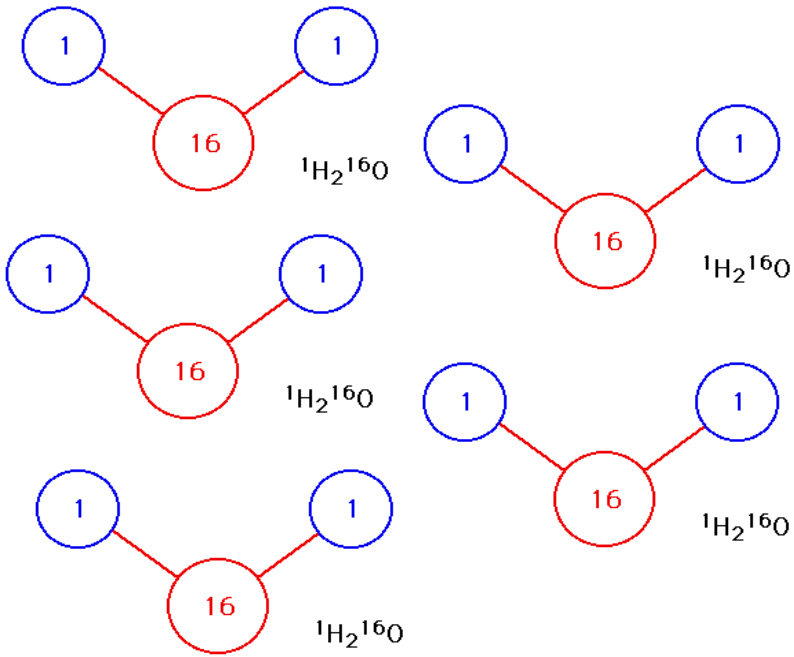
1. Ice coring (British Antarctic Survey).
2. Last Interglacial (LIG; 116-130 ky) Antarctic ice cores.
3. The temperature interpretation of LIG isotopic data.
4. The WAIS loss interpretation of LIG isotopic data?
5. The sea ice loss interpretation of LIG isotope data.
6. Current (ongoing) and future work…



The Weddell Sea ice cores – BAS led drilling projects:

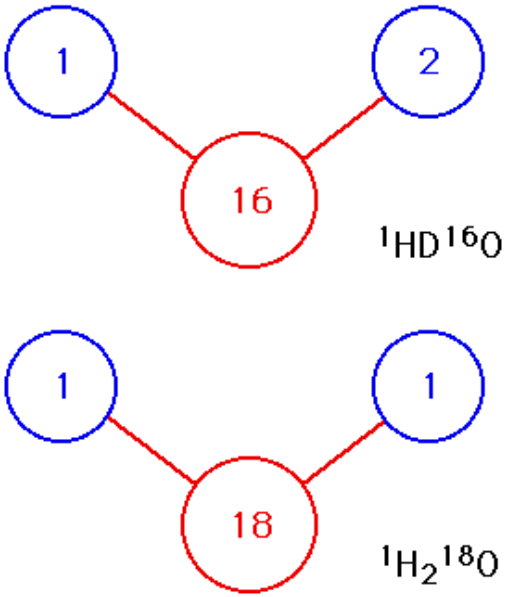


Stable water isotopes



$H_2{}^{16}O$	0.9977
$H_2{}^{18}O$	0.0020
$HD^{16}O$	0.0003

Stable water isotopes



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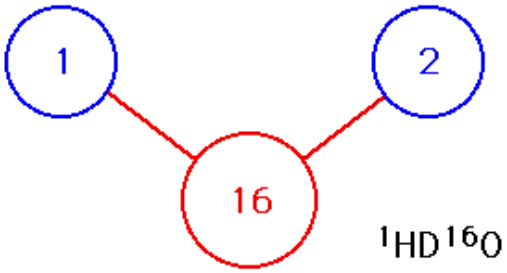

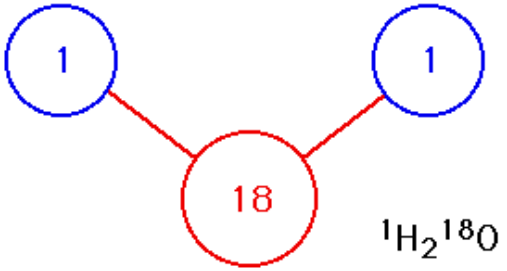

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$HD^{16}O$	0.0003

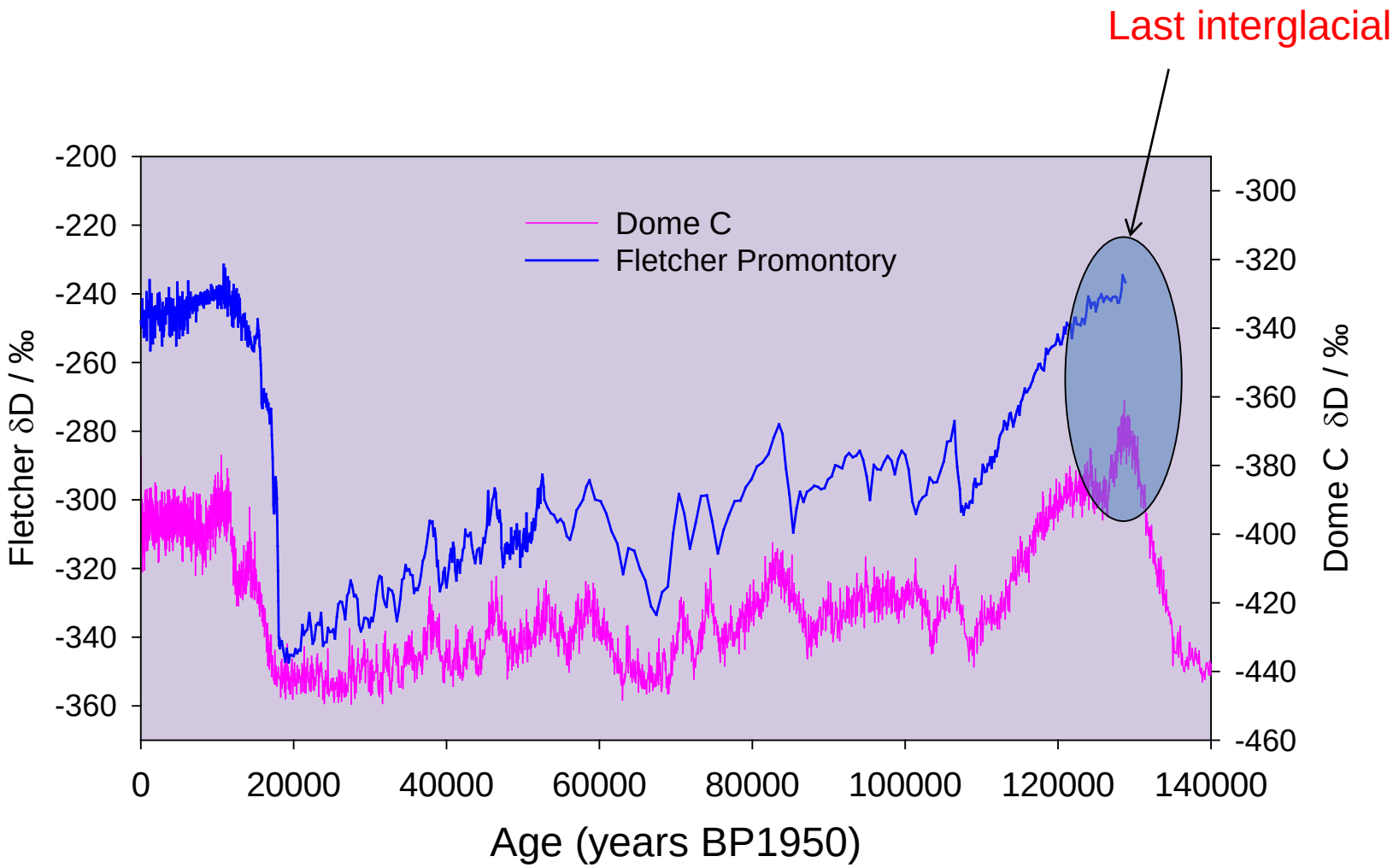
$$R = \frac{n_j}{n_0}$$

n_j moles of heavy water

n_0 moles of light water

$$\partial = \frac{R}{R_{SMOW}} - 1$$

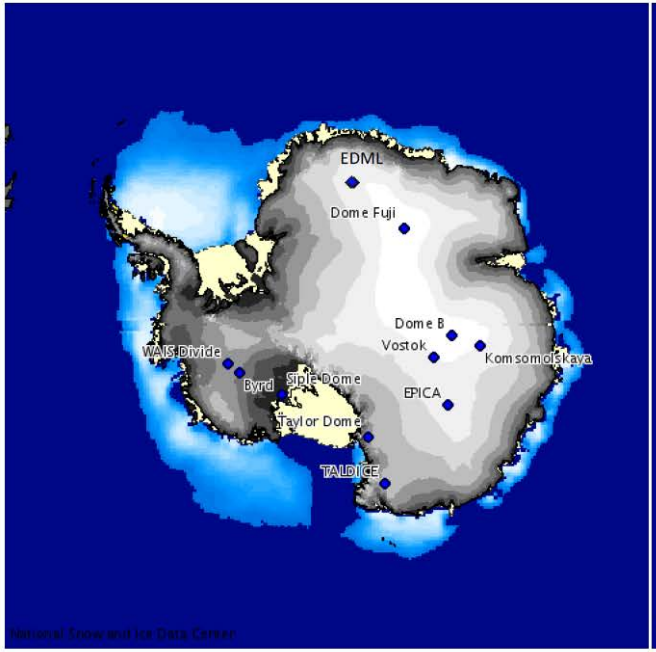
Isotopic ratios are usually written using the delta notation.

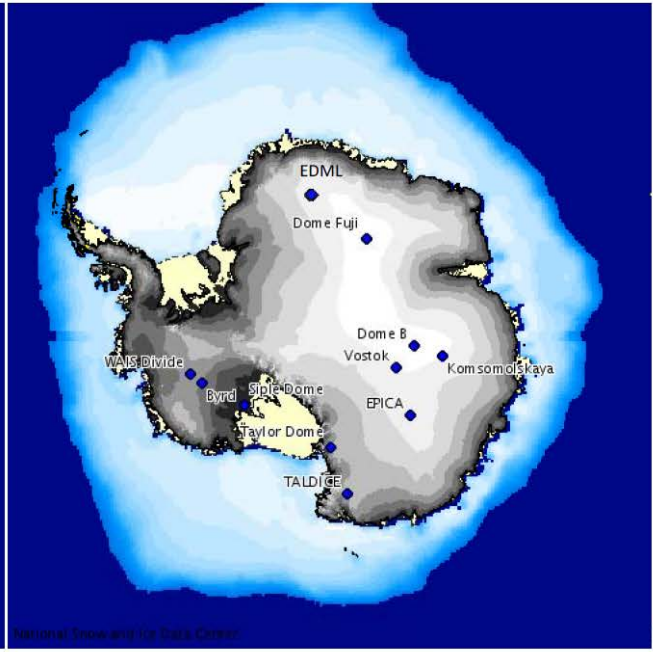


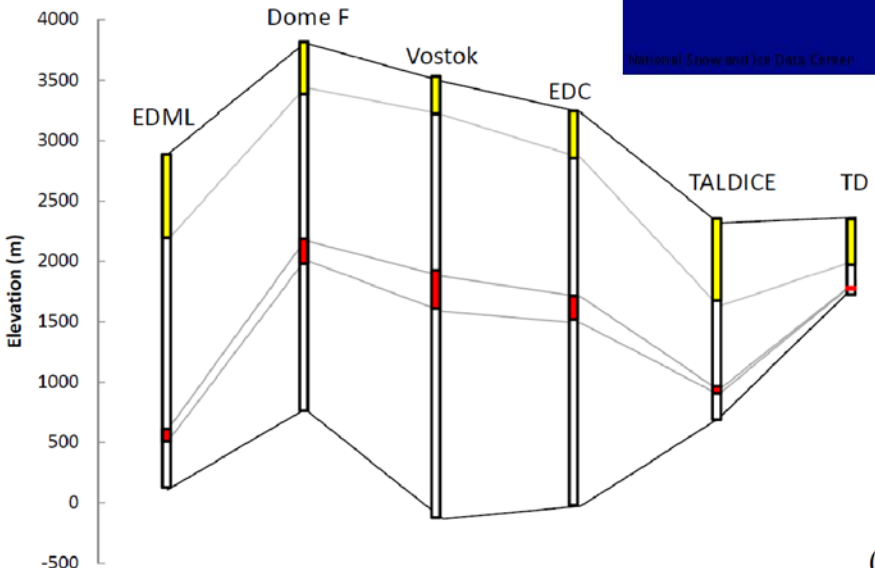
On a very preliminary age scale - maybe 125 kyrs at 10 m above bedrock?

And unpublished…

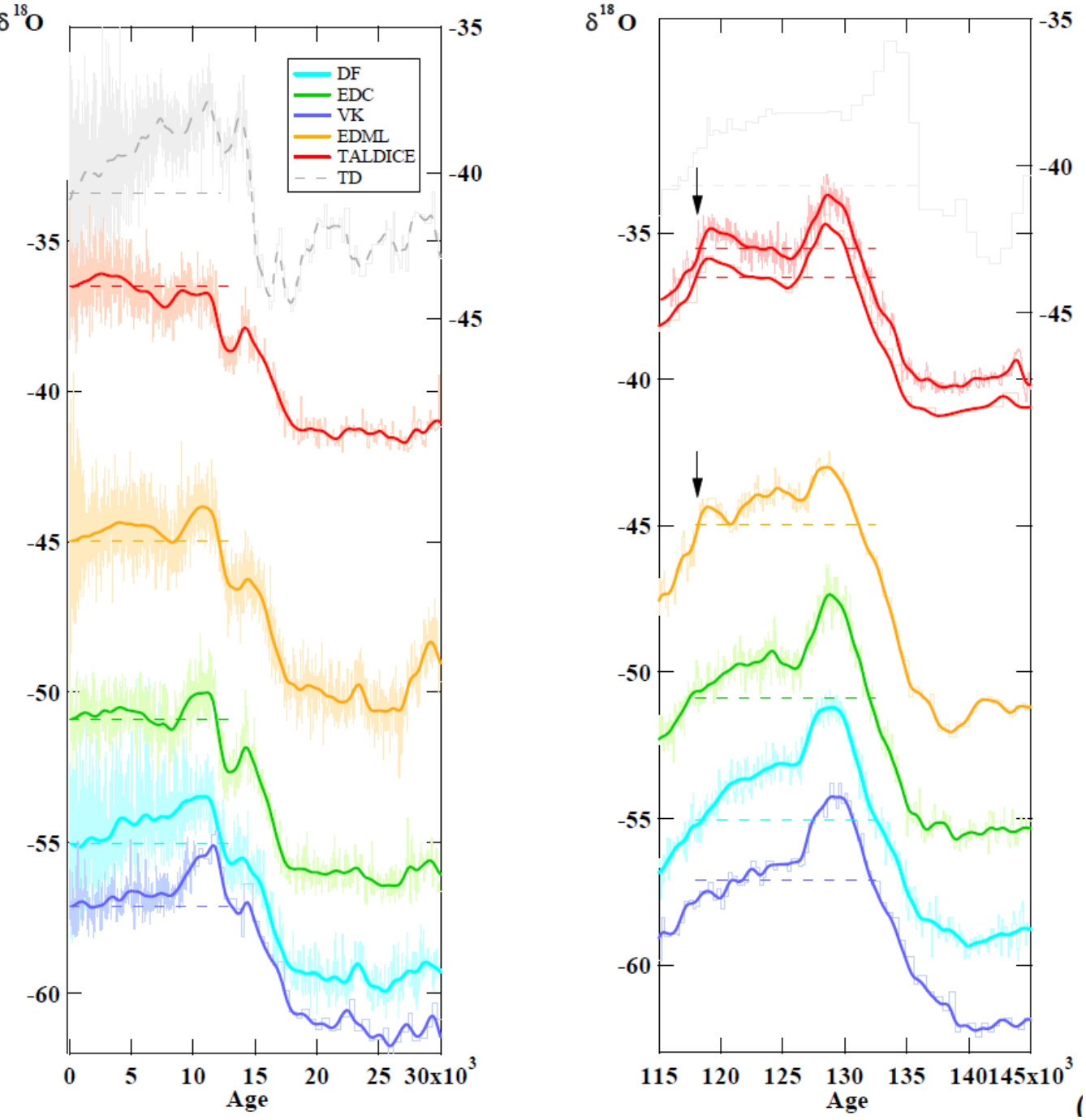
Published and dated Holocene and Last Interglacial measurements from (East) Antarctic ice cores:







