AOSC 680

The Cryosphere
: Introduction and Relation to Climate Change

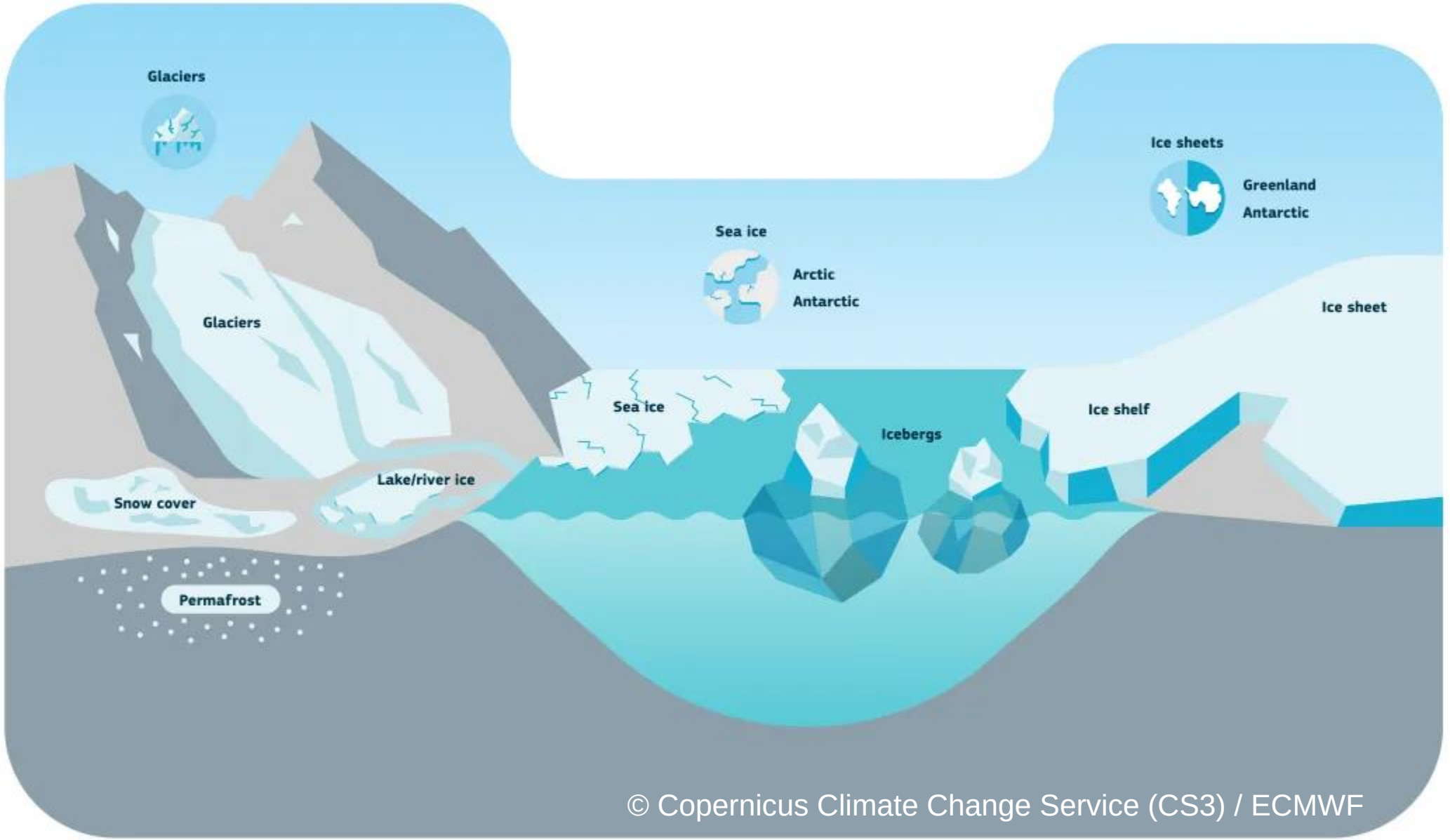
Chapters 1 and 9 of “The Cryosphere” by Shawn J. Marshall

Hee-Sung Jung
Nov. 7, 2024

Contents

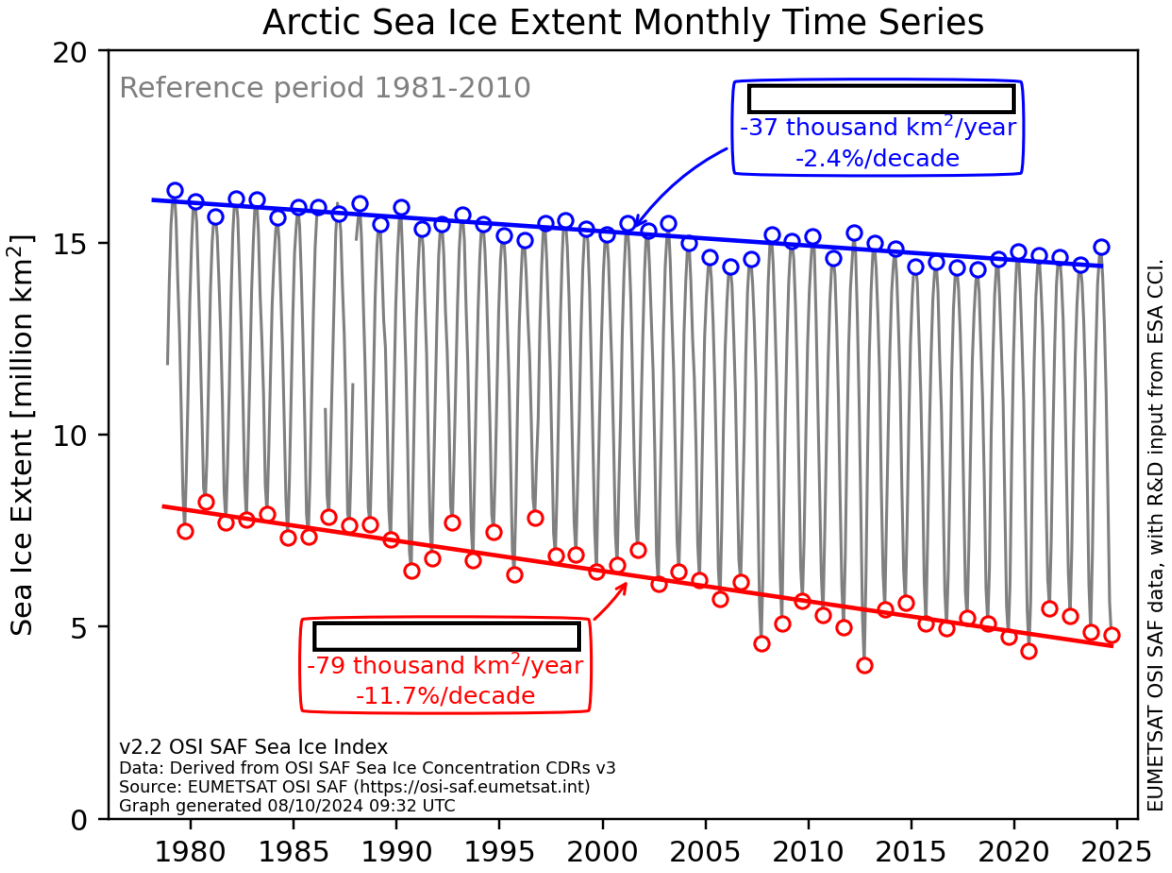
1. Introduction to the cryosphere

The cryosphere

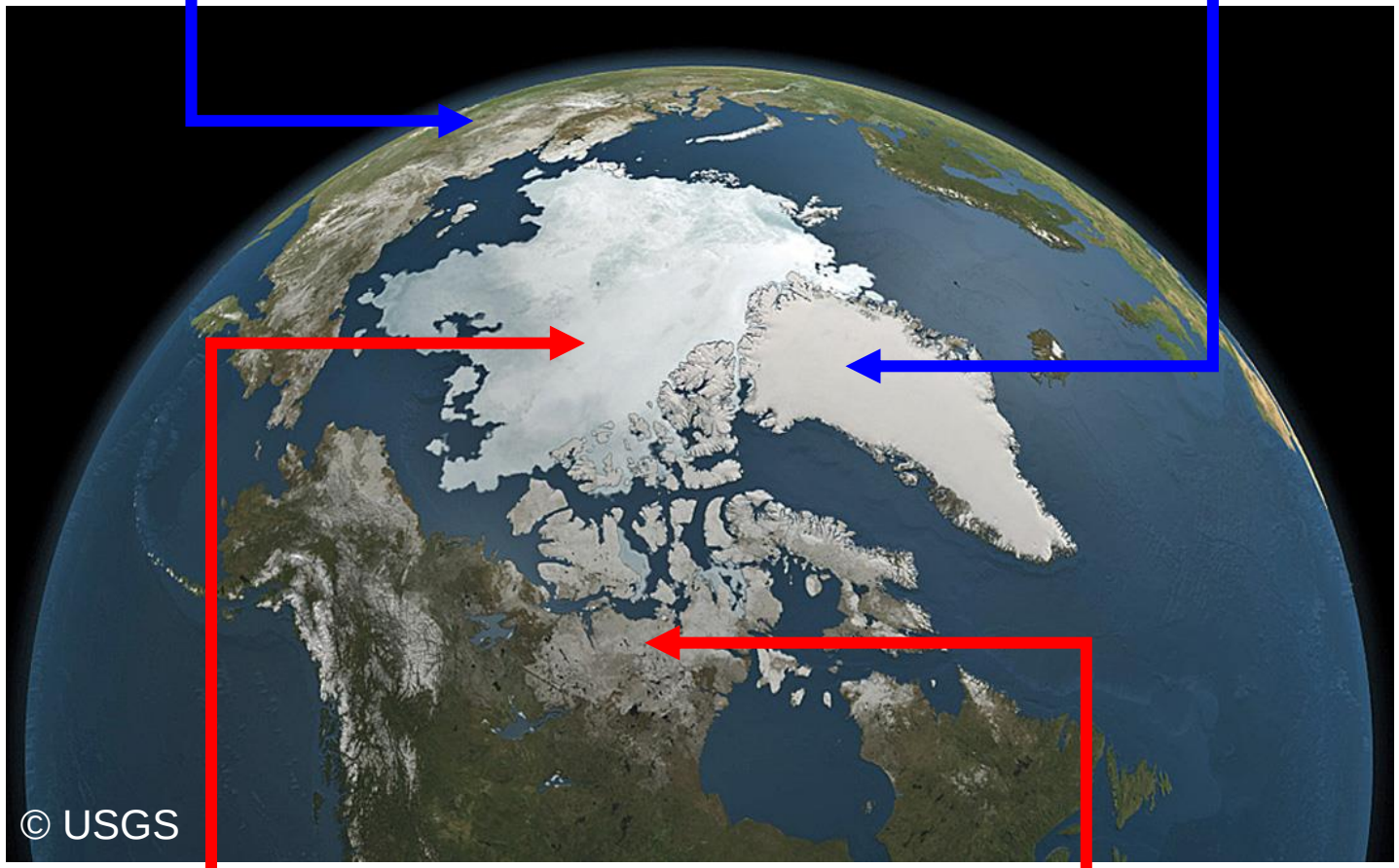


What is a characteristic property of the cryosphere?

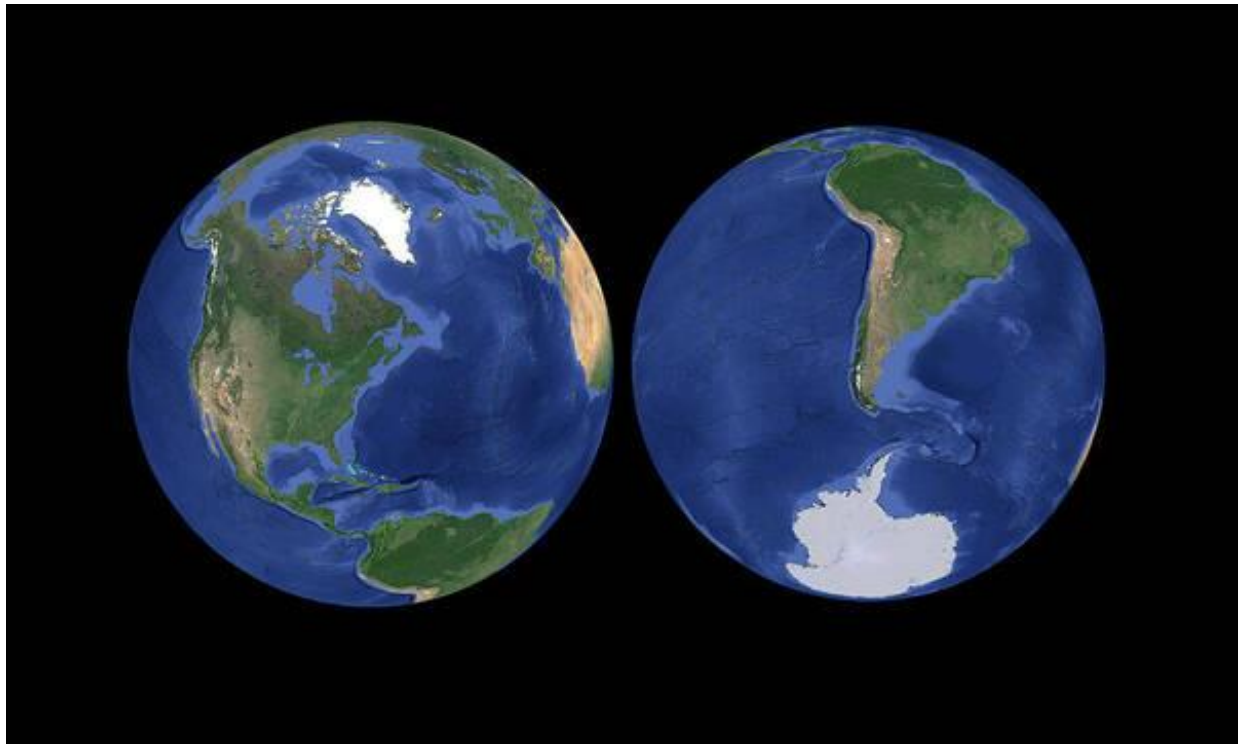
What is the consequence?



