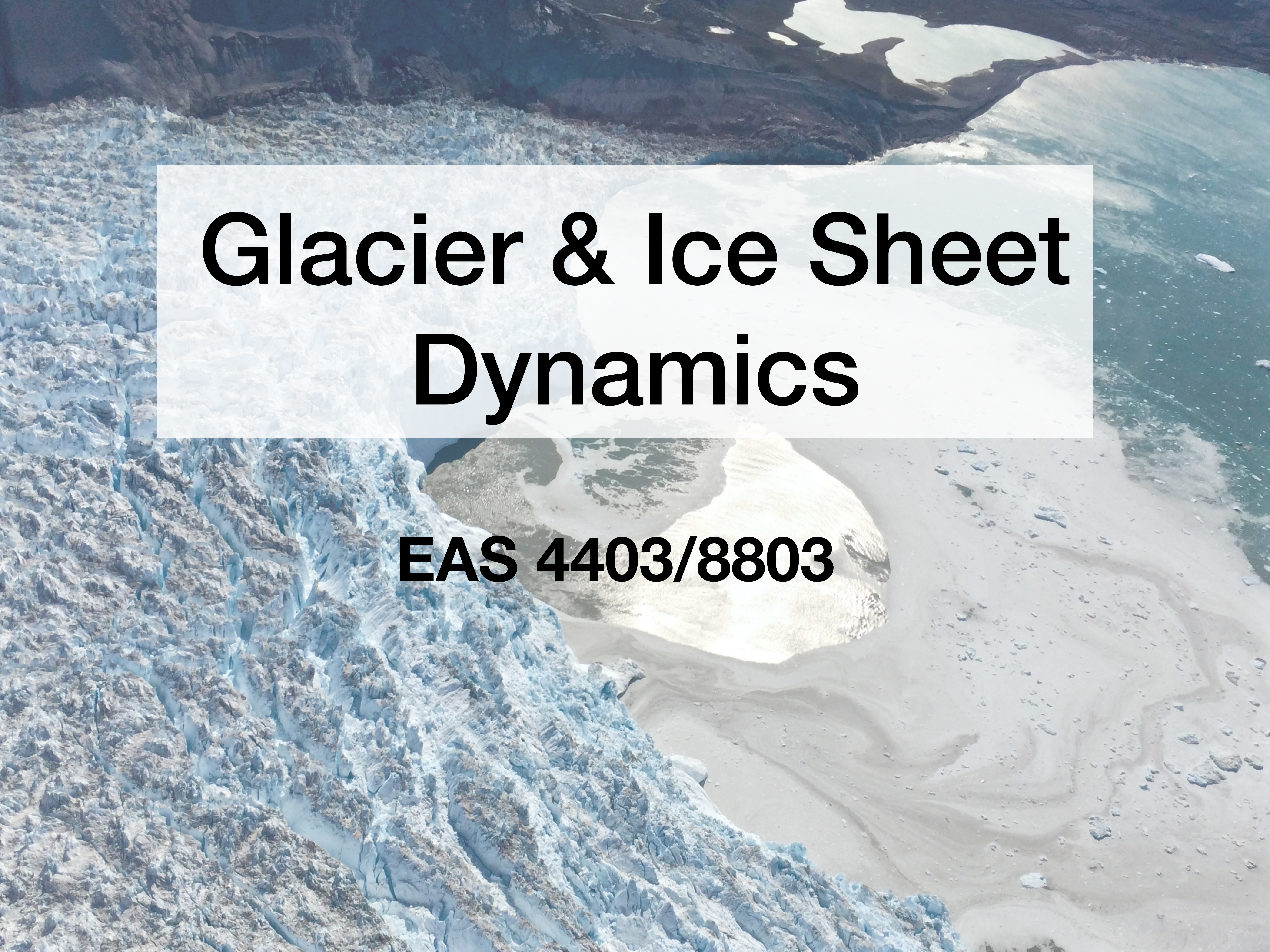


Glacier & Ice Sheet Dynamics

EAS 4403/8803

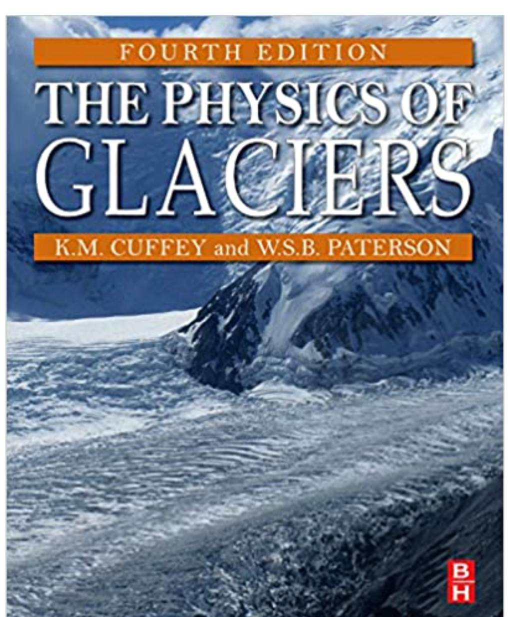
Glacier & Ice Sheet Dynamics, Spring 2021

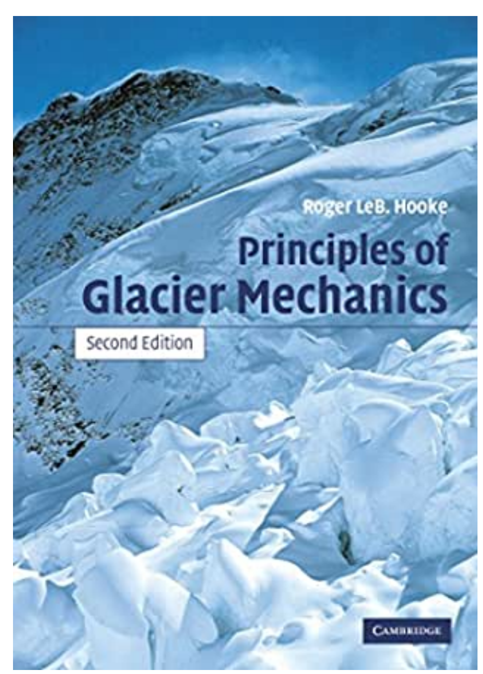
Instructors:	Office Location:	Contact Info:
Dr. Alex Robel	ES&T 3232	robel@eas.gatech.edu
Dr. Winnie Chu	ES&T 3240	winnie.chu@eas.gatech.edu

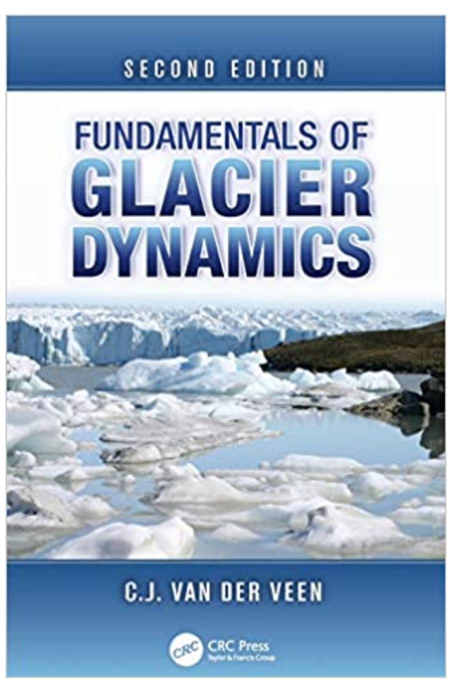
Office hours: Alex Robel: Every Friday 1 - 2 pm
Winnie Chu: Every Tuesday 11 am - 12 pm

Text: Physics of Glaciers, K. Cuffey and W.S.B. Paterson, 4th Edition

Optional: Fundamentals of Glacier Dynamics, C.J. van der Veen, 2nd Edition
Principles of Glacier Mechanics, Roger LeB. Hooke, 2nd Edition







Course Goals:

1. Demonstrate understanding of the fundamentals of glacier and ice sheet dynamics and their application to problems in sea level, paleoclimate, and planetary science.

2. Develop an understanding of the most relevant observations constraining ice sheet processes and be able to perform simple analysis of glaciological data sets.

3. Understand the equations which are used in ice sheet models and interpret output from complex ice sheet models.

4. Critically analyze literature in glaciology and have an understanding of the important ideas in the field of glaciology.

5. Recognize the limits of our knowledge about ice sheets and how this affects predictions of sea-level rise.

Evaluation:

1.	**Active participation in class**	**5%**
2.	**Problem sets**	**60%**
3.	**Final project**	**25%**
4.	**Final project presentation**	**10%**

- You are encouraged to discuss problem sets with your peers and work together towards the solutions, but you must write up your work using your own word
- Late assignments will only be accepted without penalty if you have talked to the instructors beforehand at least 24 hrs. before the due date. Otherwise, any late assignments will automatically be deducted 20% credit. Assignments will not be accepted more than 24 hrs. late.
- **Problem sets: 5 in total**, given every two weeks. They involve “by hand” calculations, some light coding. Prefer MATLAB or Python, but let us know if you would like to use something else
- **Final project:** ~10 page research paper on a topic of your choosing. Either (i) reproduce a result from an ice-related paper and slightly extend it or (ii) apply an idea learned from classes to a new problem
- **Final project presentation:** 8 mins talk + 7 min discussion. Each person will be assigned to prepare questions for certain talks to stimulate discussion

Course Schedule:

Assignments in red. Supporting reading in blue (CP=Cuffey & Paterson, VDV = van der Veen).

Week 01: Preliminaries: what is a glacier, where are glaciers, history of ice on Earth, glacial cycle models (CP Ch. 13.3)

Week 02: Surface mass balance: accumulation, ablation, equilibrium line, surface energy balance, height-mass balance feedback, mass balance measurements (CP Ch. 2, 4-5, 11)

Week 03: Ice flow: the continuity/advection equation, continuum mechanics, stress and strain, rheology, constitutive laws, plastic and viscous flow, non-newtonian fluids (VDV Ch. 1-2, CP Ch. 3)

Due on 1/28

(PS1 on glacial cycles and SMB due)

Week 04: Ice flow: Cauchy momentum equation, Stokes flow, the many flow approximations, how ice sheet models work (VDV Ch. 3-4)

Week 05: Glacier thermodynamics

(PS2 on ice flow due)

Week 06: Ice-bed interface: cavitation, regelation, till (CP Ch. 7, VDV CH. 7)

Week 07: Glacier hydrology: supra-, en- and sub-glacial drainage systems, drainage models, flow through porous media (CP Ch. 6)

Week 08: Marine ice sheets: the grounding line, basal melting, ice-ocean interactions, ice streams, the marine ice sheet instability

(PS3 on thermodynamics, the bed and hydrology due)

Week 09: Fracture: crevasses, calving, brittle materials, fracture mechanics

Week 10: Glacial geophysics: ice-penetrating radar, seismic methods

(PS4 on marine ice sheets and fracture due)

Week 11: Remote sensing of ice sheets: satellites, airborne methods

Week 12: Sea Level: gravity, glacial isostatic adjustment, future sea-level rise

(PS5 on glacier observations due)

Week 13: Cushion

Week 14: Final Project lightning talks 4/22 and 4/27 (7 minutes talk + 6 minutes discussion) (final project reports due Tuesday 4/27)

About me: Winnie Chu

Undergrad in Geophysics, University College London, U.K. (2007)

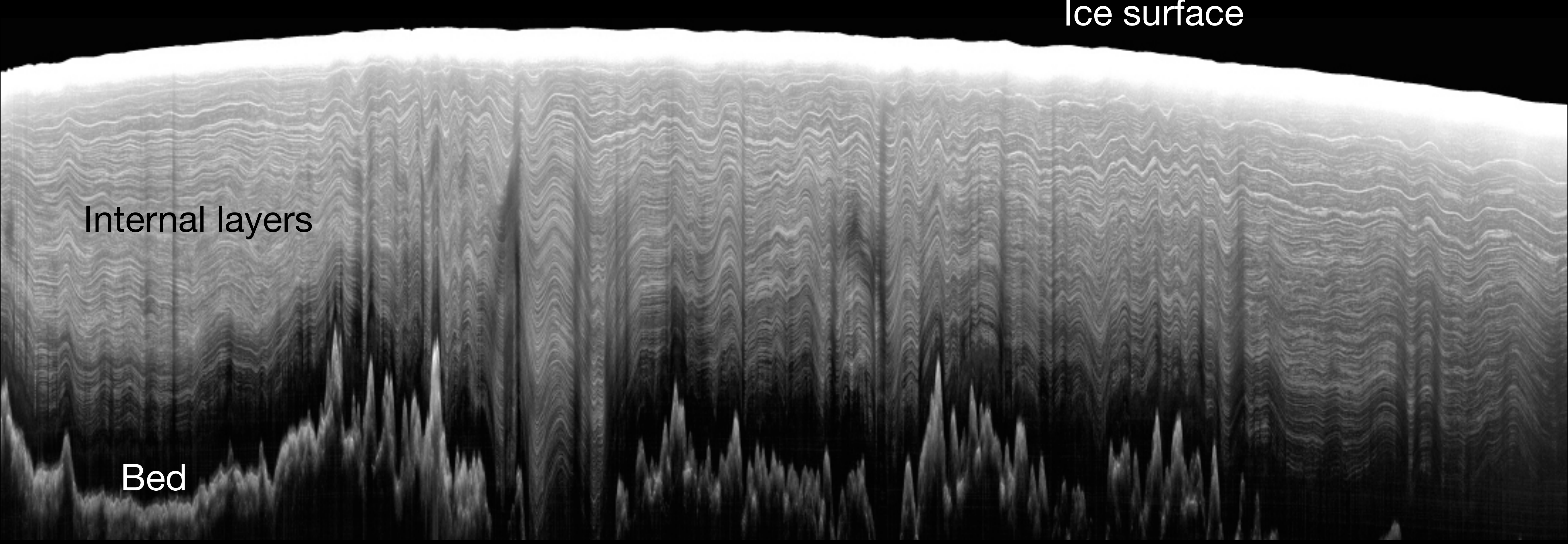
Ph.D. in Earth & Environmental Sciences, Columbia University (2011)

Visiting Student Research Scholar, NASA Jet Propulsion Laboratory (2015)

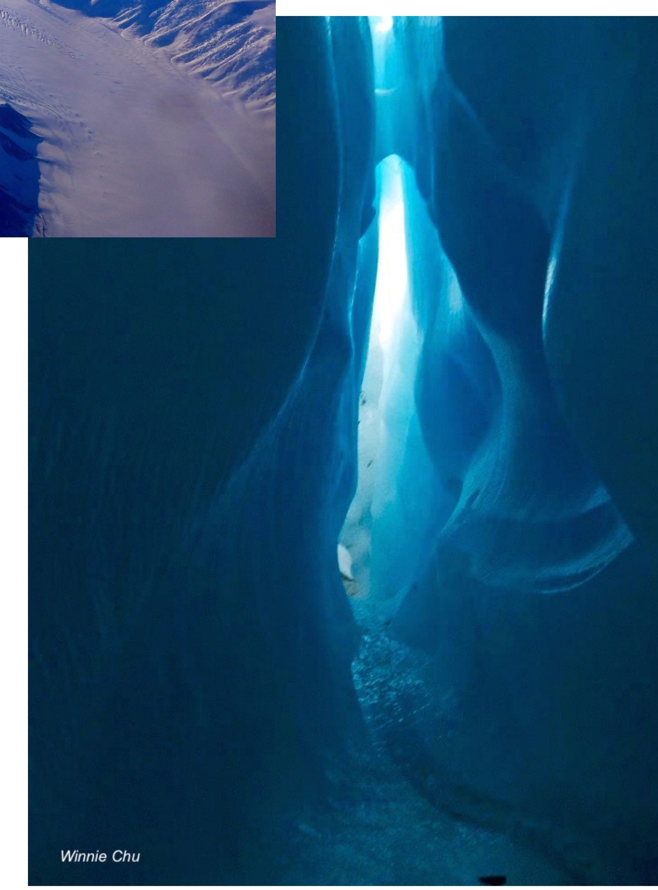
Postdoc at the Department of Geophysics, Stanford University (2019)

Assistant Professor at GT as Head of Glacial Geophysics Group (since 2020)

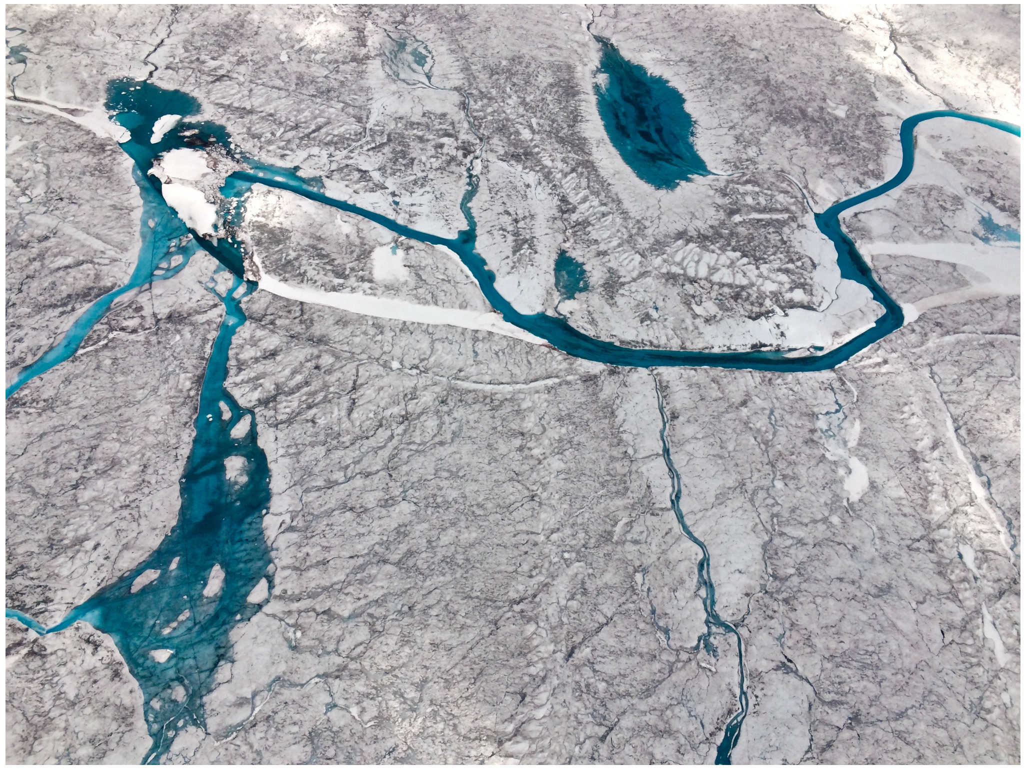
What I do: Geophysical Tools and Observations for Understanding Ice Sheet Interaction with Climate Forcing