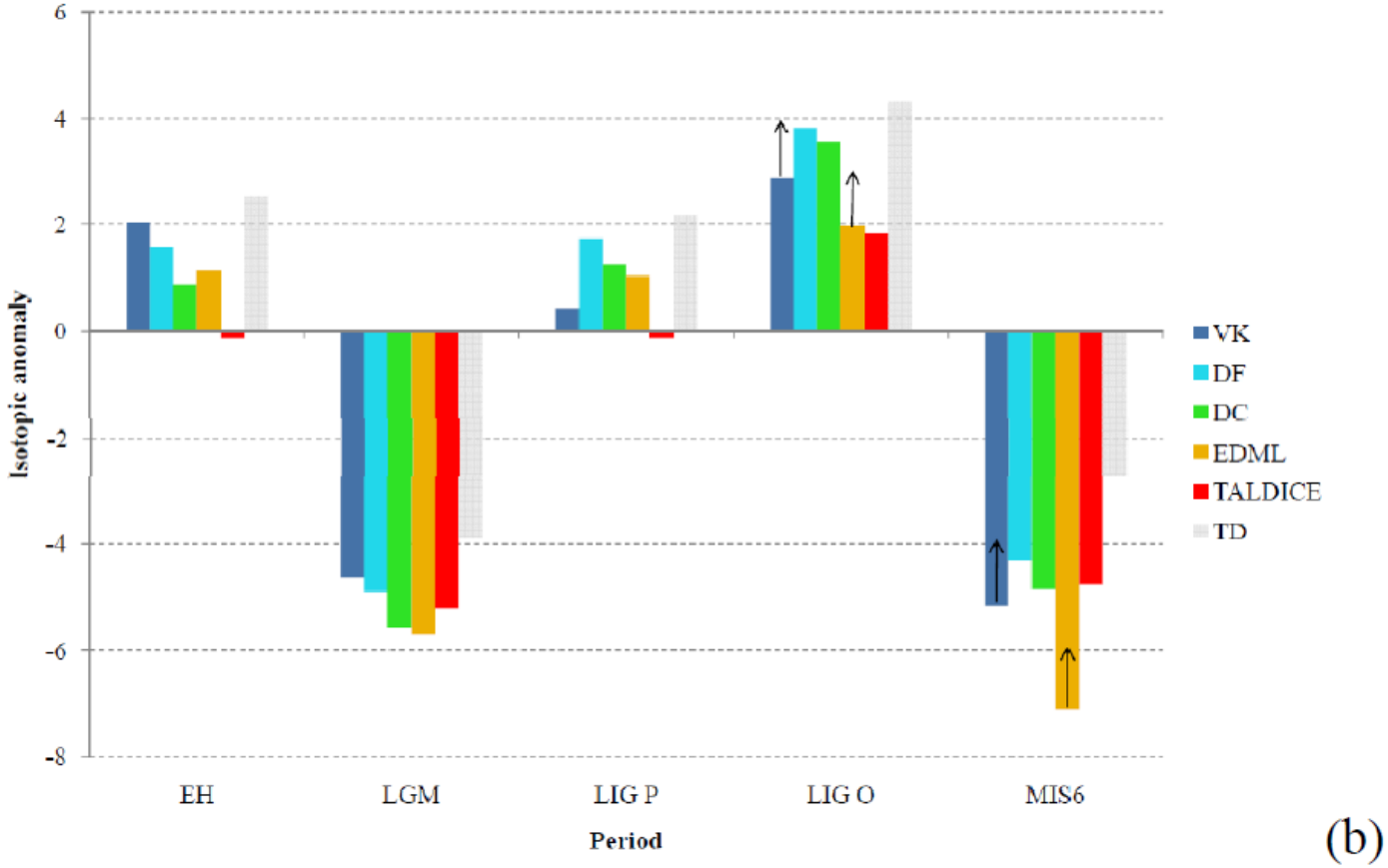
Masson-Delmotte et al 2011, Clim. Past



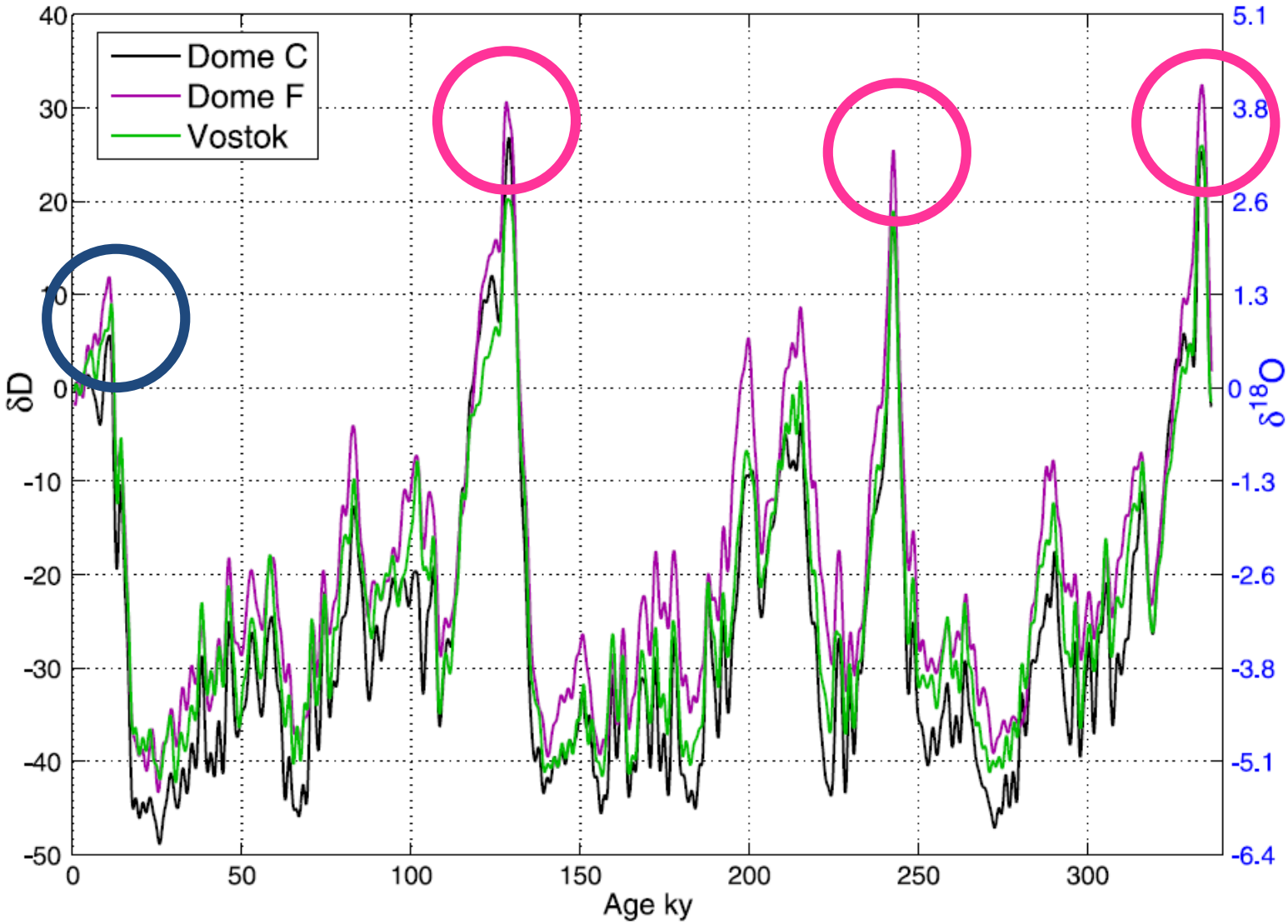
Data on the LIG in Antarctic ice cores:

Masson-Delmotte et al 2011, Clim. Past

Data on the LIG in Antarctic ice coreAnomalies from present day:



Masson-Delmotte et al 2011, Clim. Past



Records of stable water isotope content δD from East Antarctic ice cores show that the last interglacial 128 ky is not unique. (Sime *et al* 2009)

What caused the water isotope peak at 128 ky?

Sea level and sea salt data leads to two hypotheses for the cause:

- **Temperature changes alone?**
- Disintegration of the West Antarctic Ice Sheet
- Changes in Antarctic sea ice extent

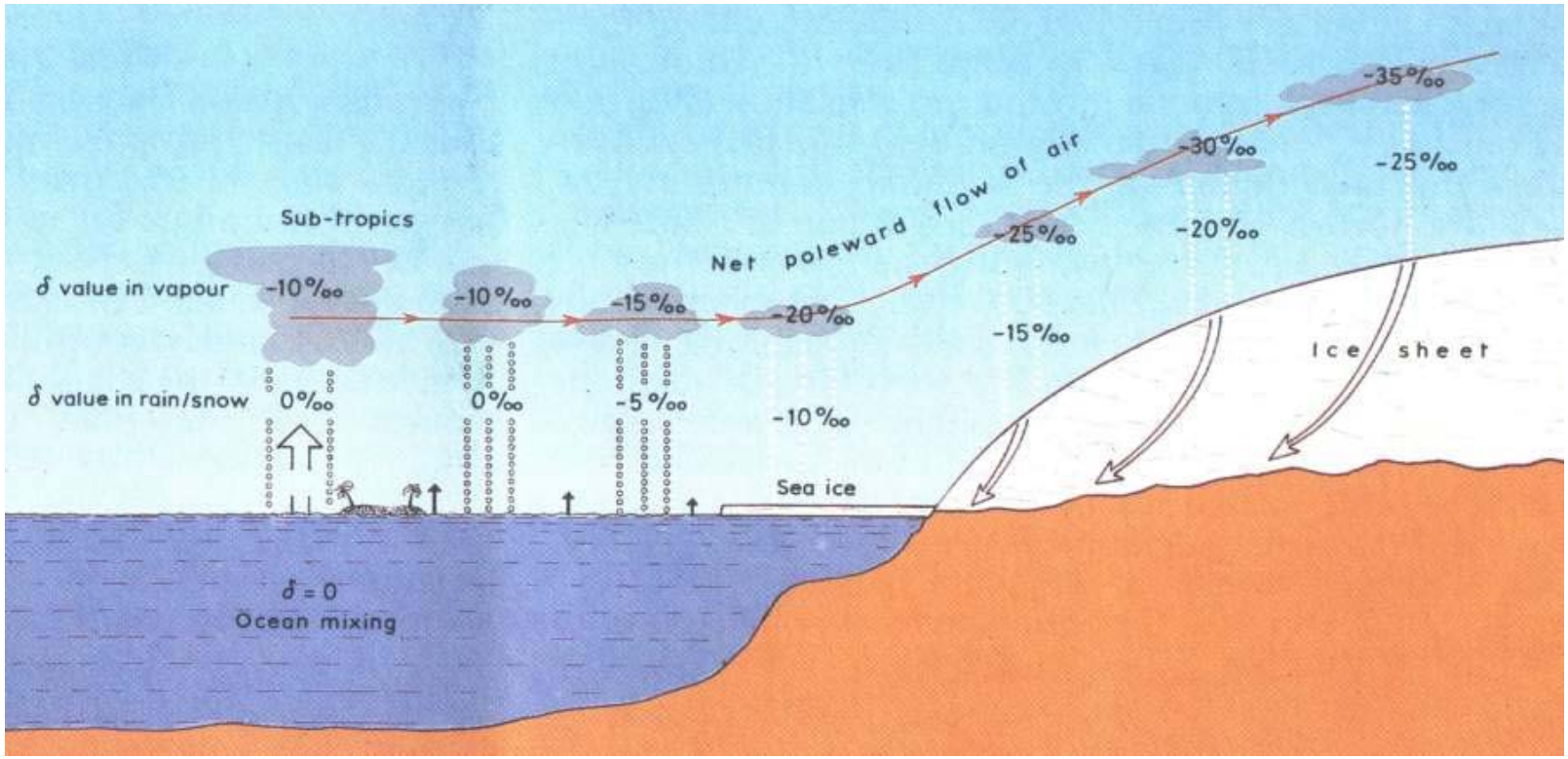
Rayleigh distillation:

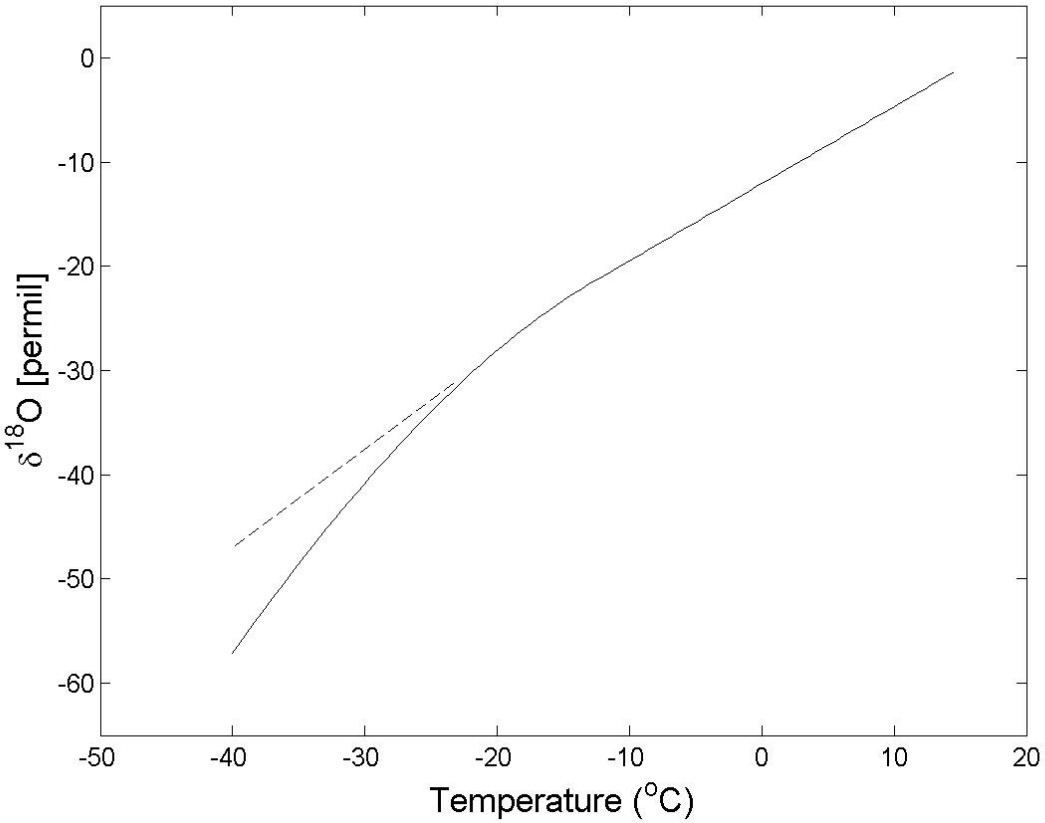
By differentiating the basic equation outlined previously; using the fact that the total moles of water are almost equivalent to the total moles of light water; using an non-temperature dependent mean value of α; and using the Clausius-Clapeyron relation, a final isotopic value of precipitation δ_p can be obtained:

$$1+\partial_p = \left[1+\partial_{p0}\right].\left[\frac{P_0}{P}\right]^{\bar{\alpha}-1} \exp\left(k.\left[\bar{\alpha}-1\right].\left[\frac{\left[T_0-T\right]}{T.T_0}\right]\right)$$