Geography of the cryosphere



Geography of the cryosphere: Ice sheets & Glaciers



Terminology

- Glacier: ice over land
- Ice sheet: A>50,000 km^2

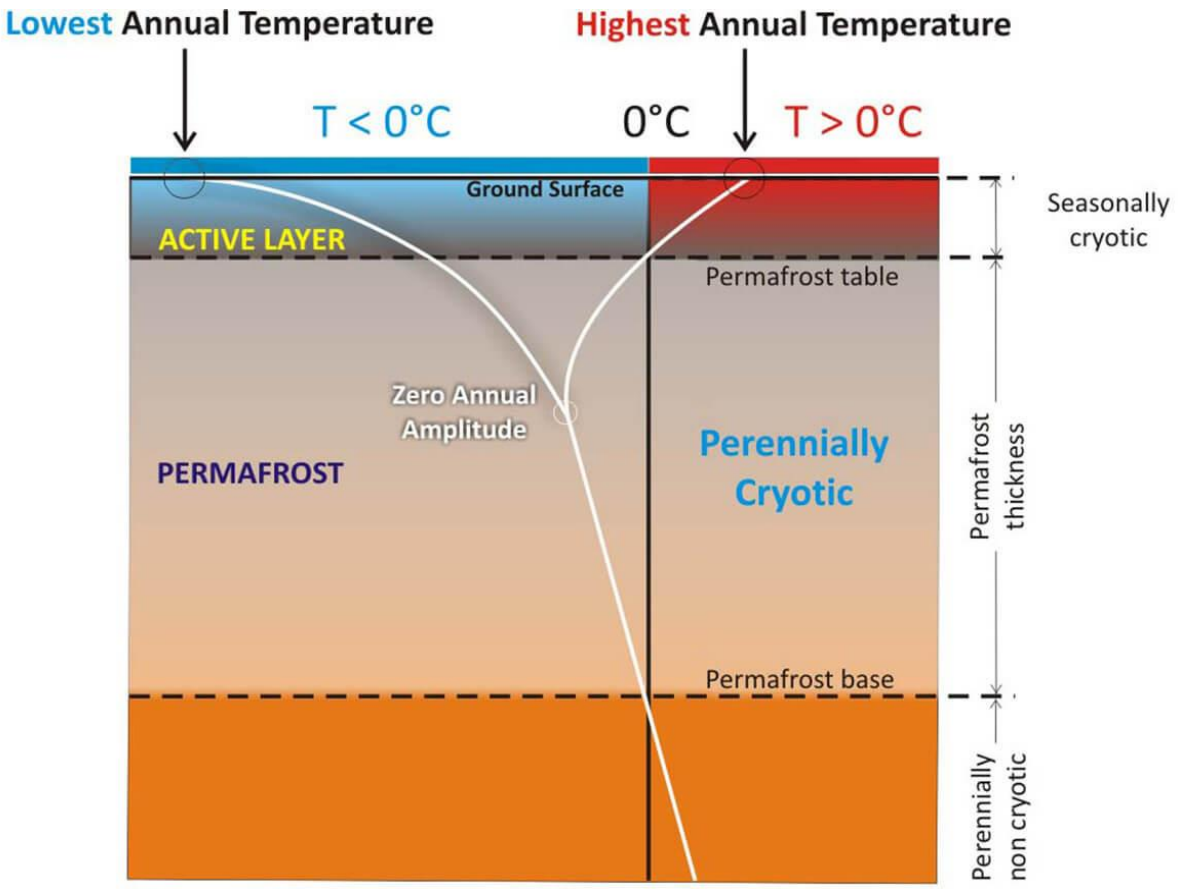
Seasonality

- Perennial

Geography

- Greenland & Antarctic ice sheet
- 200,000 mountain glaciers

Geography of the cryosphere: Permafrost



https://learnweather.com/cryosphere/what-is-permafrost-rrc/

Terminology

- Perennially frozen ground (T<0°C)
- Active Layer: seasonally frozen ground

Seasonality

- Perennial

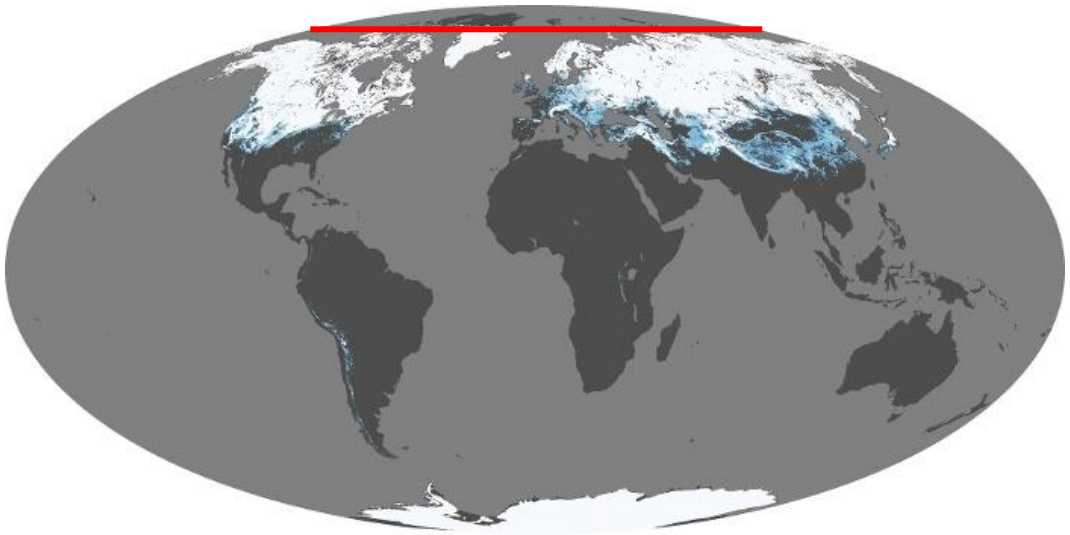
Geography

- Mostly in NH (% of NH land area)

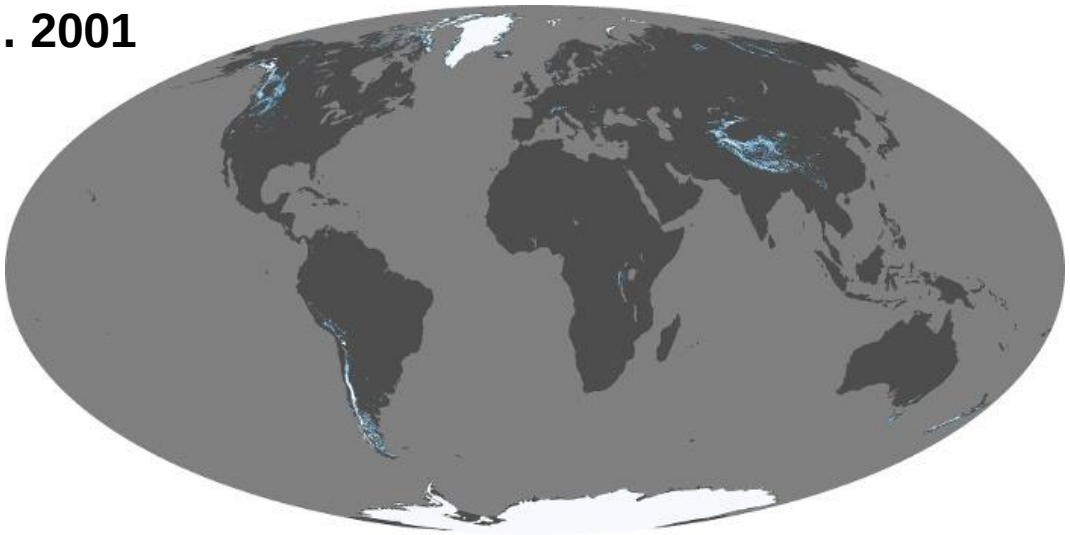
Geography of the cryosphere: Snow cover

Why is there no data up here?

Feb. 2001



Aug. 2001



https://earthobservatory.nasa.gov/global-maps/MOD10C1_M_SNOW

Terminology

- Snow cover on land (∋ice sheet)

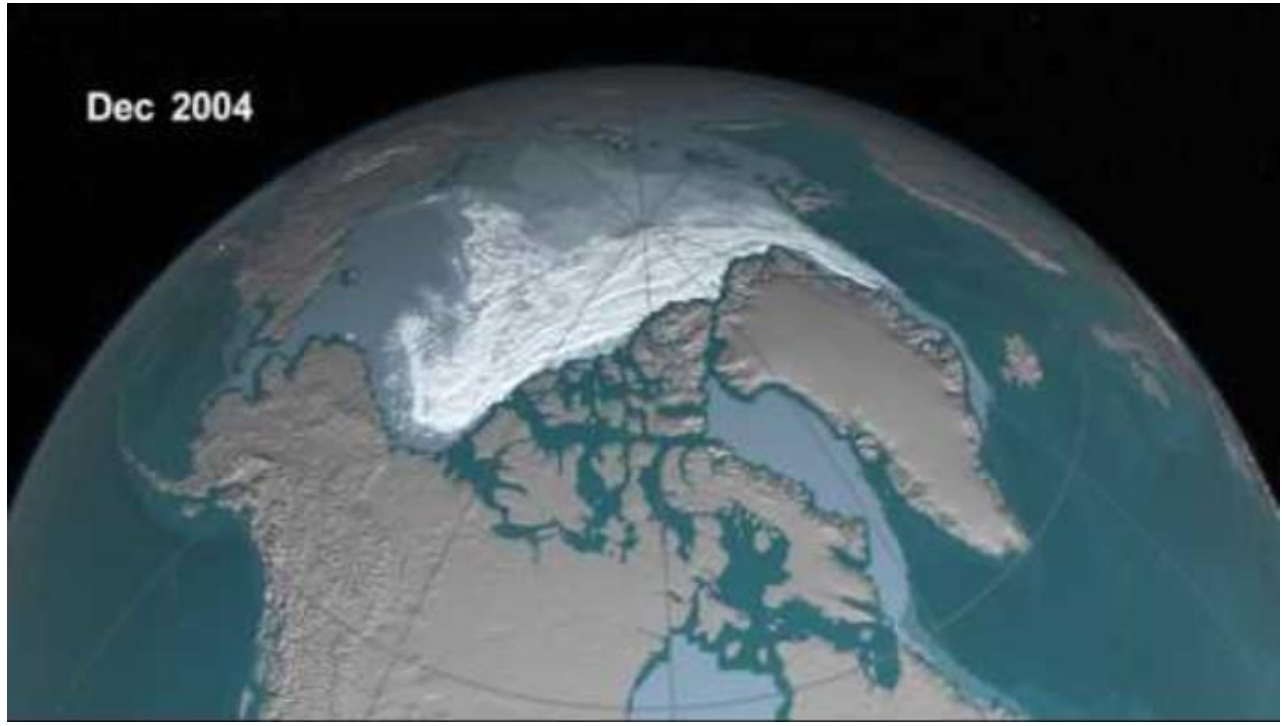
Seasonality

- Seasonal

Geography

- Larger seasonality in ☐ than ☐

Geography of the cryosphere: Sea ice



https://www.youtube.com/watch?v=Vj1G9gqhkYA

Terminology

- Frozen sea water
- First-year ice (FYI): ice less than 1 year old
- Multi-year ice (MYI): ice more than 2 years old

Seasonality

- Seasonal

Geography

- Larger seasonality in SH than NH

How can the cryosphere influence the climate?

