

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

- Properties of the cryosphere
- Components of the cryosphere

2. History of the cryosphere

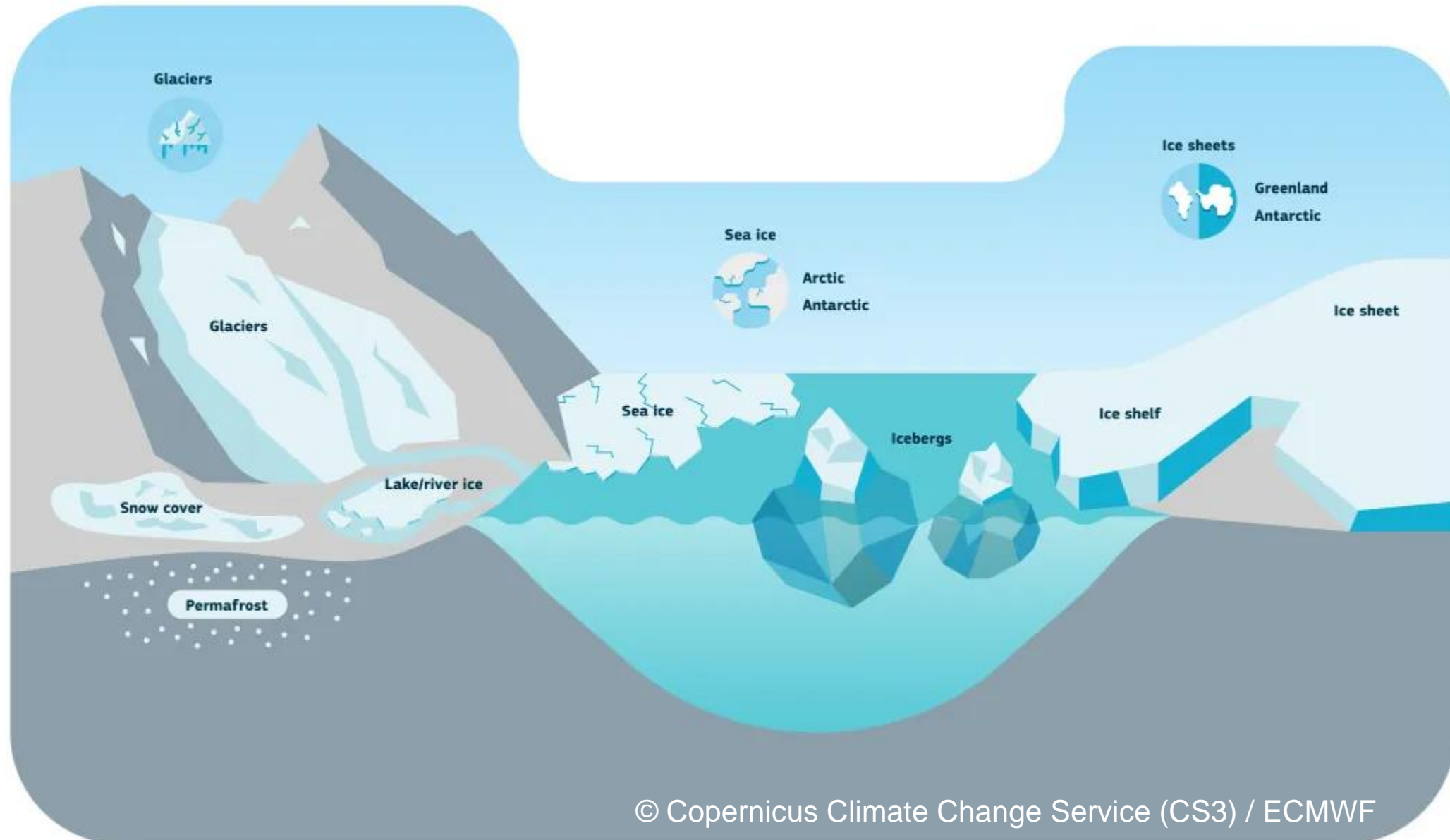
- Formation of the ice sheets
- Glacial & Interglacial cycles

3. Recent changes in the cryosphere and its projections

- Ice sheets
- Sea ice

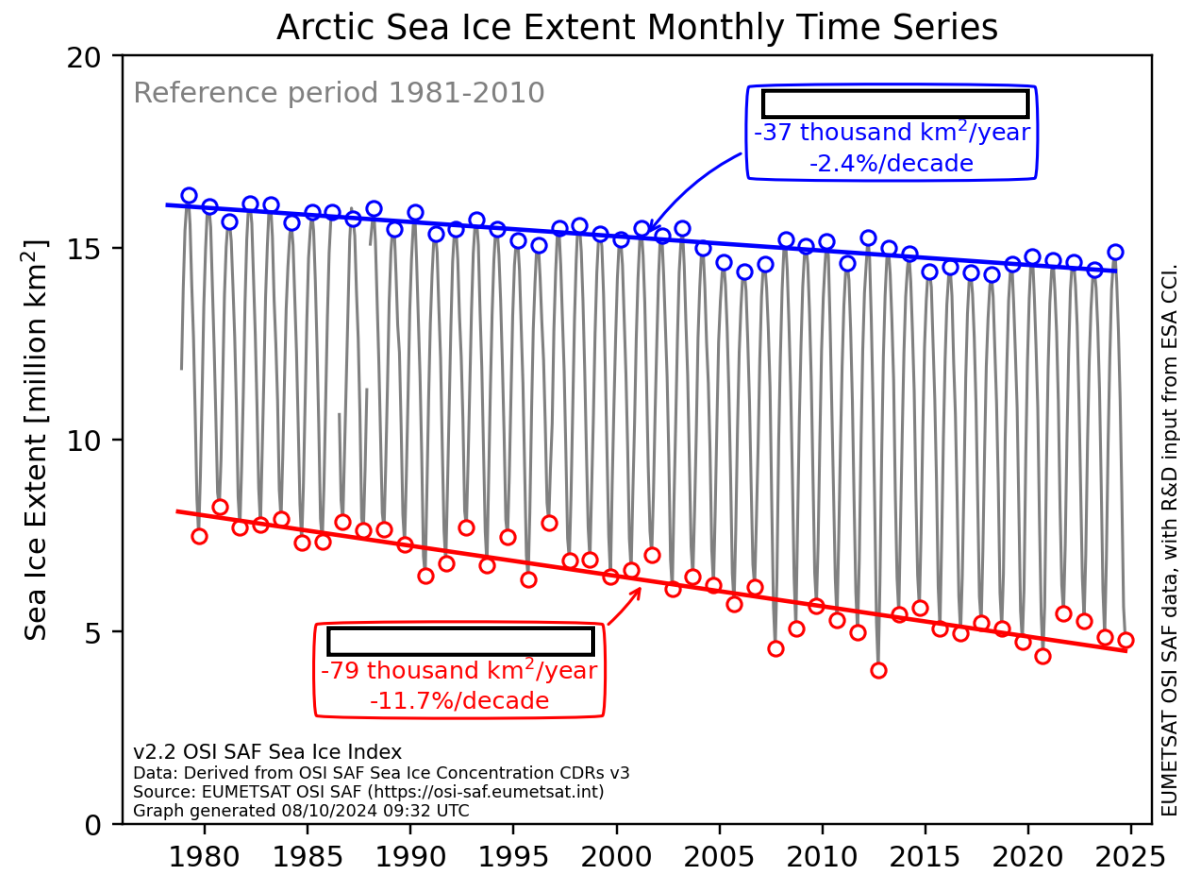
1. Introduction to the cryosphere

The cryosphere



What is a characteristic property of the cryosphere?