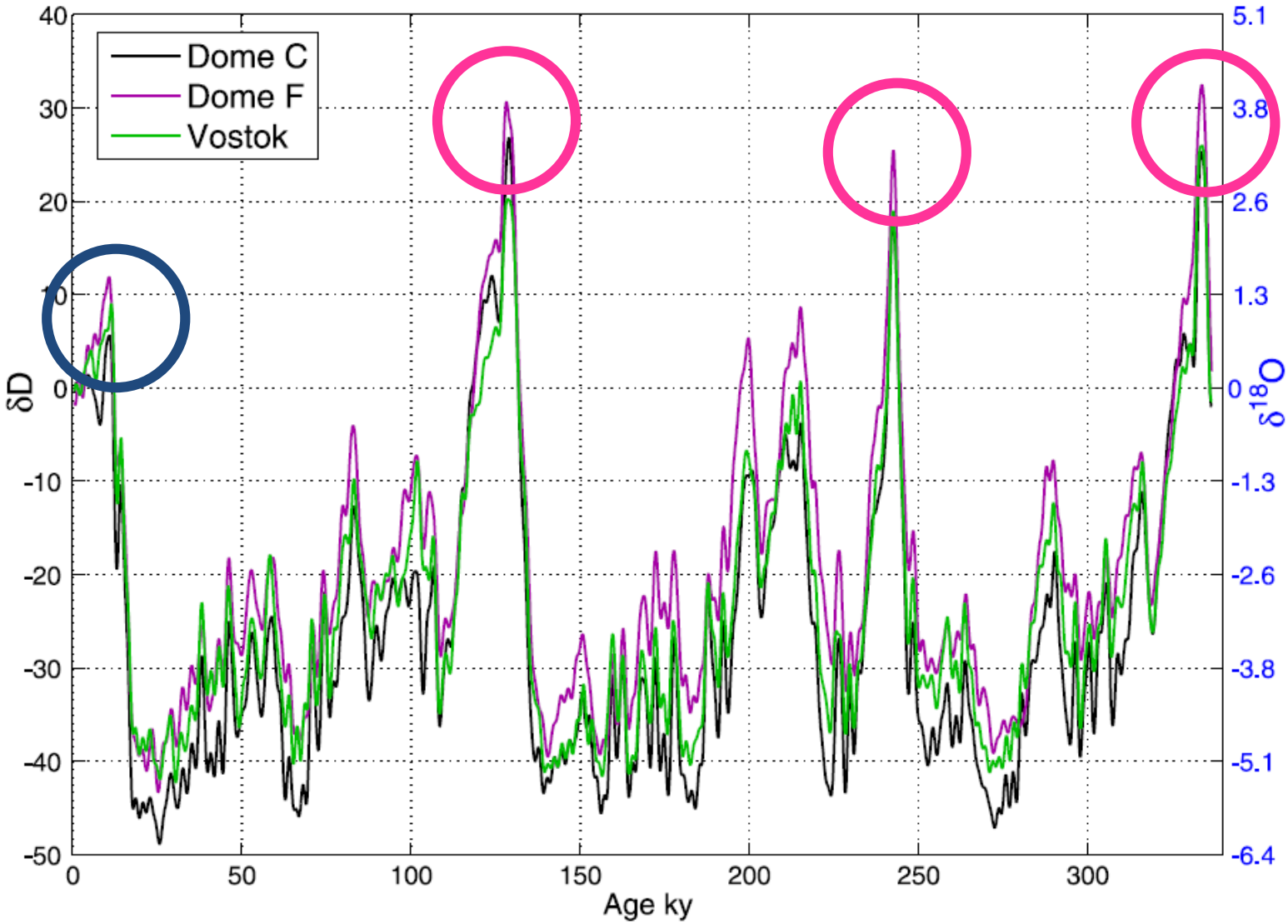
The temperature drop from T_o to T (or a pressure drop from P_o to P), depletes the air mass of heavy isotopes.

This is sometime called the *Rayleigh distillation* relation.


Sub-tropics
δ value in vapour
δ value in rain/snow
-10‰
-10‰
-15‰
-20‰
-25‰
-30‰
-35‰
-25‰
-20‰
-15‰
-10‰
0‰
0‰
-5‰
Net poleward flow of air
Ice sheet
Sea ice
δ = 0
Ocean mixing



Distillation results. The variation of $\delta^{18}O$ due solely to the cooling of an air mass.



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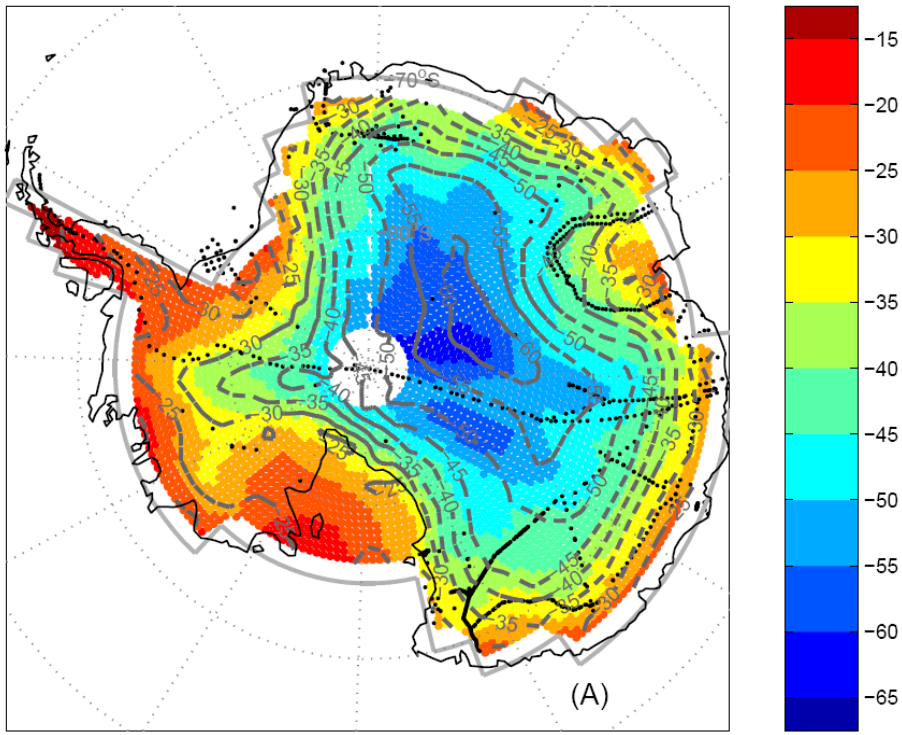
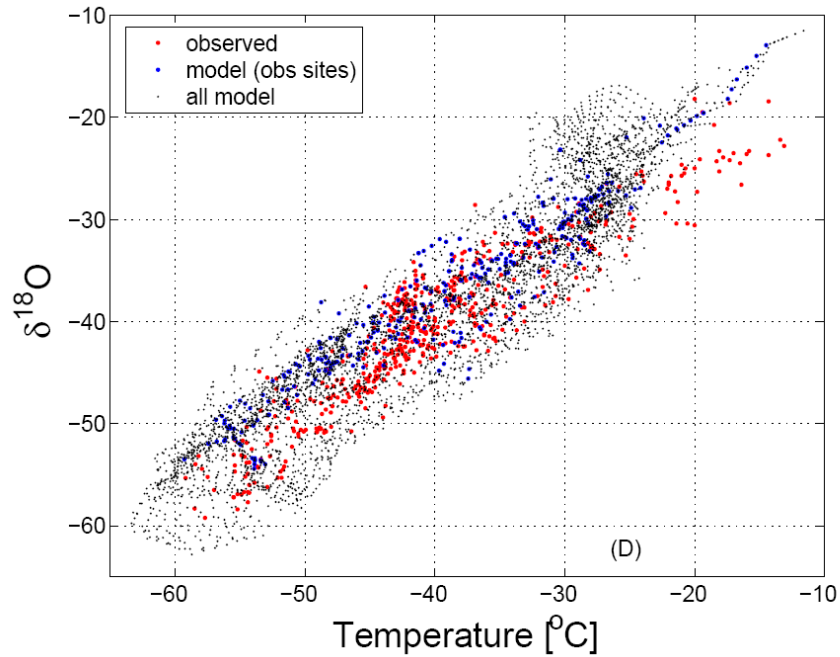
Water isotope enabled general circulation modelling:

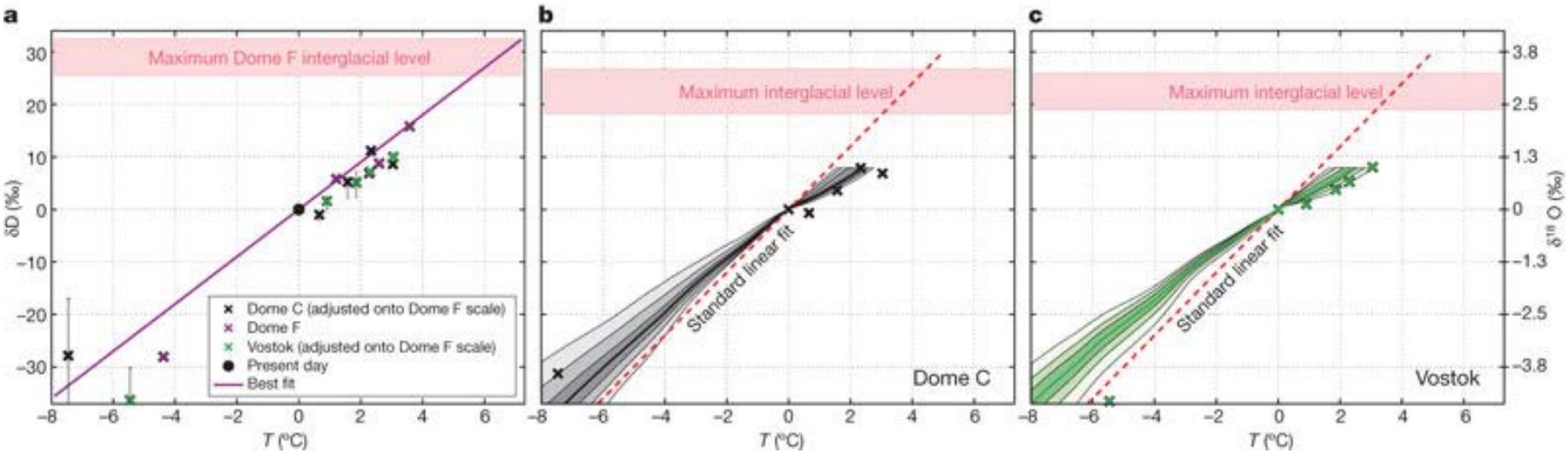




$\delta^{18}O$ is shaded T_S is contoured. Black dots show location of observations (Masson-Delmotte et al., 2008)

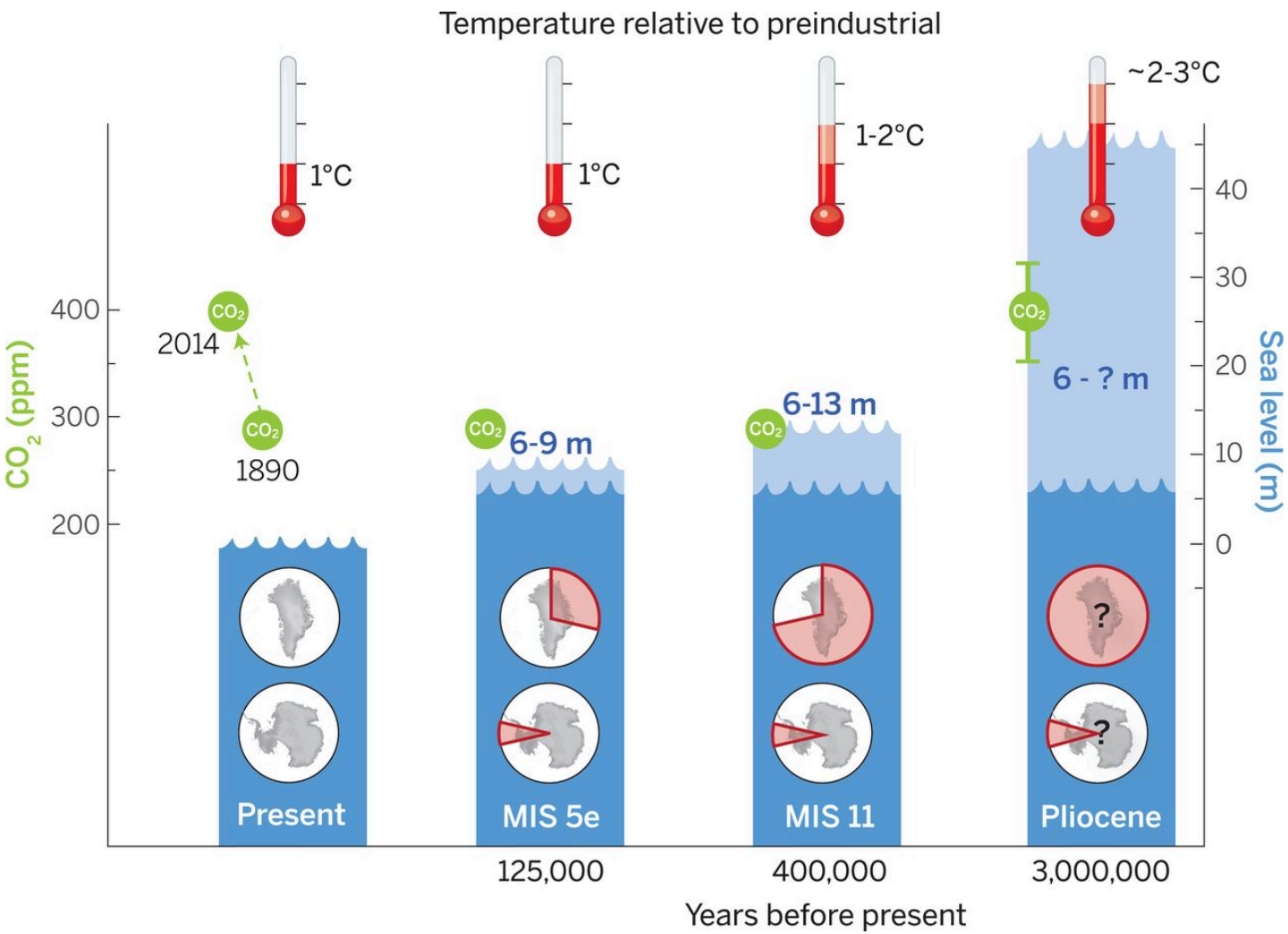
Modelled HadCM3 $\delta^{18}O$ and surface temperature generally match observations (Sime *et al* 2008)

The δ versus T palaeothermometer relationship: its hard to get high enough isotopic values using temperature changes alone