2. History of the cryosphere

The cryosphere in the distant past

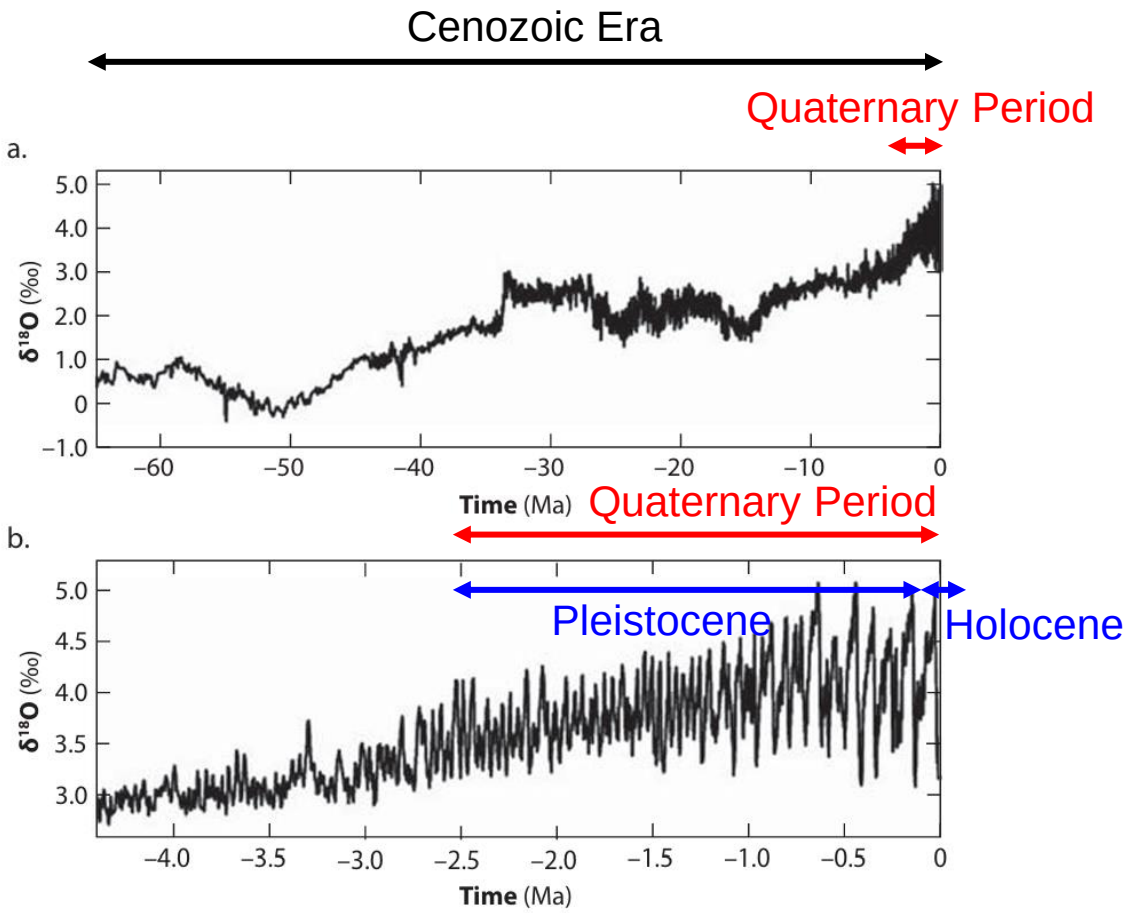


Fig 9.1 from “The Cryosphere” by S. Marshall

How is marine benthic $\delta^{18}O$ related to temperature?

How has surface temperature changed through Cenozoic Era?

How has surface temperature changed through Pleistocene?

Birth of the Antarctic ice sheet

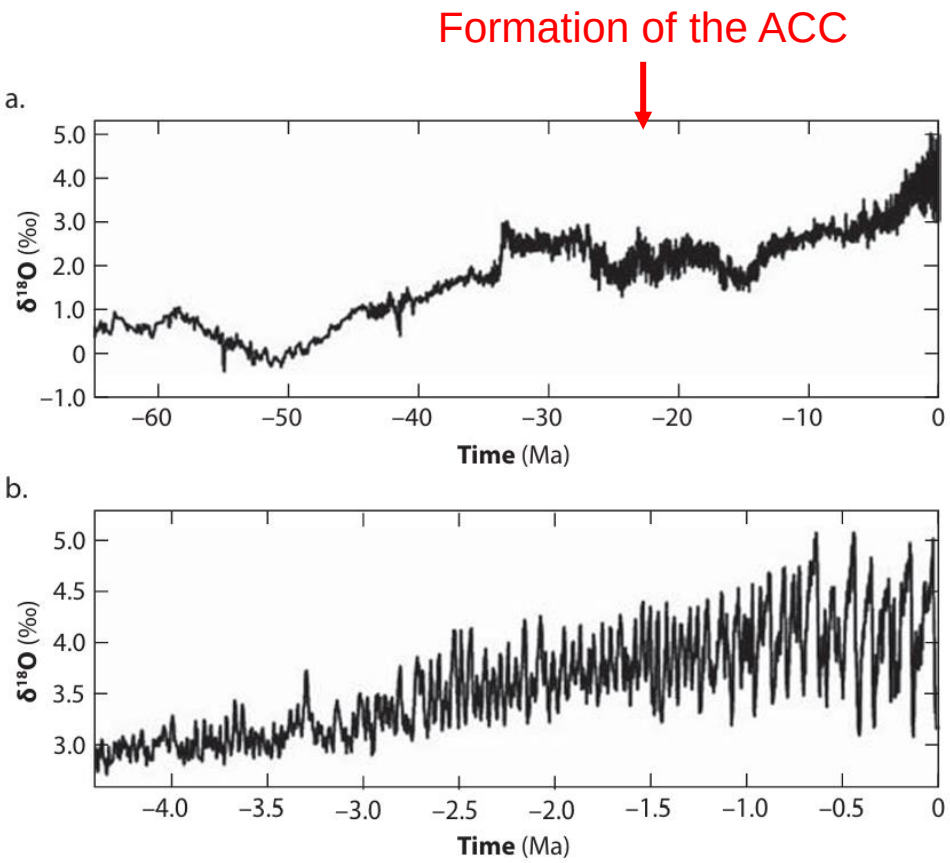
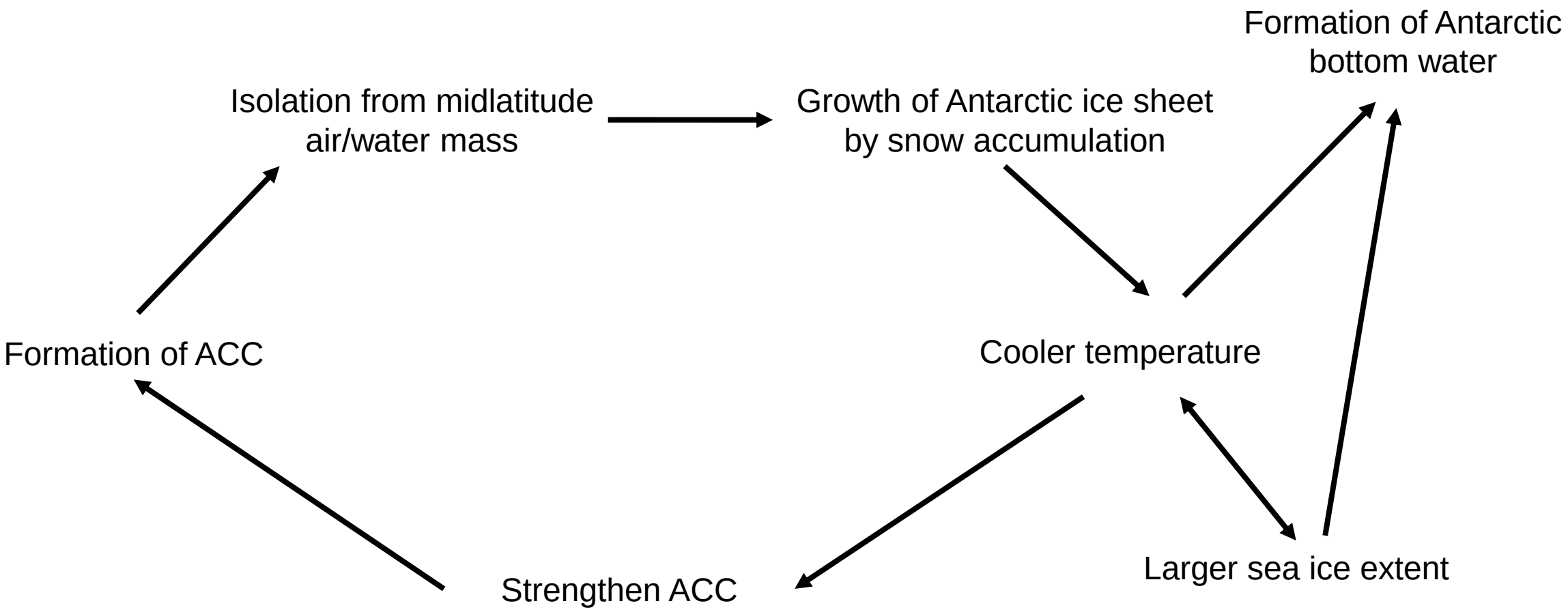


Fig 9.1 from “The Cryosphere” by S. Marshall

Development of a specific ocean circulation was important for the birth of the Antarctic ice sheet. What is this circulation?

AT1. When did the ACC develop and what caused it?

Birth of the Antarctic ice sheet



Birth of the Greenland ice sheet

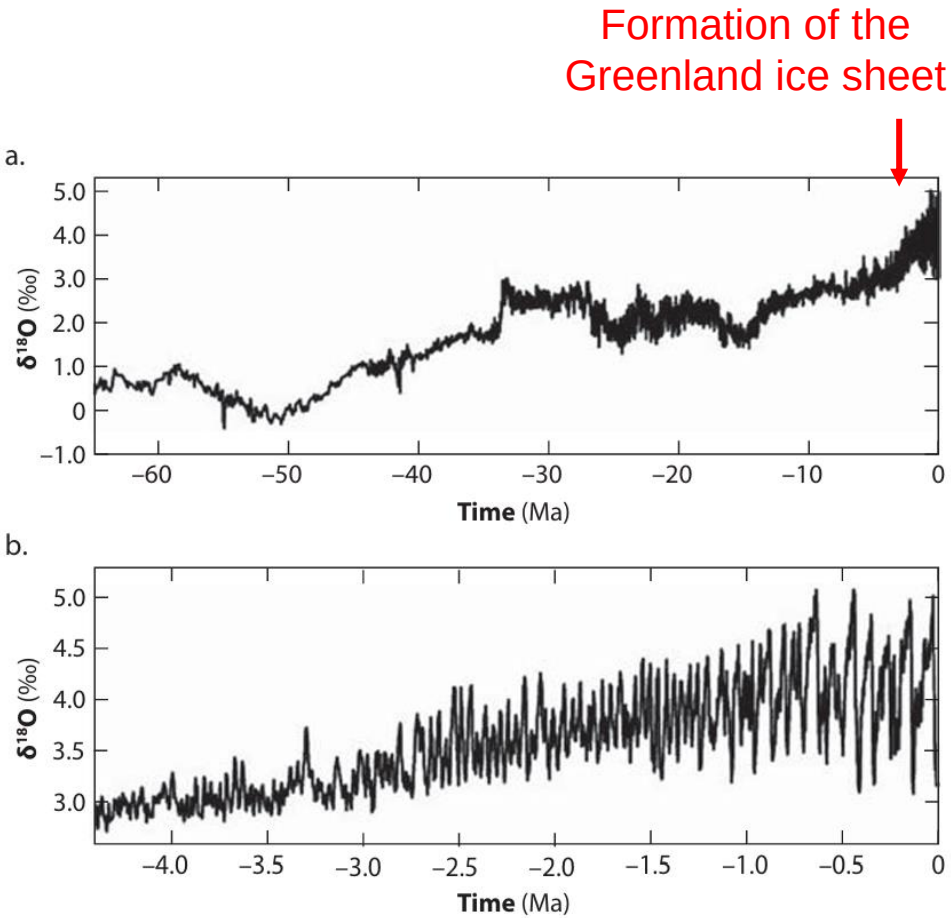


Fig 9.1 from “The Cryosphere” by S. Marshall

AT2. Development of a geographic barrier was important for the formation of the Greenland ice sheet. What is this geographic barrier?

What impact did the formation of this geographic barrier have on the ocean circulation?