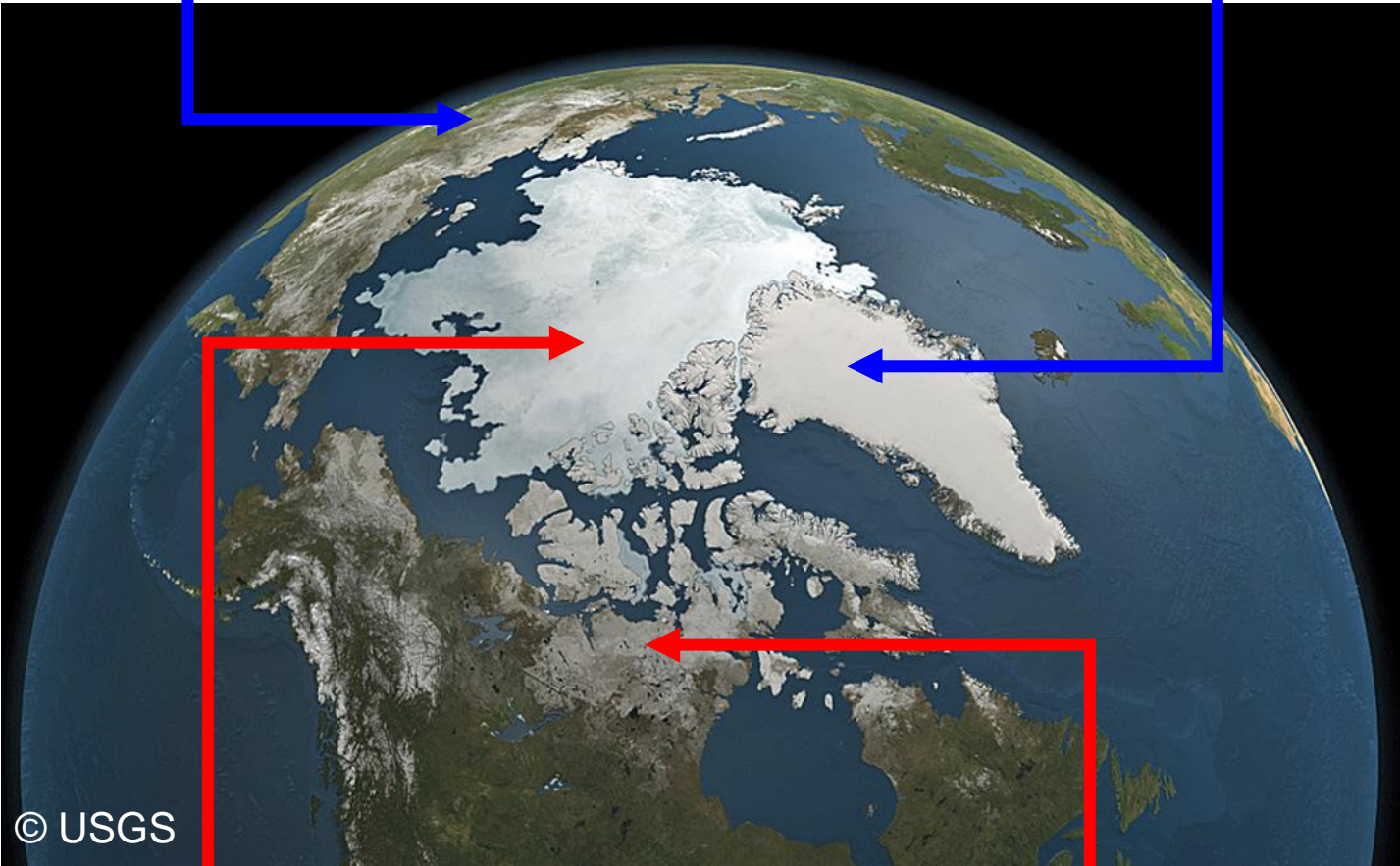
What is the consequence?



© Danish Meteorological Institute (DMI)

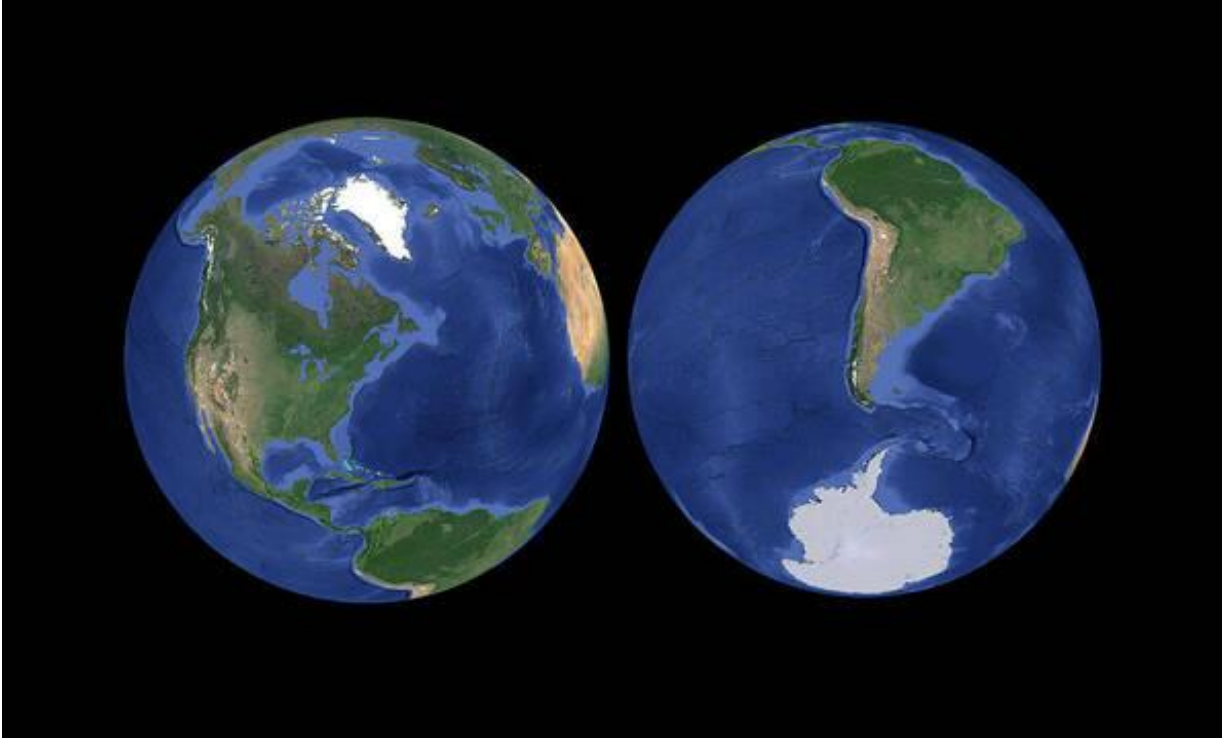
Permafrost

Ice sheet & Glaciers



Sea ice

Snow cover



Terminology

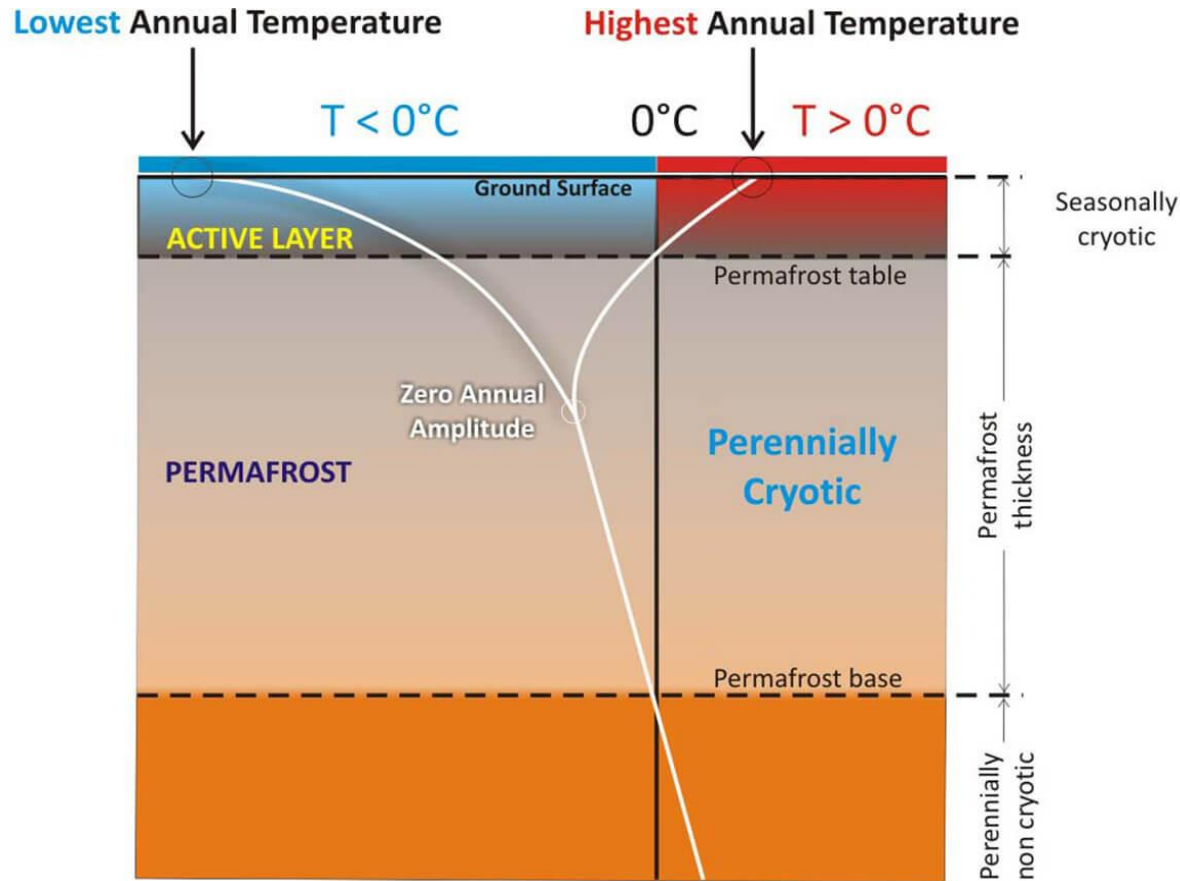
- Glacier: ice over land
- Ice sheet: $A > 50,000 \text{ km}^2$

Seasonality

- Perennial

Geography

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



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

Terminology

- Perennially frozen ground ($T < 0^{\circ}\text{C}$)
- Active Layer: seasonally frozen ground