LC Sime *et al*. *Nature* **462**, 342-345 (2009) doi:10.1038/nature08564

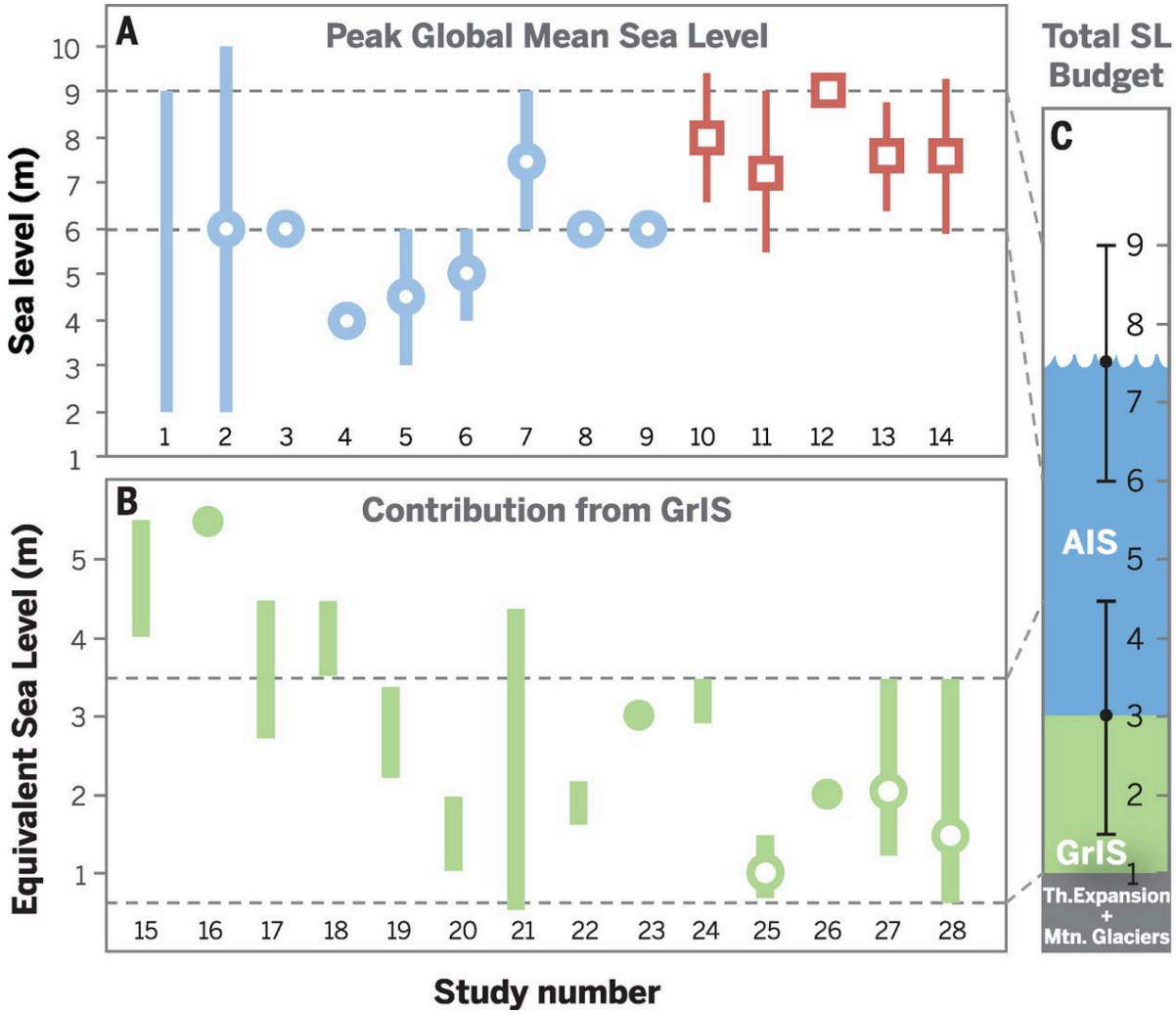
Long term global mean sea level (GMSL) changes and source(s) of meltwater.



A. Dutton et al. Science 2015;349:aaa4019

Published by AAAS

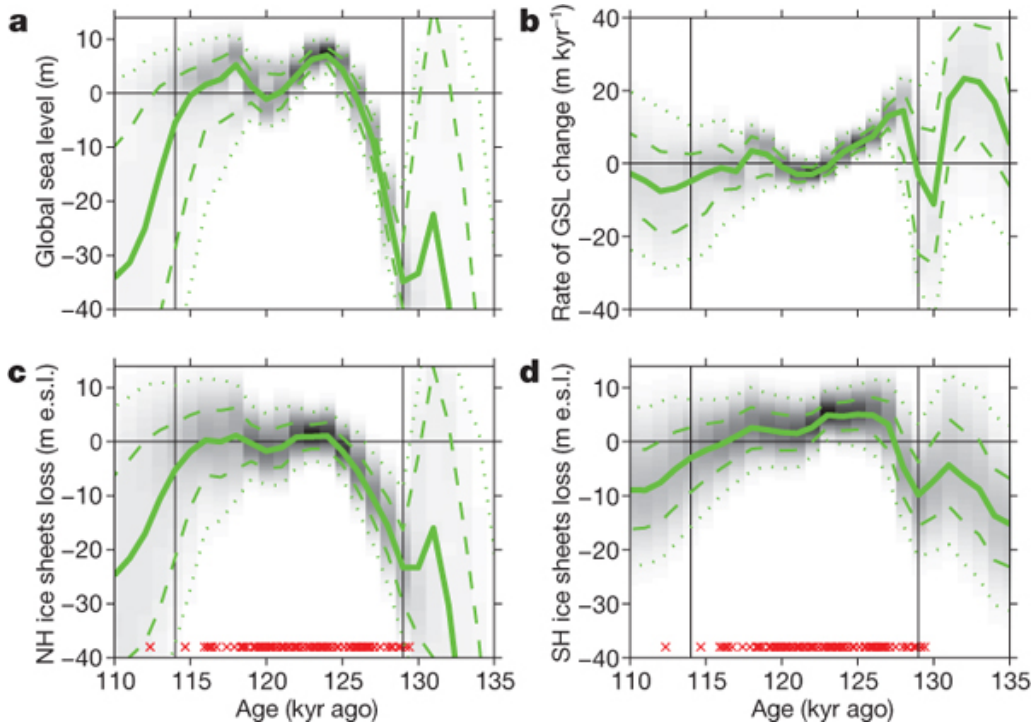
Compilation of LIG reconstructions for peak GMSL and GrIS contribution.



A. Dutton et al. Science 2015;349:aaa4019

Published by AAAS

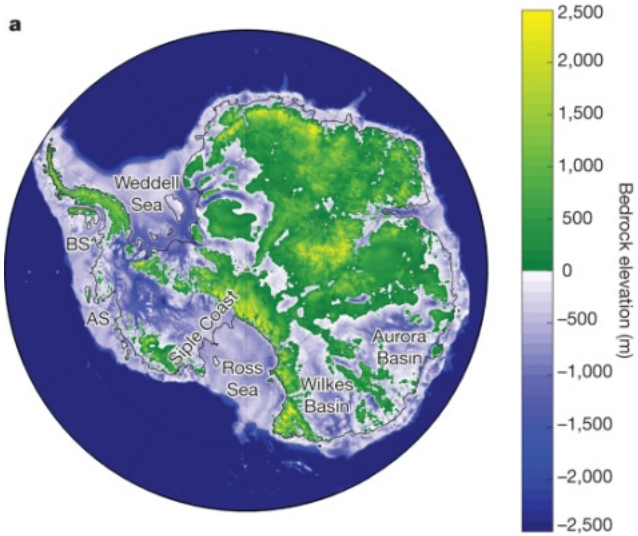
Probability density plots of GSL and ice volume during the LIG.

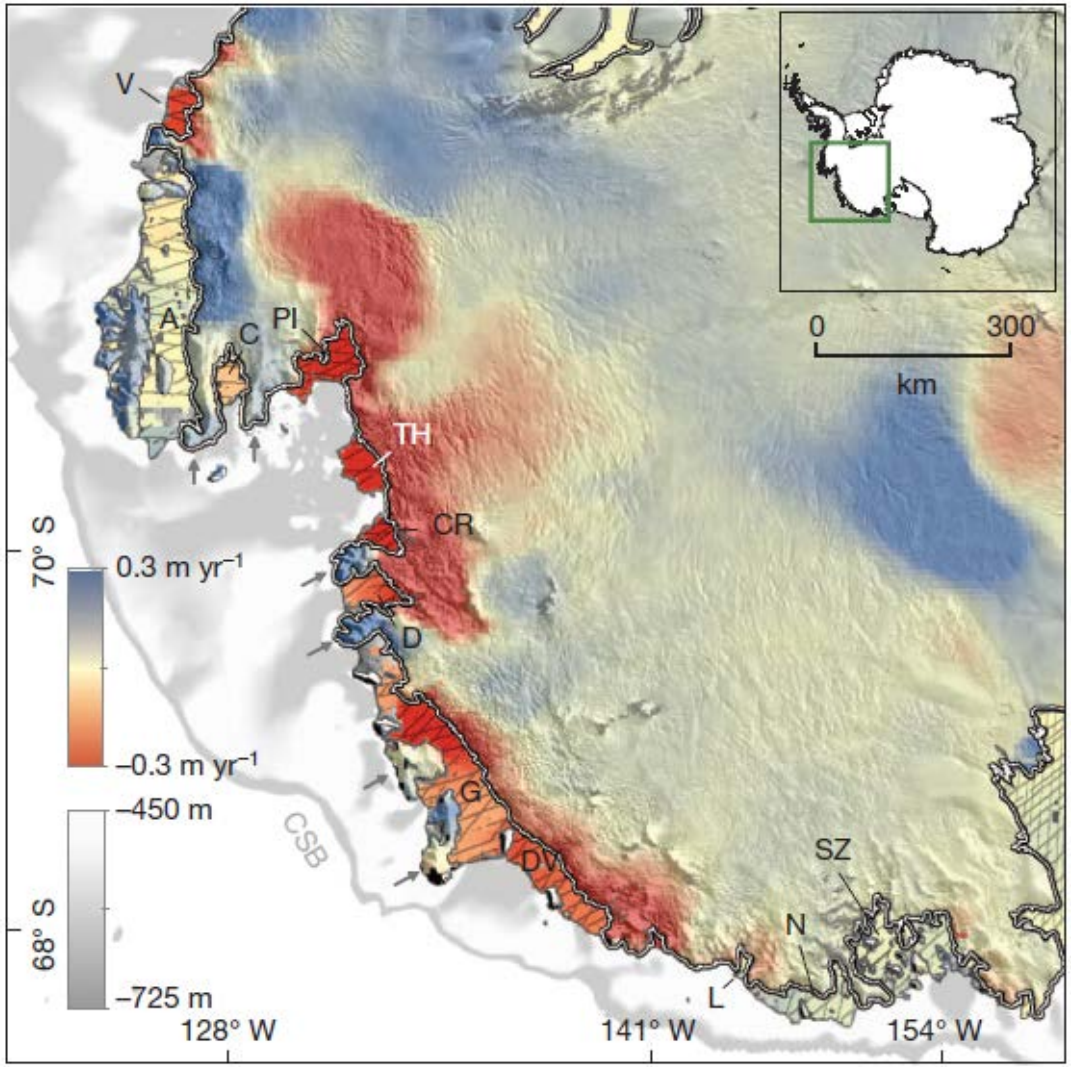


RE Kopp *et al. Nature* **462**, 863-867 (2009) doi:10.1038/nature08686

Loss of the West Antarctic Ice Sheet (WAIS)?

Complete collapse of present day WAIS could add >6m to sea level:





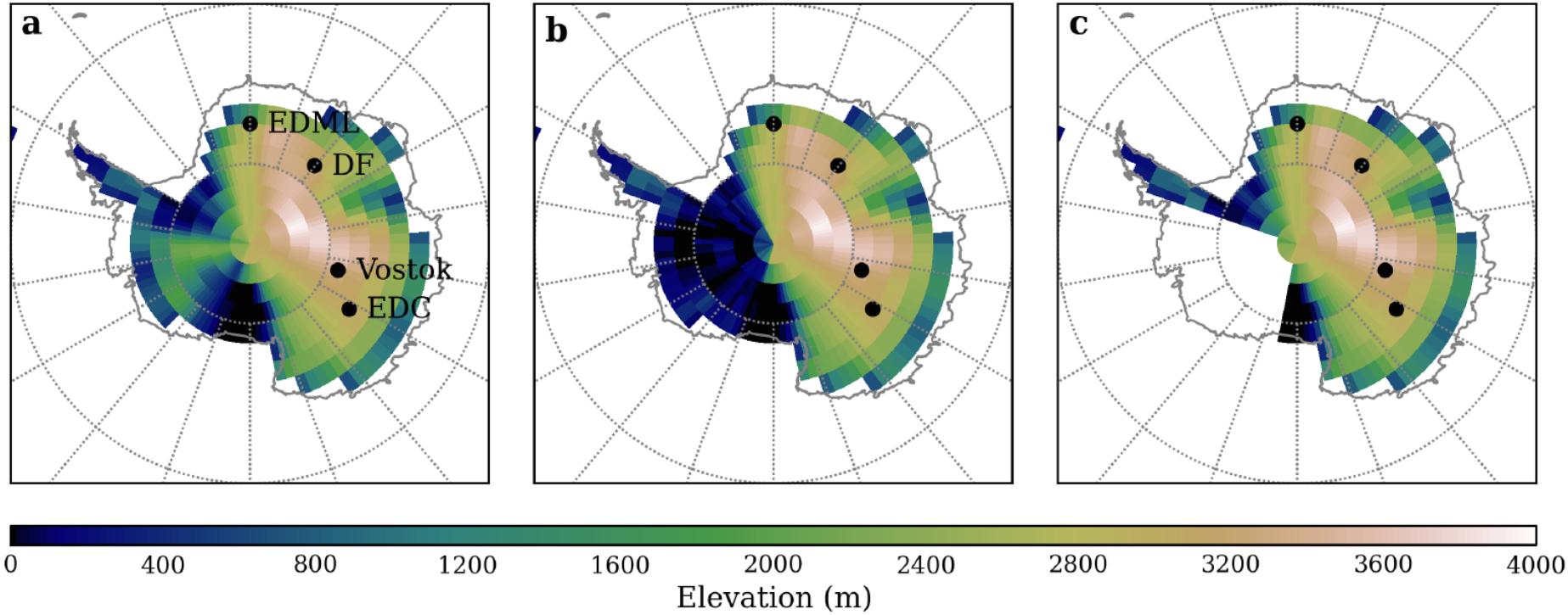
Pritchard et al, Nature 2012

What caused the water isotope peak at 128 ky?