Pleistocene glacial cycles

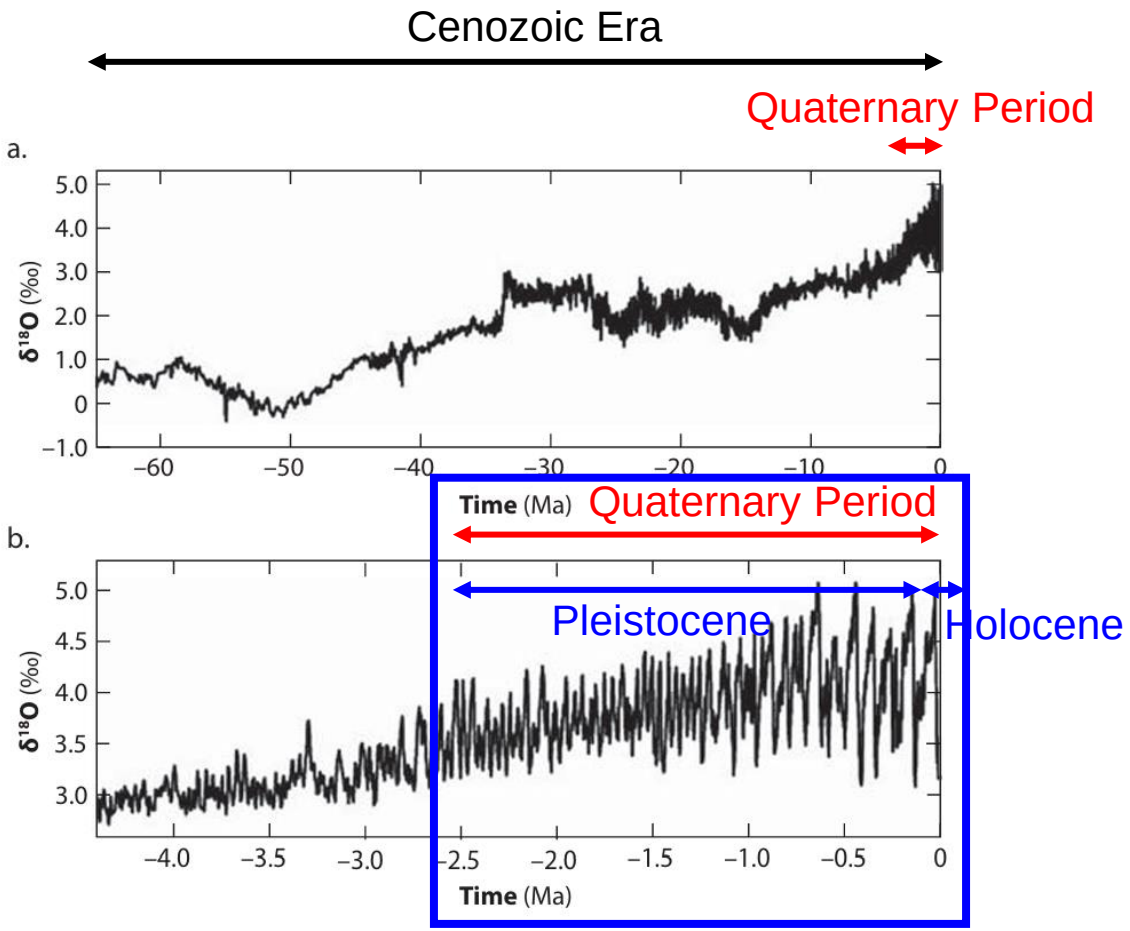


Fig 9.1 from “The Cryosphere” by S. Marshall

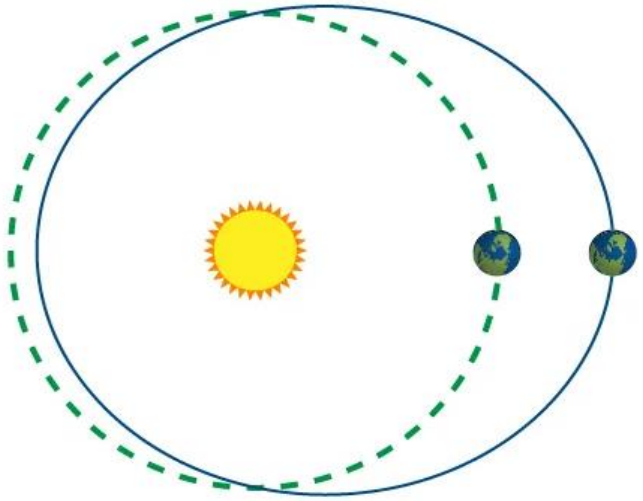
How has surface temperature changed through Pleistocene?

- Surface temperature fluctuates
- Magnitude of fluctuation has increased
- Period of fluctuation has increased

What are the causes of the fluctuations?

- Trigger:
- Amplification:

Pleistocene glacial cycles : Orbital variation

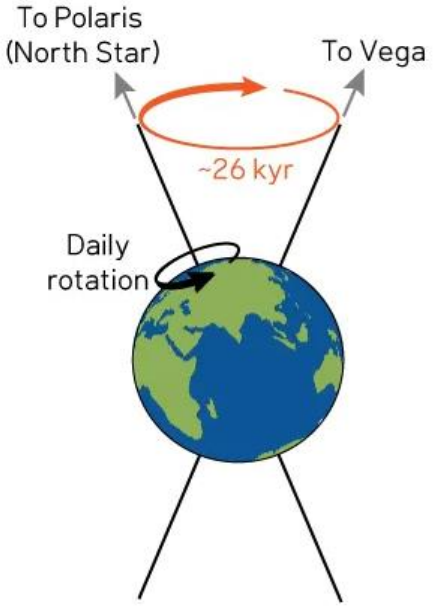


Eccentricity

100,000 yrs

Obliquity (Tilt)

43,000 yrs



Orbital Precession

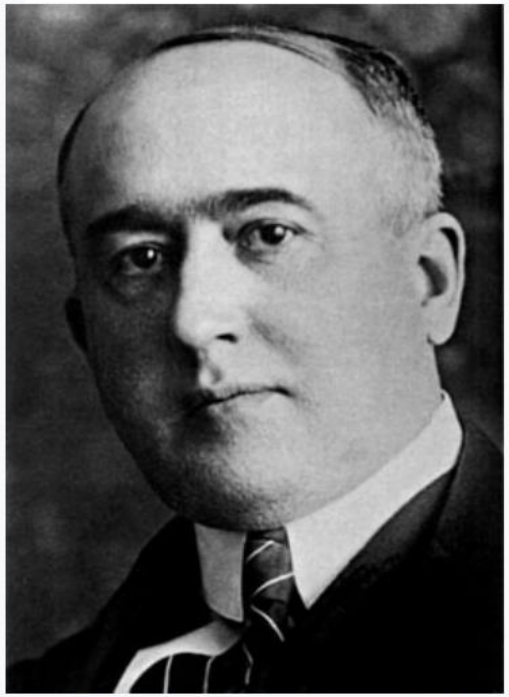
24,000 / 19,000 yrs

By what order of magnitude does eccentricity change?

Is this figure an exaggeration?

➔ Minor change in global annual solar irradiance

➔ Substantial change in the **seasonality** of solar irradiance



Born	28 May 1879[1] Dalj, Austria-Hungary (modern day Croatia)
Died	12 December 1958 (aged 79) Belgrade, PR Serbia, Yugoslavia (modern Serbia)

What is his name?

Pleistocene glacial cycles
: Internal climate system feedback

Why was the orbital variation theory first met with skepticism?

Milankovitch did not live to see the confirmation of his theory. His *Canon of Insolation of the Earth and Its Application to the Problem of the Ice Ages*, published in 1941, was met with skepticism and was not translated to English until 1969. By then, deep-sea sedimentary re-

Pleistocene glacial cycles : Millennial climate variability

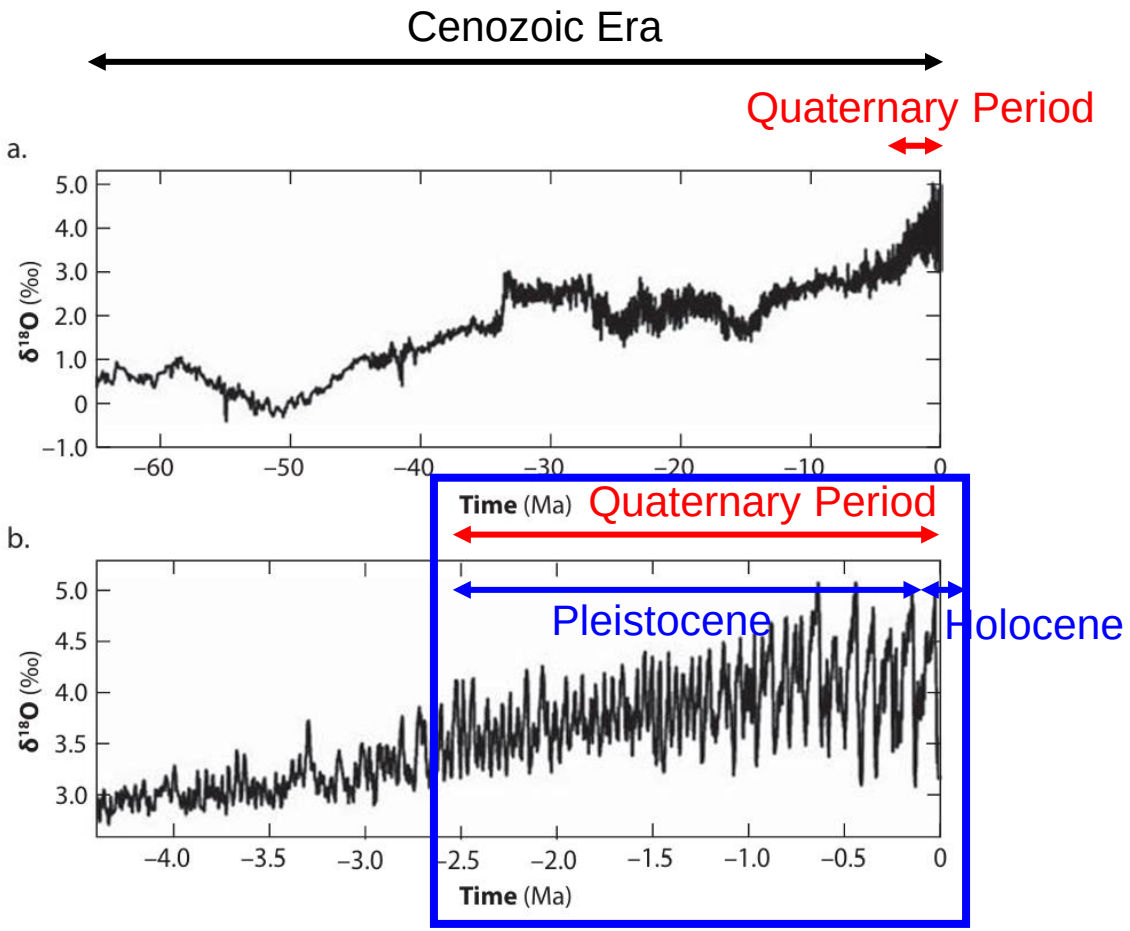


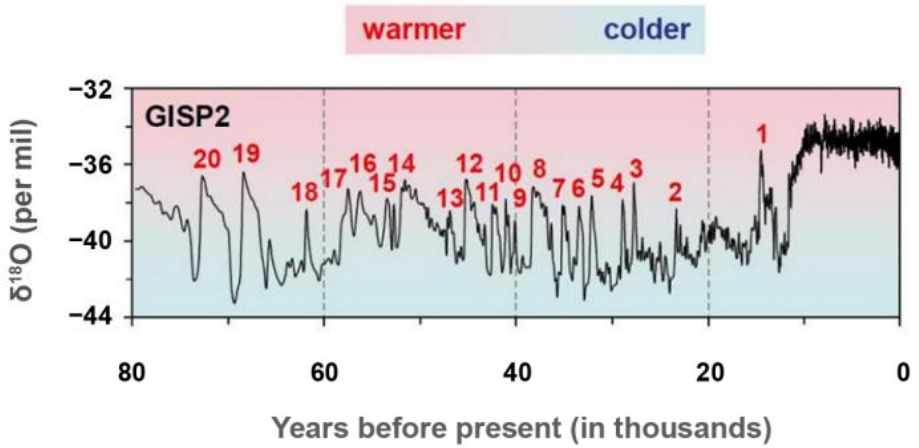
Fig 9.1 from “The Cryosphere” by S. Marshall

Millennial climate variability

- Climate fluctuations on timescales of centuries to millennia
- “Sub-orbital”

What were the two examples that were given?