Seasonality

- Perennial

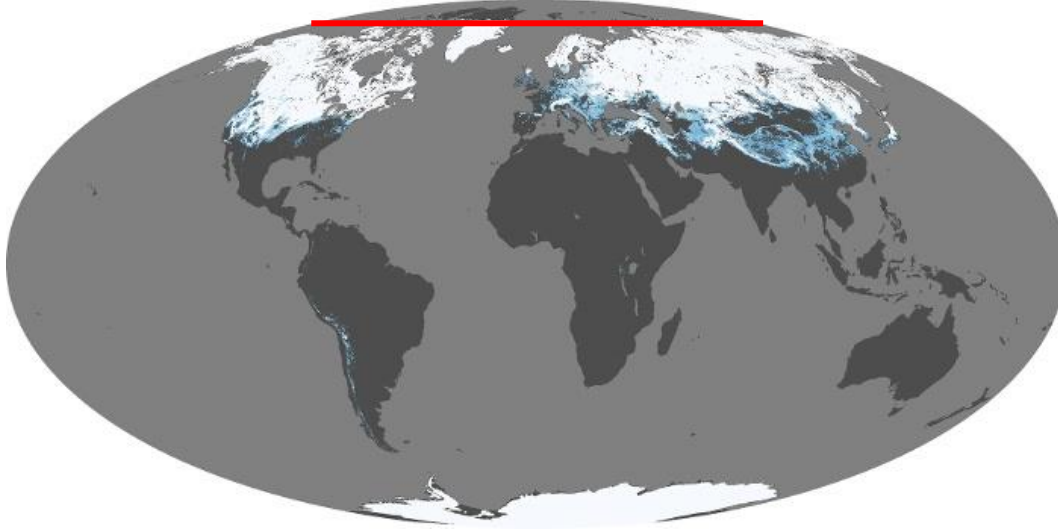
Geography

- Mostly in NH (% of NH land area)

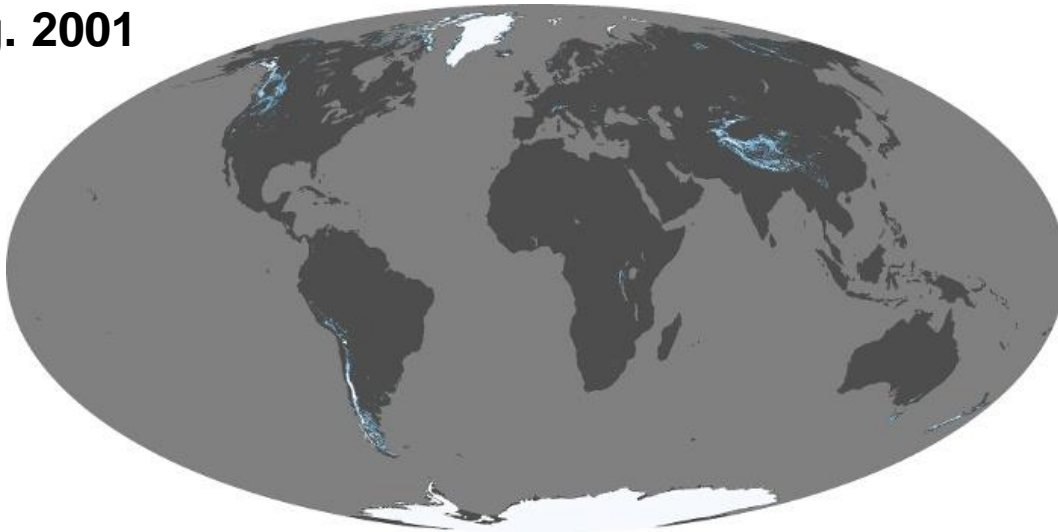
Geography of the cryosphere: Snow cover

Feb. 2001

Why is there no data up here?



Aug. 2001



Terminology

- Snow cover on land (≠ ice sheet)

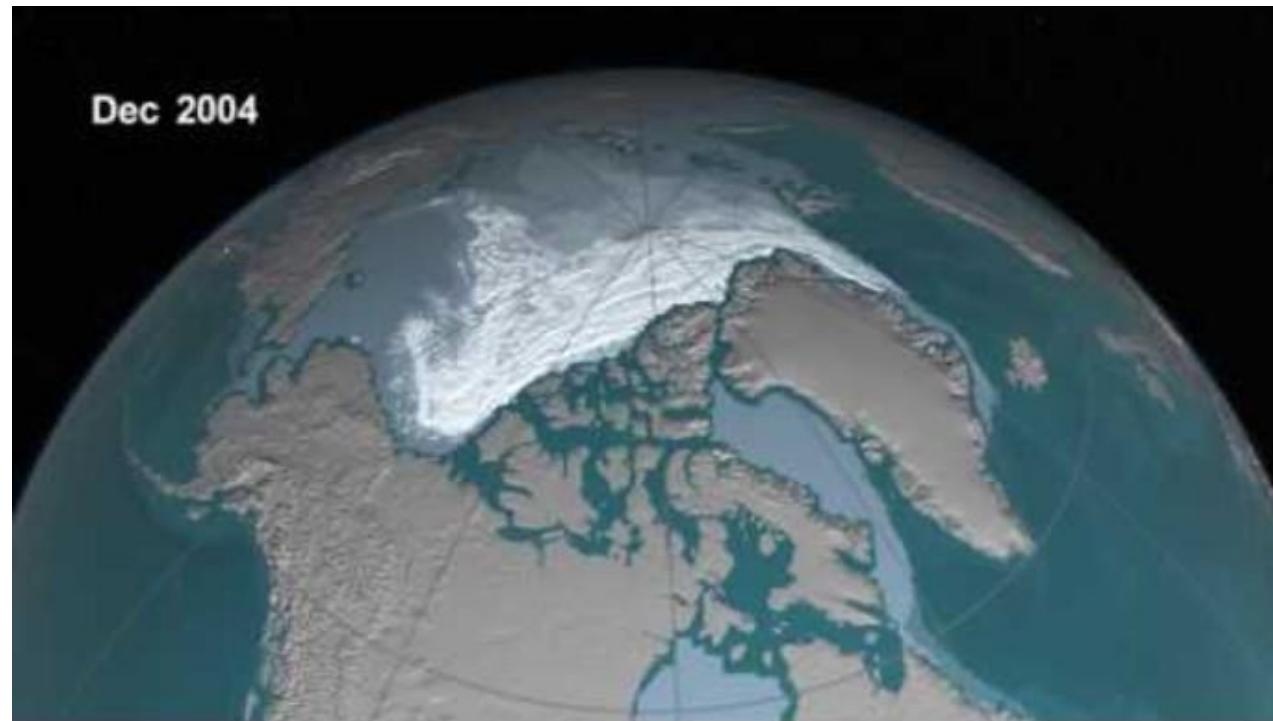
Seasonality

- 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

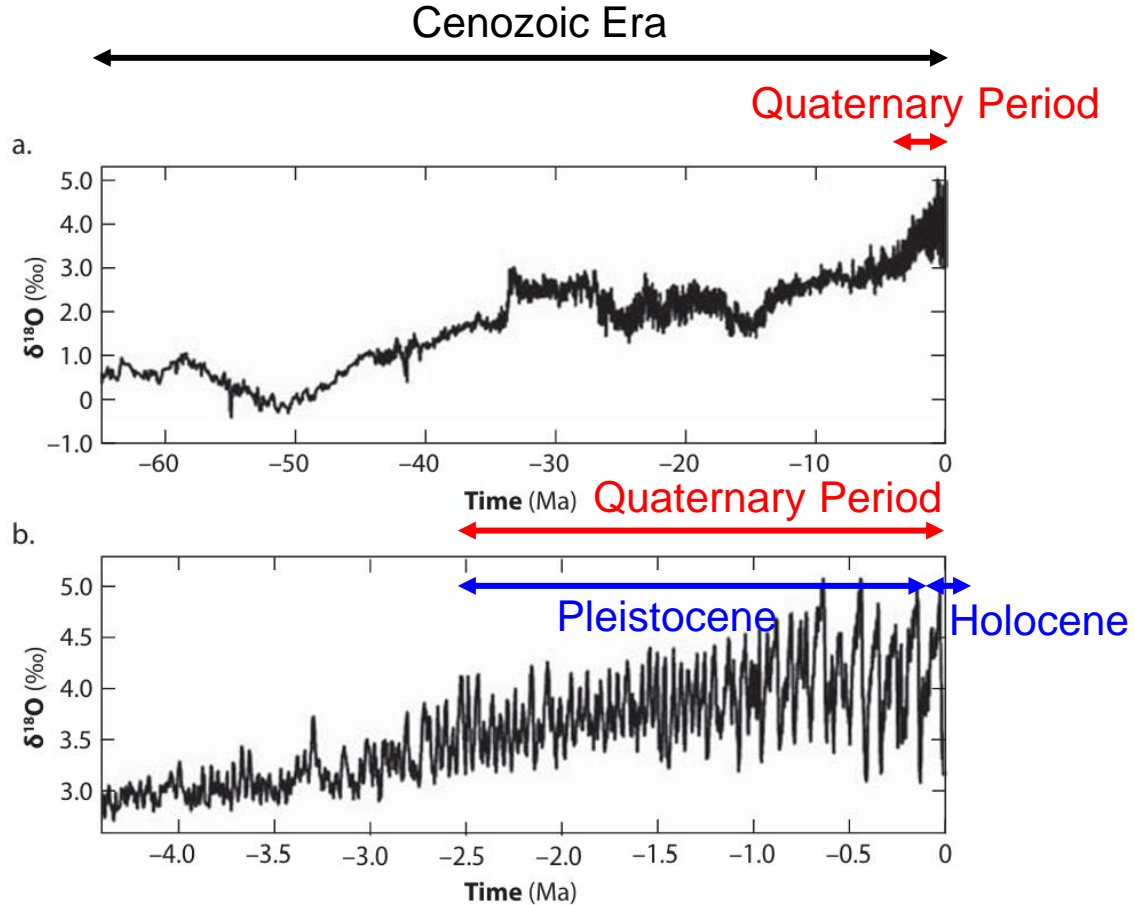


Fig 9.1 from "The Cryosphere" by S. Marshall

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

How has surface temperature changed through Cenozoic Era?