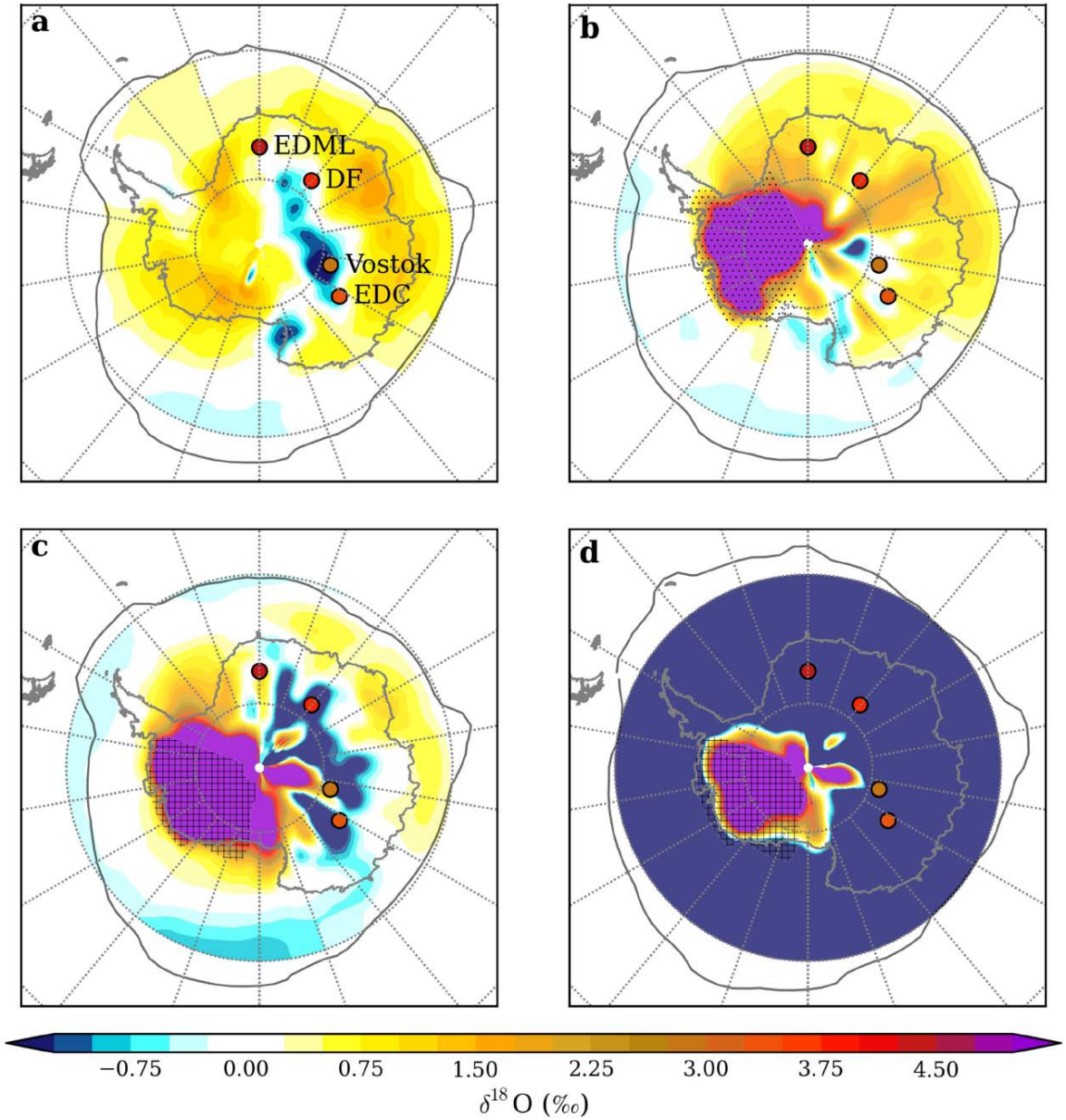
Sea level and sea salt data leads to additional hypotheses for the cause:

- **Temperature changes alone?**
- **Disintegration of the West Antarctic Ice Sheet**
- **Changes in Antarctic sea ice extent**

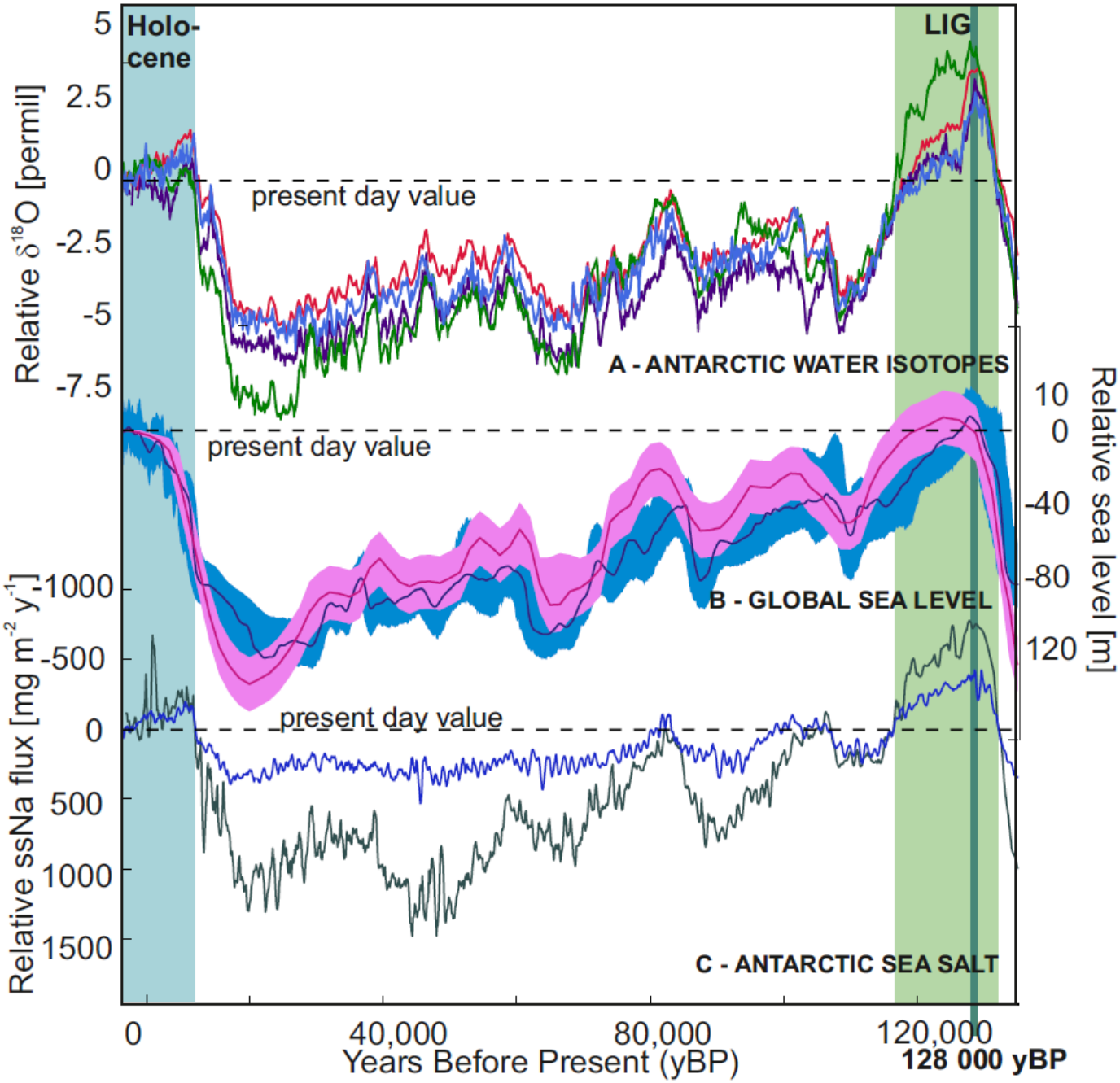
Removing the West Antarctic Ice Sheet:



Orographic/ ice sheet configurations: (a) a modern WAIS configuration, (b) the WAIS flattened, (c) the WAIS removed and replaced with a new region of ocean. Holloway *et al.* 2016.



δ18O anomalies for 128 ky. Holloway *et al*. 2016.



East Antarctic Ice core measurements and sea level data from 135 000 to 0 years BP.

What caused the water isotope peak at 128 ky?

Sea level and sea salt data leads to additional hypotheses for the cause:

- **Temperature changes alone?**
- **Probably not just disintegration of the West Antarctic Ice Sheet**
- **Changes in Antarctic sea ice extent instead?**

A loss of sea ice around Antarctica; result!

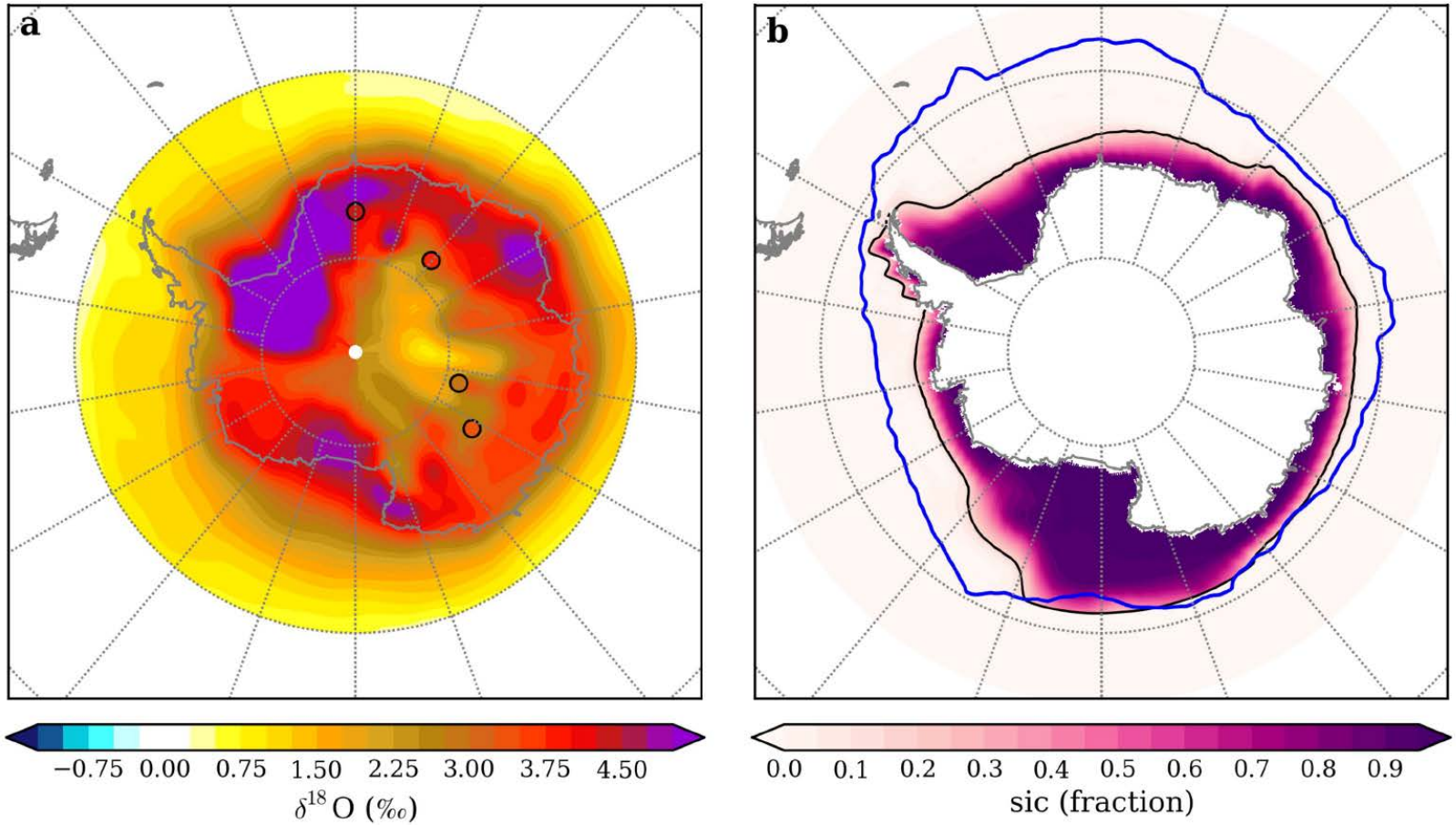


Figure: (a) δ18O anomalies for 128 000 yBP. (b) September sea ice concentration fraction. Black contour signifies the simulated 15 % September sea ice concentration threshold. Blue contour signifies 1978-2013 satellite observations. Holloway *et al* 2016.

What caused the water isotope peak at 128 ky?

Sea level and sea salt data leads to additional hypotheses for the cause:

- **Temperature changes alone?**
- **Probably not just disintegration of the West Antarctic Ice Sheet**
- **Changes in Antarctic sea ice extent instead?**
- **But how about disintegration of the West Antarctic Ice Sheet AND changes in Antarctic sea ice extent?**

Reducing sea ice AND the West Antarctic Ice Sheet

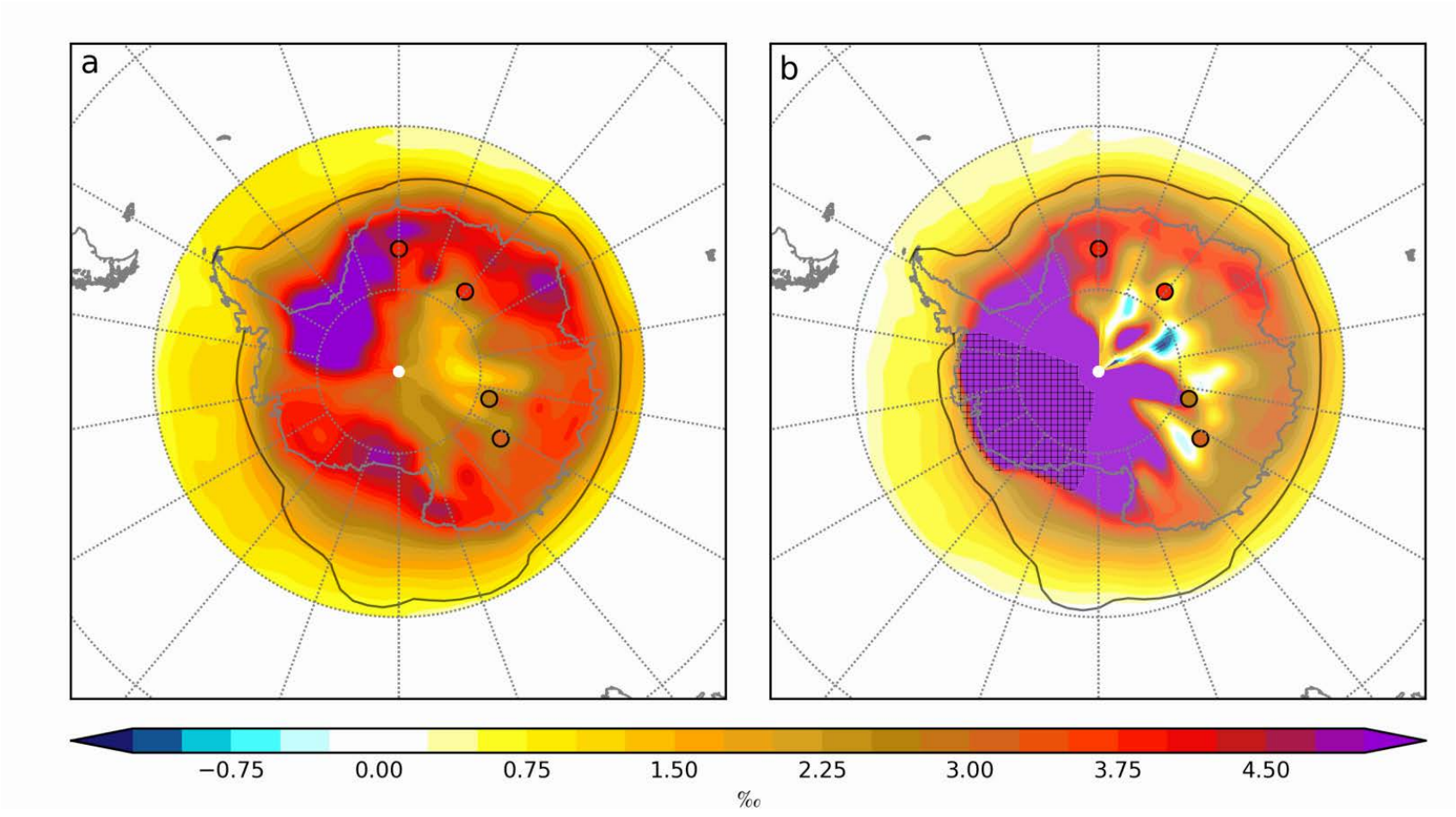


Figure: δ18O anomalies for 128 000 yBP. (a) With and (b) without WAIS. Holloway *et al* 2016.