Pleistocene glacial cycles : Dansgaard-Oeschger Cycles



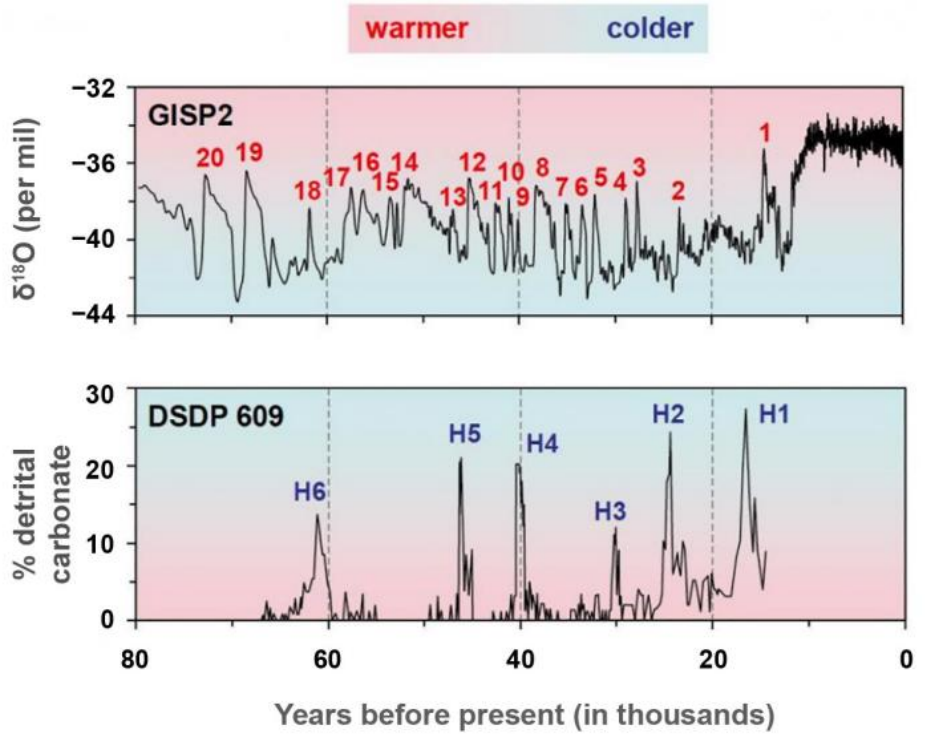
The $\delta^{18}O$ record from the GISP2 ice core in Greenland (top), showing 20 of the 25 observed Dansgaard–Oeschger events during the last glacial period (Grootes et al. 1993). A record of ice-rafted material during Heinrich events (bottom) from a deep-sea core in the North Atlantic (Bond and Lotti 1995).

https://www.ncei.noaa.gov/sites/default/files/2021-11/2%20Heinrich%20and%20Dansgaard%E2%80%93Oeschger%20Events%20-%20Final-OCT%202021.pdf

Dansgaard-Oeschger (DO) Cycles

- ~1500-year temperature oscillations
- Cause:

Pleistocene glacial cycles : Dansgaard-Oeschger Cycles



The $\delta^{18}O$ record from the GISP2 ice core in Greenland (top), showing 20 of the 25 observed Dansgaard–Oeschger events during the last glacial period (Grootes et al. 1993). A record of ice-rafted material during Heinrich events (bottom) from a deep-sea core in the North Atlantic (Bond and Lotti 1995).

https://www.ncei.noaa.gov/sites/default/files/2021-11/2%20Heinrich%20and%20Dansgaard%E2%80%93Oeschger%20Events%20-%20Final-OCT%202021.pdf

Heinrich Events

- Intermittent large-scale fluxes of ice sheet ➔ ocean
- Cause: surging or tidewater retreat of ice streams
- Effects
  - Ice raft debris
  - Freshening & cooling of ocean surface waters

Tidewater glacier: marine terminating glacier

3. Recent changes in the cryosphere and its projections

Recent and future cryospheric change

McCarty Glacier, Alaska

Recent and future cryospheric change

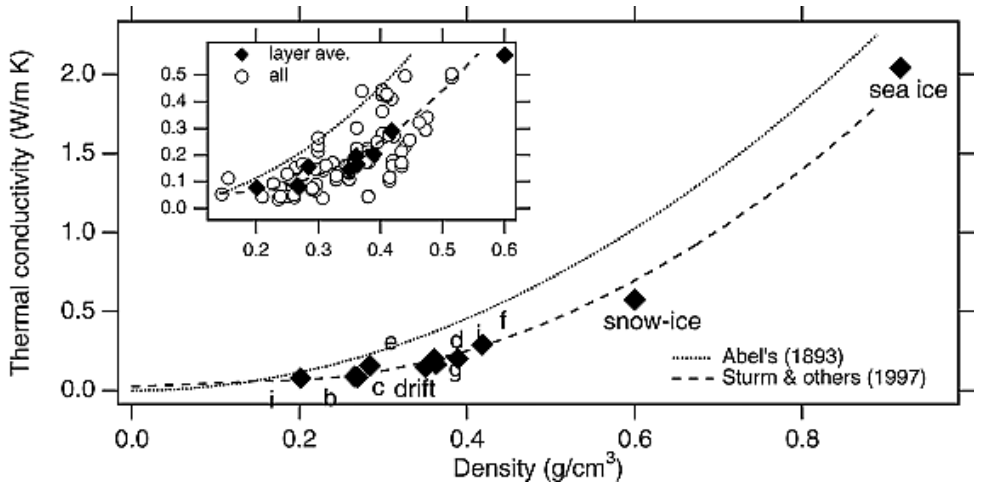
The change in what variable is the most influential to the recent changes in the cryosphere?

In recent years, how has that variable changed?

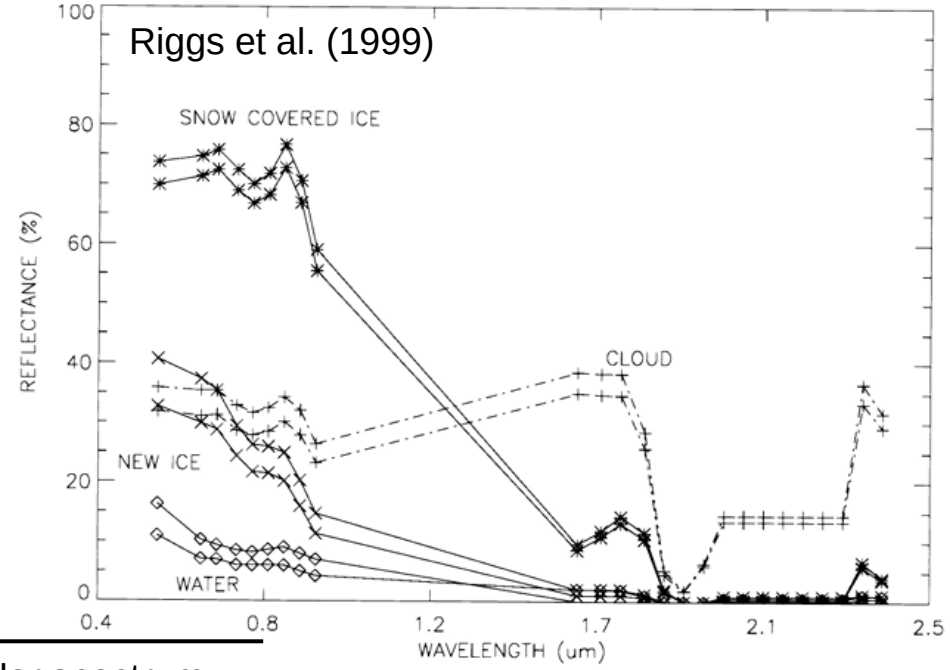
What is the main driver for this change?

Recent and future cryospheric change

Sturm et al. (2002)



Riggs et al. (1999)



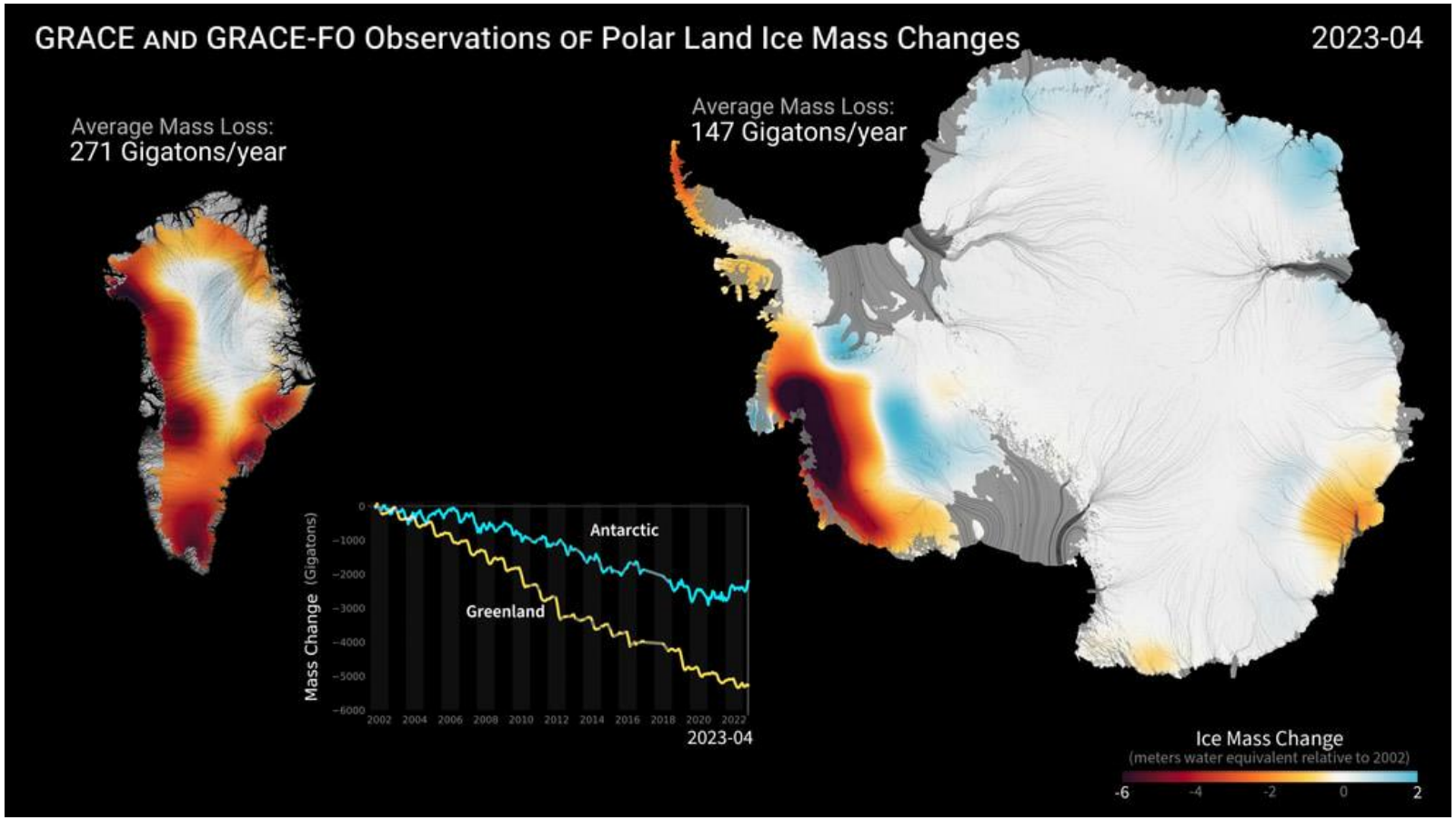
Solar spectrum

Besides temperature, what variable is influential in the change of the cryosphere?

How does this variable change with increased temperature?

AT4. Does this reinforce or offset the effects of increased temperature on the cryosphere?