How has surface temperature changed through Pleistocene?

Birth of the Antarctic ice sheet

Formation of the ACC

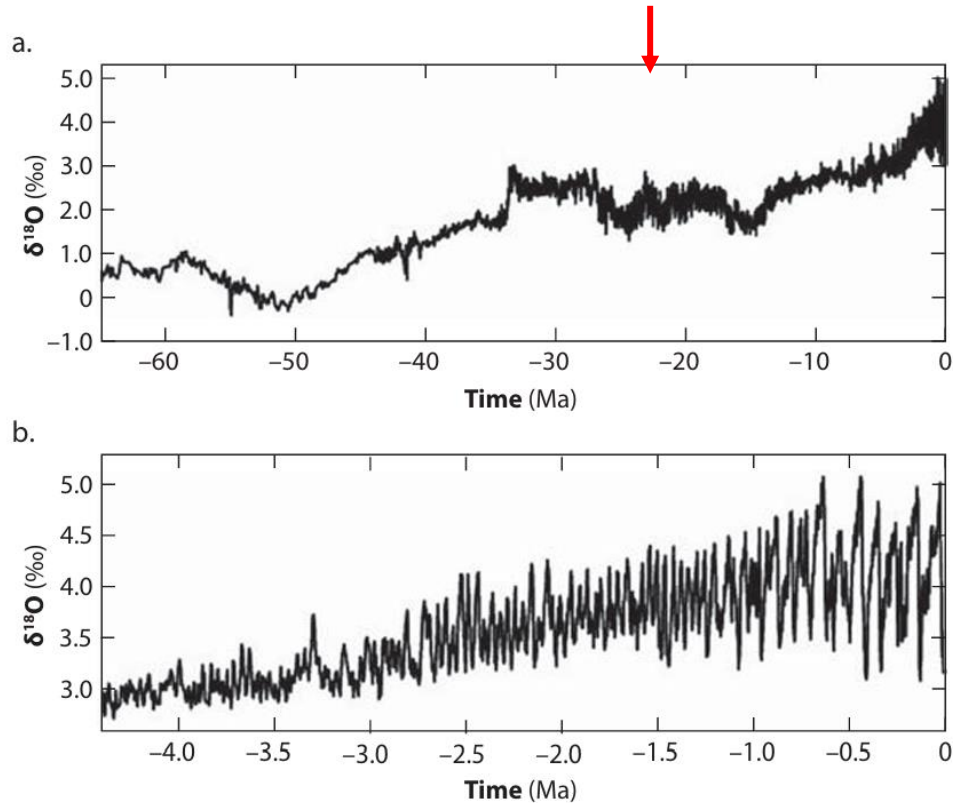
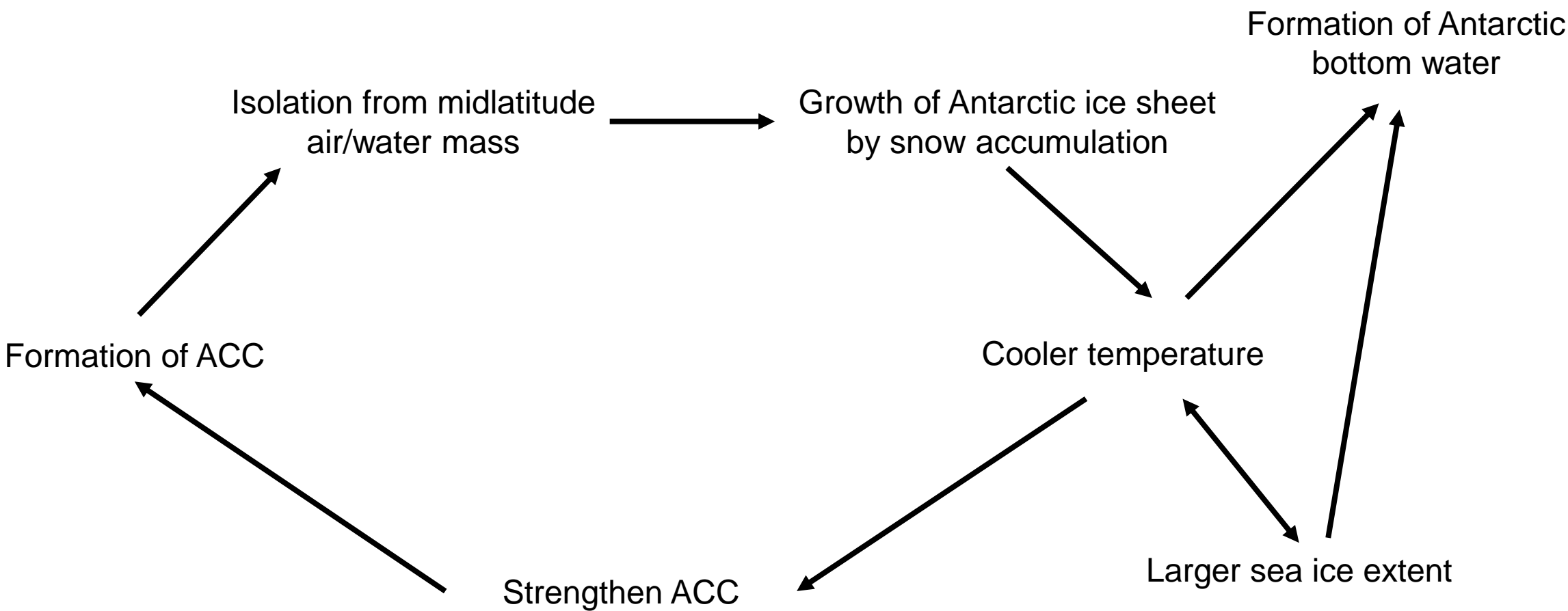


Fig 9.1 from “The Cryosphere” by S. Marshall

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

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?