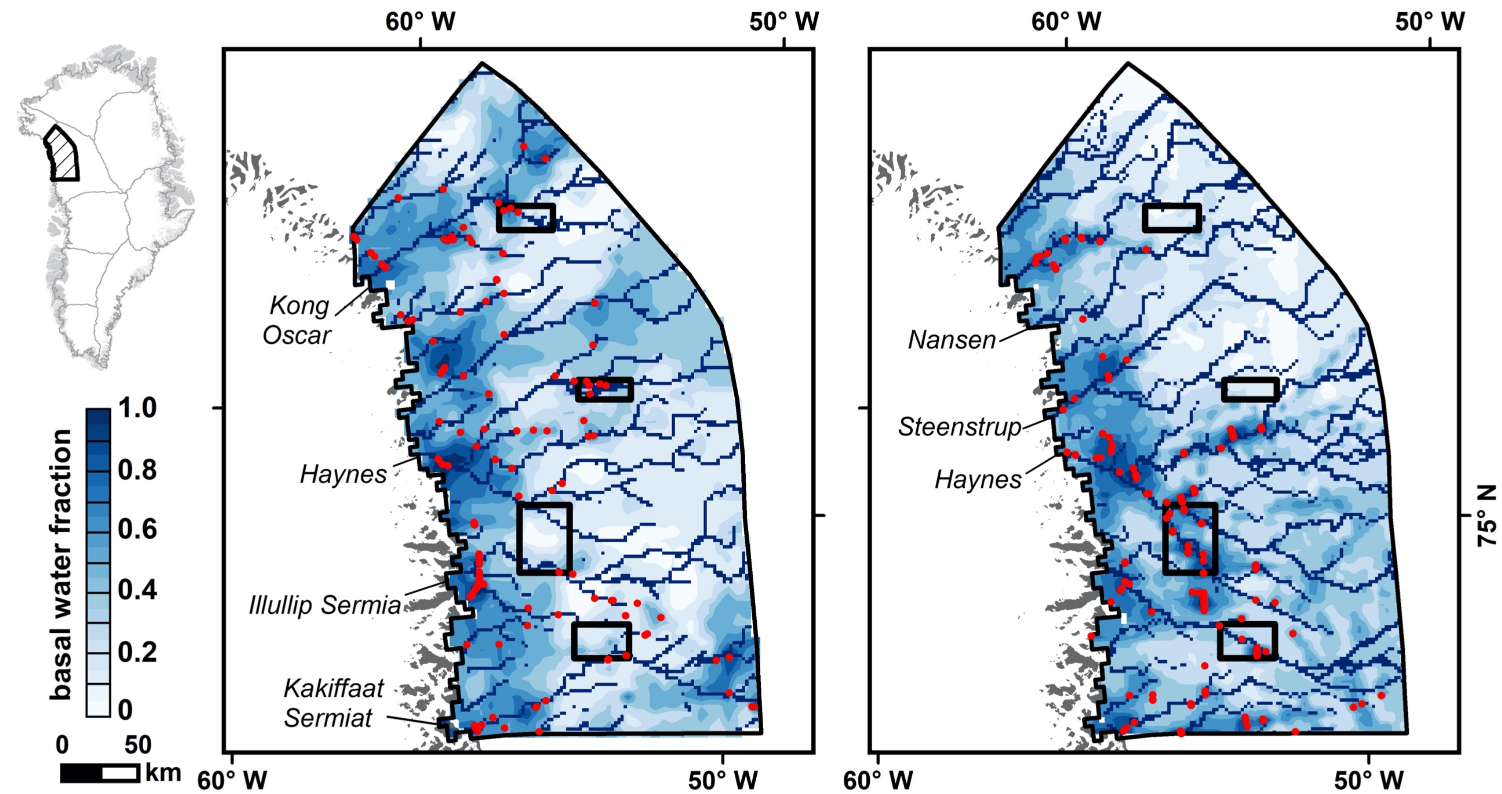


A few perks of being a glacial geophysicist!



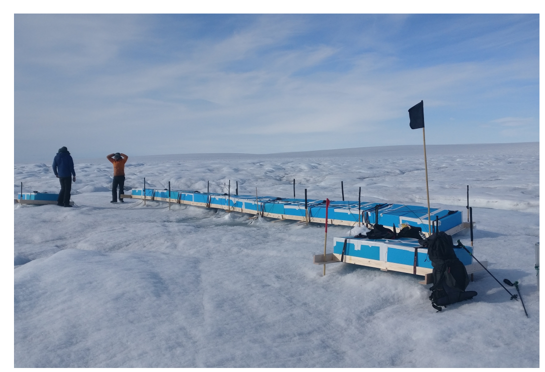
Impact of surface melting on subglacial hydrology

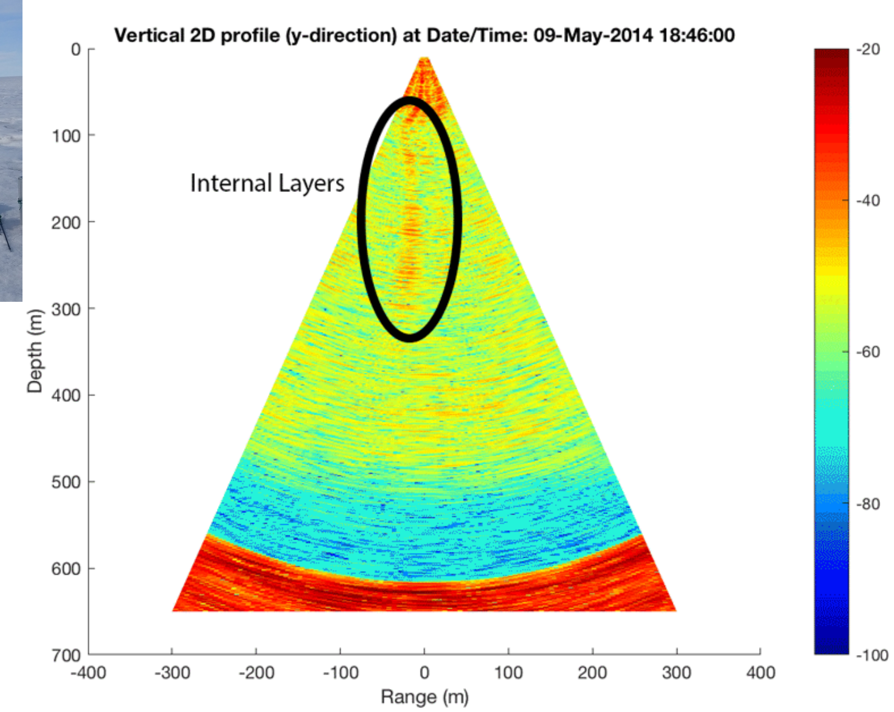




Grounding zones & ice shelf properties

Ice sheet hydrogeophysics





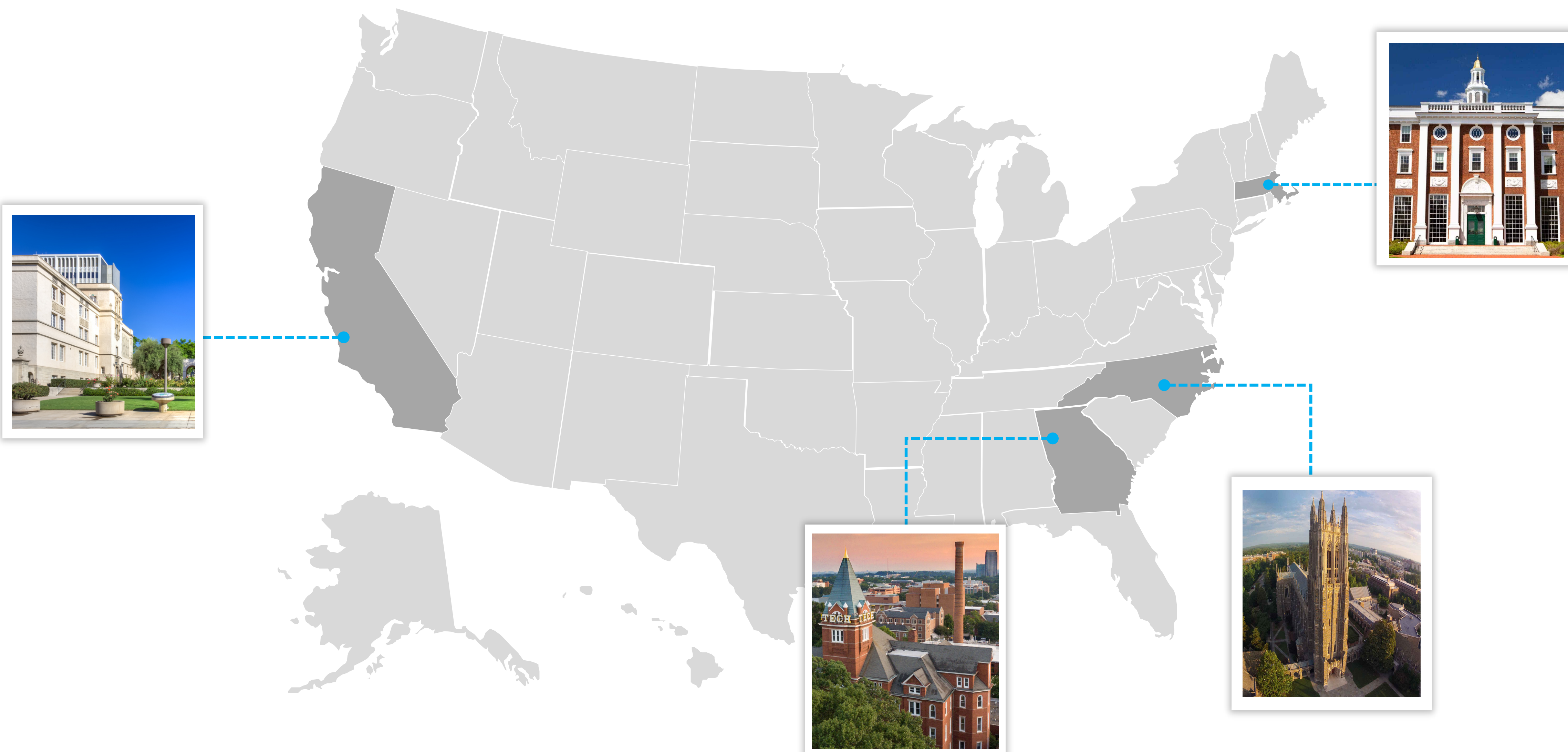
About me: Alex Robel

Undergrad in Physics, Earth Science, Math, Duke U (2010)

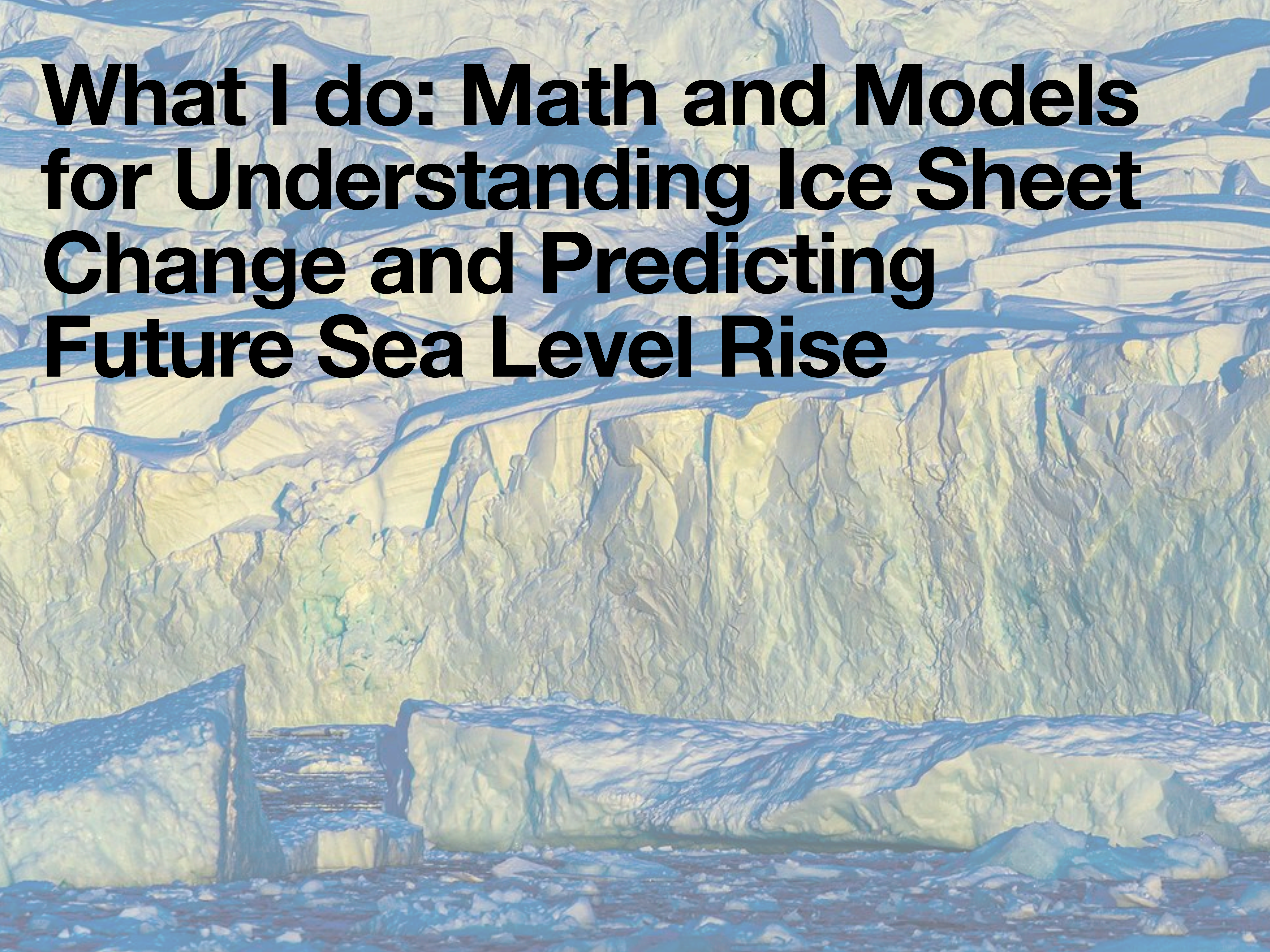
Ph.D. in Earth & Planetary Sciences, Harvard University (2015)

Postdoctoral Fellowship at Caltech (2018)

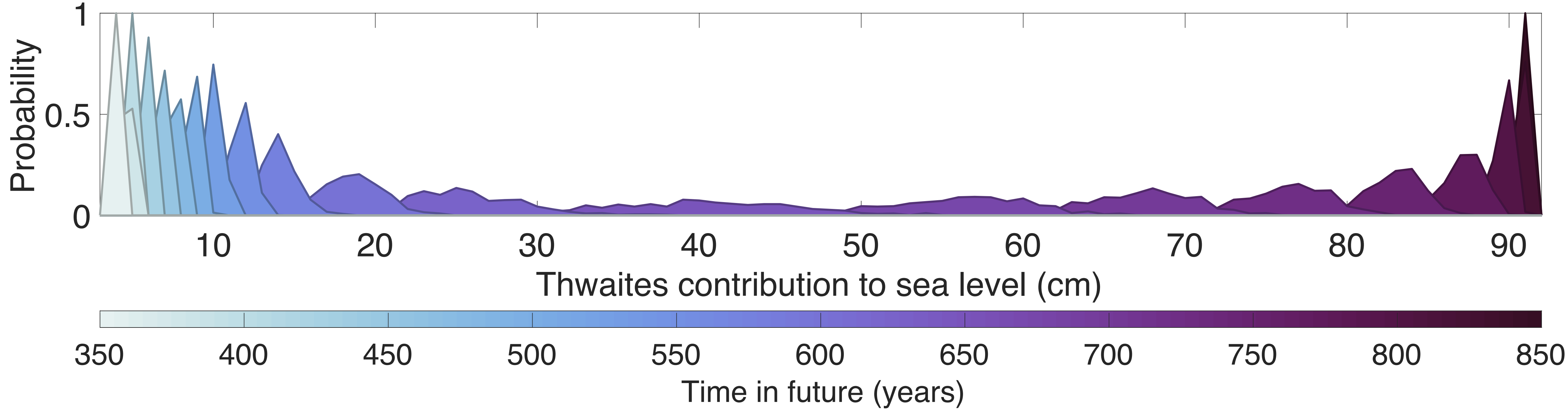
Assistant Professor at GT as Head of Ice & Climate Group (since 2018)

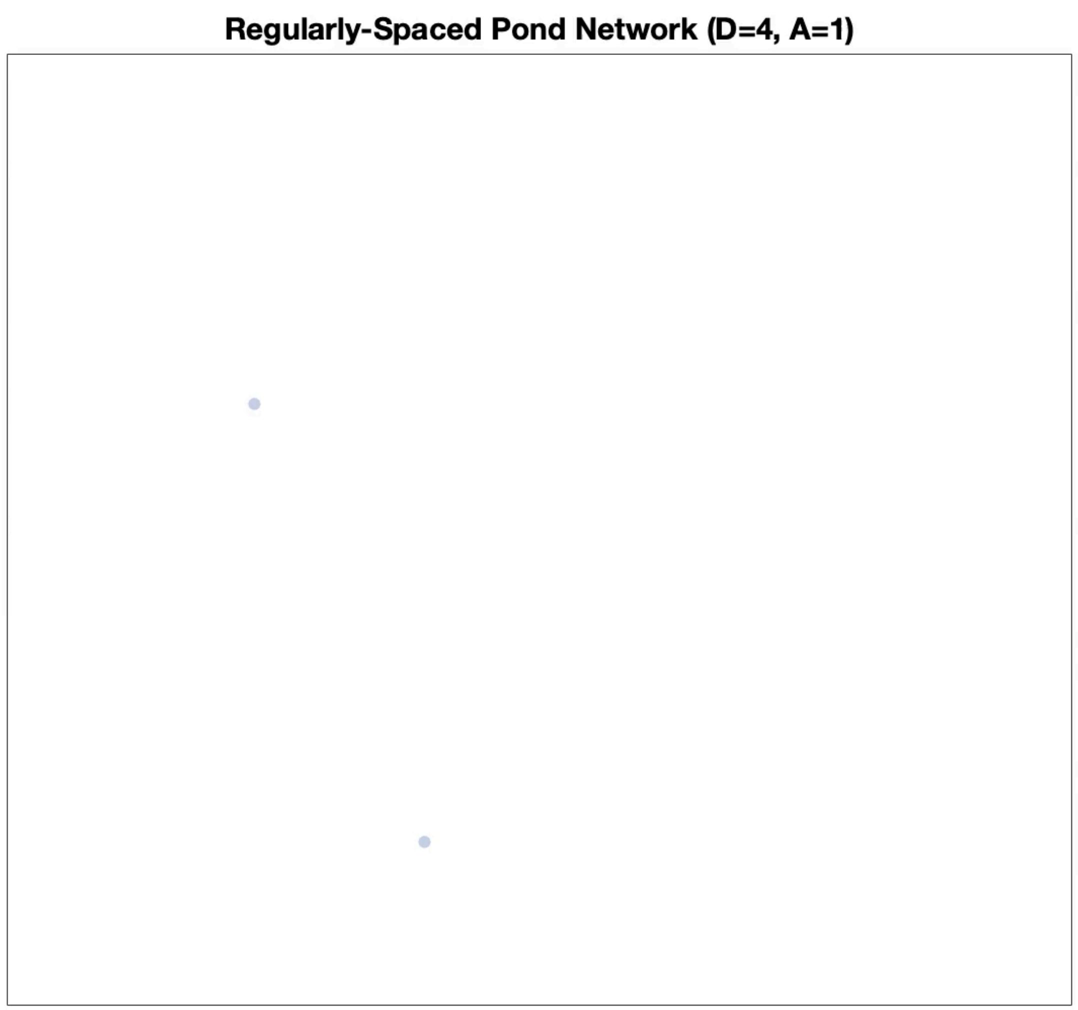


What I do: Math and Models for Understanding Ice Sheet Change and Predicting Future Sea Level Rise