Reducing sea ice AND the West Antarctic Ice Sheet; more results:

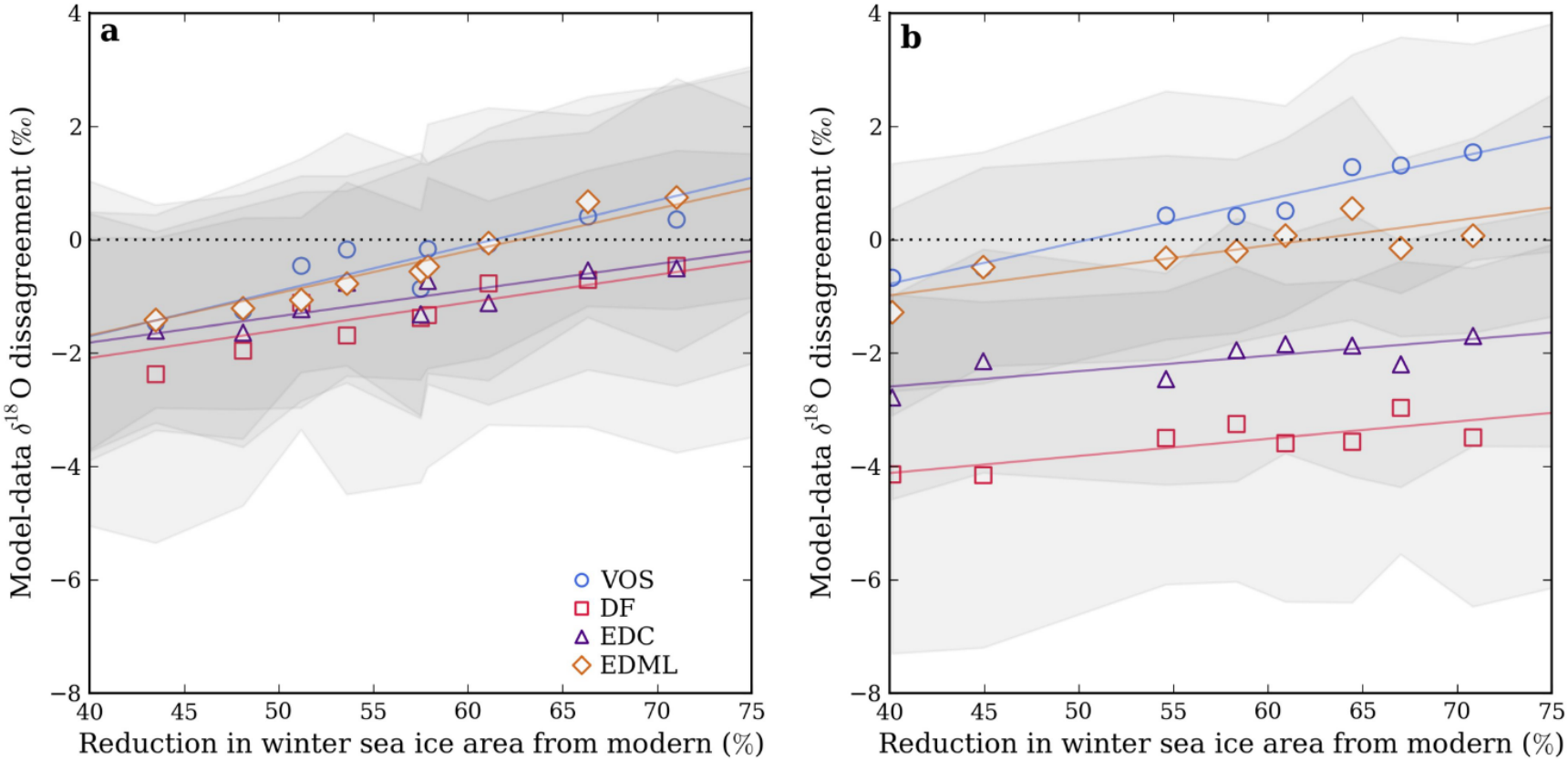


Figure: Model-data δ18O match at ice core sites. (a) With and (b) without WAIS.

This model based investigation of water isotopes in Antarctic Ice Cores at 128 ky indicates that:

- Unlikely that the West Antarctic Ice Sheet was lost (**at this time**).
- Likely that **a large reduction in Antarctic sea ice** caused the 128 ky isotope peak.

Given the lack of any robust Antarctic satellite period sea ice trend, the LIG may be a useful (comparable to 2200) target for the CMIP modelling community:

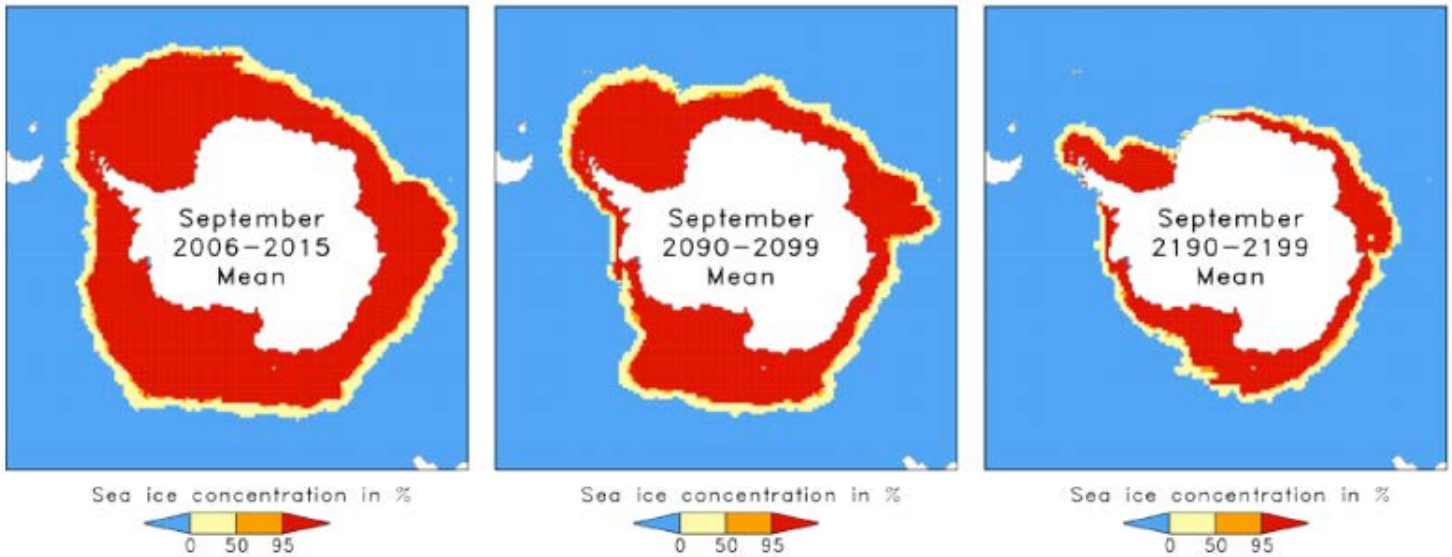


Figure: HadGEM2-ES 2000, 2100, and 2200 changes Antarctic sea ice using RCP8.5.

Further work which explores LIG sea ice change:

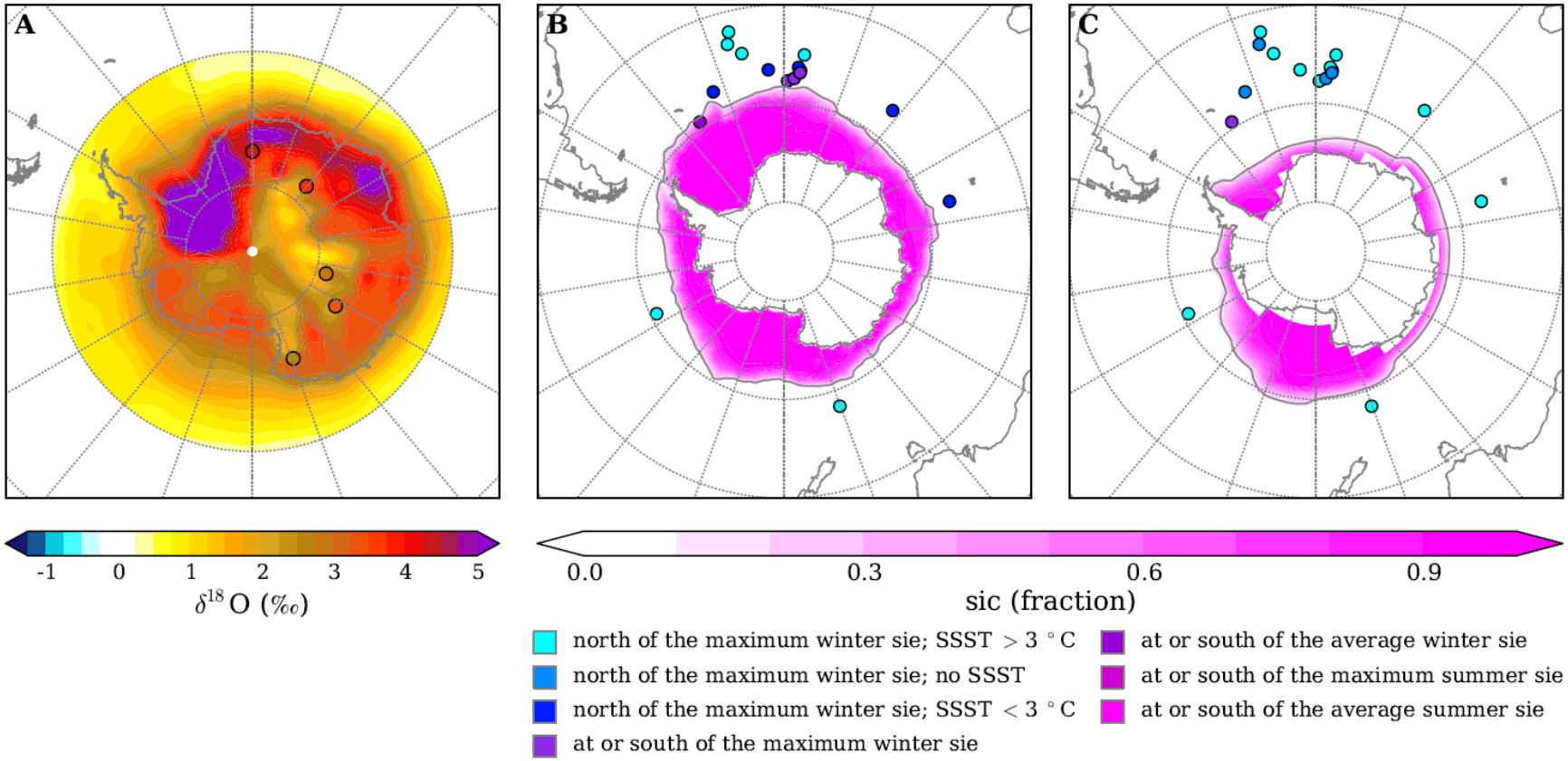


Figure: marine core evidence – rather scant. Holloway *et al*. (Unpublished).

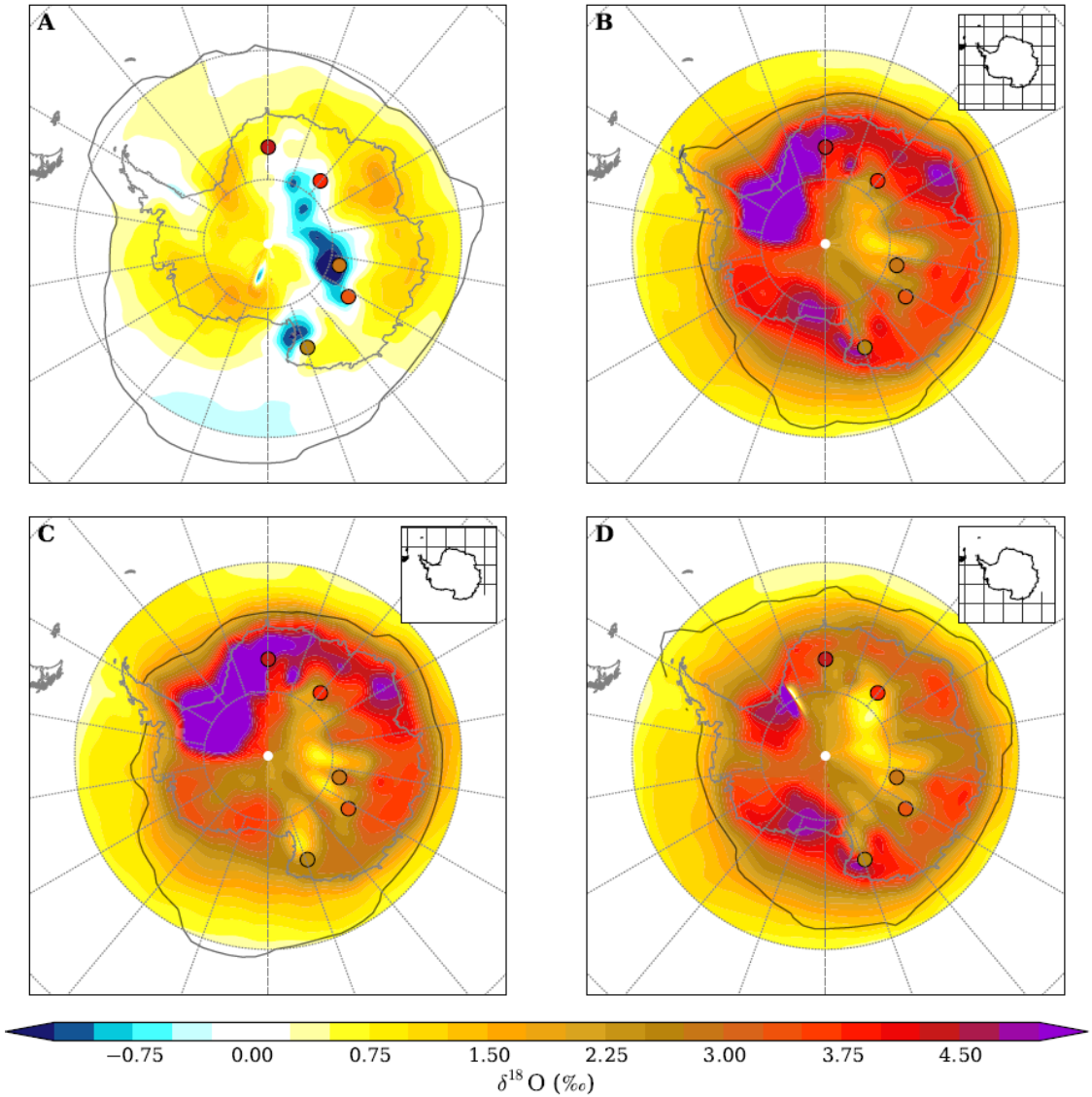


Figure: the ice cores will record sector by sector change. Holloway *et al.* (Unpublished).