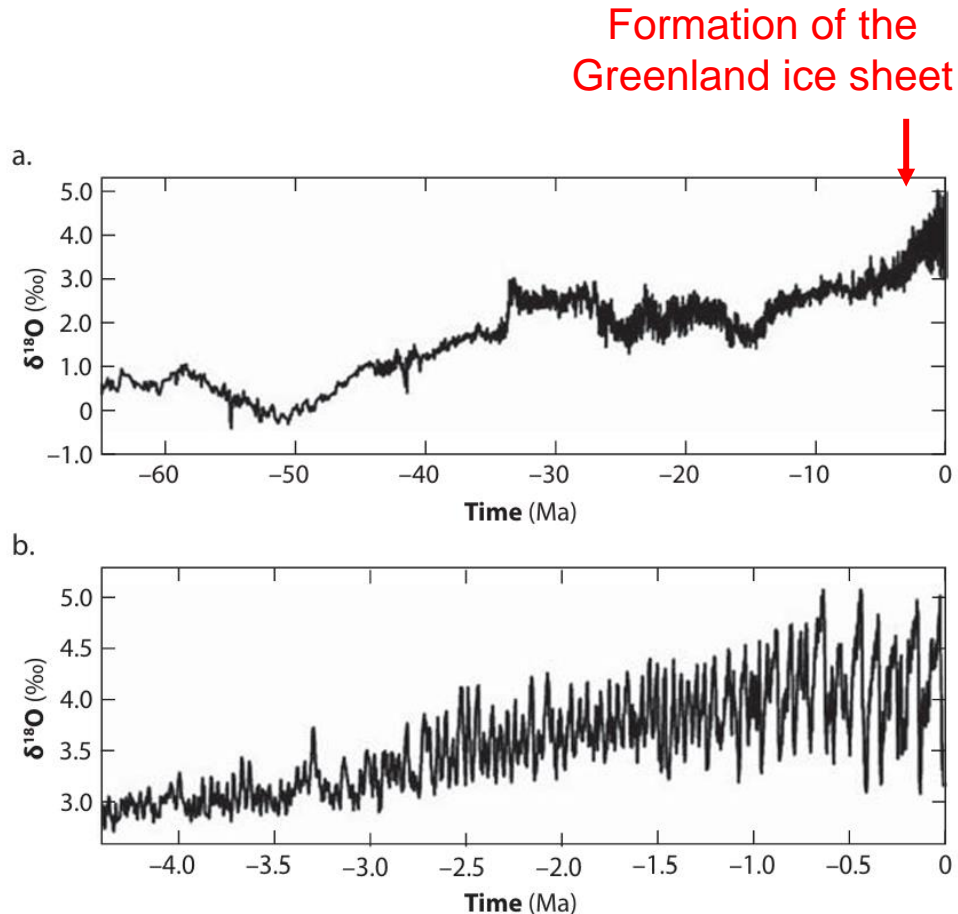


Fig 9.1 from “The Cryosphere” by S. Marshall

Pleistocene glacial cycles

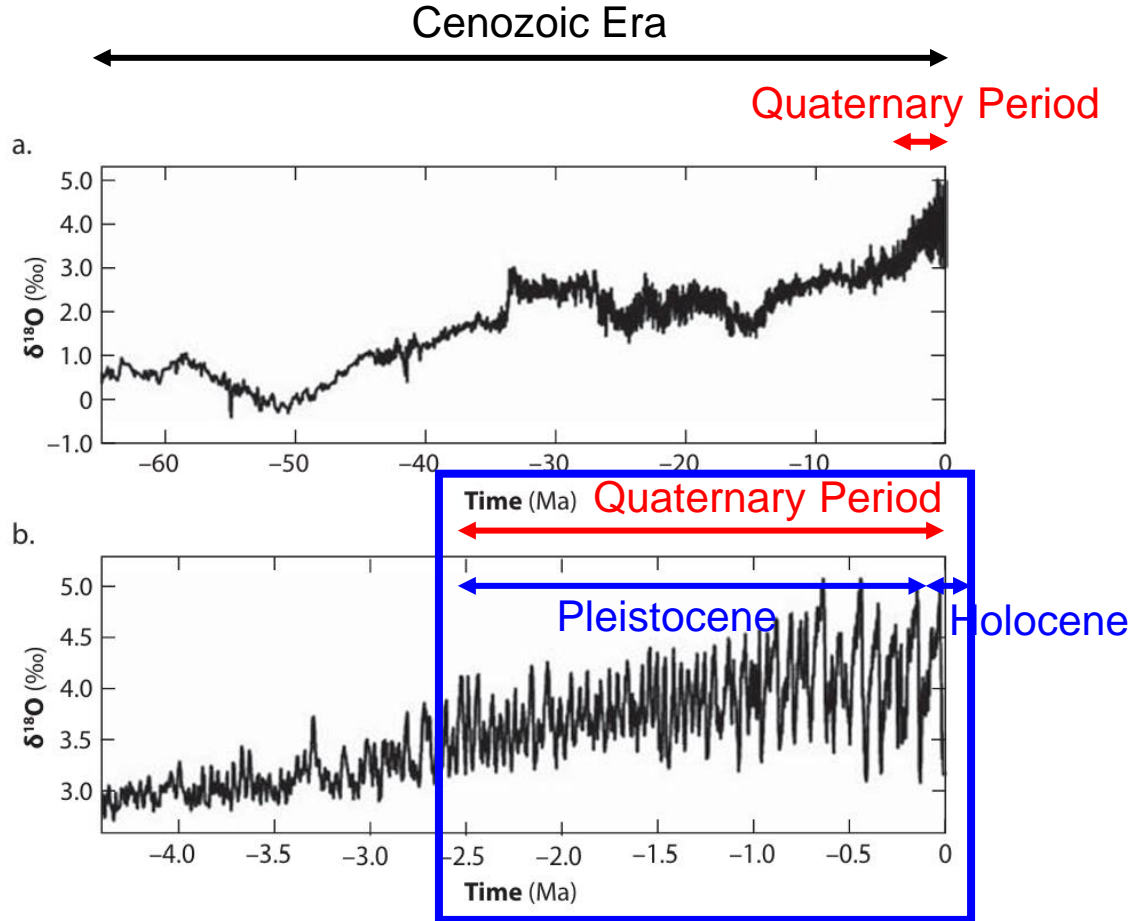


Fig 9.1 from “The Cryosphere” by S. Marshall

How has surface temperature changed through Pleistocene?

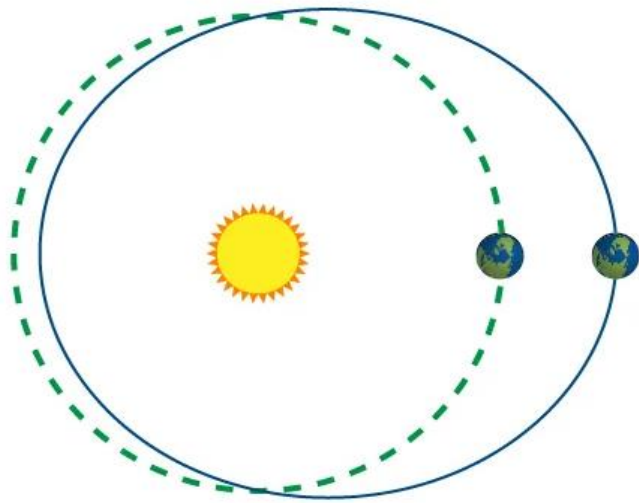
- Surface temperature fluctuates
- Magnitude of fluctuation has increased
- Period of fluctuation has increased

What are the causes of the fluctuations?

- Trigger:
- Amplification:

Pleistocene glacial cycles

: Orbital variation



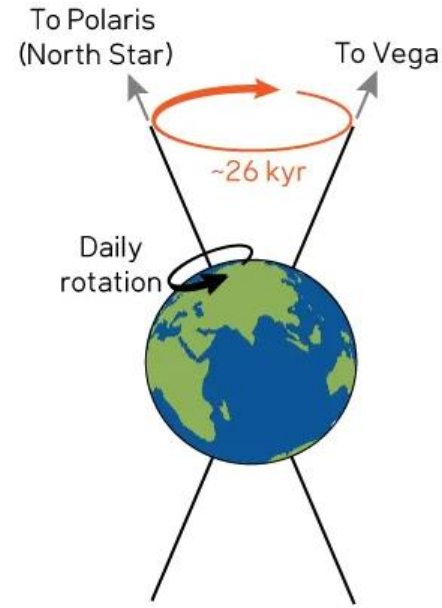
Eccentricity

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



What is his name?

Born 28 May 1879^[1]
Dalj, Austria-Hungary (modern day
Croatia)

Died 12 December 1958 (aged 79)
Belgrade, PR Serbia, Yugoslavia
(modern Serbia)

Pleistocene glacial cycles

: Internal climate system feedback

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-



Why was the orbital variation theory first met with skepticism?

Pleistocene glacial cycles : Millennial climate variability

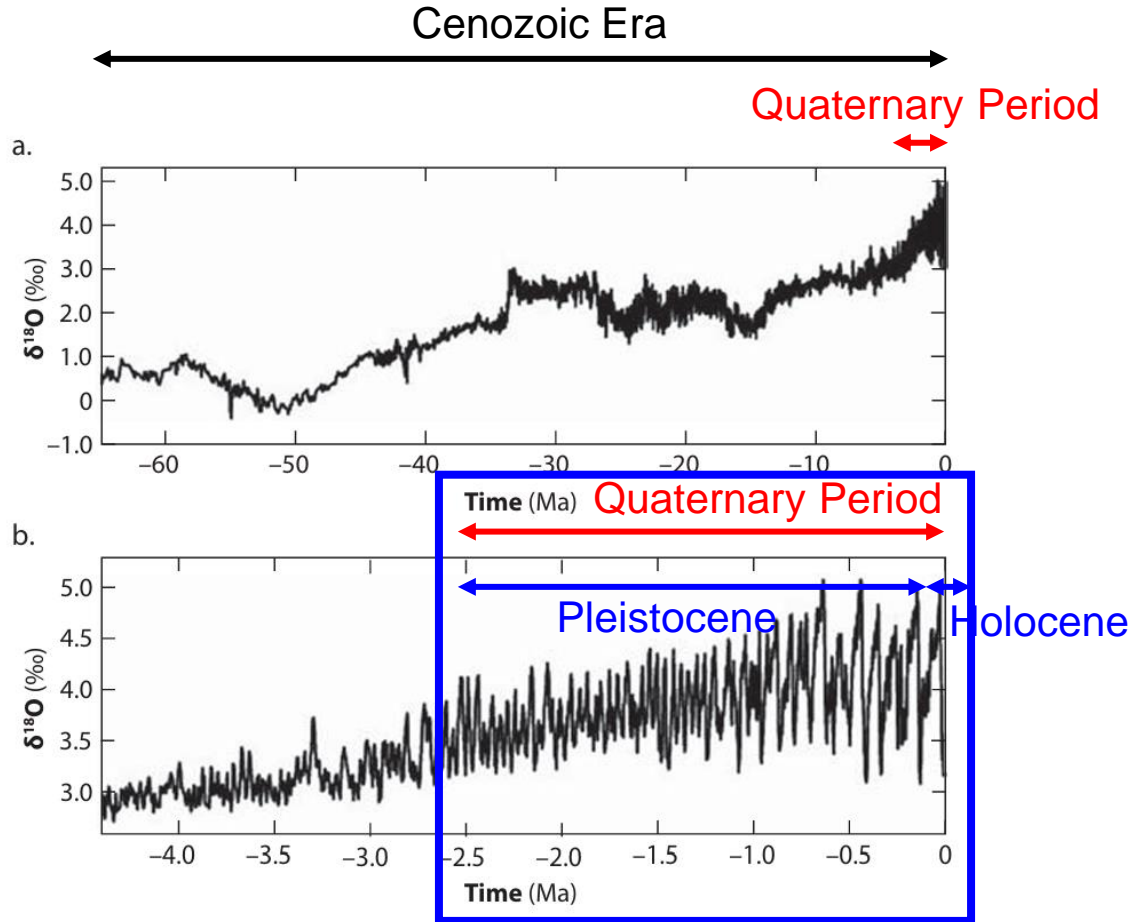


Fig 9.1 from "The Cryosphere" by S. Marshall

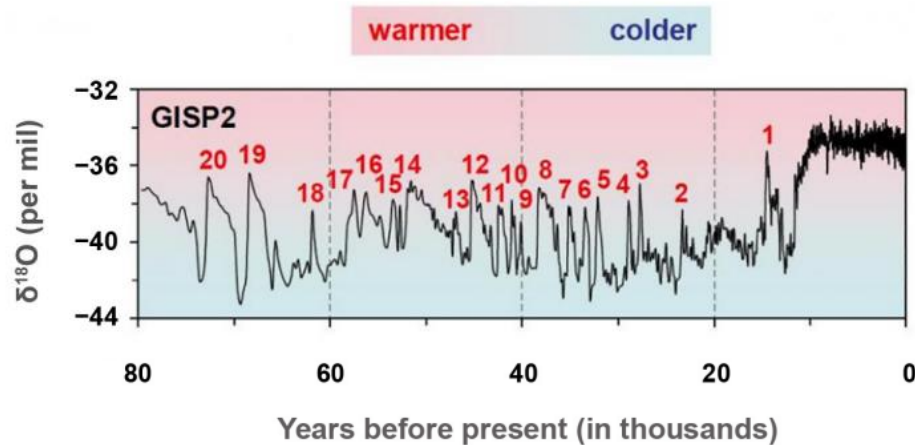
Millennial climate variability

- 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 $\delta^{18}\text{O}$ 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](#)).