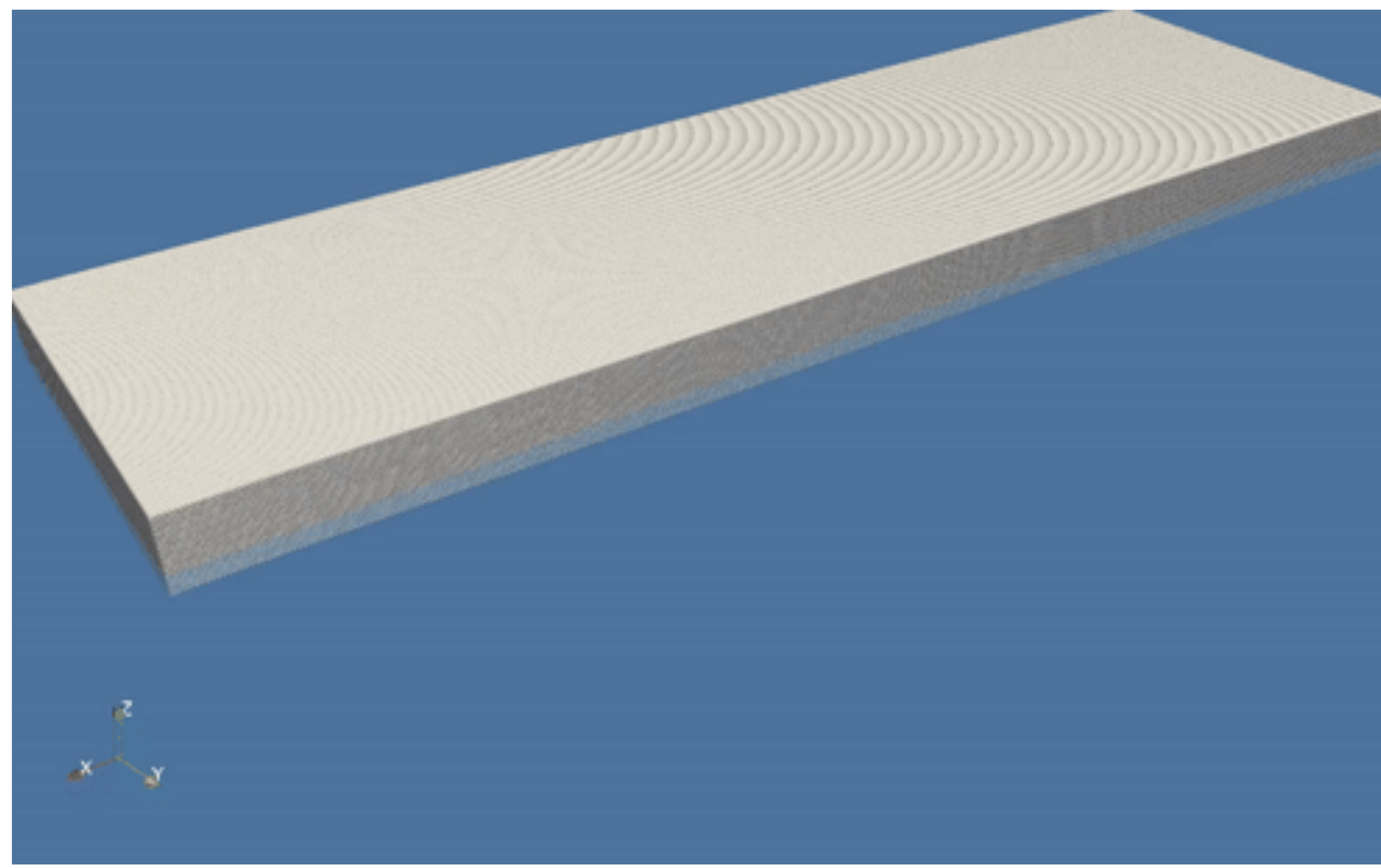


Probabilistic projection of one glacier's contribution to sea level rise over 1000 years





A simple model of water collecting and fracturing an ice shelf



A not-so-simple model of iceberg calving (by Ziad Rashed)

About you?

Who are you?

Where are you from?

What program and year are you in?

Why are interested in glacier dynamics?

What do you like to do in your free time?

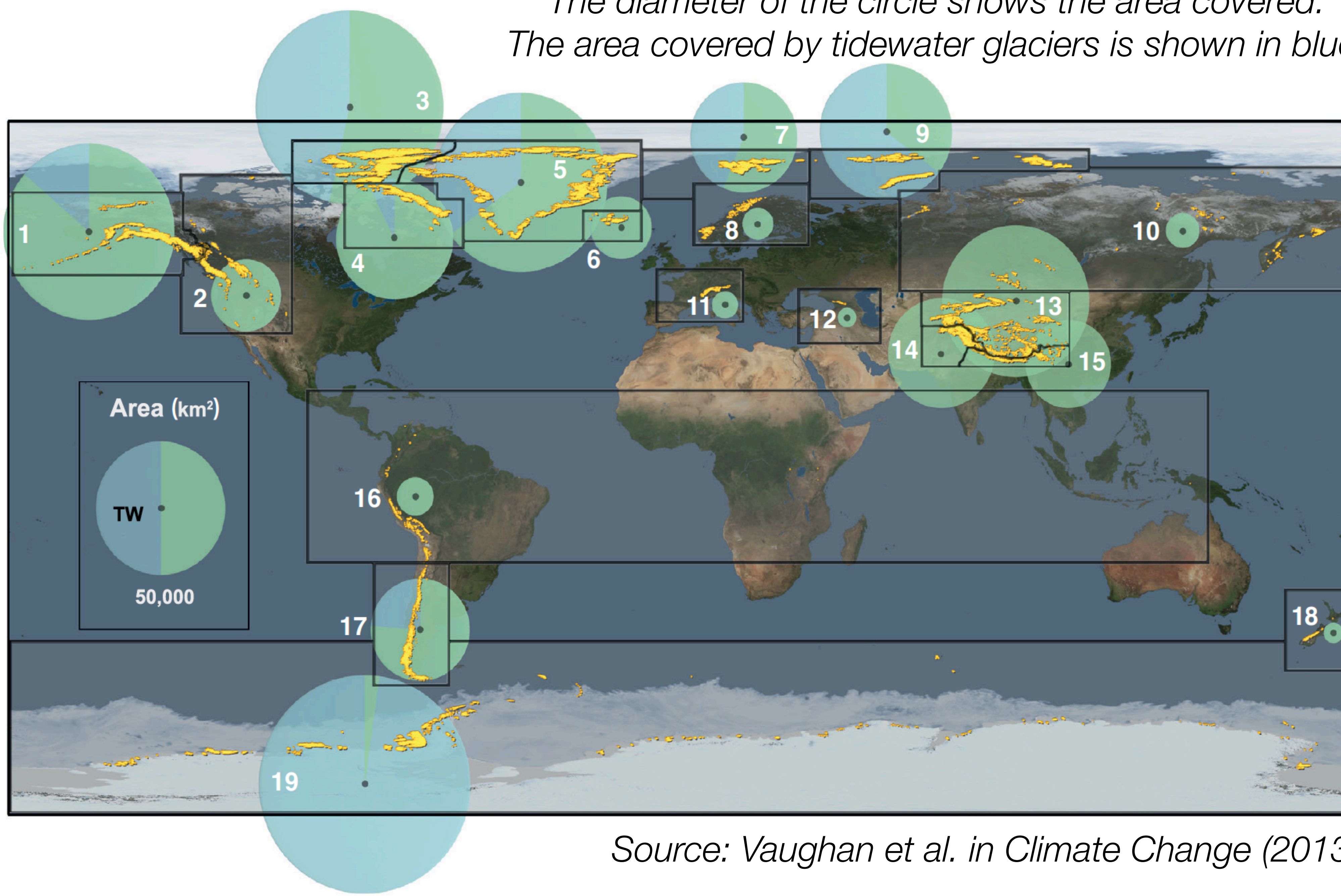
Glaciers!

What is the “cryosphere”?

The word “cryosphere” comes from the Greek word for cold, “kryos”

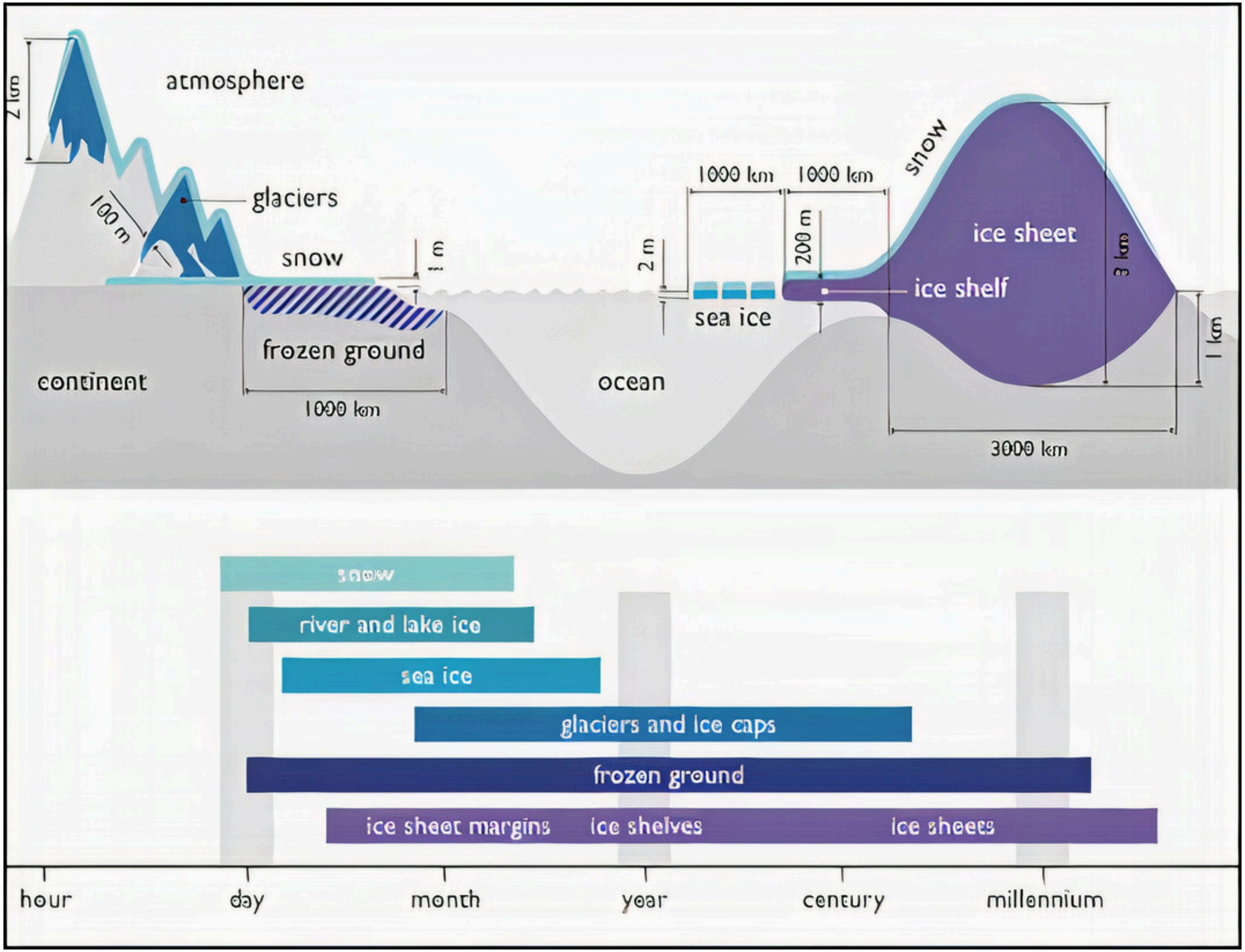
Collectively describes the frozen water part of the Earth system located in areas around the Arctic, Antarctica, and high elevation regions in between:

The diameter of the circle shows the area covered.
The area covered by tidewater glaciers is shown in blue.



Source: Vaughan et al. in Climate Change (2013)

Components of the Cryosphere



Source: IPCC Fourth Assessment Report: Climate Change 2007

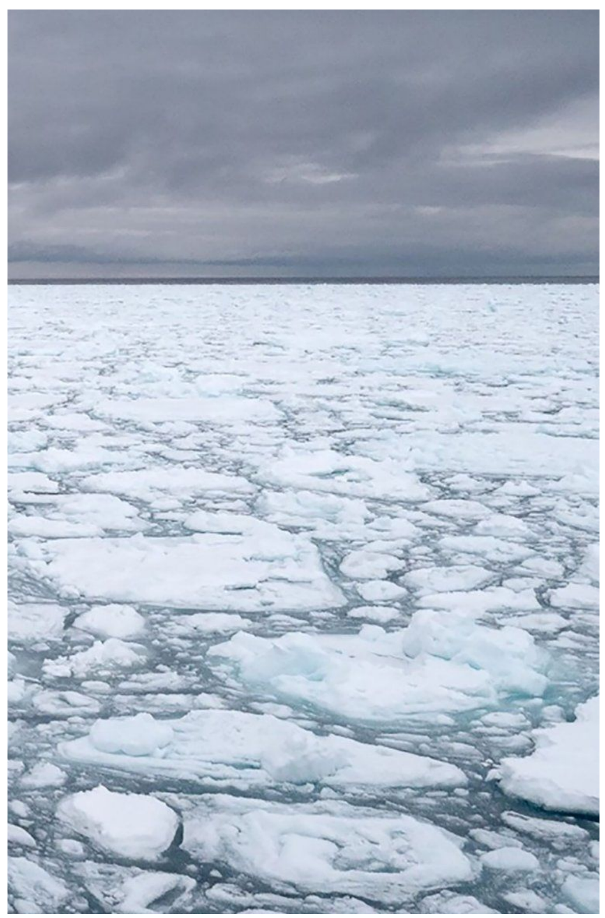
Why is the cryosphere important?

- The cryosphere is tightly coupled with the global climate system with important linkages and feedback to **radiation budget** through its impact on surface albedo

Albedo (α) is a non-dimensional, unitless quantity that indicates how well a surface reflects solar energy

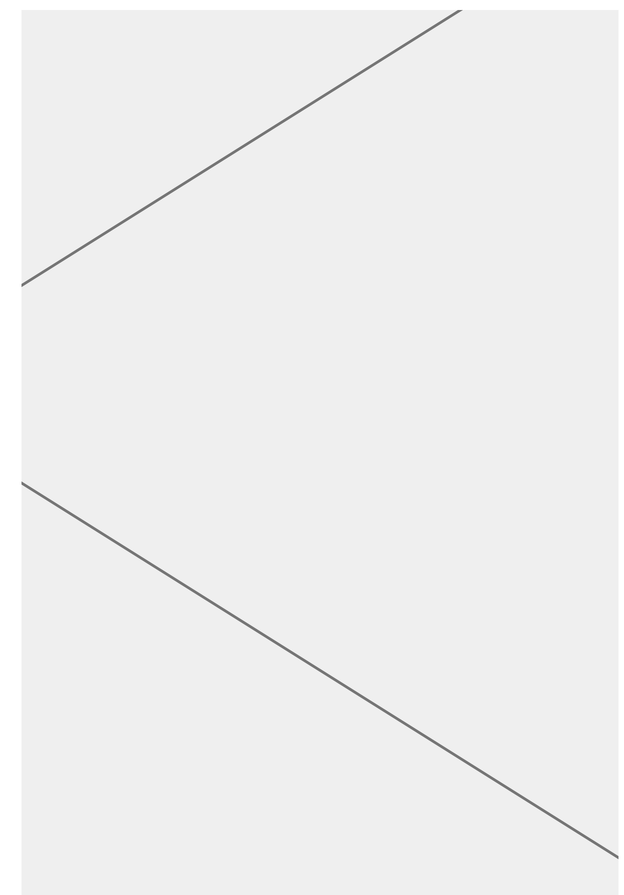
Ocean (α ~ 0.06)

Sea ice (α ~ 0.4)



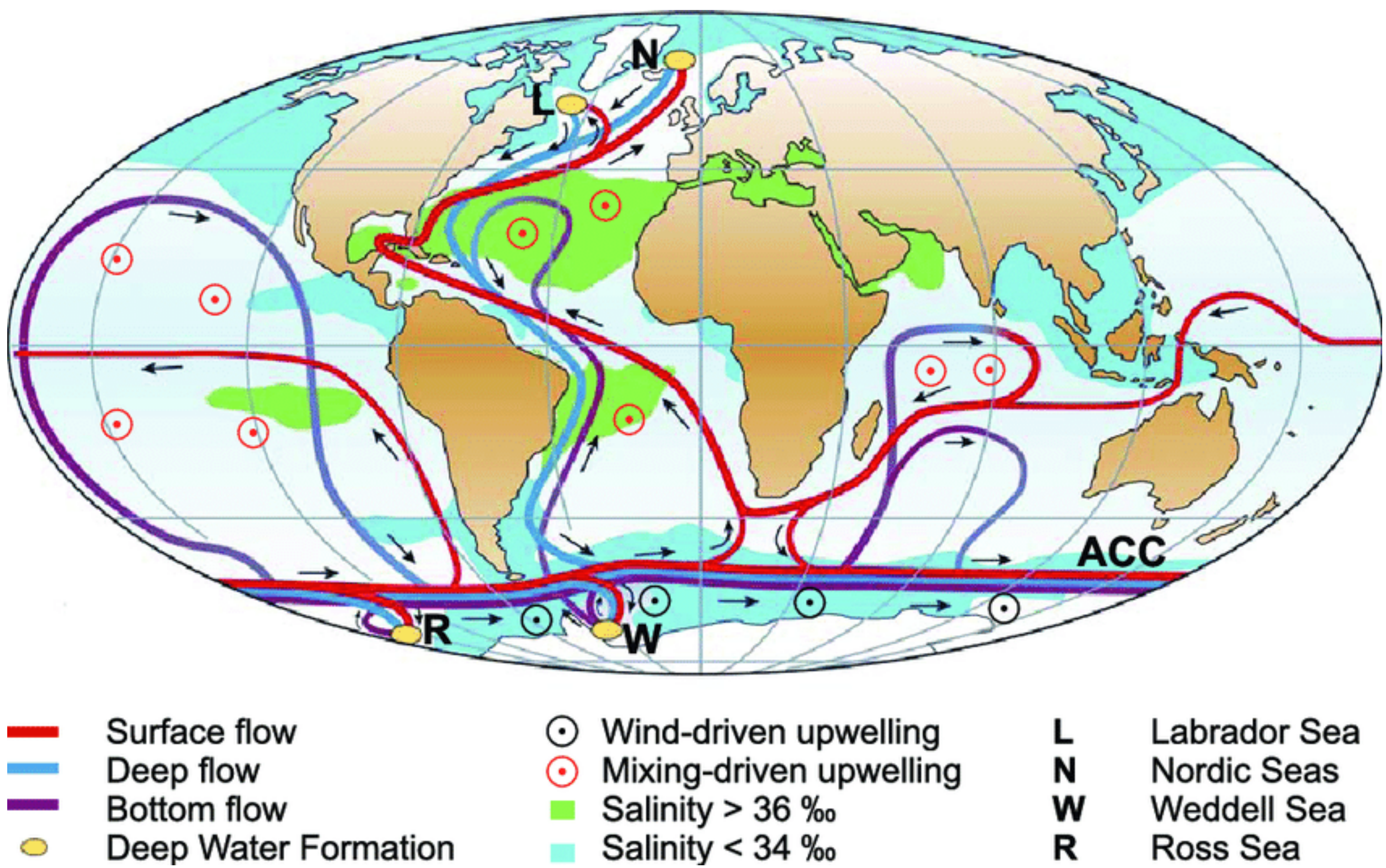
Glacier (α ~ 0.6)

Fresh snow (α ~ 0.9)



Why is the cryosphere important?