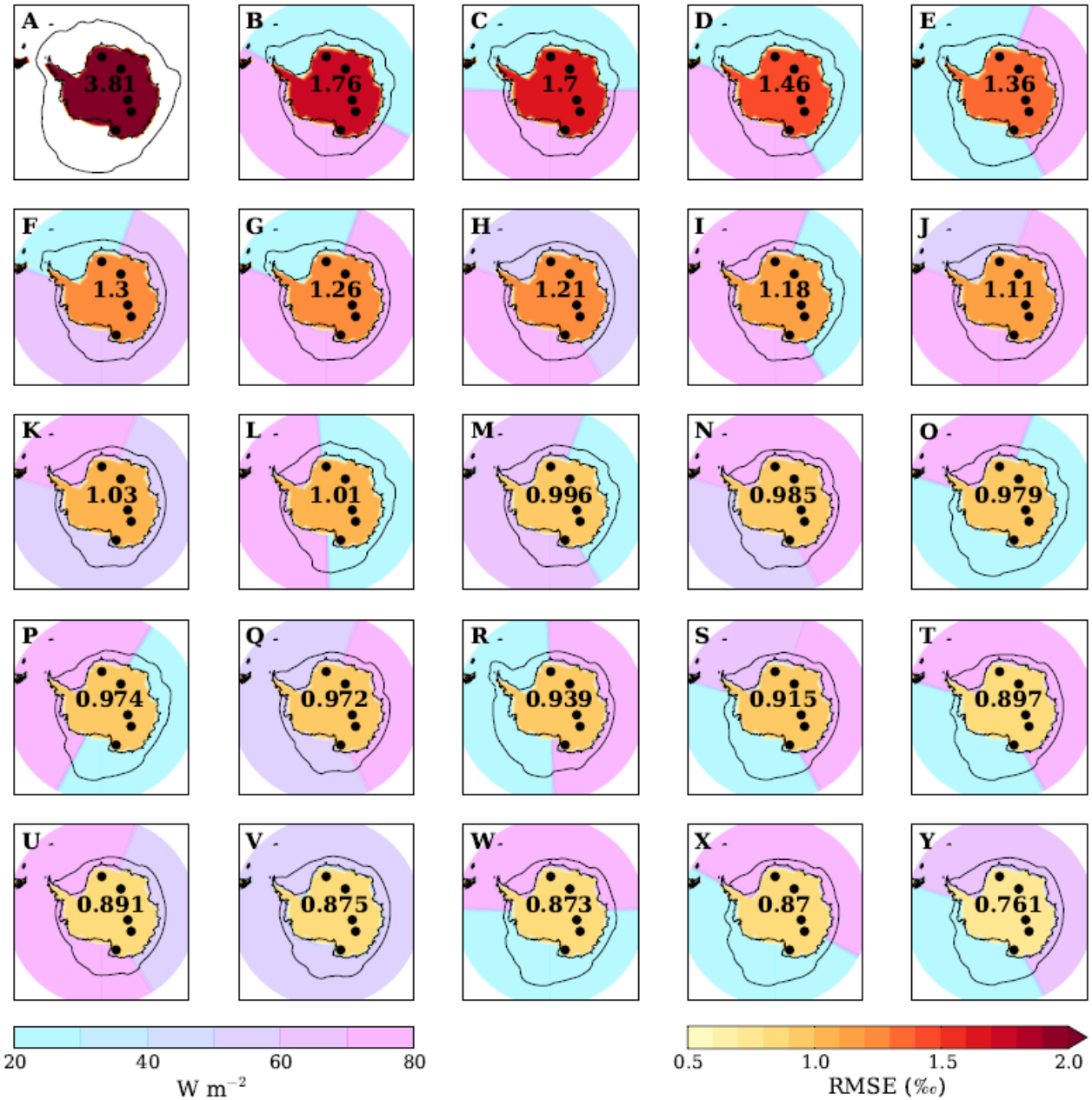
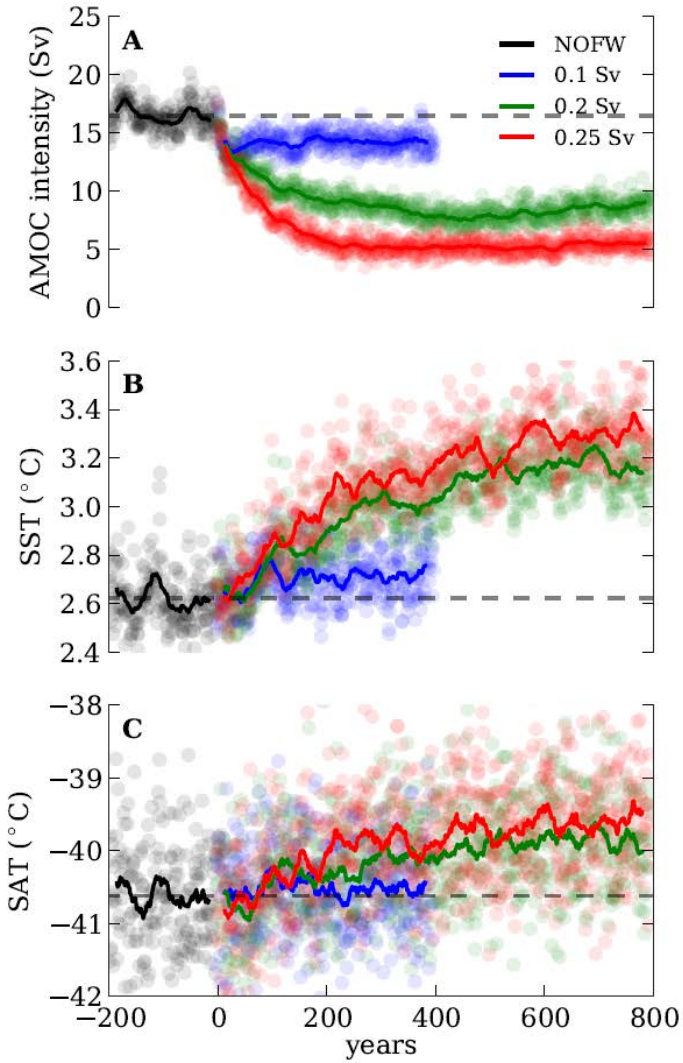


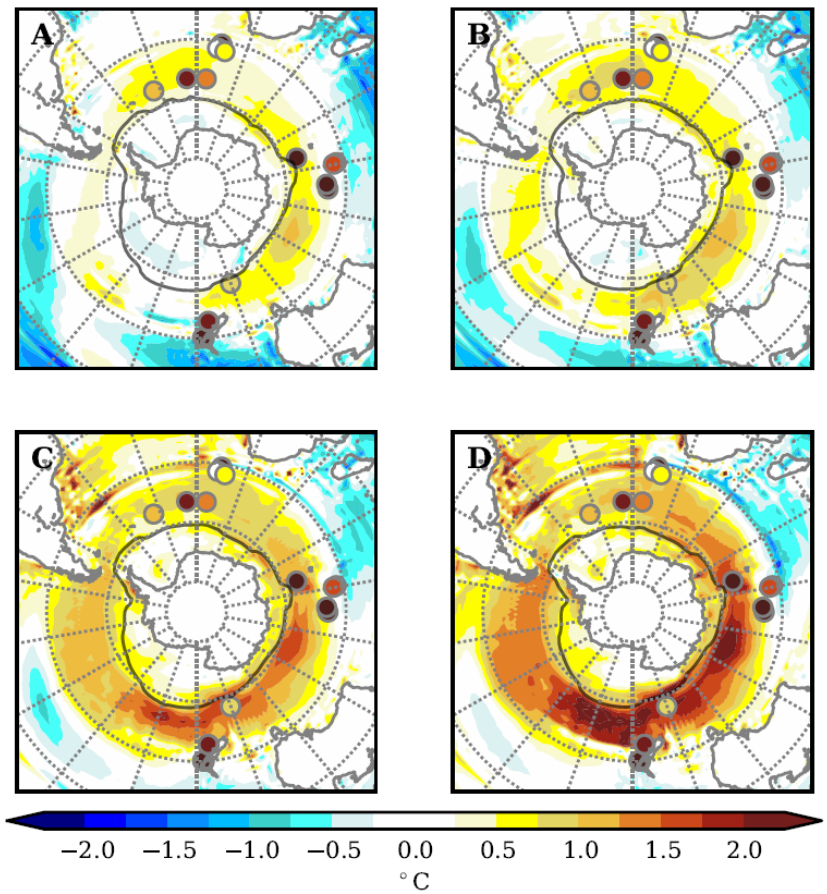
Figure: more sea ice retreat in the Atlantic and Indian sectors. Holloway *et al*.

So, we can also do better in terms of using ice core data to constrain the spatial structure of the LIG Antarctic winter sea ice extent.

- Loss likely more extensive in the **larger Atlantic and Indian sectors of the Southern Ocean**.

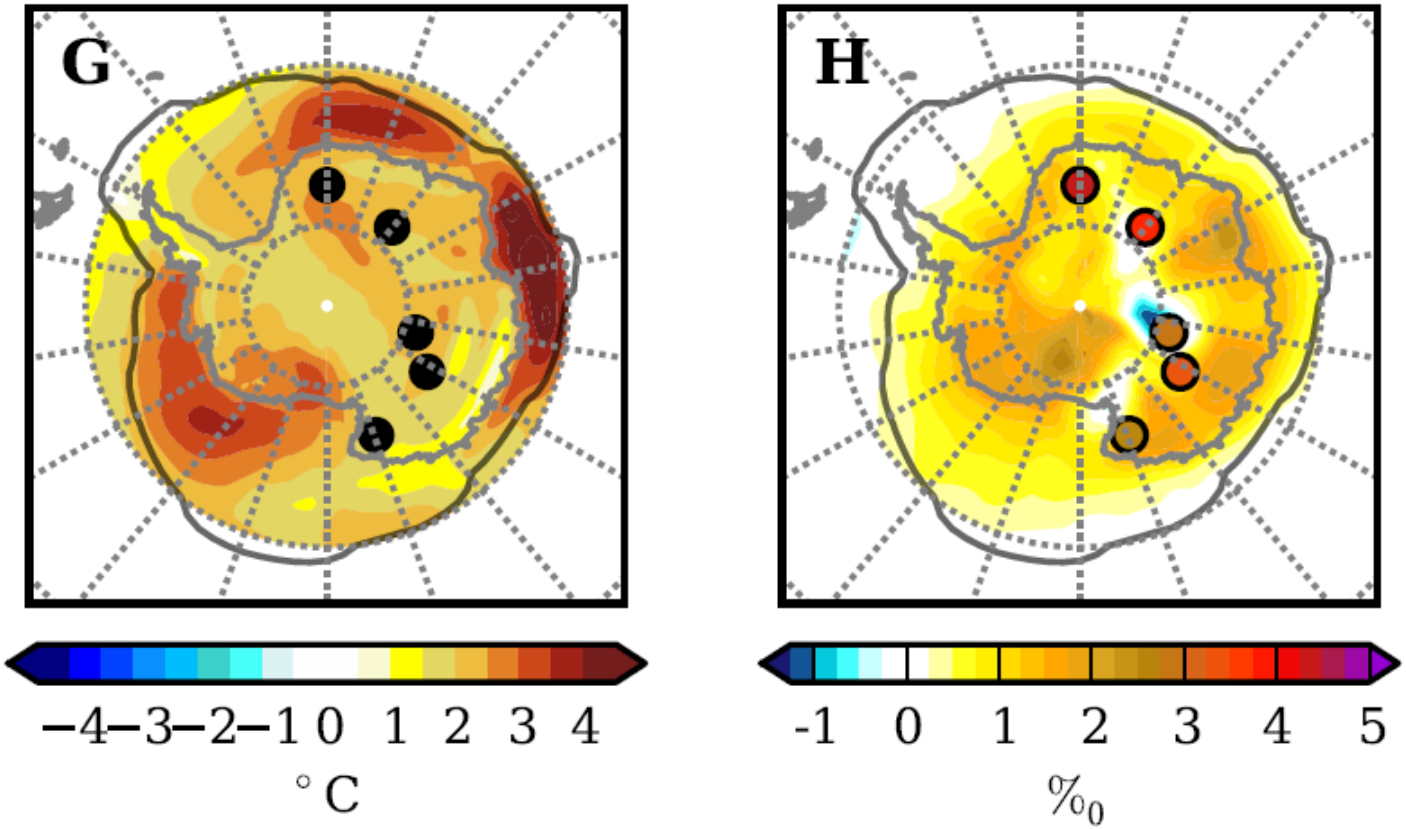
Investigation of the LIG sea ice changes using HadCM3 and NH meltwater fluxes





Ocean responses to North Atlantic meltwater input: Atlantic Meridional Overturning Circulation and Temperature (Holloway *et al.* in revision).

Not enough ocean warming or sea ice loss..



Ocean responses to North Atlantic meltwater input: Temperature and Stable Water Isotope (Holloway *et al*. in revision).

Summary and Future:

Ice cores show a large positive LIG isotopic anomaly - which peaks at 128 ky.

Our (isotopic model based) investigation of this water isotope anomaly indicates that:

- Unlikely that the West Antarctic Ice Sheet was lost at 128 ky.
- Likely that there was a large (+50%) reduction in Antarctic sea ice.

Current GCMs do not simulate a large enough LIG Southern Ocean warming in response to sustained melting of the Northern Hemisphere ice sheets.

The next step is to start testing the IPCC AR6 relevant (UKESM1) components to see if the next generation of models are any more capable of simulating our large LIG sea ice retreat.

- Reminder… we will not have a robust sea ice change (retreat) to test models against for many more years.
- So a reasonable argument can be made for using the LIG as a test case for climate/sea ice models.

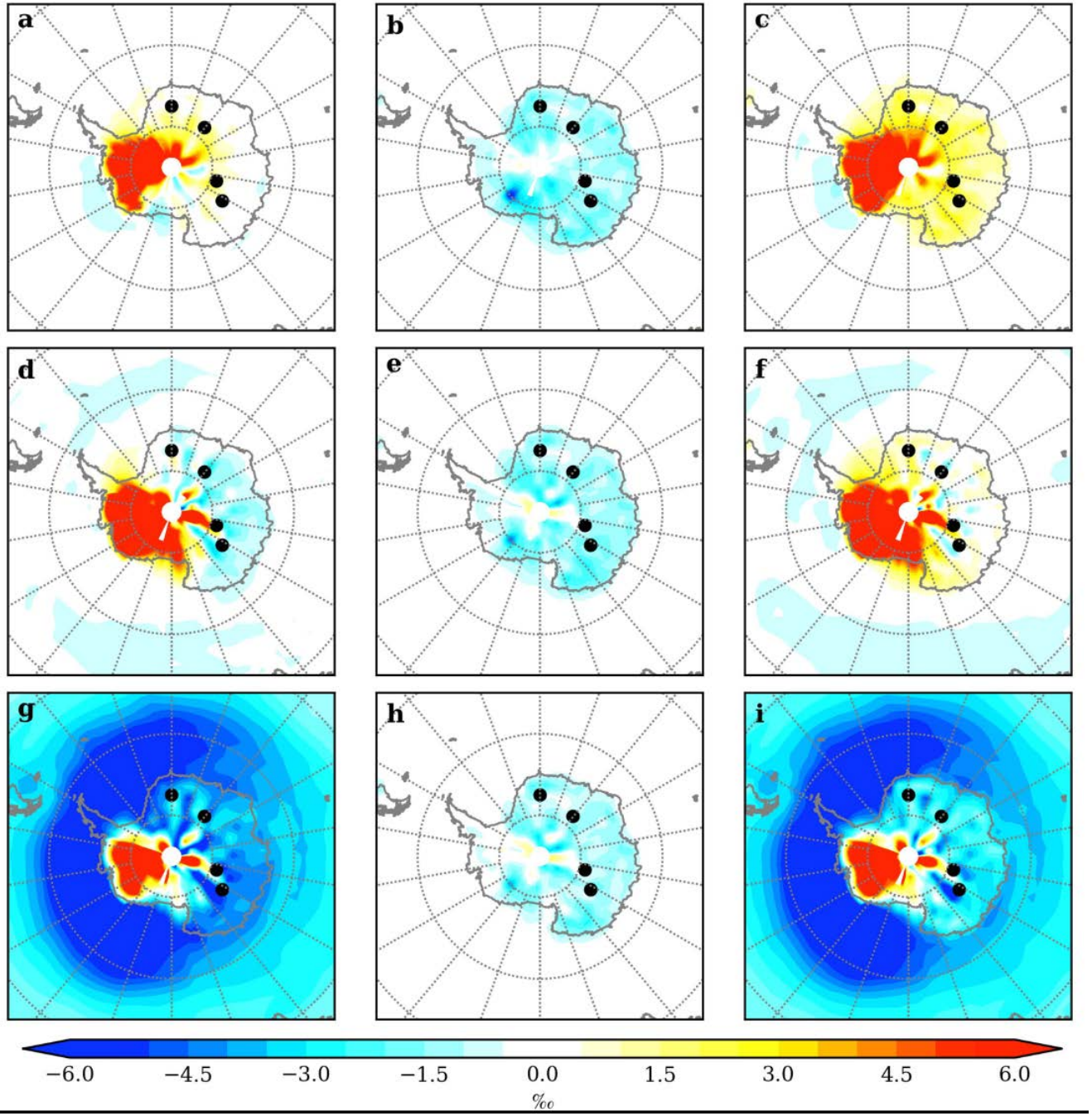


Figure: Decomposition of δ18O anomalies from 128 ka WAIS retreat experiments. (a-c) A remnant flat WAIS; (d-f) WAIS removed and replaced with ocean; (g-i) WAIS removed and meltwater added to the surface Southern Ocean. (a,d,g).