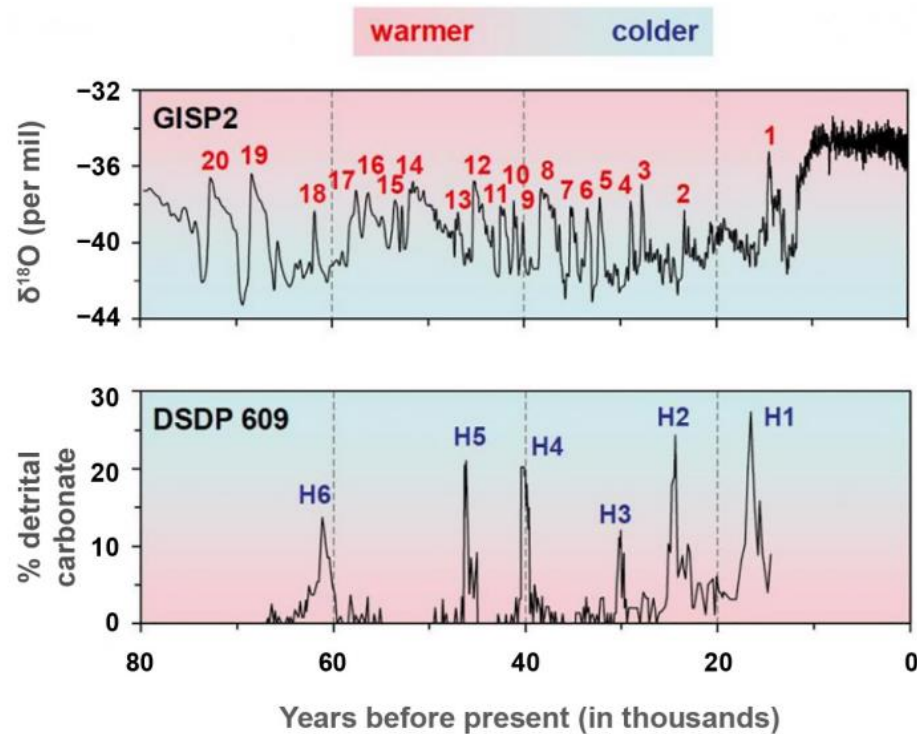
<https://www.ncei.noaa.gov/sites/default/files/2021-11/2%20Heinrich%20and%20Dansgaard%E2%80%93Oeschger%20Events%20-%20Final-OCT%202021.pdf>

Dansgaard-Oeschger (DO) Cycles

- ~1500-year temperature oscillations
- Cause:

Pleistocene glacial cycles

: Dansgaard-Oeschger Cycles



The $\delta^{18}\text{O}$ record from the GISP2 ice core in Greenland (top), showing 20 of the 25 observed Dansgaard–Oeschger events during the last glacial period (Groote 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

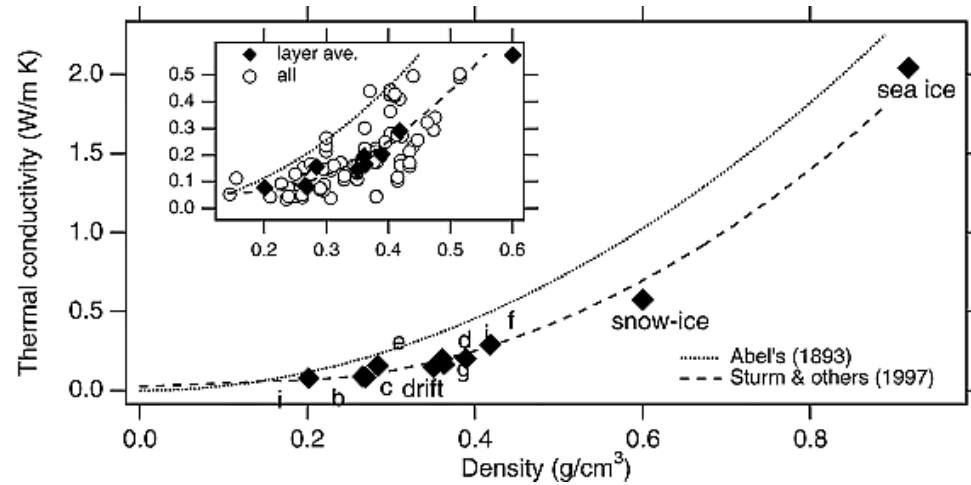
The change in what variable is the most influential to the recent changes in the cryosphere?

In recent years, how has that variable changed?

What is the main driver for this change?

Recent and future cryospheric change

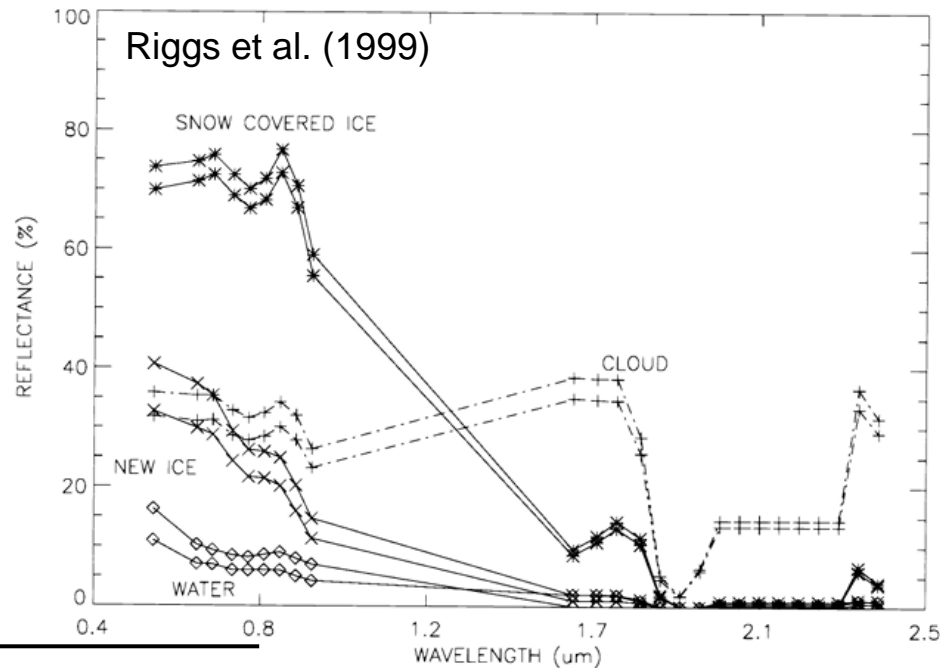
Sturm et al. (2002)