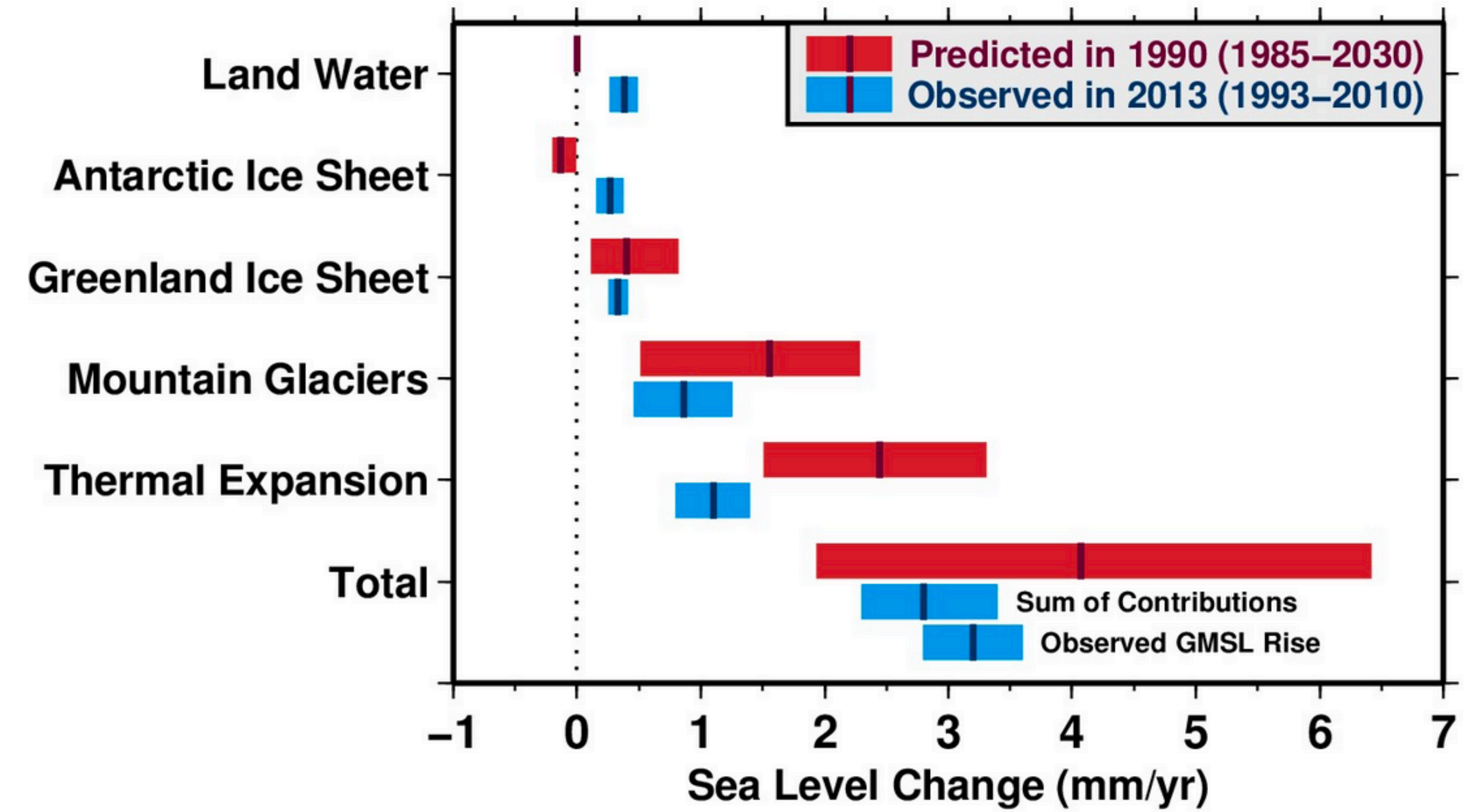
- The cryosphere is tightly coupled with the global climate system with important linkages and feedback to **the thermohaline circulation (THC)**
- The influx of freshwater from the melting ice causes ocean freshening and therefore has the potential to disrupt or slow down the THC.



Source: Rahmstorf, 2002

Why is the cryosphere important?

- It is one of the factors of largest uncertainty among contributors to mean sea level rise



Source: 2013 IPCC AR5 Climate Change Report

Why is the cryosphere important?

- While mountain glaciers are the largest contributors to sea level within the current climate, ice sheets in Greenland and Antarctica hold the potential to eventually dwarf other cryospheric contributors to sea level rise

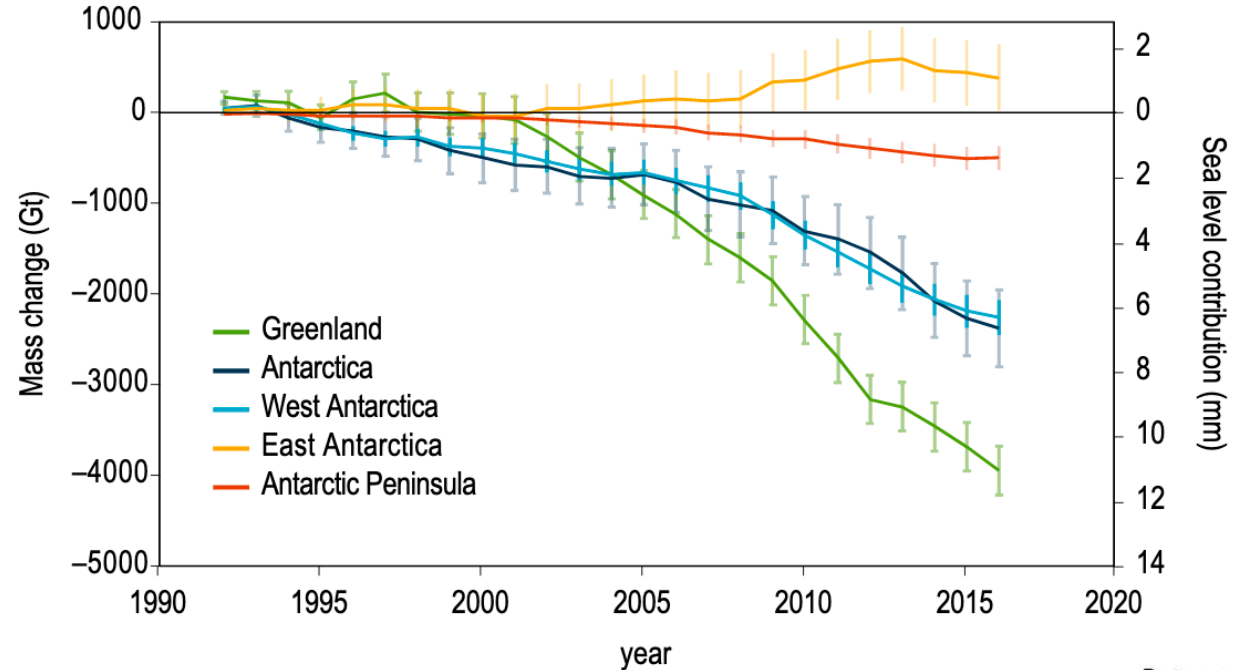
Cryosphere Component	Area (10^6 km^2)	Volume (10^6 km^3)	Potential Sea-level rise (m)
Sea ice	19 - 27	0.019 - 0.025	0
Land snow	1.9 - 45.2	0.0005 - 0.005	0.001 - 0.01
Permafrost	22.8	0.011 - 0.037	0.03 - 0.10
Mountain glaciers & ice caps	0.51 - 0.54	0.05 - 0.13	0.15 - 0.37
Greenland Ice Sheet	1.7	2.9	**7.3**
Antarctic Ice Sheet	12.3	24.7	**56.6**

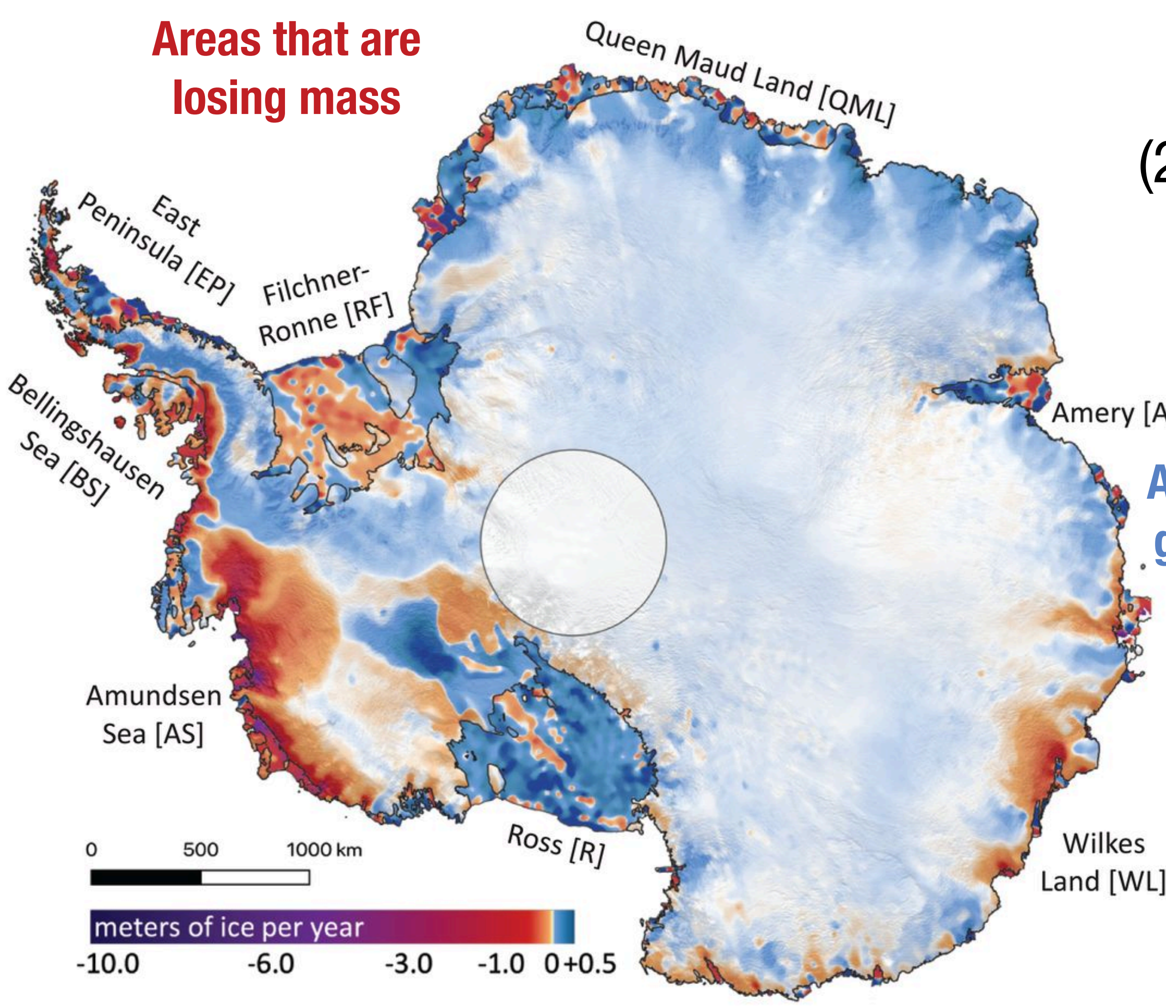
Source: 2013 IPCC AR5 Climate Change Report

How is the Cryosphere changing?

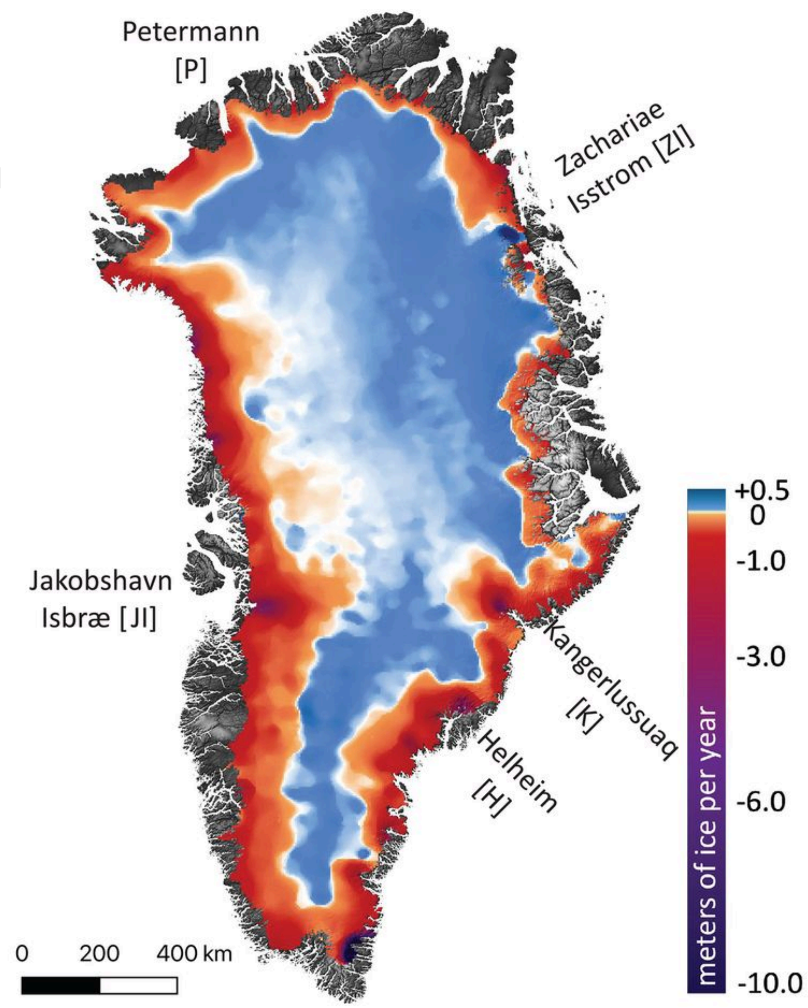
Average mass loss:

- Greenland - 281 Gt/yr
- Antarctica -125 Gt/yr



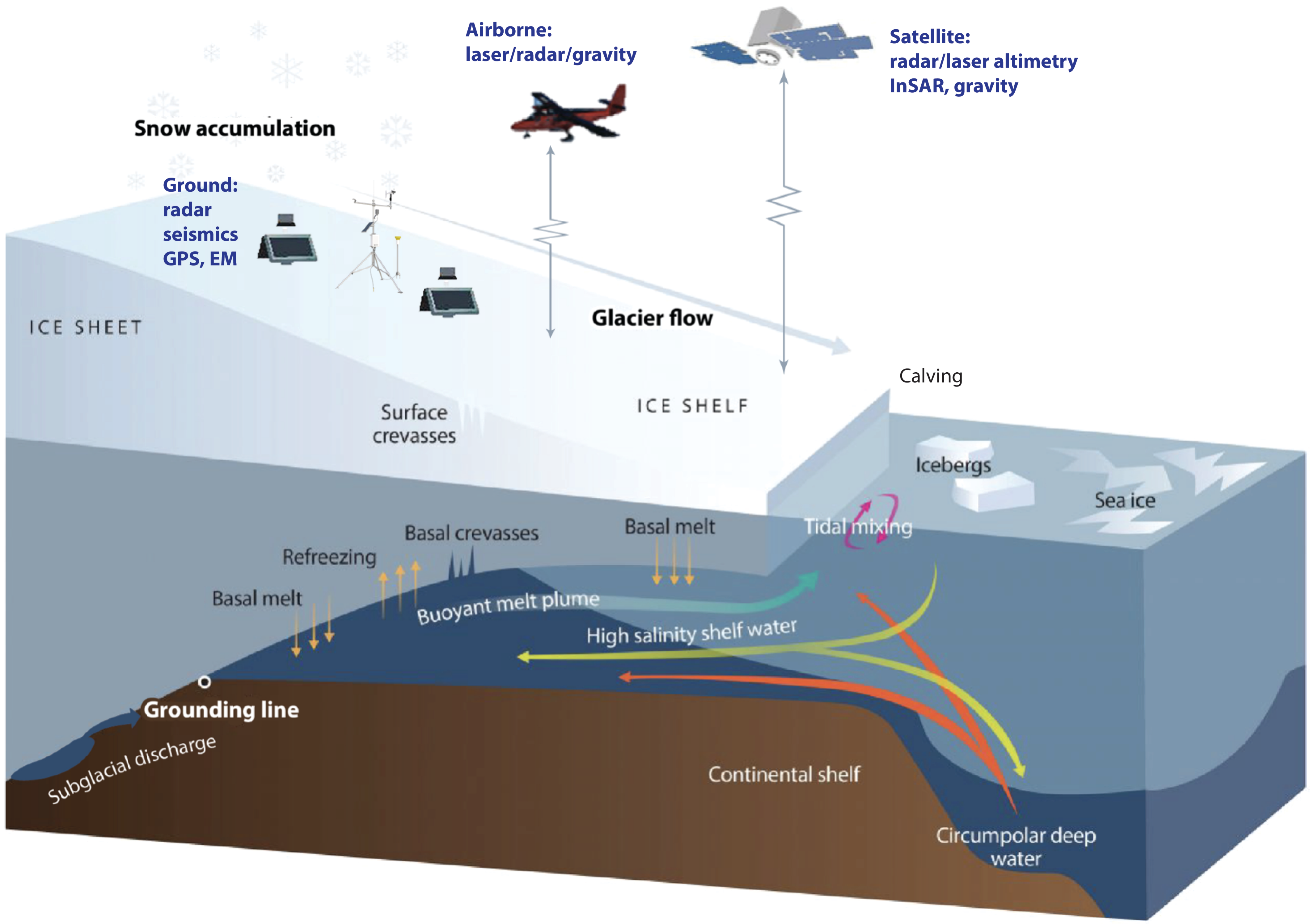


Ice sheet mass losses (2003 to 2019) based on ICESat & ICESat-2 measurements



Source: (Top) IPCC SROCC 2019; (Bottom) Smith et al., Science, 2020

Primary processes that drive ice mass loss

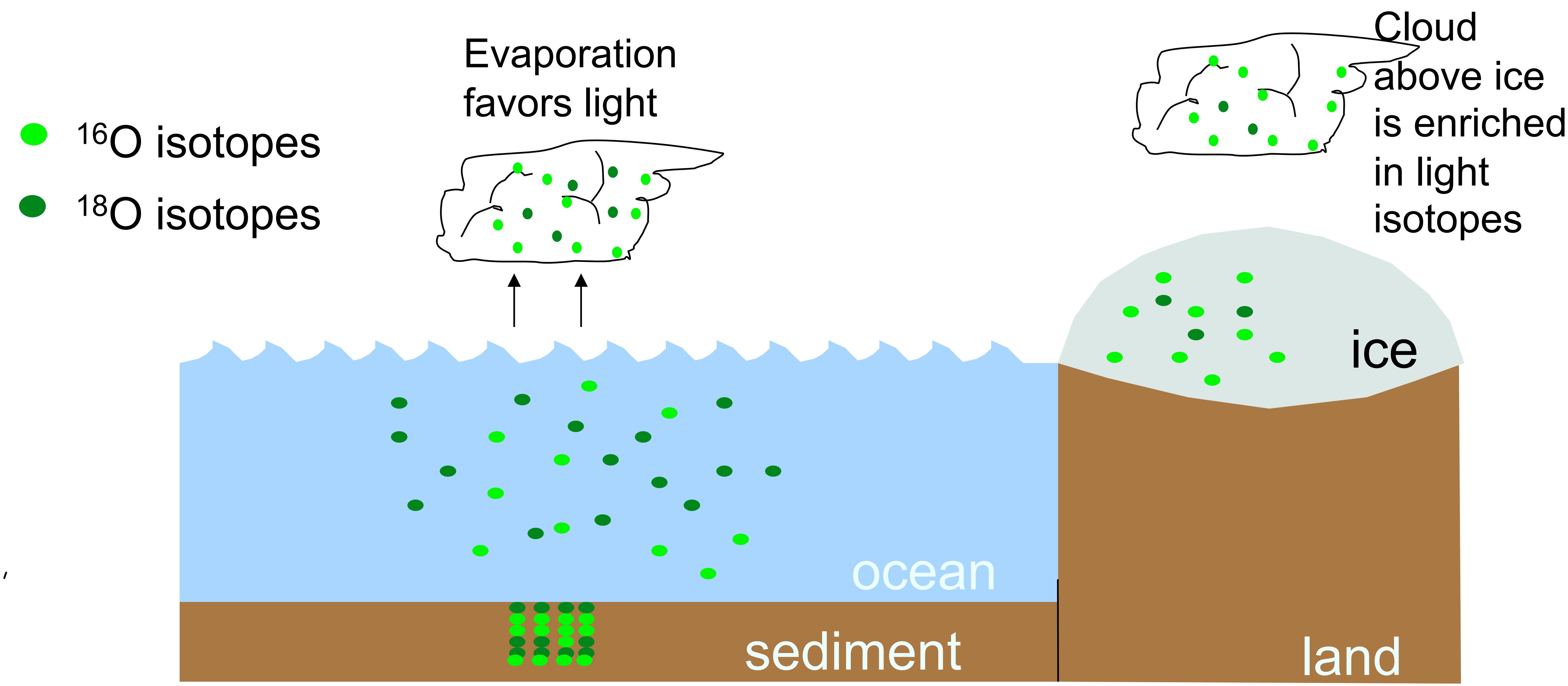


Source: Modified from Scambos et al., Global & Planetary Change, 2017

Earth’s icy history

How do we know about past ice?

$\delta^{18}O$ from ocean sediments as proxy for ice volume



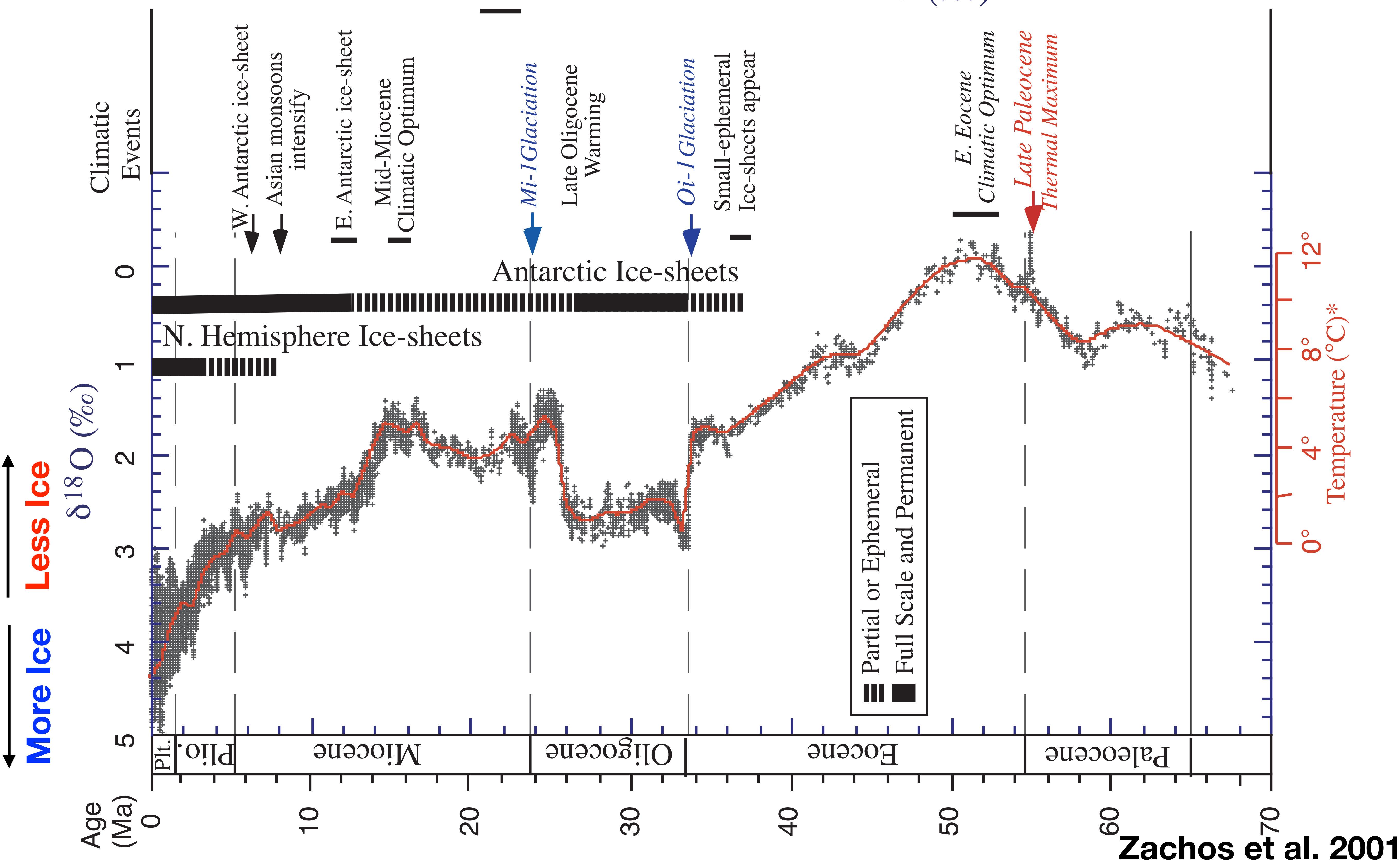
When water evaporates from the ocean, it preferentially takes light oxygen isotopes with it, its leaves heavier oxygen in the ocean. When the water is precipitated as snow, it deposits H20 with light oxygen. The H20 left in the ocean has more heavy oxygen (it is enriched).

Schematic from C. Bitz

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) * 1000\ ^o/_{oo}$$

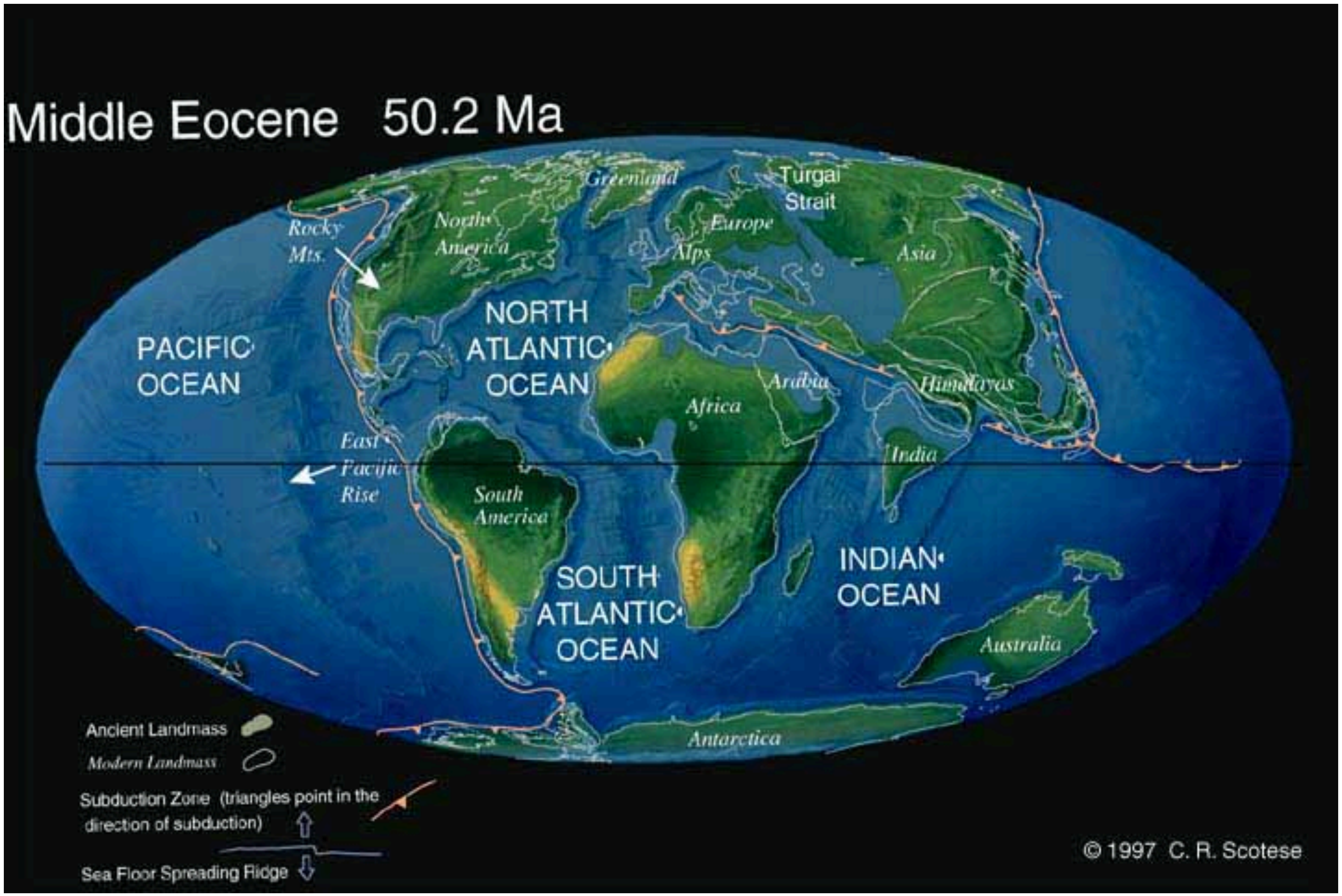
When?

Ocean sediment $\delta^{18}O$ (‰)



Zachos et al. 2001

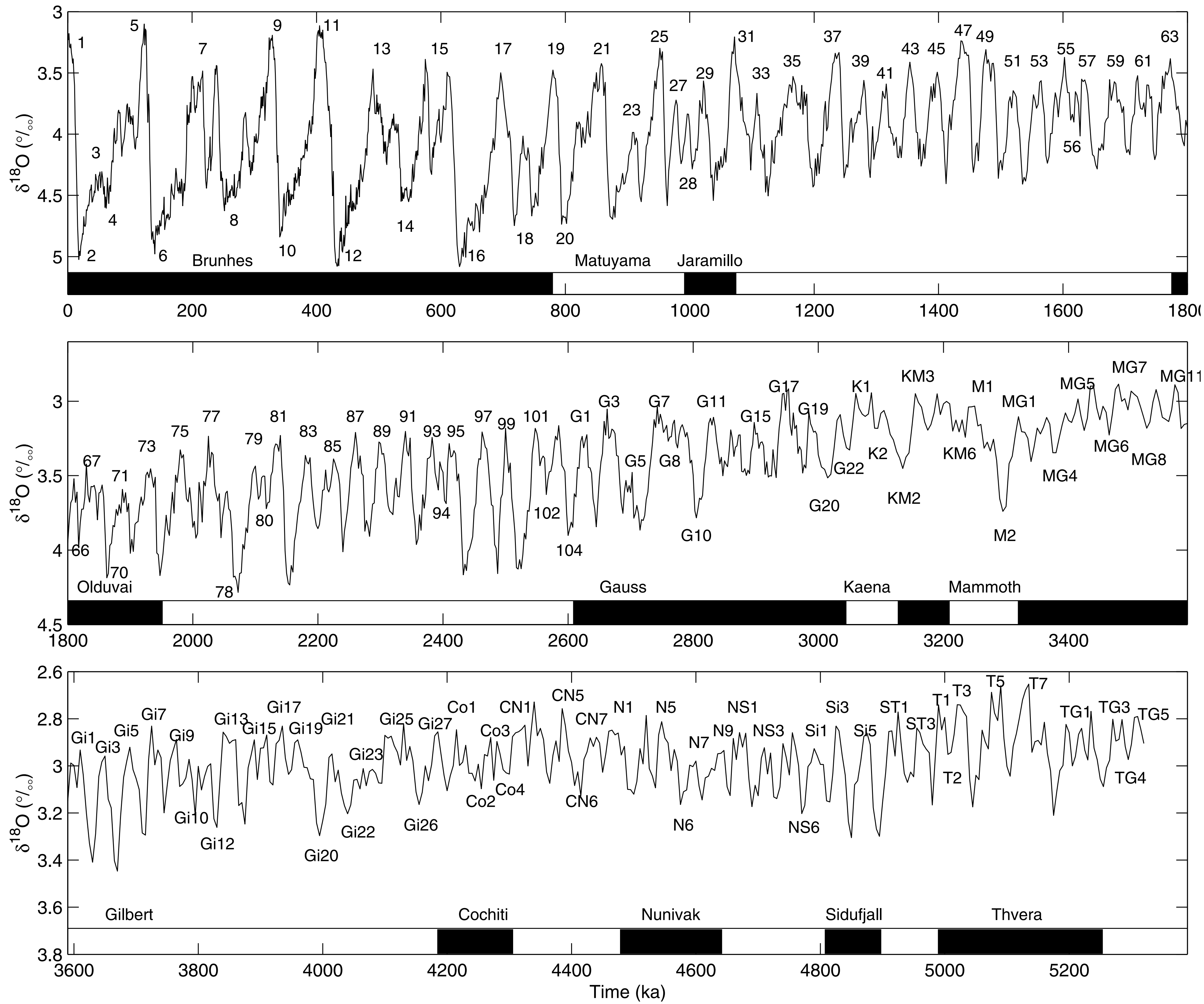
Eocene - No Ice in Antarctica



Eocene - No Ice in Antarctica

(Not actual picture of Antarctica…but it looks cool)

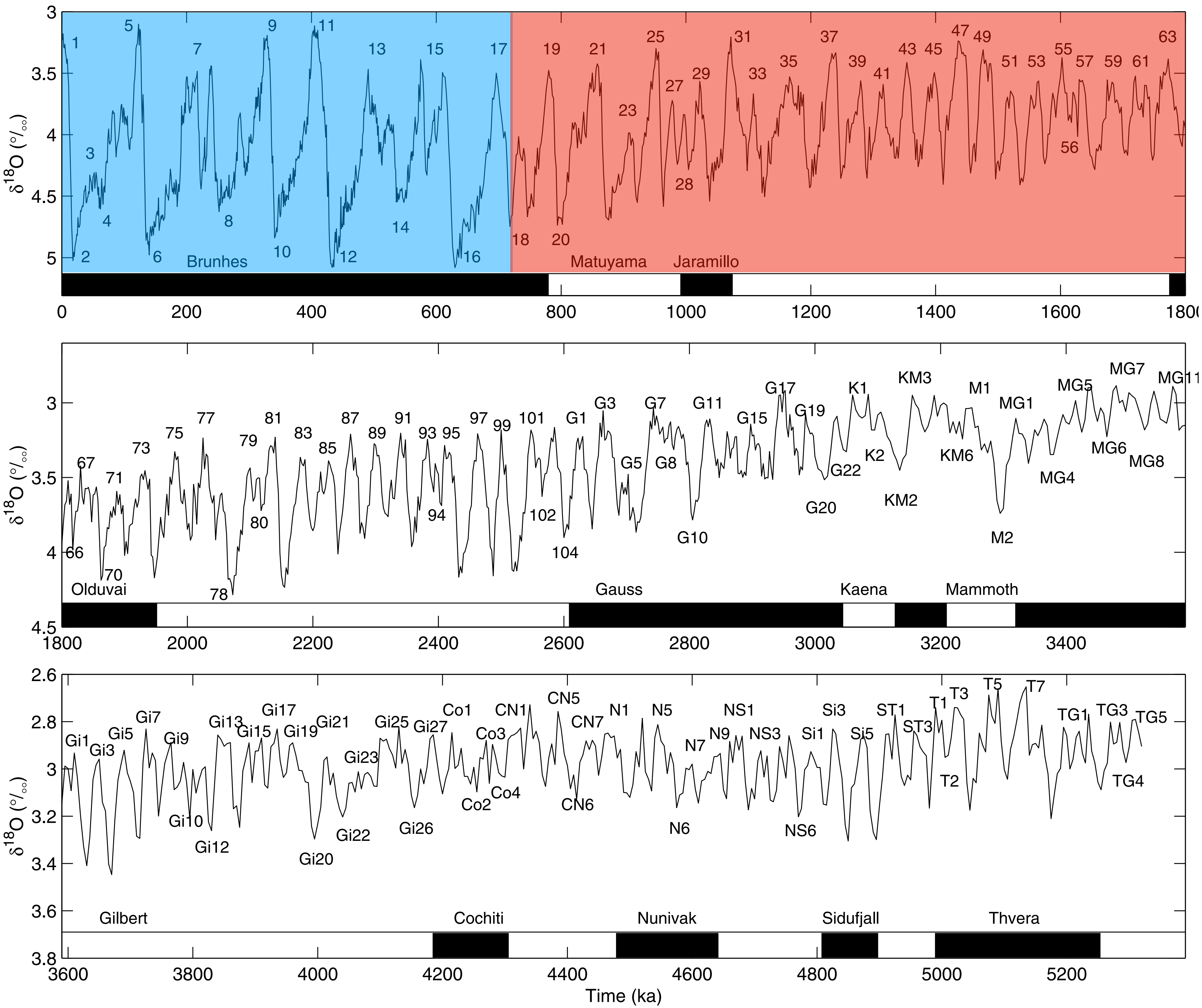
When?