Decomposing biasing:

$$B(x,y) = T_{SPt}(x,y) - T_S(x,y)$$

B the precipitation weighted biasing is the difference between T_S (surface temperature) and the precipitation weighted temperature T_{SPt}.

Biasing *B* can be split into different frequency bands:

$$B(x,y) = \overset{\textbf{synoptic}}{B^{SYNOP}(x,y)} + \overset{\textbf{seasonal}}{B^{SEAS}(x,y)} + \overset{\textbf{interannual}}{B^{INTER}(x,y)}$$

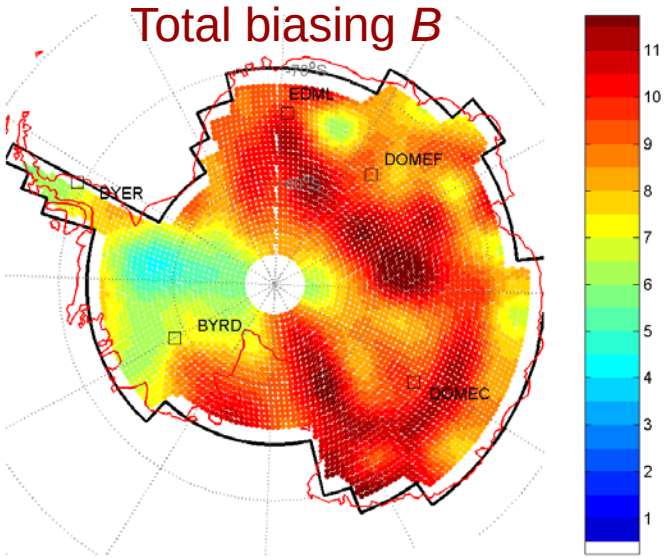
For example, where the synoptic biasing is calculated:

$$B^{SYNOP}(x,y) = \sum_t (T'_{HPSt}(x,y) P'_{HPt}(x,y)) / \sum_t P(x,y)$$

$T_{'HPSt}$ is the high pass filtered synoptic (sub-seasonal) frequency signal of $T_{'S}$. We define $T_{'S}$ as T_S with the time mean removed. $T_{'HPSt}$ is calculated using a standard inverse discrete fast Fourier transform of $T_{'S}$.

Decomposed biasing (*B*) for present day

Total biasing *B*

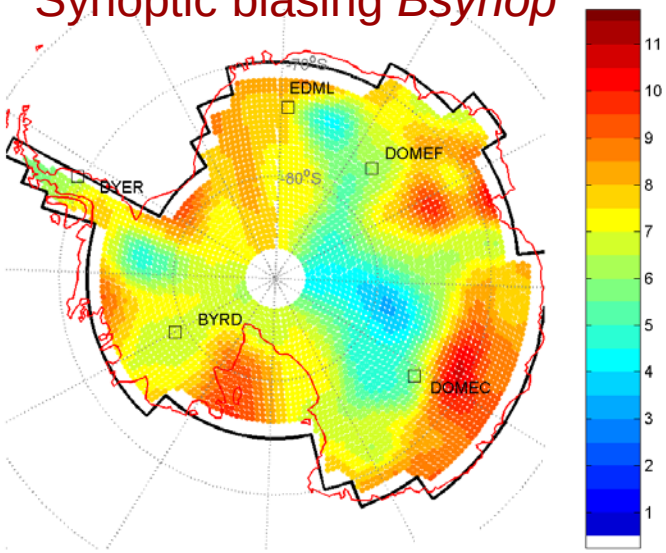


$$B(x,y) = B^{SYNOP}(x,y) + B^{SEAS}(x,y) + \cancel{B^{INTER}}(x,y)$$

Biasing *B* is mainly synoptic, i.e. the covariance is in frequencies below 60 days though seasonal biasing occurs in East Antarctica

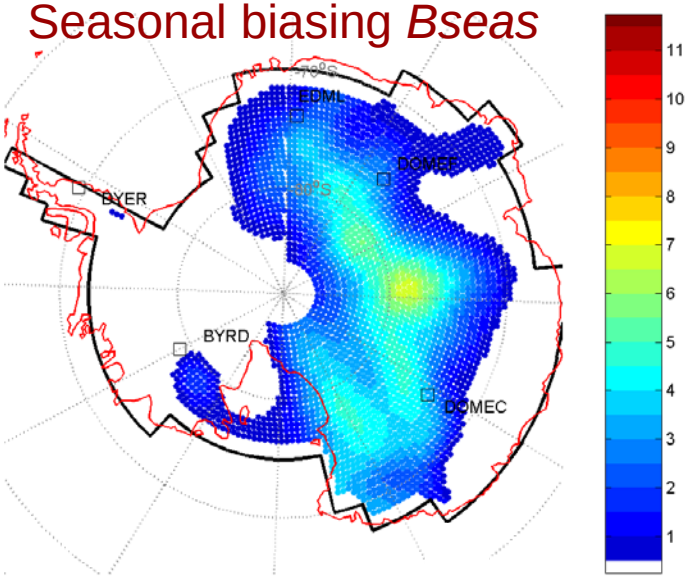
Synoptic biasing *Bsynop*

=



+

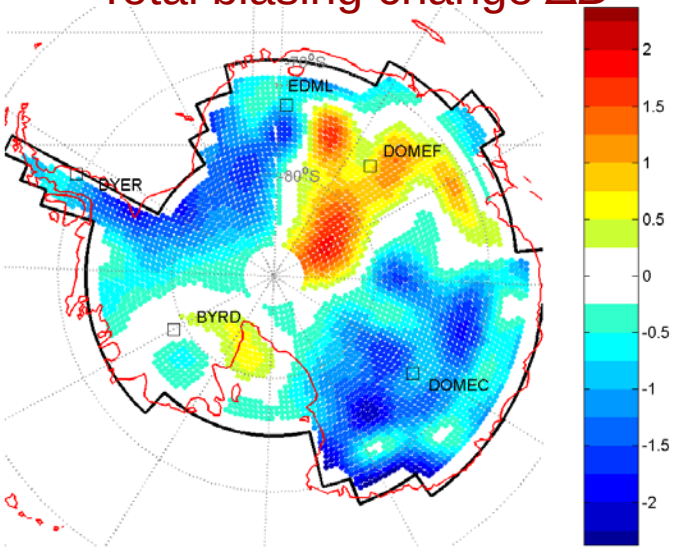
Seasonal biasing *Bseas*



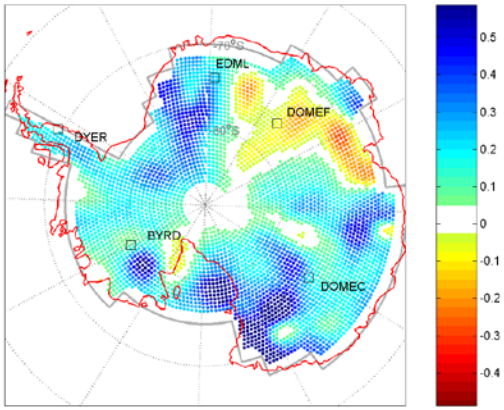
Changes in biasing:

$$\Delta B(x,y) = B_{2100}(x,y) - B_{PD}(x,y)$$

Total biasing change Δ*B*



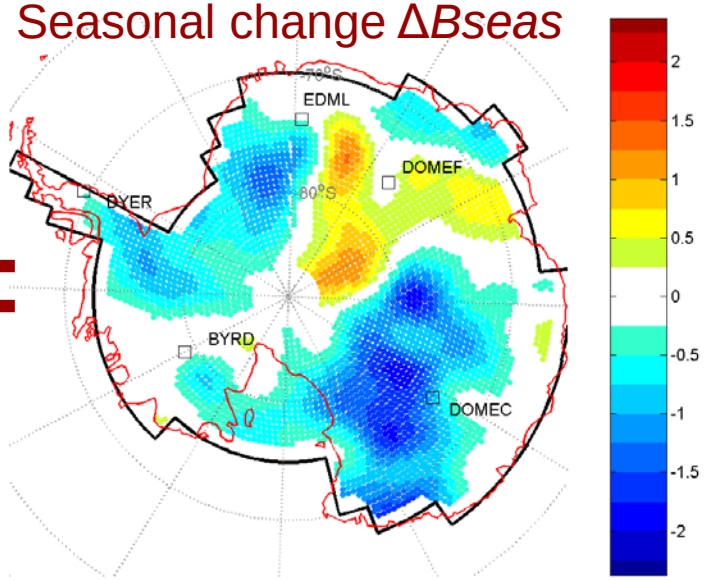
~=



Difference between temporal warming gradients a(T_{SPt}) - a(T_S).

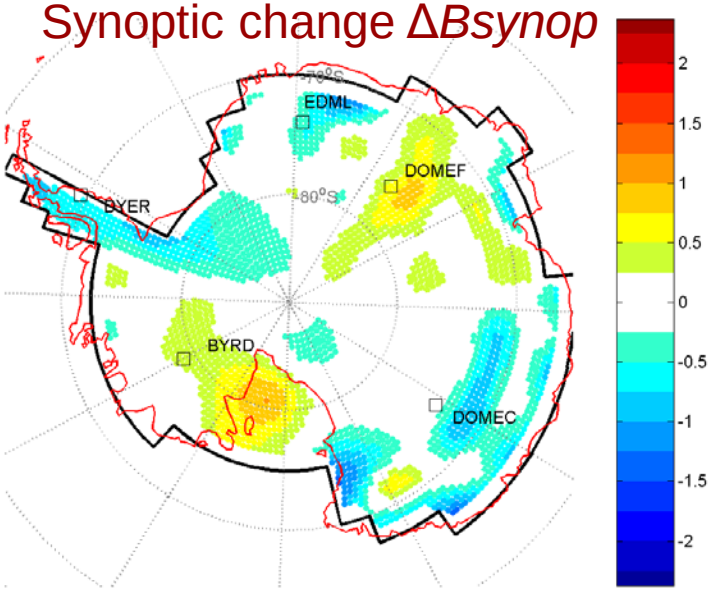
Seasonal change Δ*Bseas*

=



+

Synoptic change Δ*Bsynop*



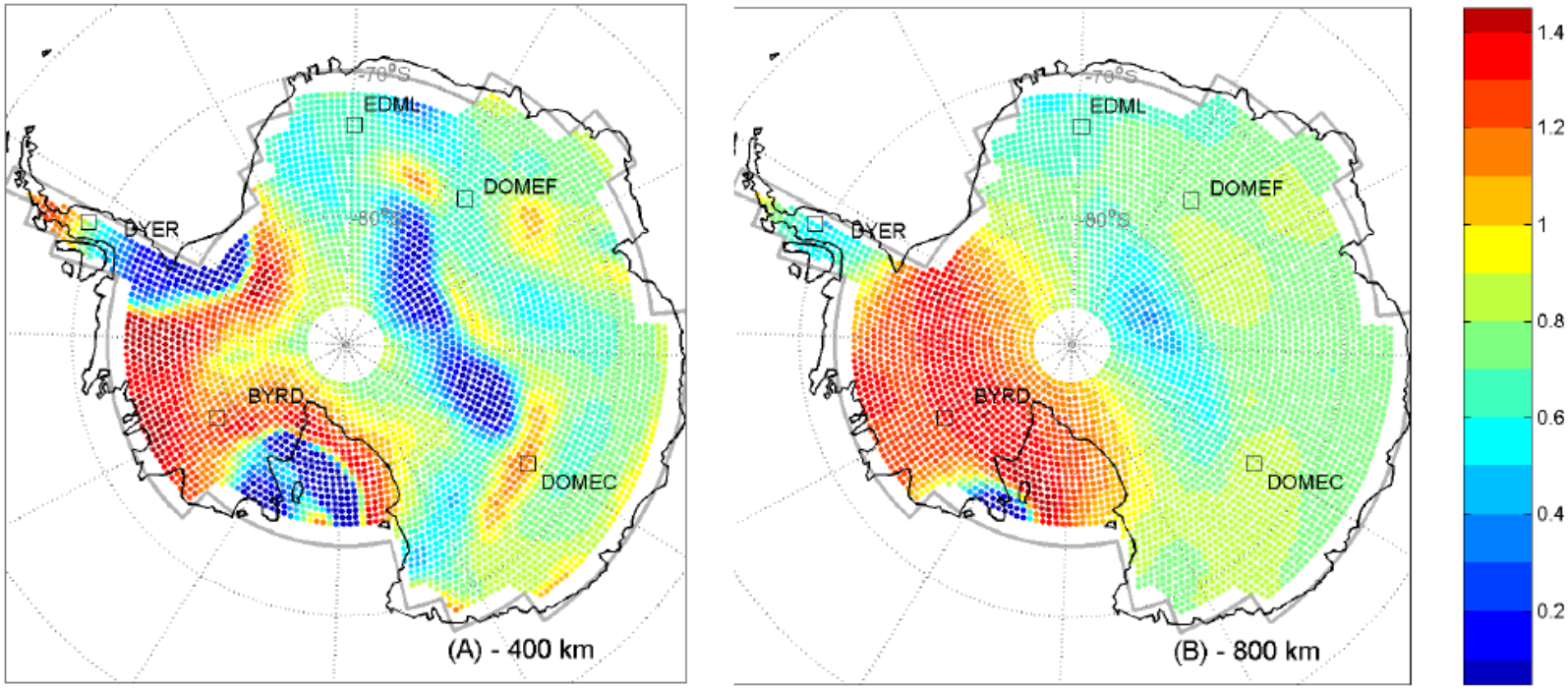


Figure 5: Upper panels show gradients a_S^{SPACE} for the PD using fits across radiuses as noted. Results for a_{SP}^{SPACE} are very similar, not shown.

Fletcher Promontory

654 m to bedrock

7 people total in field

Total time in field 72 days

Drilling time 40 days for 654 m

17 days at
- 16 hours per day
- 3 persons per 4-hour shift

23 days at
- 24 hours per day
- 2 persons per 4-hour shift

Clear site to clear site in single season – everything removed including fluid from hole
(except 'brittle ice' – removed 2013)