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

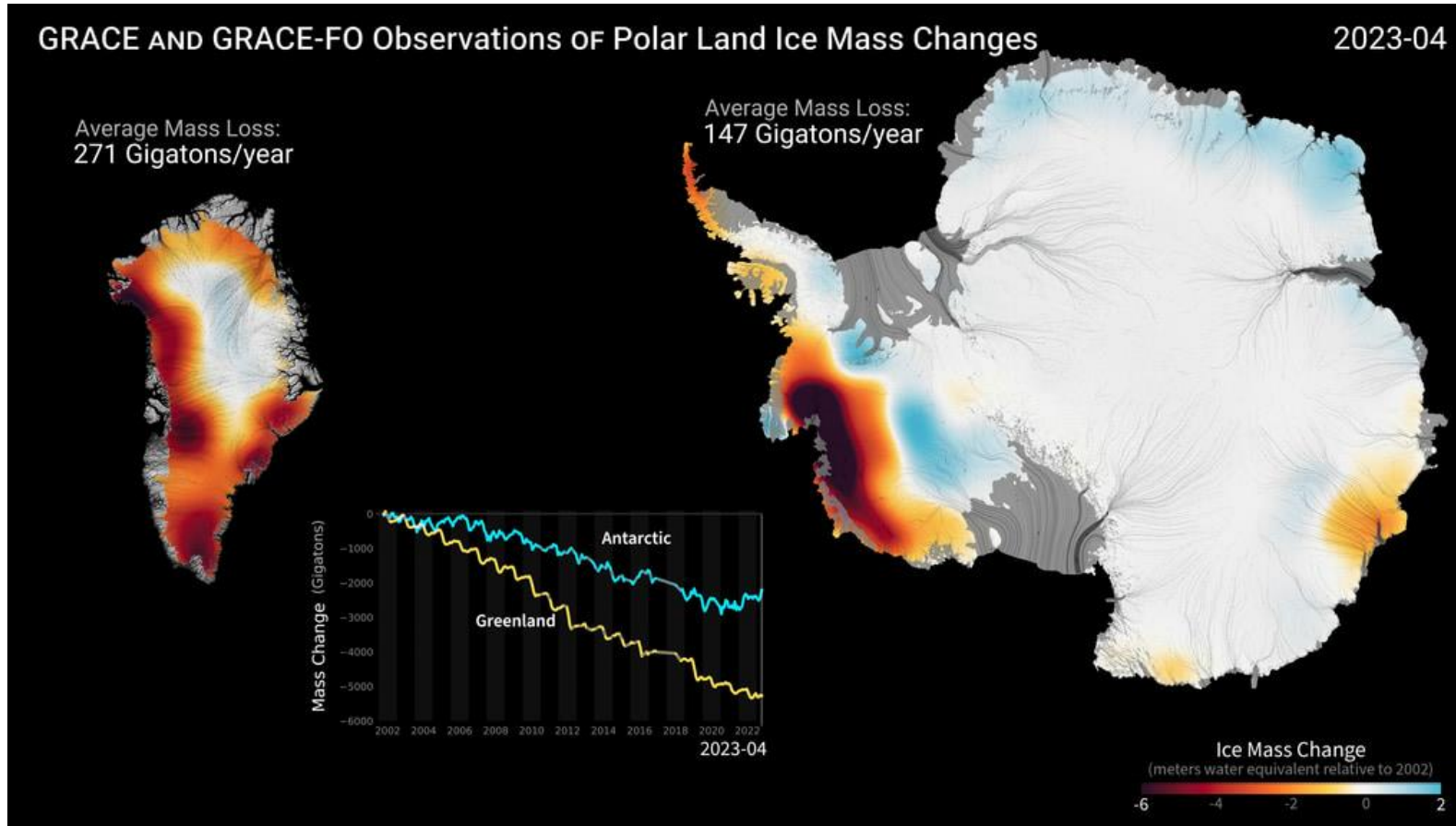
How does this variable change with increased temperature?

Riggs et al. (1999)



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 $\sim 1000 \text{ kg/m}^3$
- Surface area of ocean $\sim 3.57 \times 10^8 \text{ km}^2$

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

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

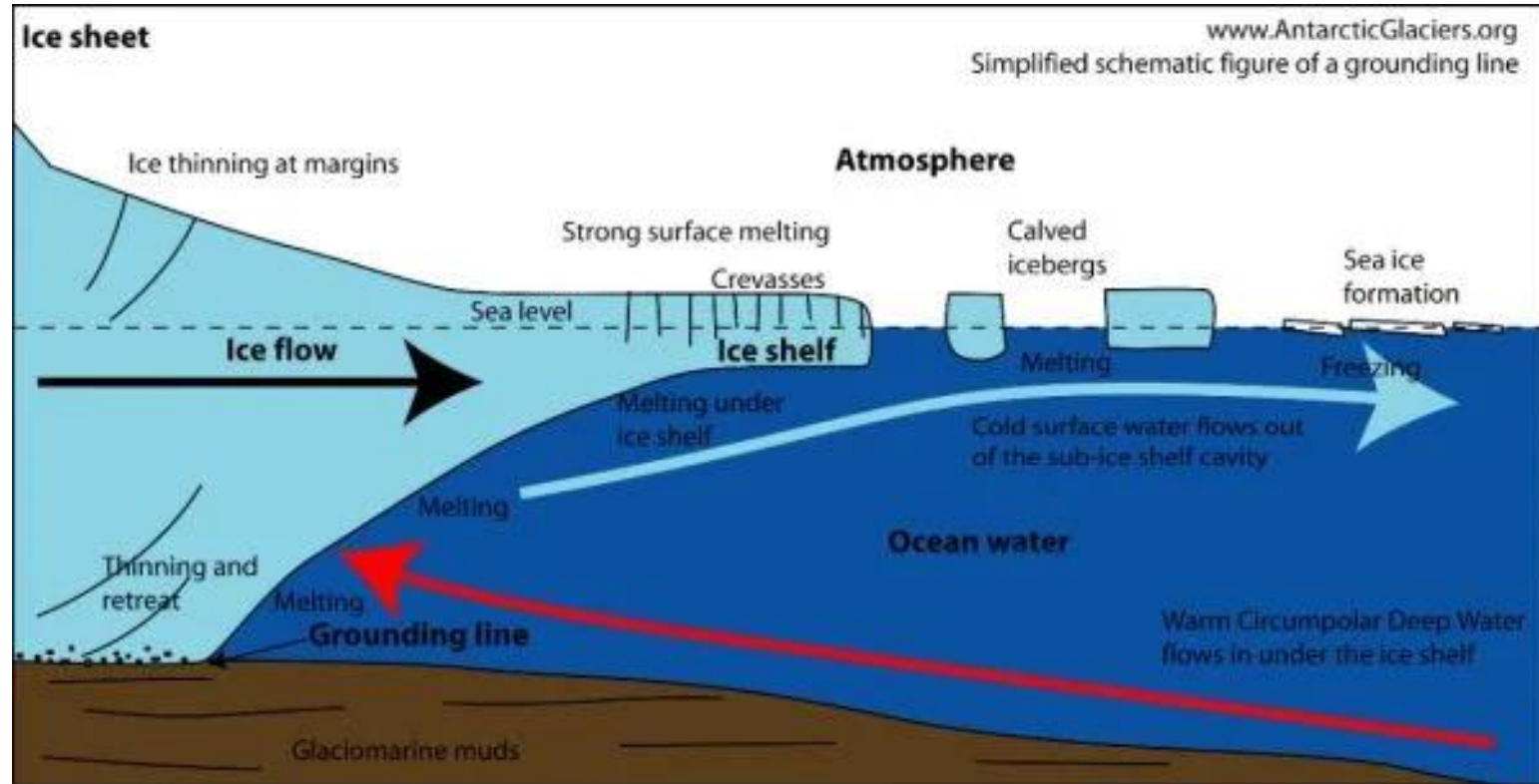
$$\Delta V = A_{ocean} \Delta h$$

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

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

$$= 0.00117 \text{ m/yr} = 0.117 \text{ cm/yr}$$

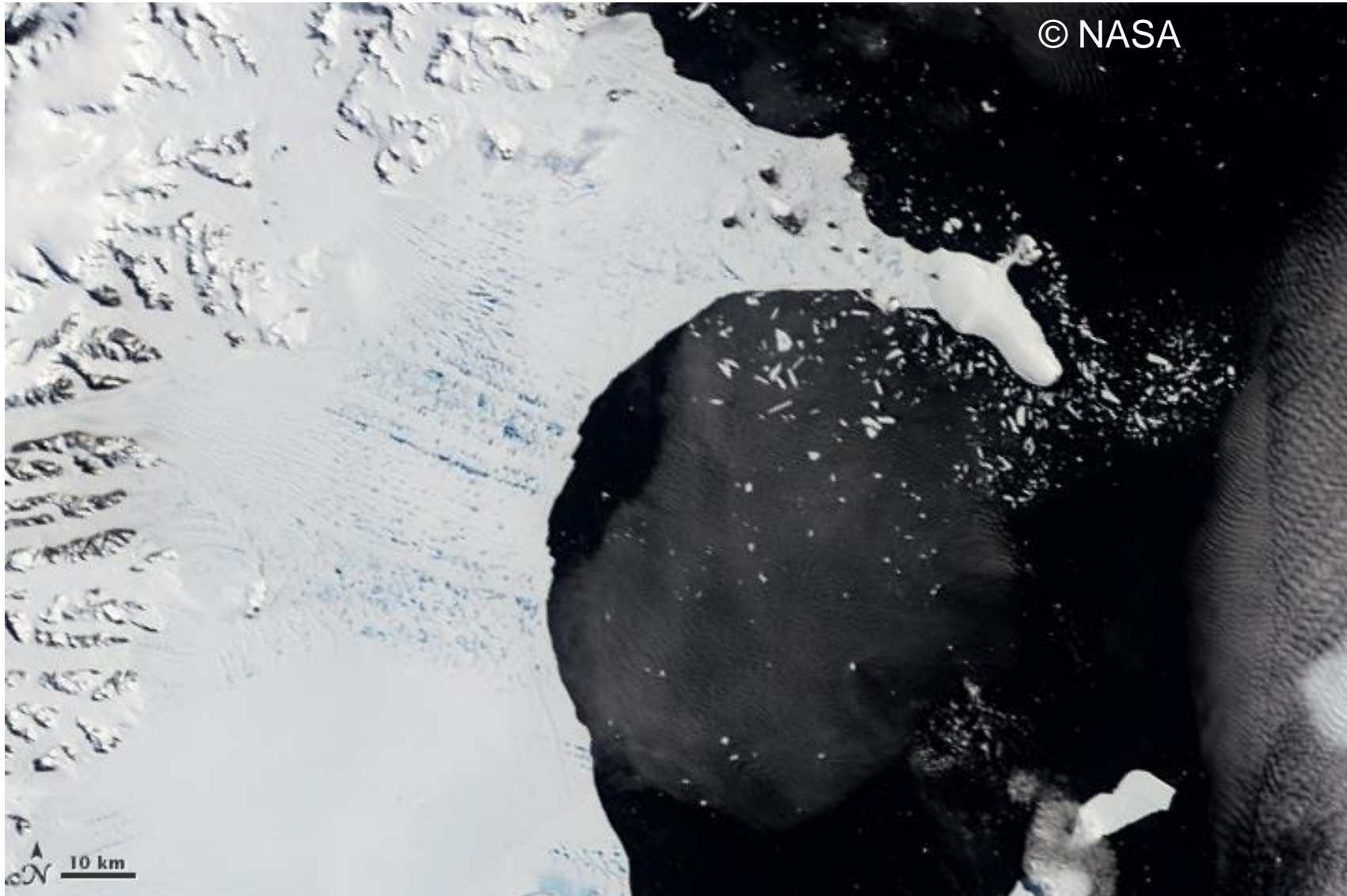
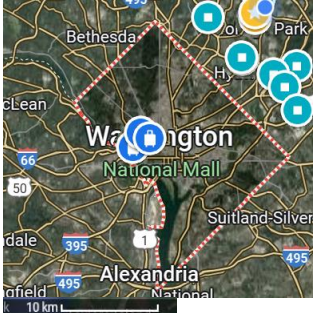
Recent and future cryospheric change : Glacier and Ice Sheet