Lisiecki & Raymo 2005

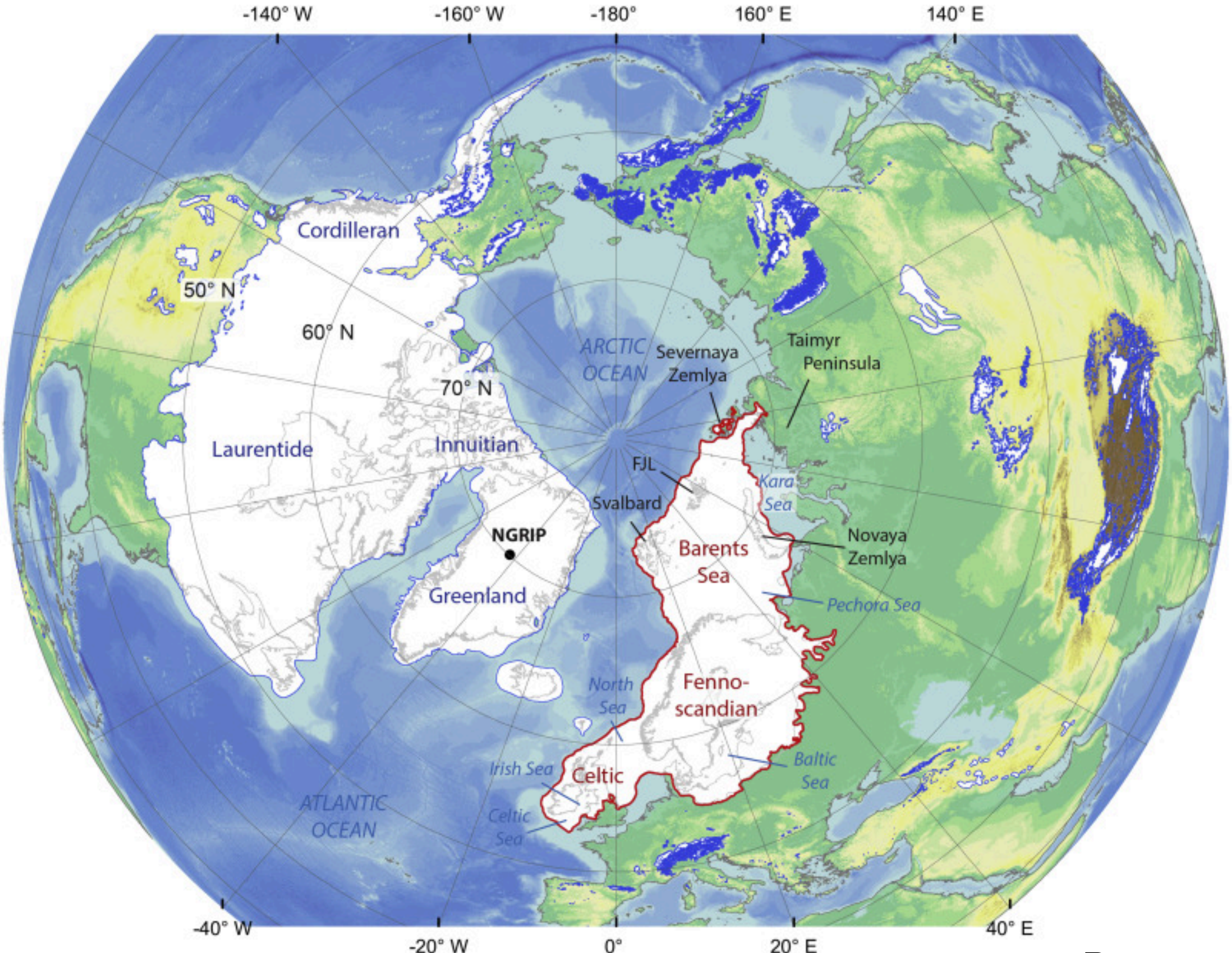
When?

Pleistocene - N. Hemisphere Ice Sheets



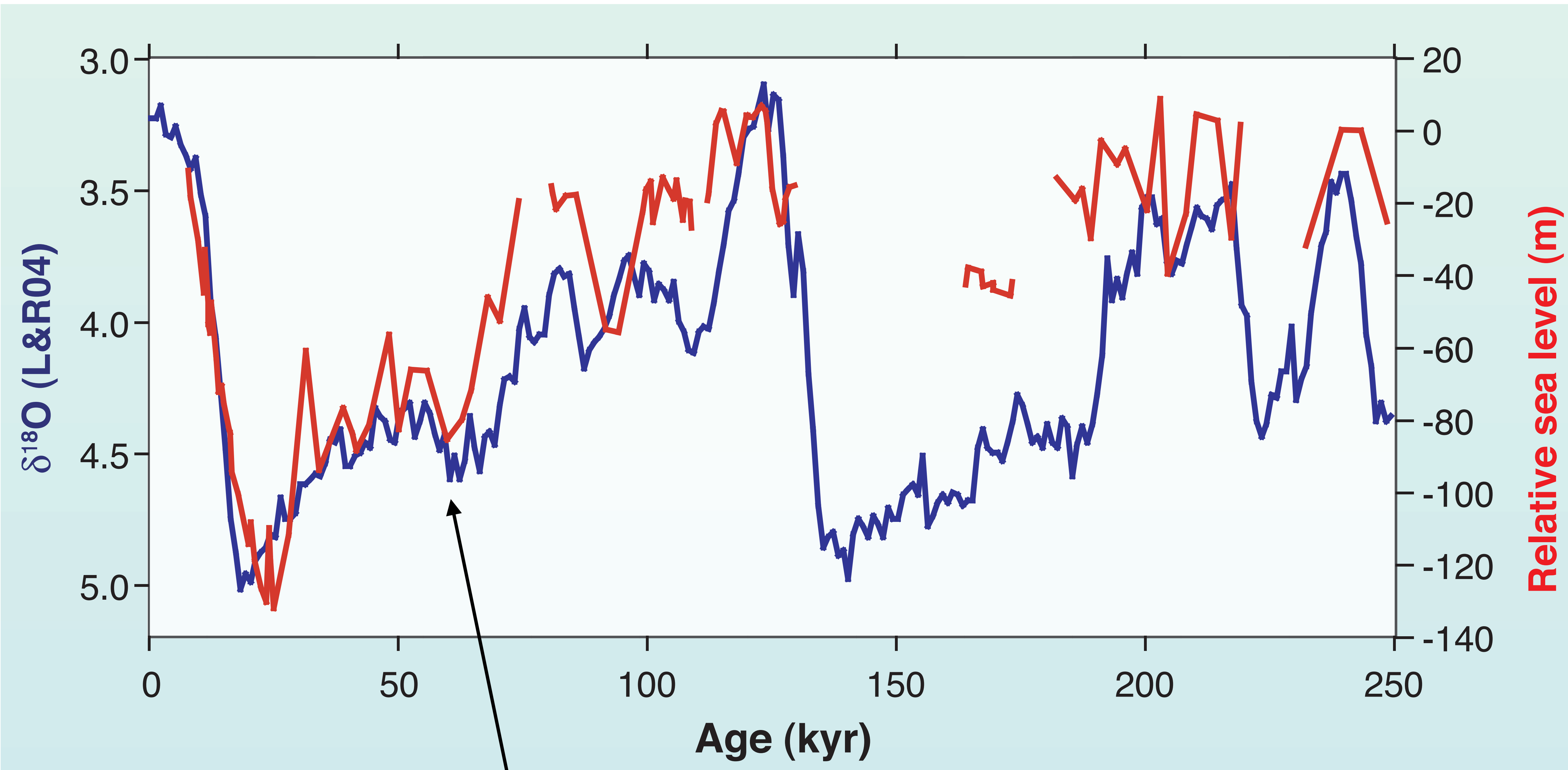
Lisiecki & Raymo 2005

Past NH Ice Sheets



Patton et al. 2016

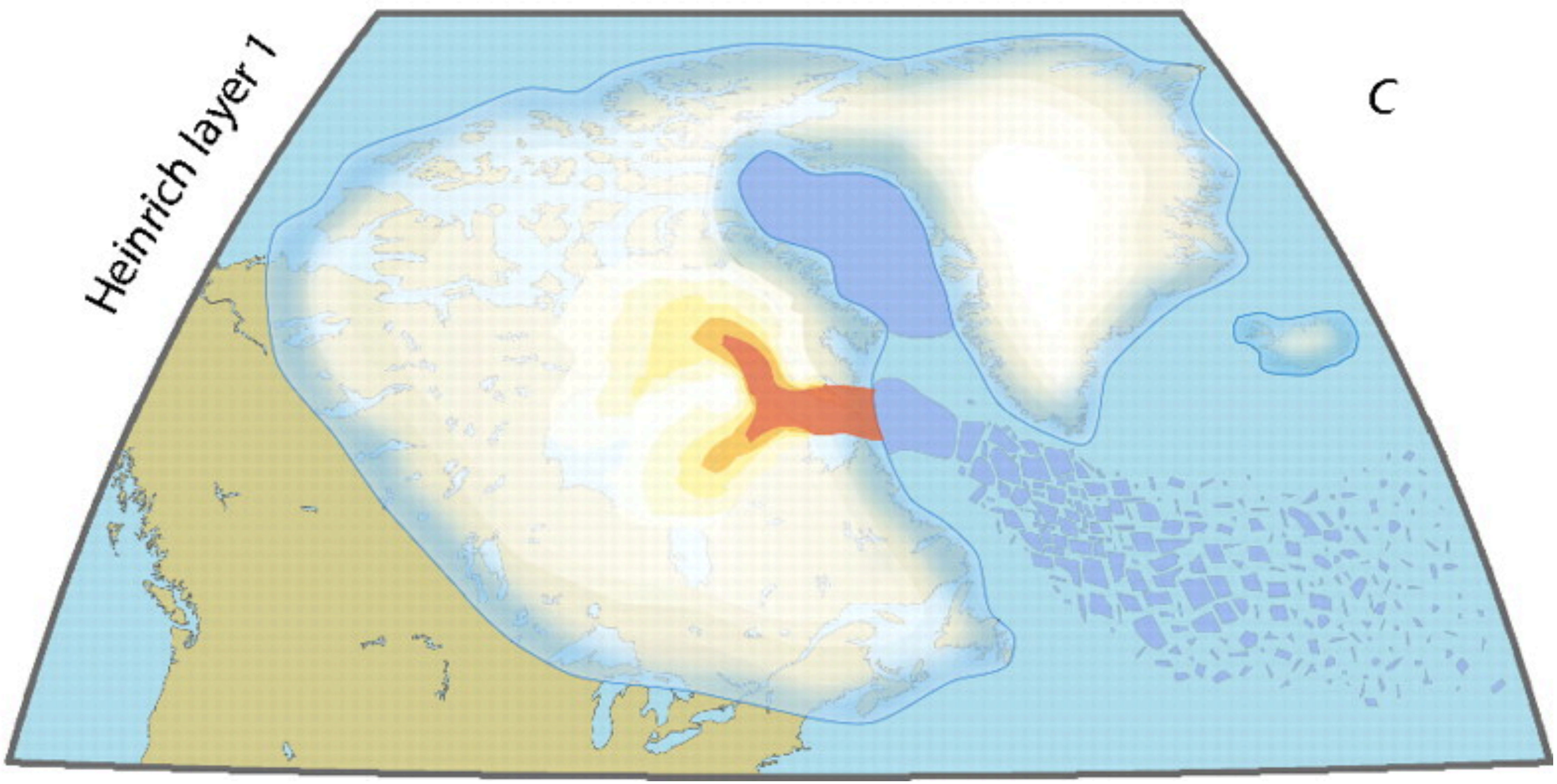
When?



Variations in glacial ice volume - Heinrich events
Changing ice sheet size? We'll talk about later in class

Denton et al. 2010 (from LR05)

Heinrich events - large discharges of ice from Laurentide Ice Sheet

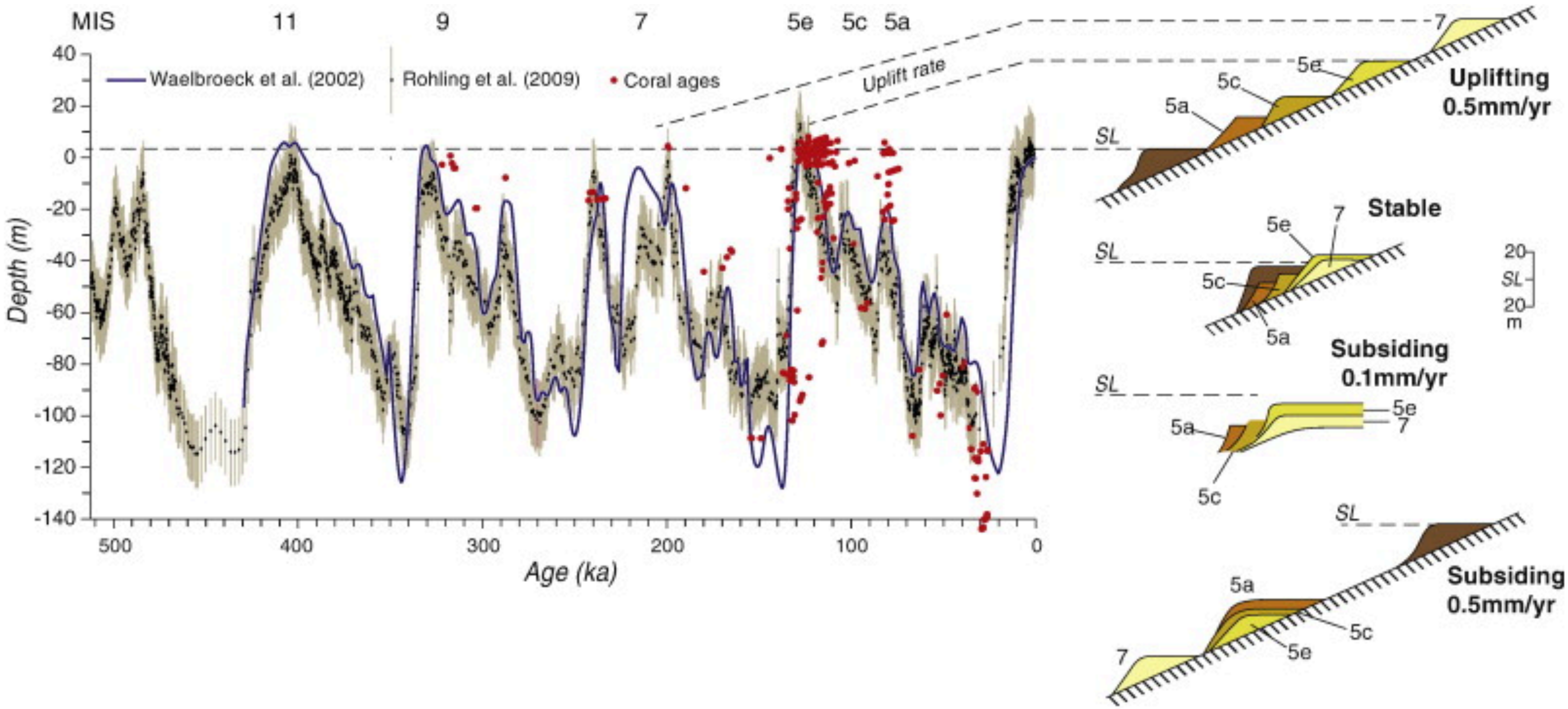


More to come on this when we talk about ice streams

Alvarez-Solas & Ramstein 2011

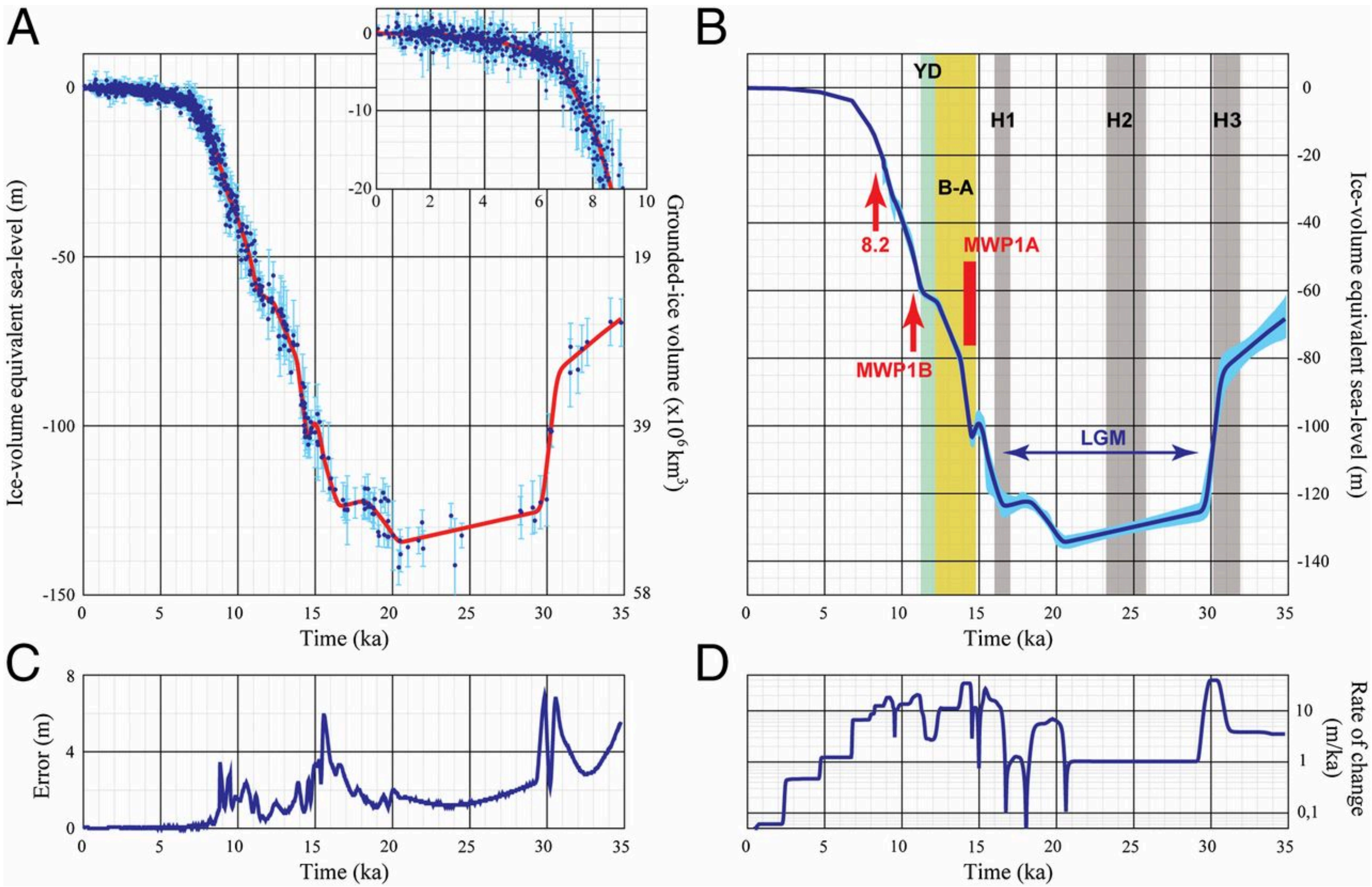
How do we know about past ice?