Recent and future cryospheric change : Glacier and Ice Sheet



https://svs.gsfc.nasa.gov/31166

Quick conversion to sea level rise

- Density of water ~ 1000 kg/m^3
- Surface area of ocean ~ 3.57×10^8 km^2

$$\Delta m_{ice,melt} = \Delta m_{water,melt}$$

$$\Delta m_{water,melt} = \rho \Delta V$$

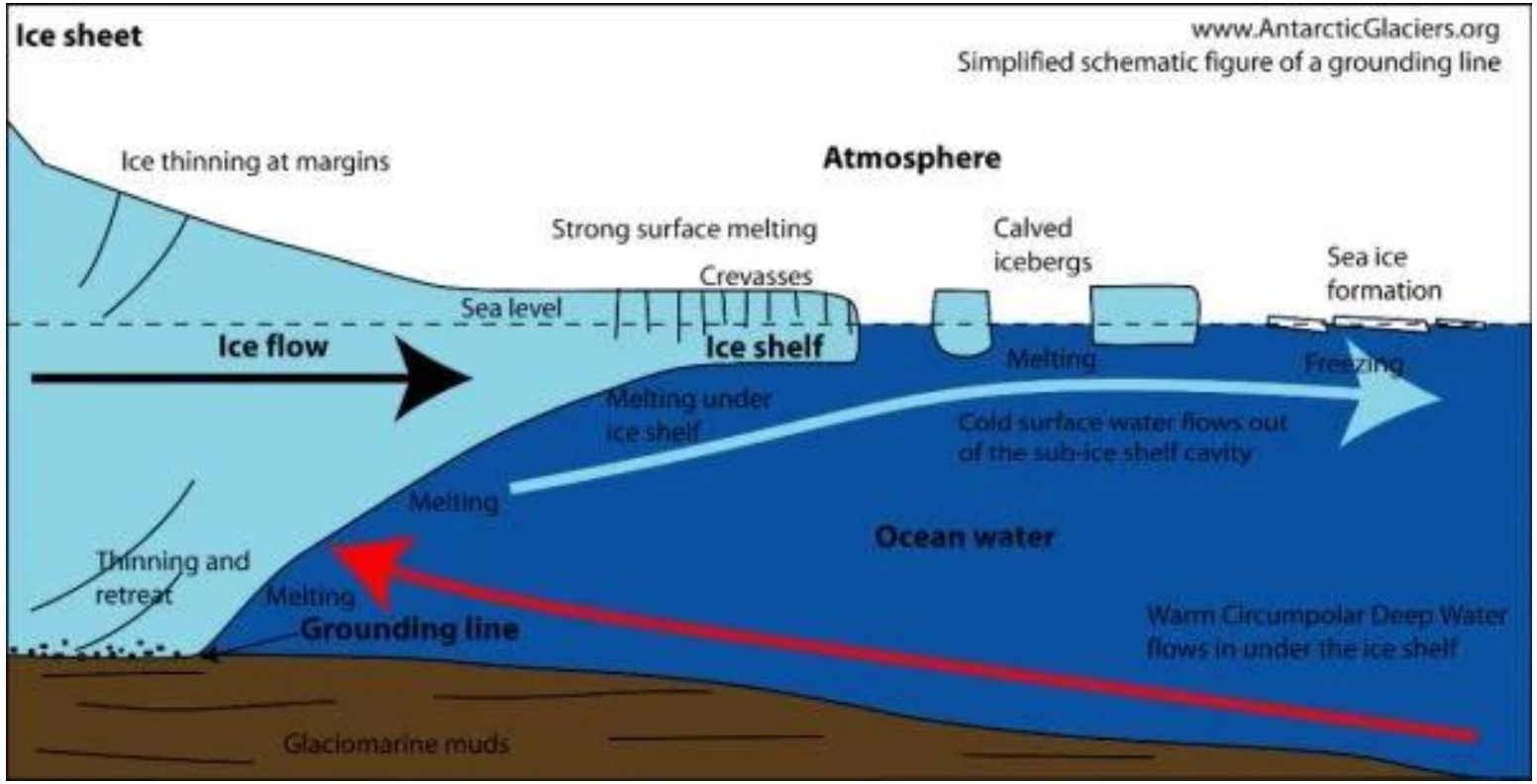
$$\Delta V = A_{ocean} \Delta h$$

$$\Delta h = \frac{\Delta m_{ice,melt}}{\rho A_{ocean}}$$

$$= \frac{418 \times 10^{12}\ kg/yr}{1000\ kg/m^3 \times 3.57 \times 10^8\ km^2} \times \frac{1\ km^2}{10^6\ m^2}$$

$$= 0.00117\ m/yr = 0.117\ cm/yr$$

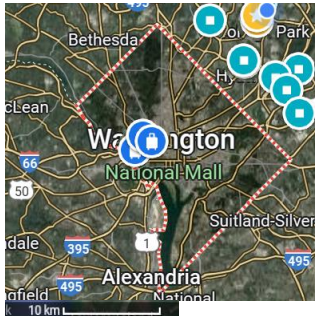
Recent and future cryospheric change : Glacier and Ice Sheet

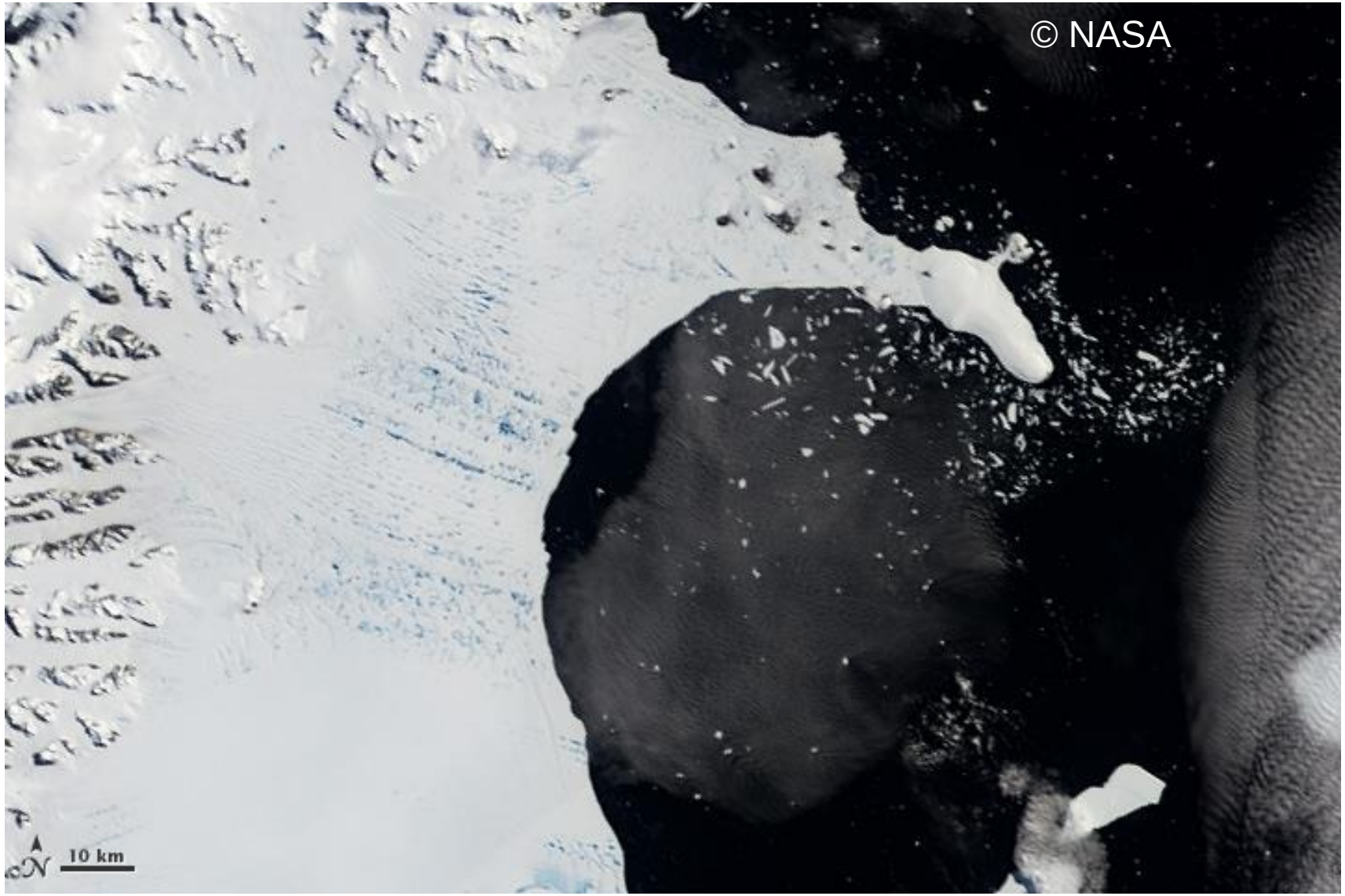


Through what processes are the ice sheets lost?

Recent and future cryospheric change : Glacier and Ice Sheet

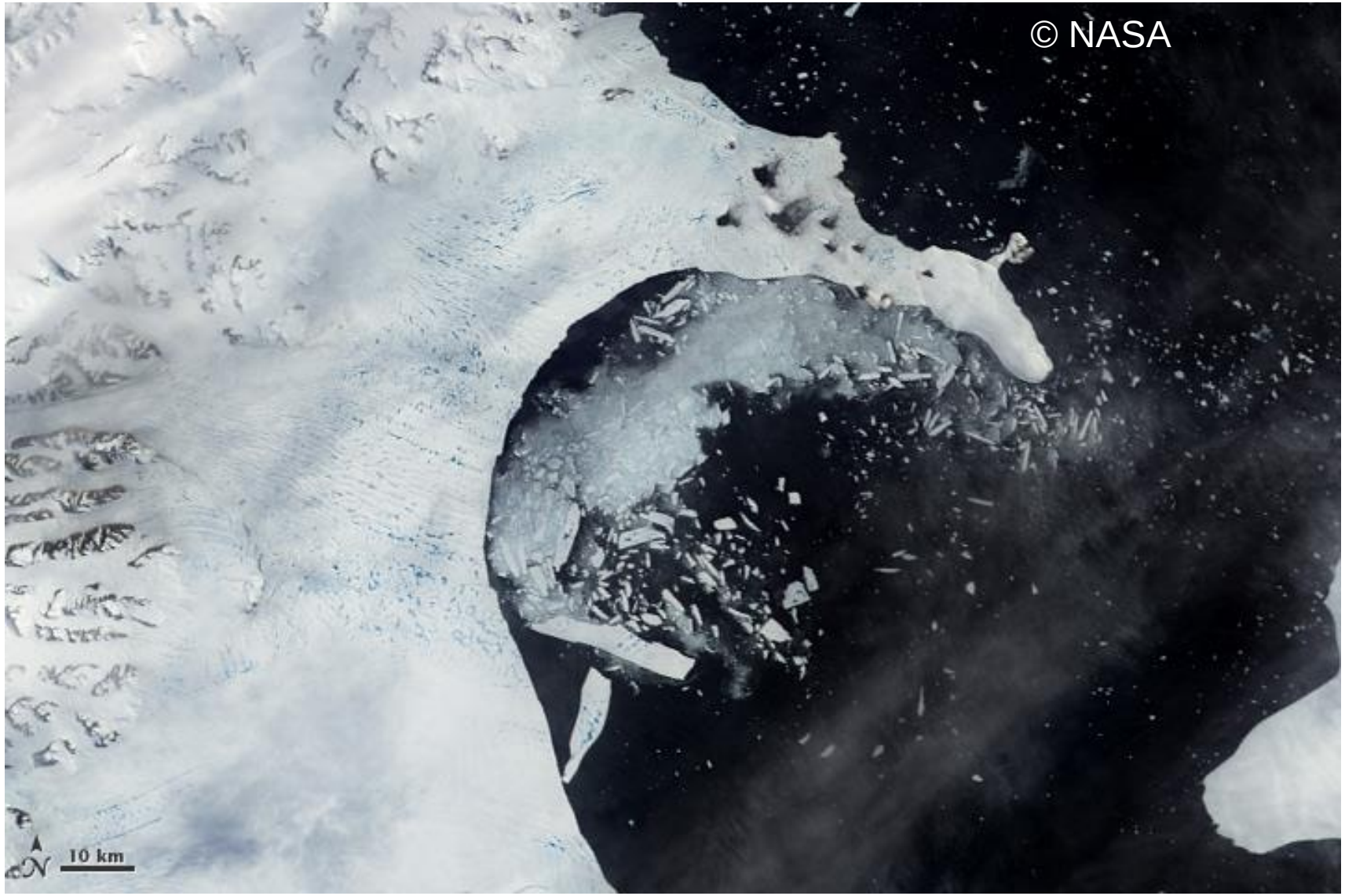
Jan 31, 2002





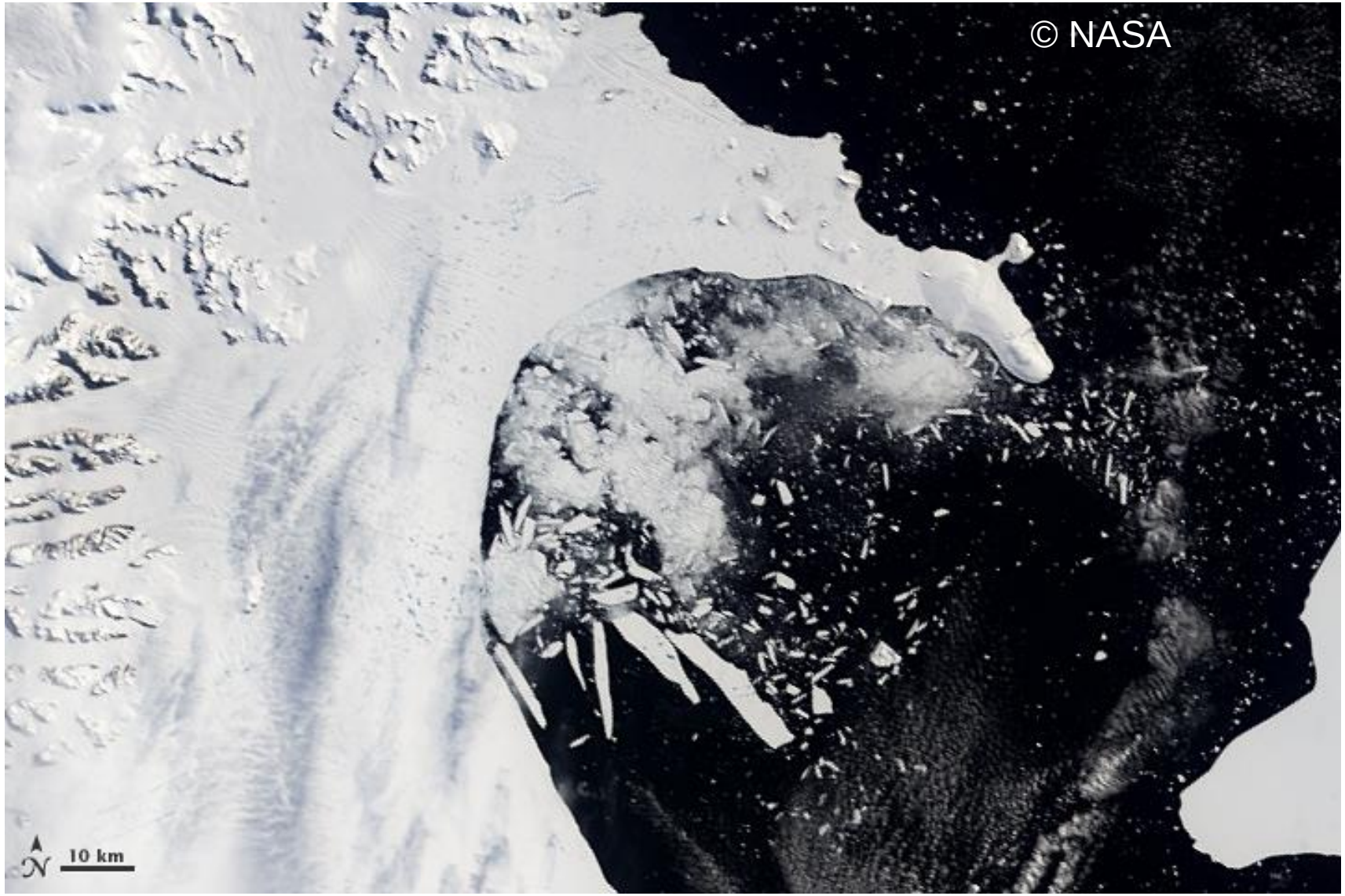
Recent and future cryospheric change : Glacier and Ice Sheet