Fossil coral depth as a proxy for past sea level



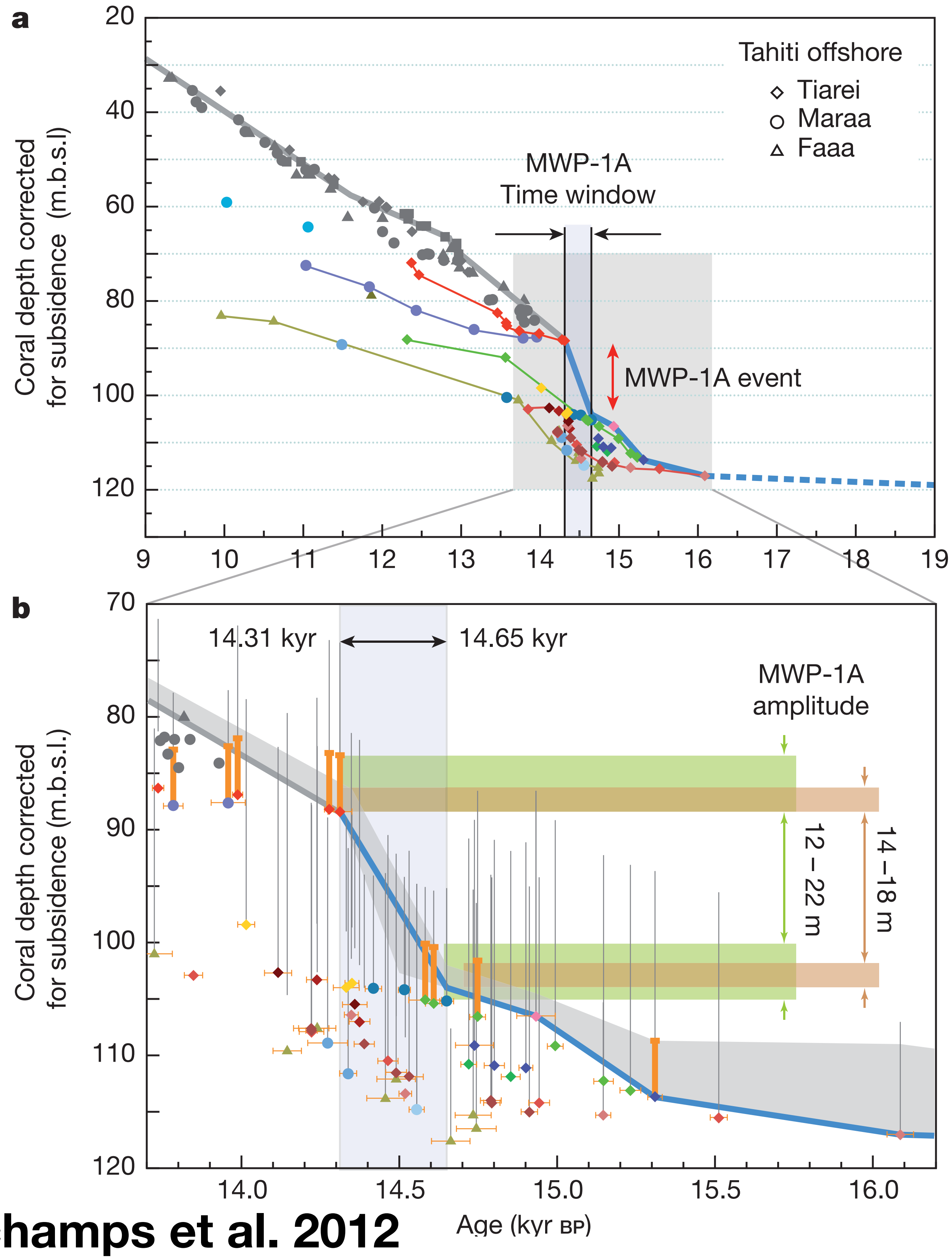
"…corals occupy a narrow vertical depth range and have good geological preservation potential." -Woodroffe & Webster 2016

When? (how fast)



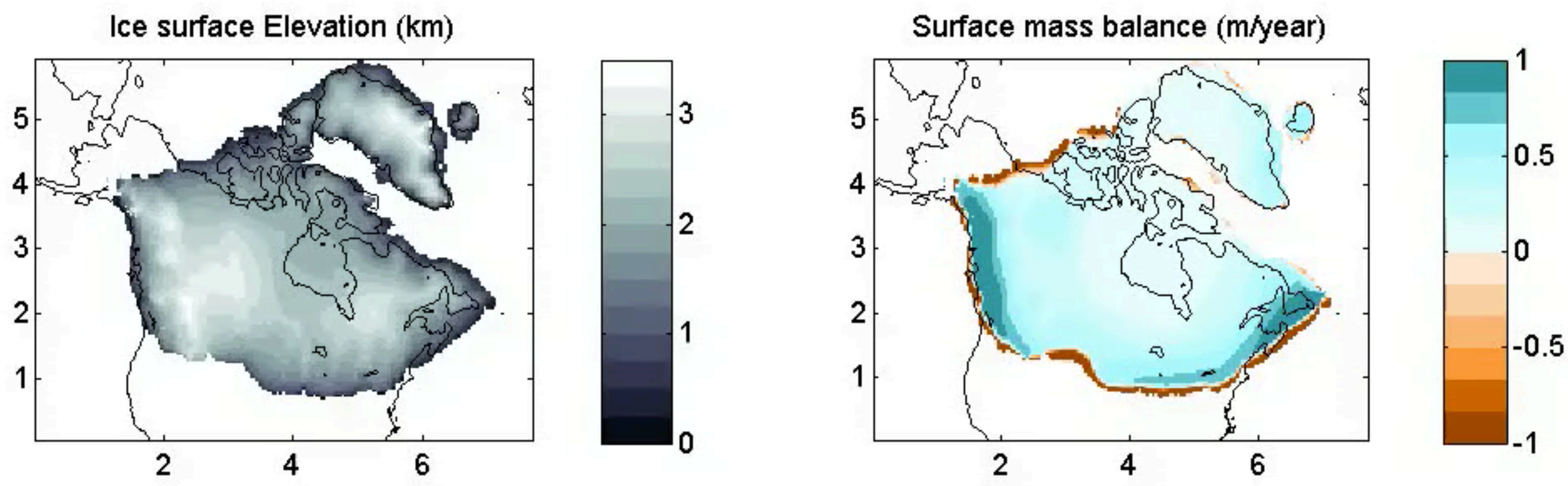
Lambeck et al. 2014

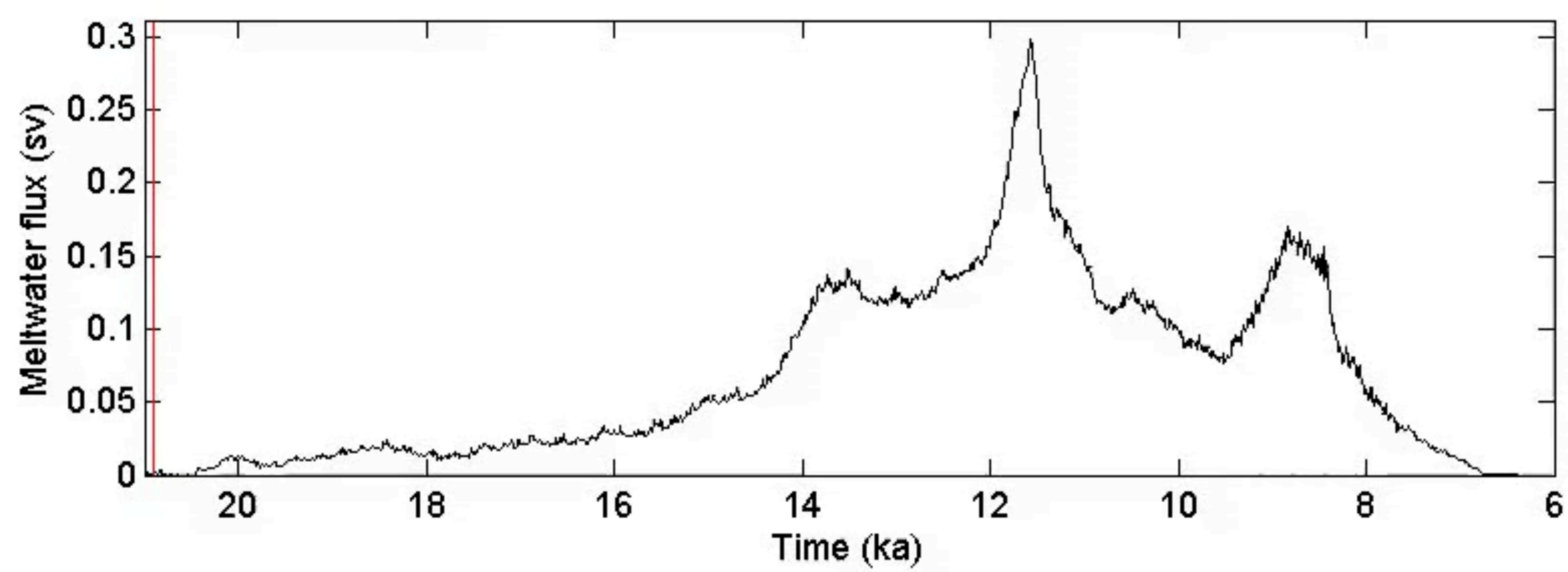
When? (how fast)



Deschamps et al. 2012

Meltwater Pulse 1A - fastest sea level rise in geological record (10-20 meters in <500 years)

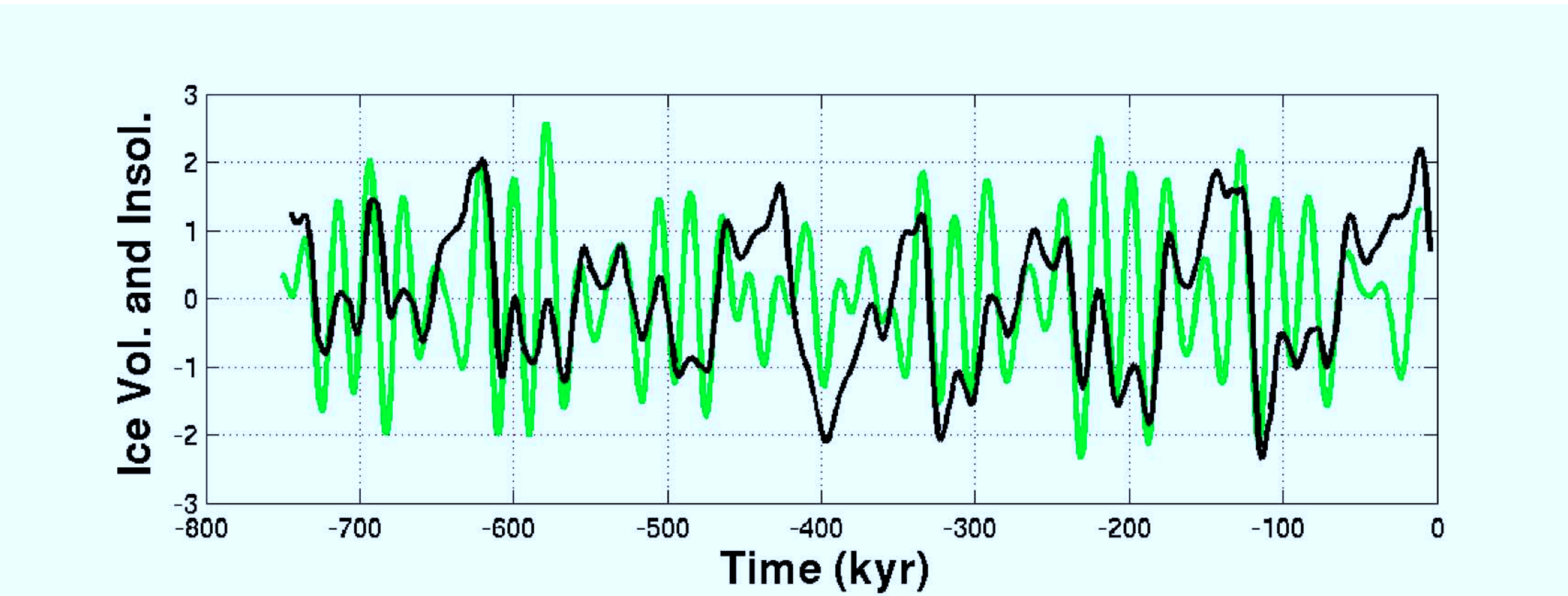




Gregoire et al. 2012

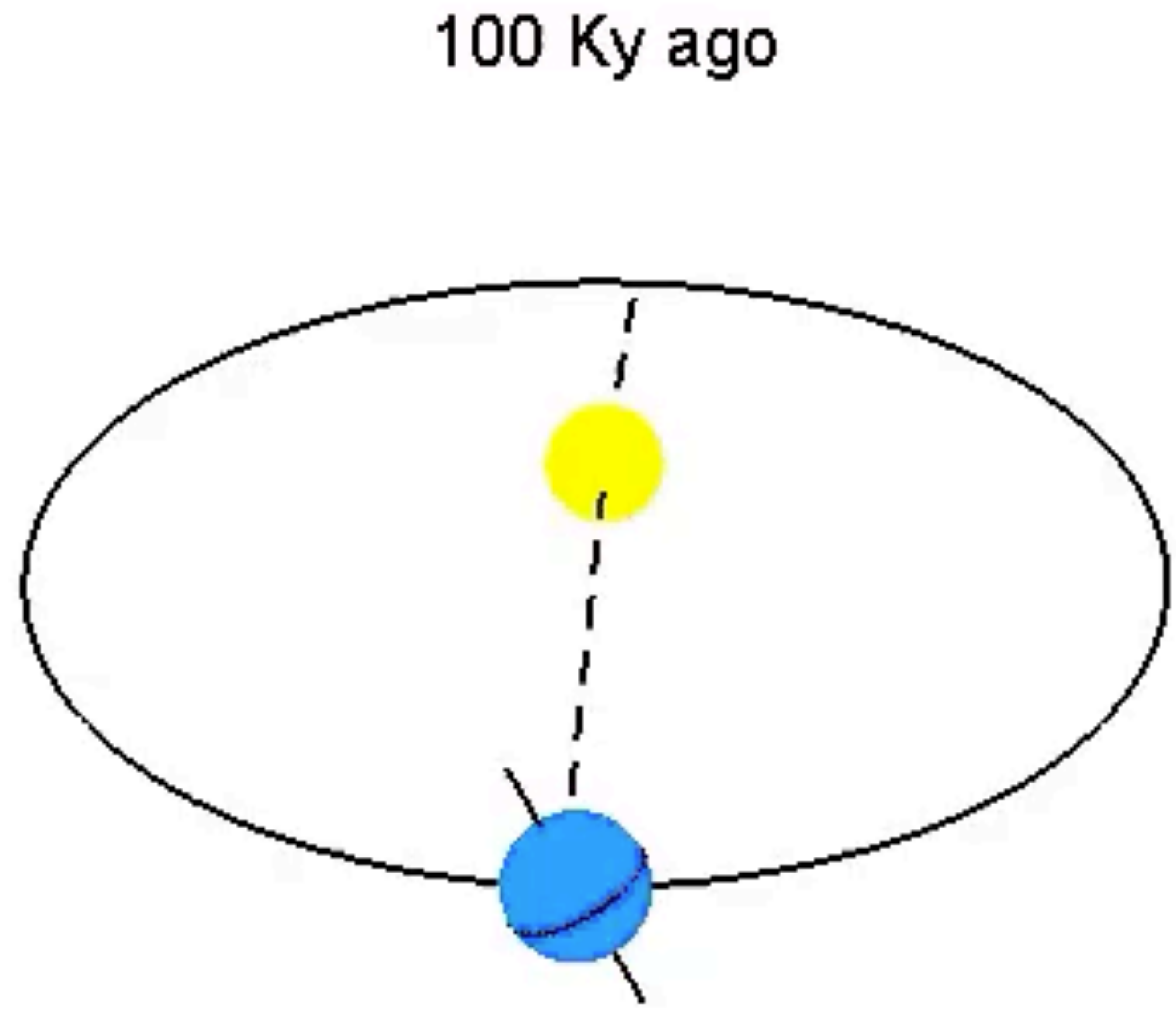
Glacial cycle models

Why are there glacial cycles?