Feb 17, 2002



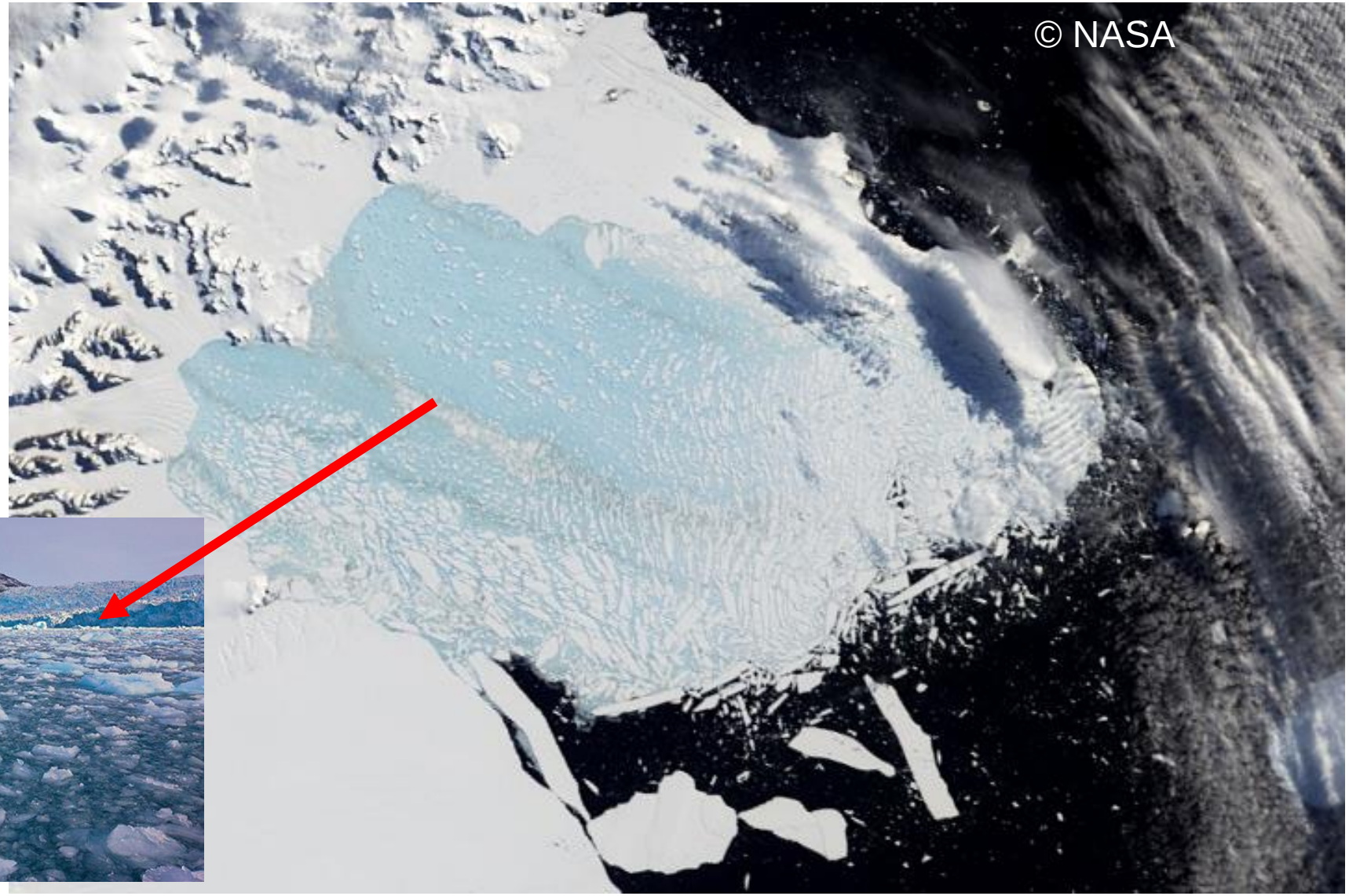
Recent and future cryospheric change : Glacier and Ice Sheet

Feb 23, 2002

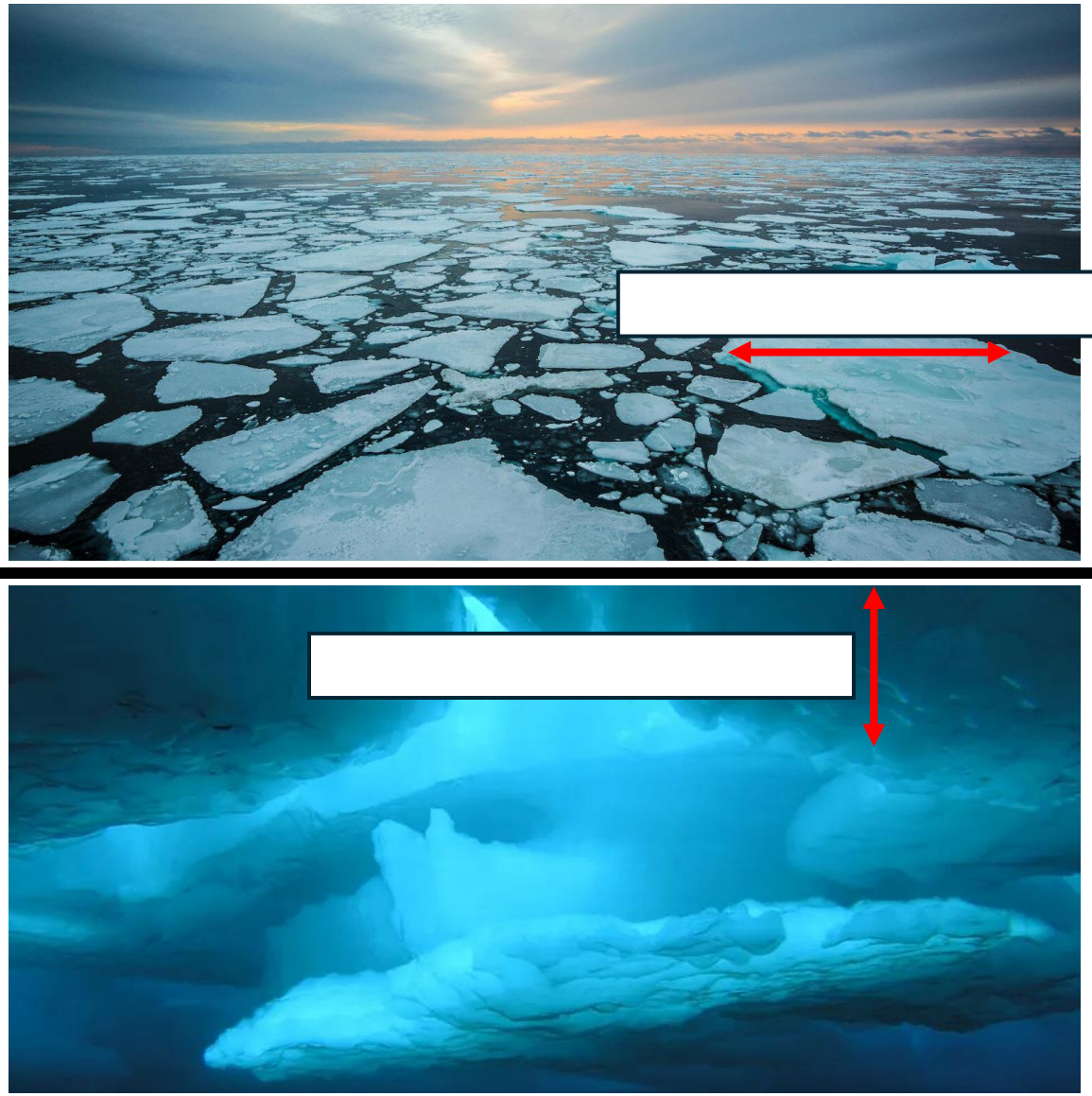


Recent and future cryospheric change : Glacier and Ice Sheet

Mar 7, 2002



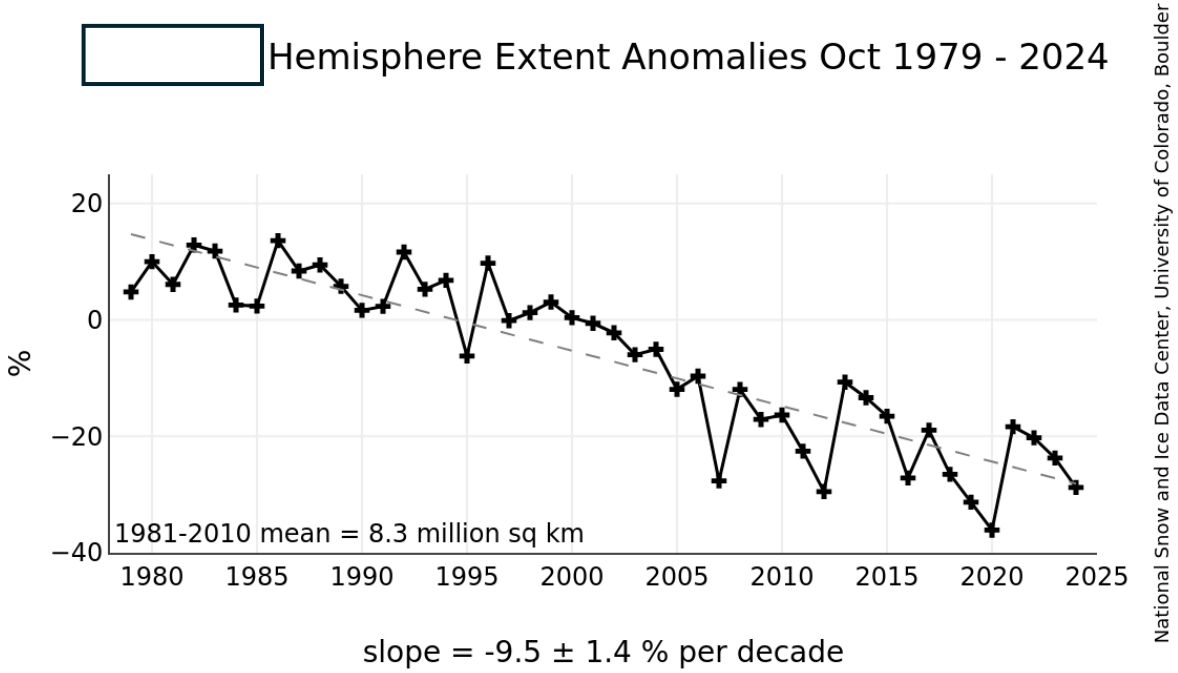
Recent and future cryospheric change : Sea Ice



Sea ice has both horizontal and vertical dimension!