Changing insolation from the sun

Milankovitch cycles



https://youtu.be/n5bKzBZ7XuM?t=15

Precession (wobble): 26 kyr
Obliquity (wobble angle): 40 kyr
Eccentricity (oval-ness): 100 kyr

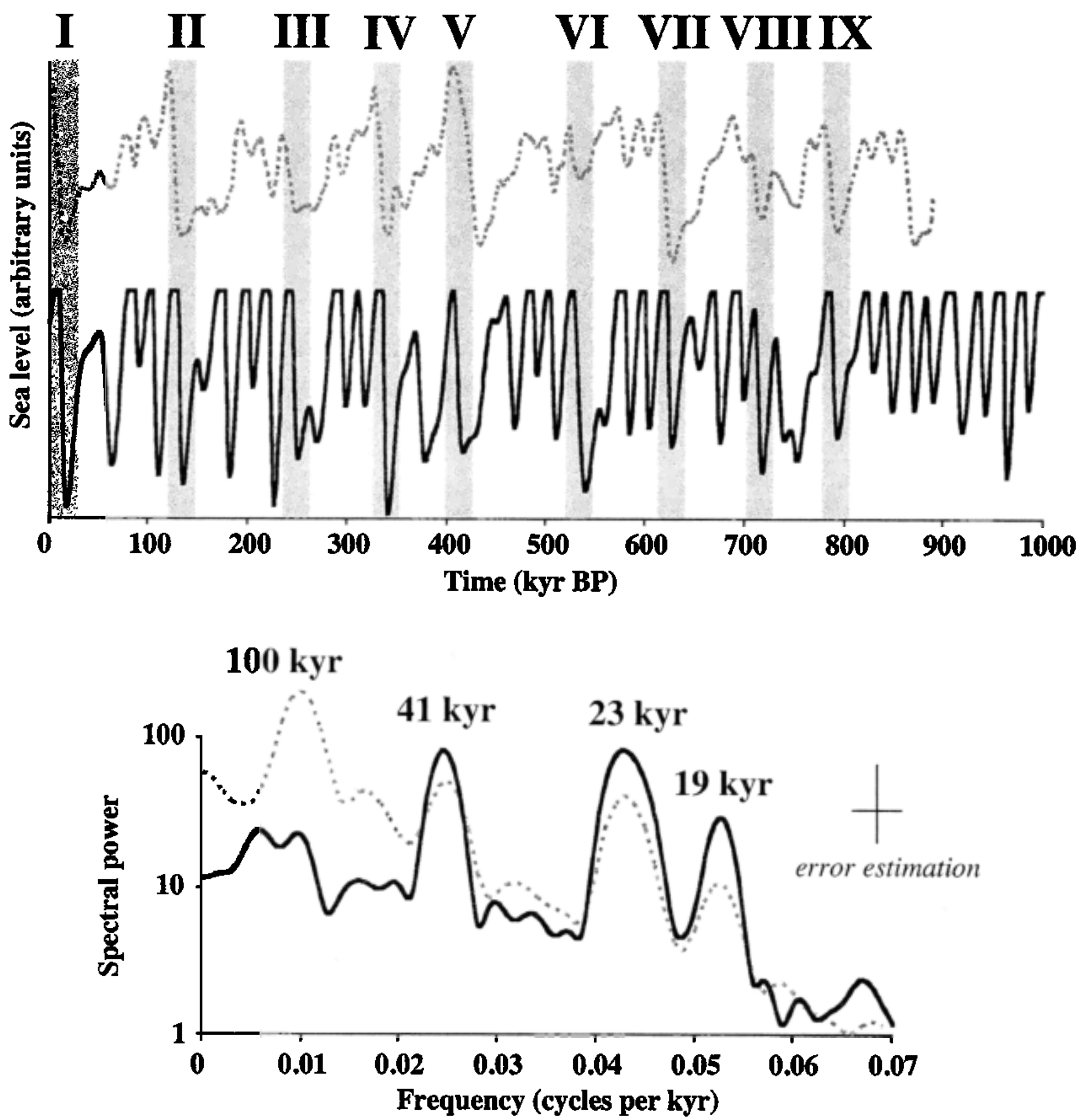
Glacial cycle models

To the board/
MATLAB!

Nonlinear Phase Locking

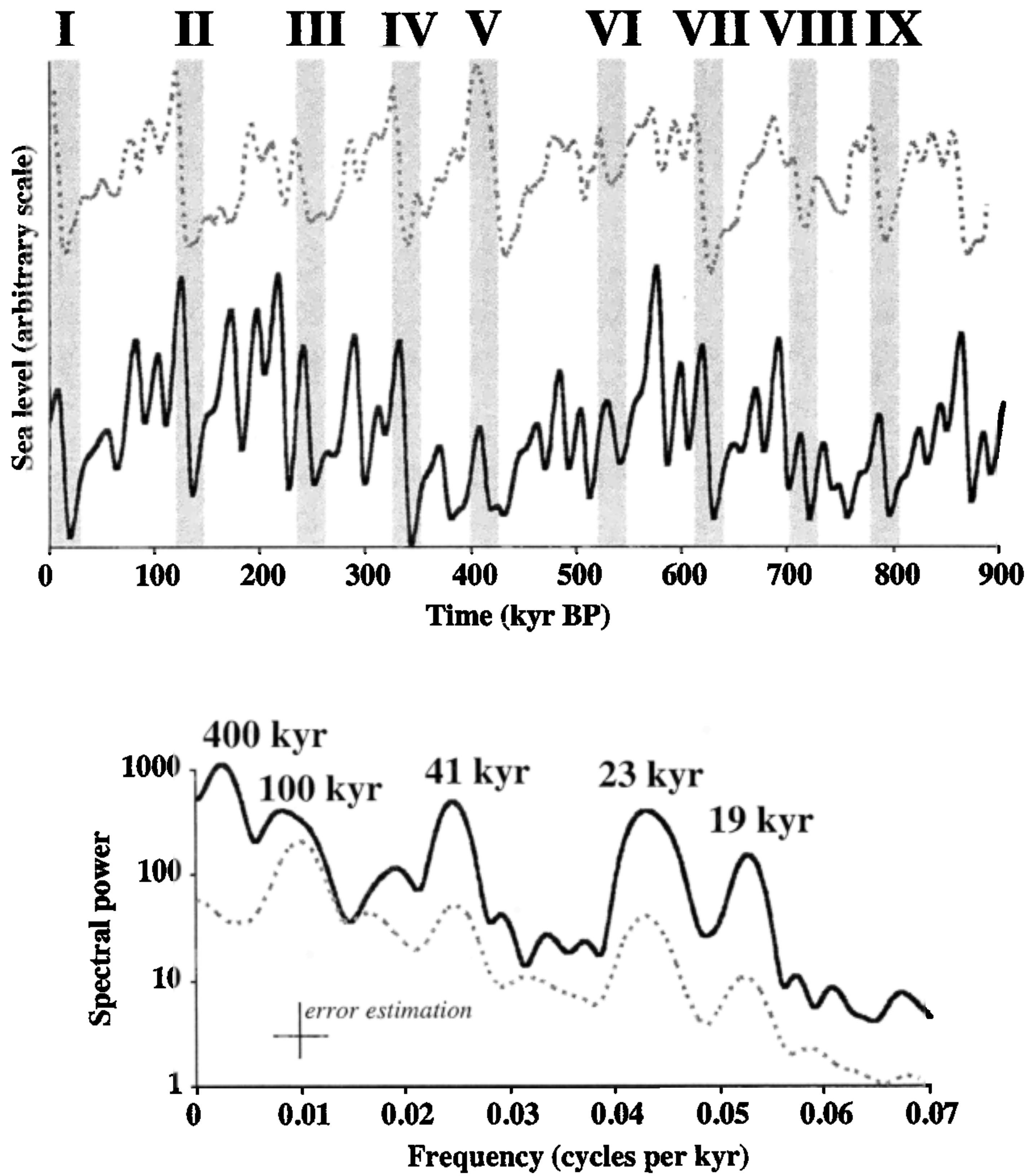
An oscillating process is “nudged” into sync with a (potentially very weak) external forcing with some period

https://www.youtube.com/watch?v=W1TMZASCR-I



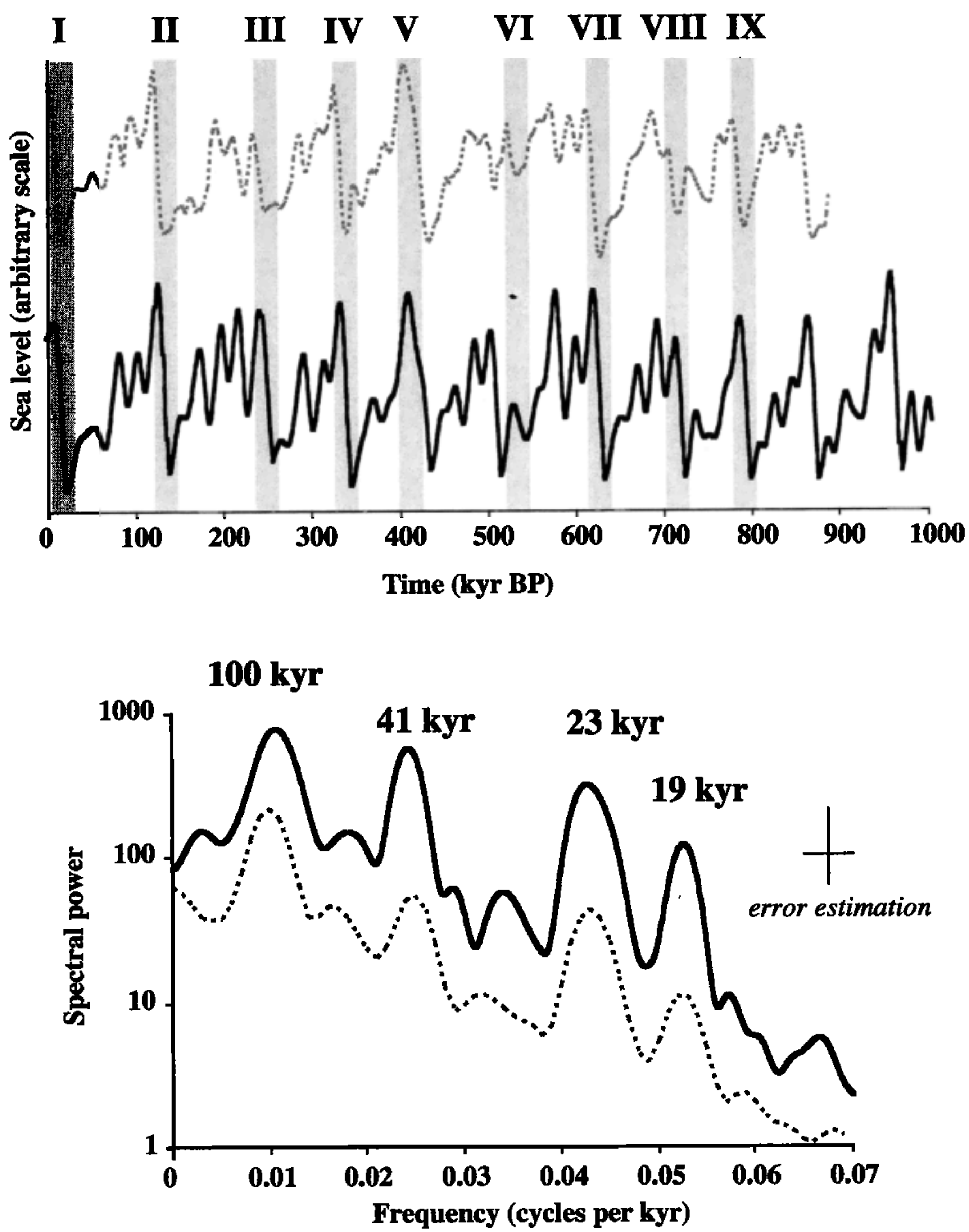
Calder model (from Paillard 2001)

Figure 9. Results from the *Calder* [1974] model. The threshold i_0 is equal to 502 W m^{-2}, and the ratio k_A/k_M is chosen equal to 0.22. The forcing i is the summer solstice insolation at 65°N [*Laskar*, 1990]. The result is very sensitive to these choices. The agreement with the record is quite poor, but this crude model still predicts the major transitions at the right time, a feature that many, more sophisticated models do not reproduce well. An isotopic record is given here for comparison [*Bassinot et al.*, 1994b].



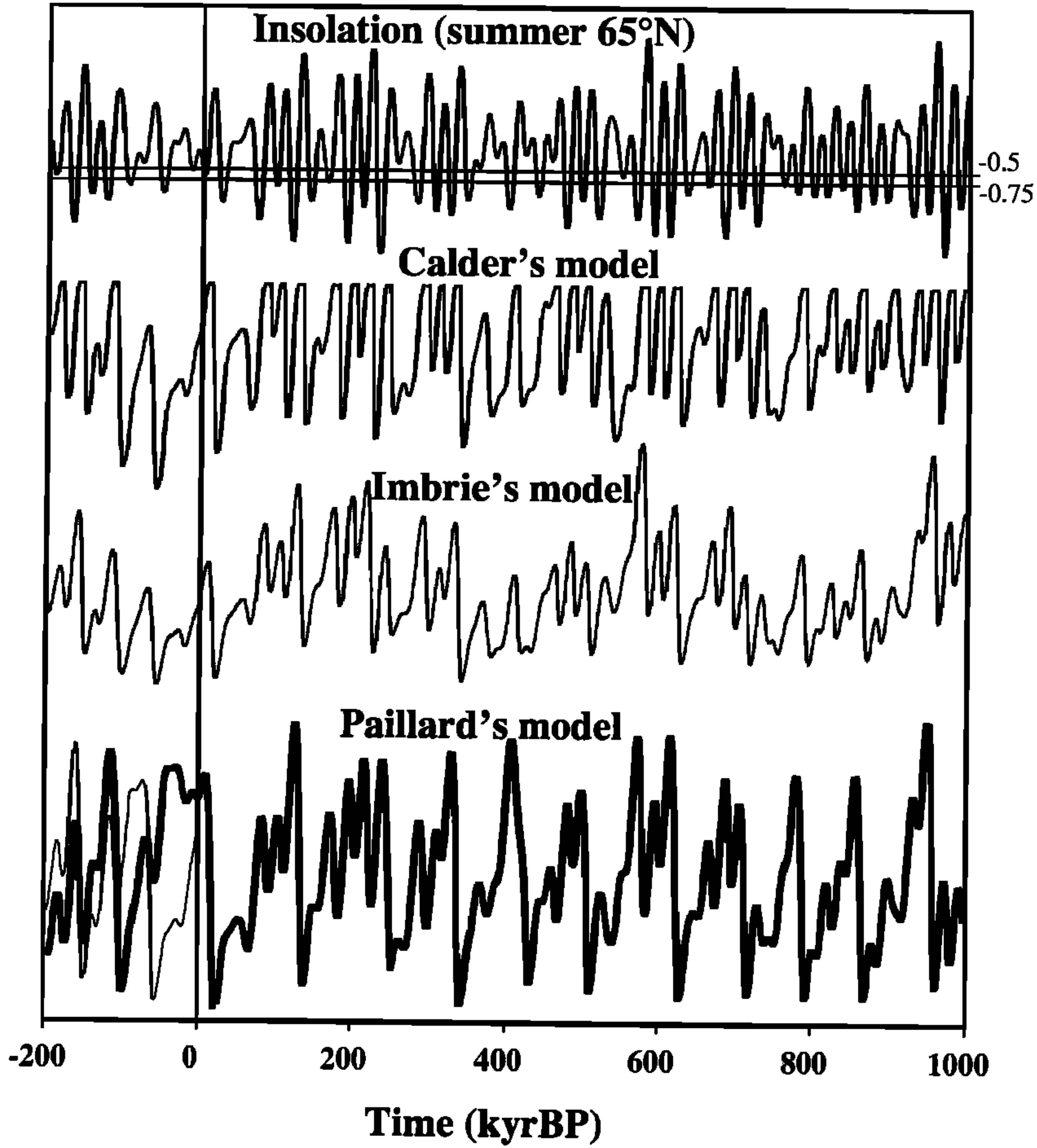
Imbrie² model (from Paillard 2001)

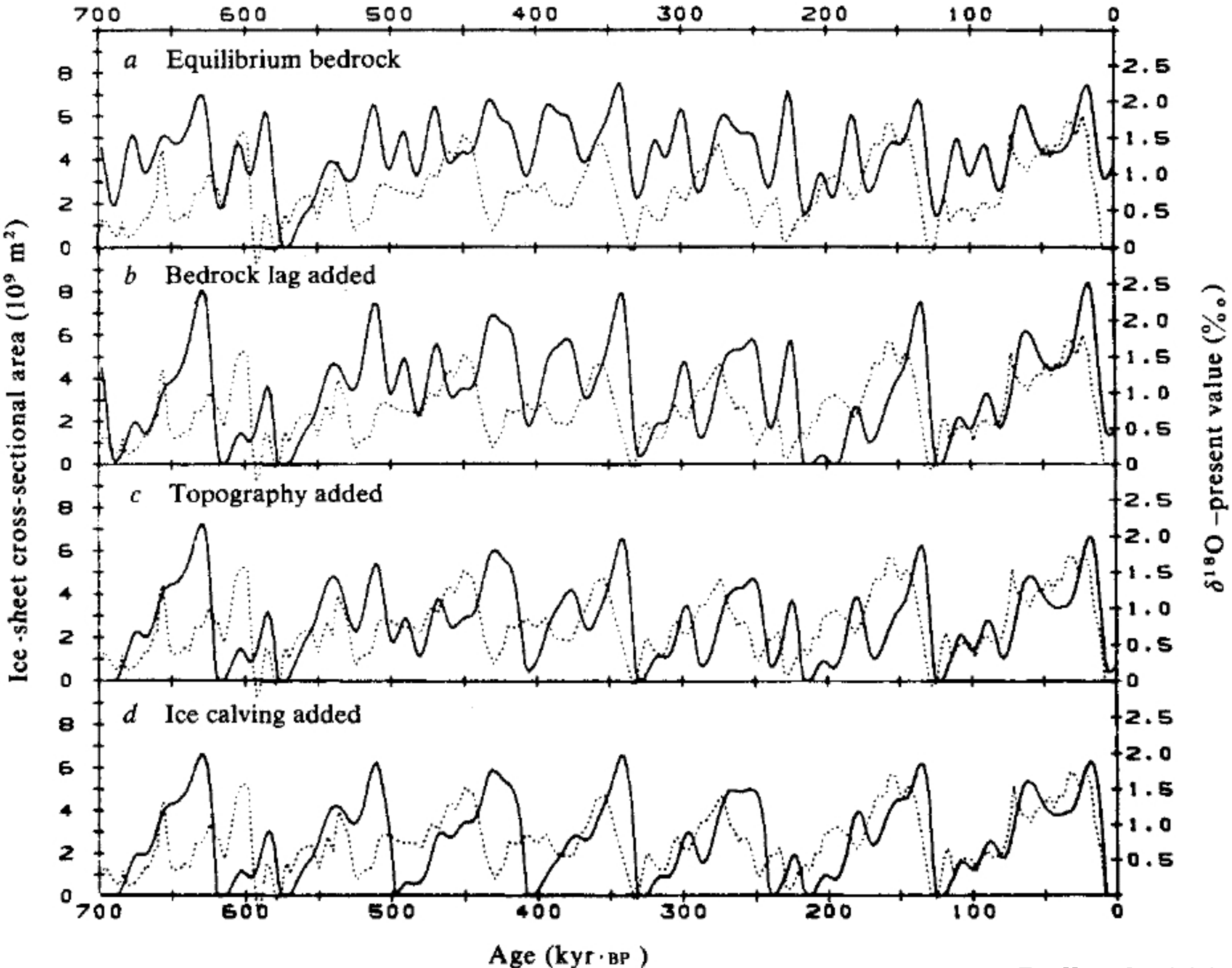
Figure 10. Same as Figure 9, but for the Imbrie model [*Imbrie and Imbrie*, 1980]. The forcing i is the summer solstice insolation at 65°N. The time constants are $\tau_M = 42$ kyr and $\tau_A = 10$ kyr.



Paillard model (from Paillard 2001)

Figure 13. Same as Figure 9, but for *Paillard*'s [1998] model. Threshold values are $i_0 = -0.75$ and $i_1 = 0$. Time constants are $\tau_i = 10$ kyr, $\tau_G = \tau_g = 50$ kyr, and $\tau_F = 25$ kyr.


Insolation (summer 65°N)
-0.5
-0.75
Calder's model
Imbrie's model
Paillard's model
-200
0
200
400
600
800
1000
Time (kyrBP)



Pollard 1982

Supplementary Video V1.

Simulated ice sheet change for the last 400 kyr with IcIES-MIROC model

Abe-Ouichi et al. (2013): A modern high-dimensional model of glacial cycles (climate+ice sheets+bedrock)