https://ocean.si.edu/ecosystems/poles/under-arctic-ice

Recent and future cryospheric change : Sea Ice



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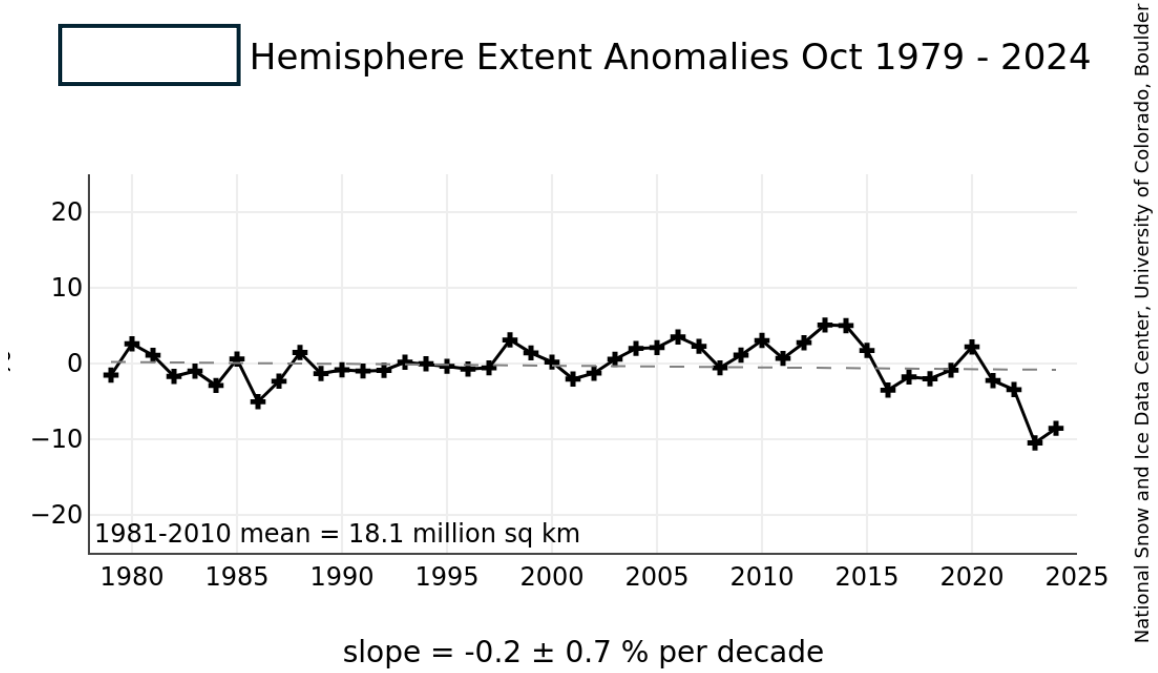

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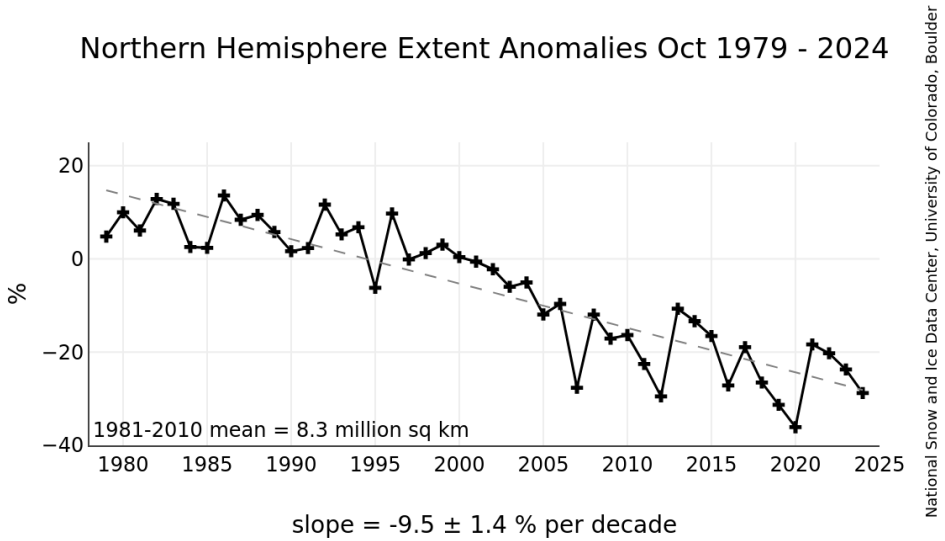
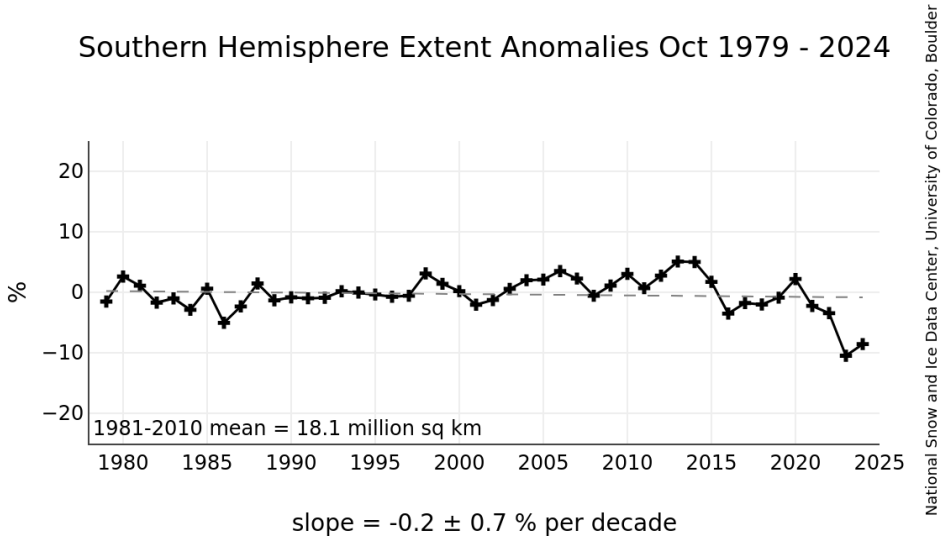
Recent and future cryospheric change : Sea Ice

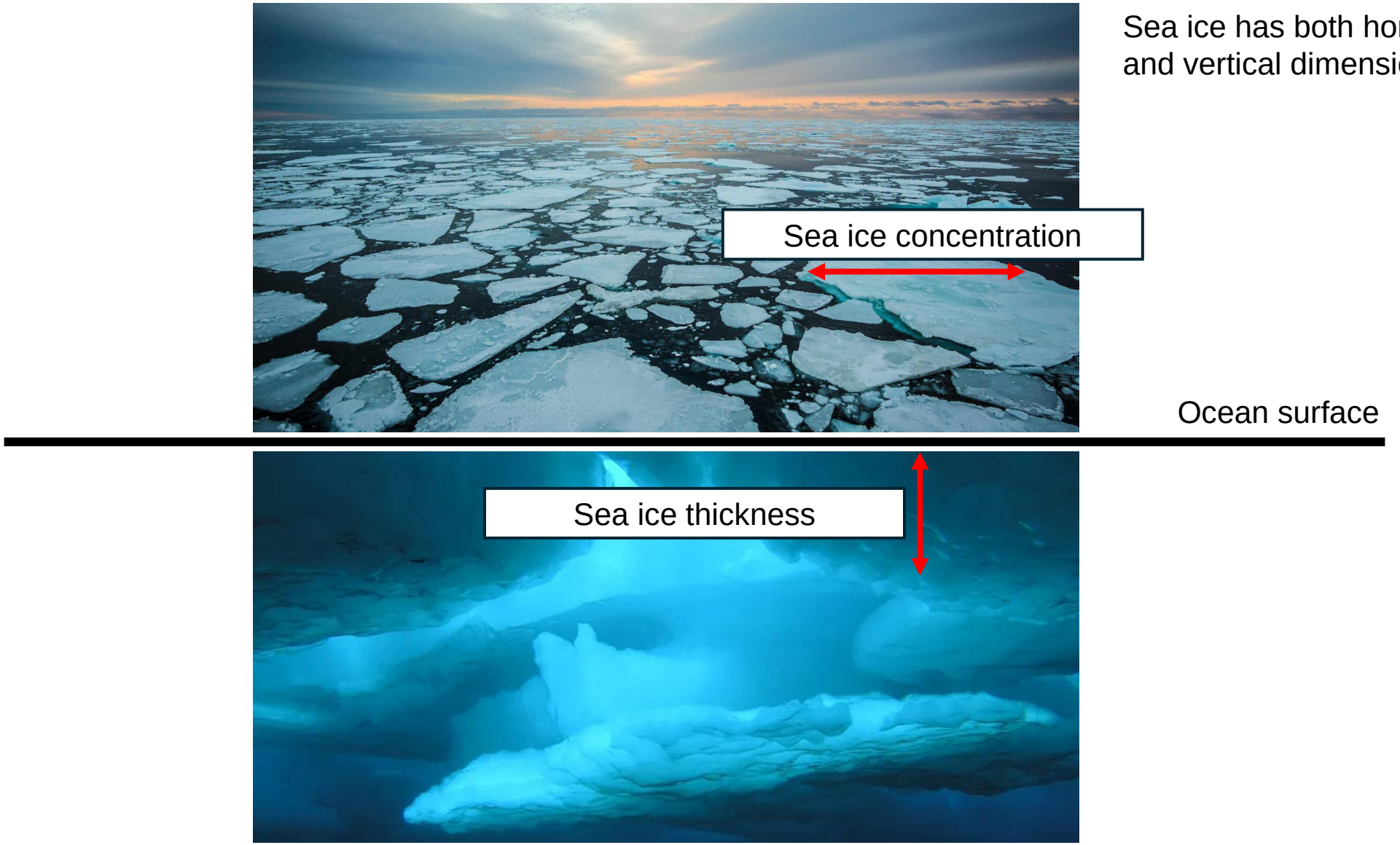




AT5. What mechanism caused the difference in trend between the two hemispheres?

How are these observations (since 1970s) obtained?

Recent and future cryospheric change : Sea Ice



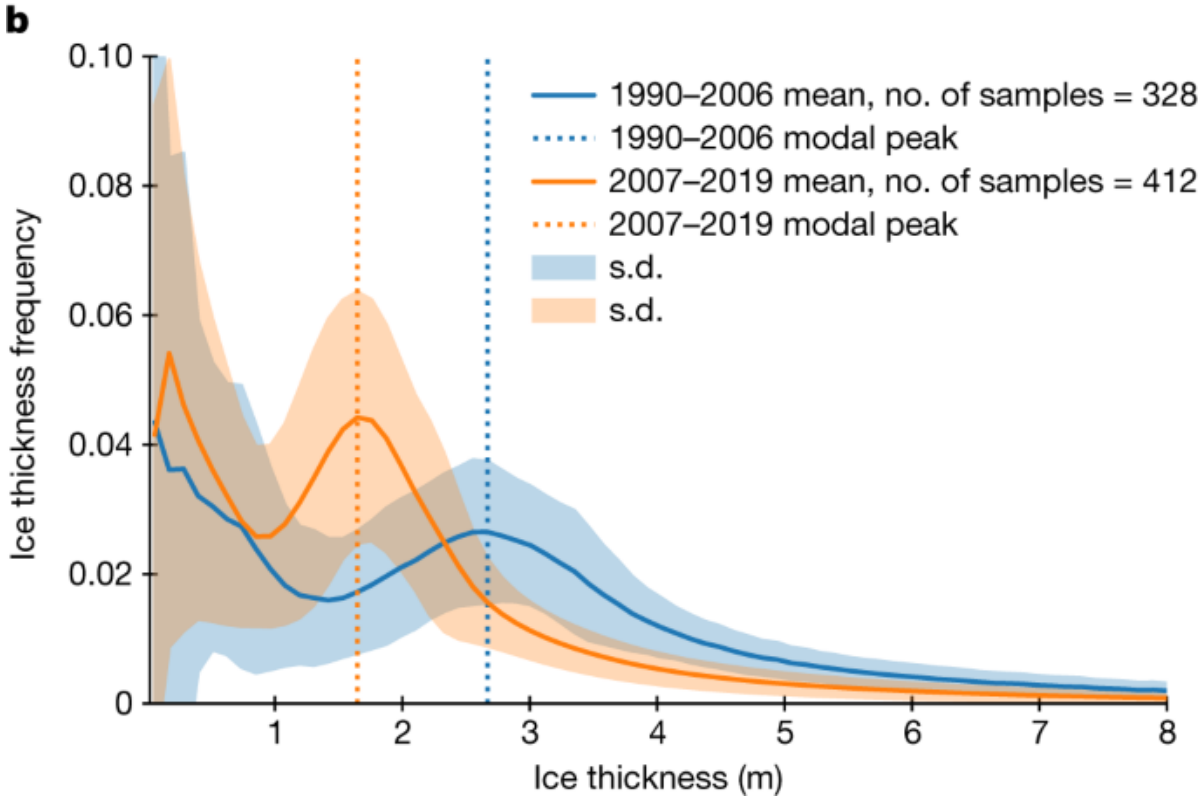
Sea ice has both horizontal and vertical dimension!

https://ocean.si.edu/ecosystems/poles/under-arctic-ice

Recent and future cryospheric change : Sea Ice

What are some ways to measure sea ice thickness?

Recent and future cryospheric change : Sea Ice



Sumata et al. (2023)

How has sea ice thickness changed?

How is thickness correlated to ice age?

What does this imply about the abundance of older ice?

Social ecological effects

What are some possible effects of Arctic sea ice loss on ecology?

What are some possible effects of Arctic sea ice loss on transportation?

What are some consequences of glacier mass loss?

Future directions

Why is sea level rise hard to forecast?

Future directions

view of the cryosphere. In many cases, observations are pointing out important new directions for theoretical and field-based studies, and these different strands of re-