Through what processes are the ice sheets lost?

Recent and future cryospheric change : Glacier and Ice Sheet

Jan 31, 2002



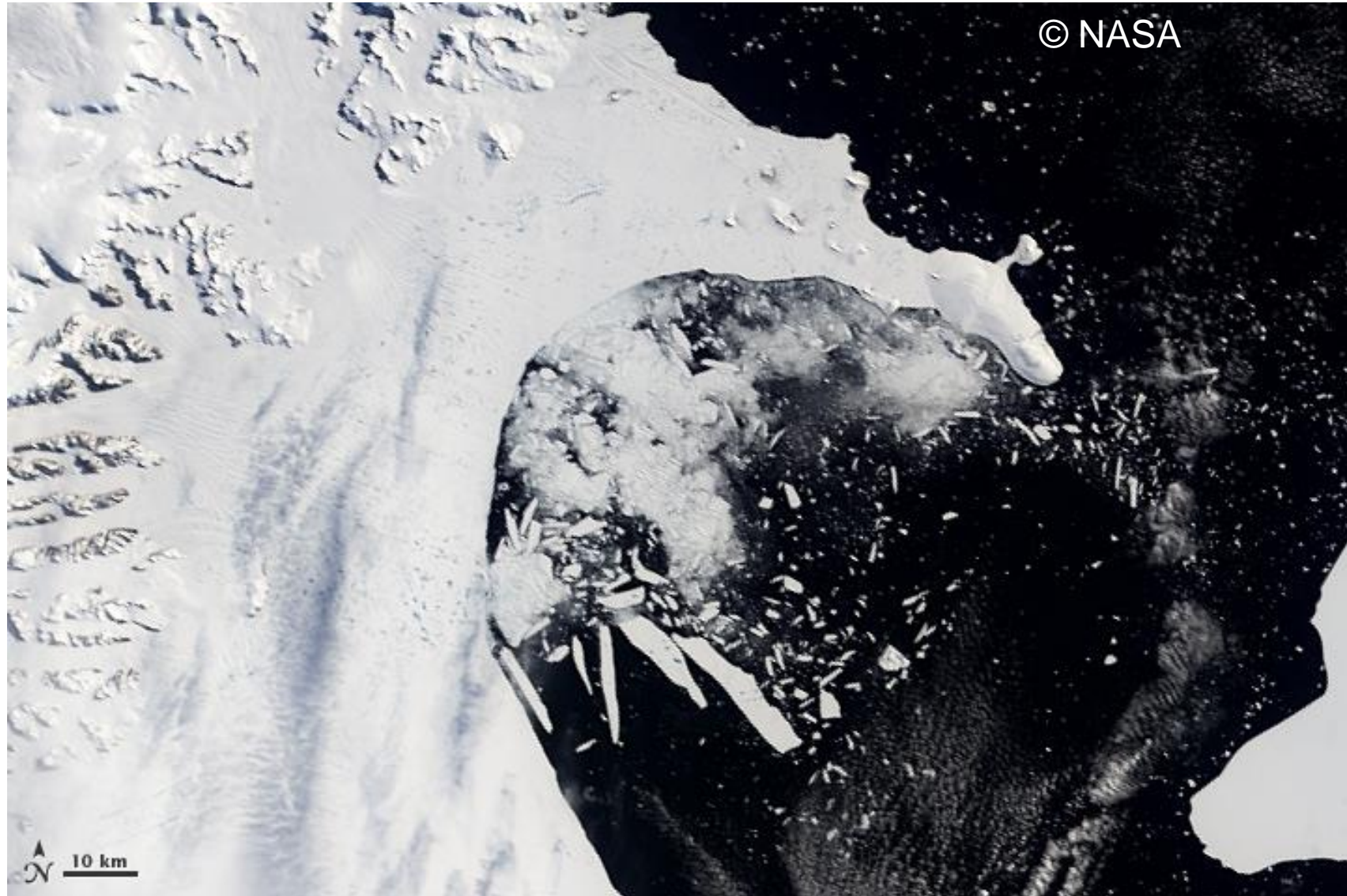
Recent and future cryospheric change : Glacier and Ice Sheet

Feb 17, 2002



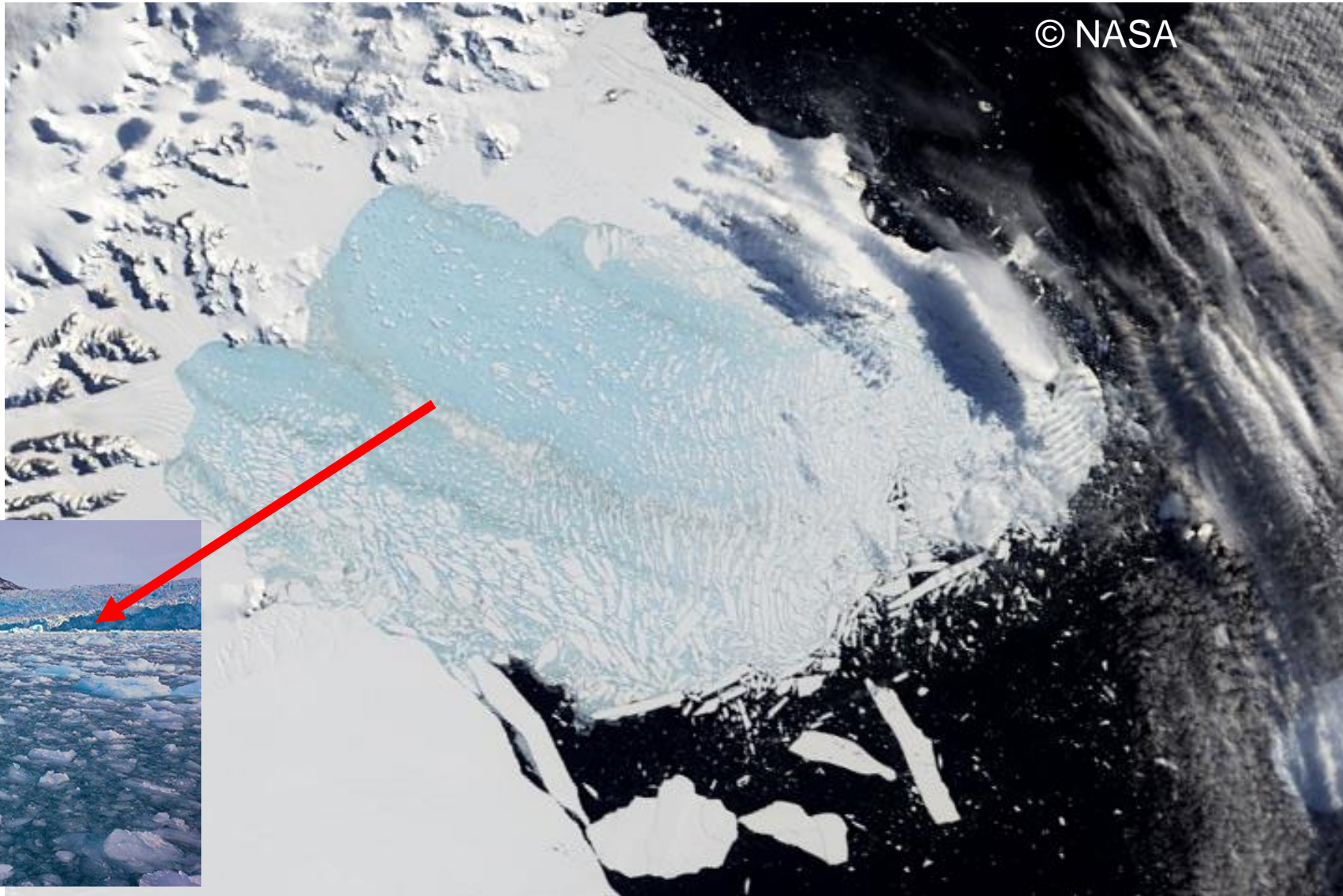
Recent and future cryospheric change : Glacier and Ice Sheet

Feb 23, 2002



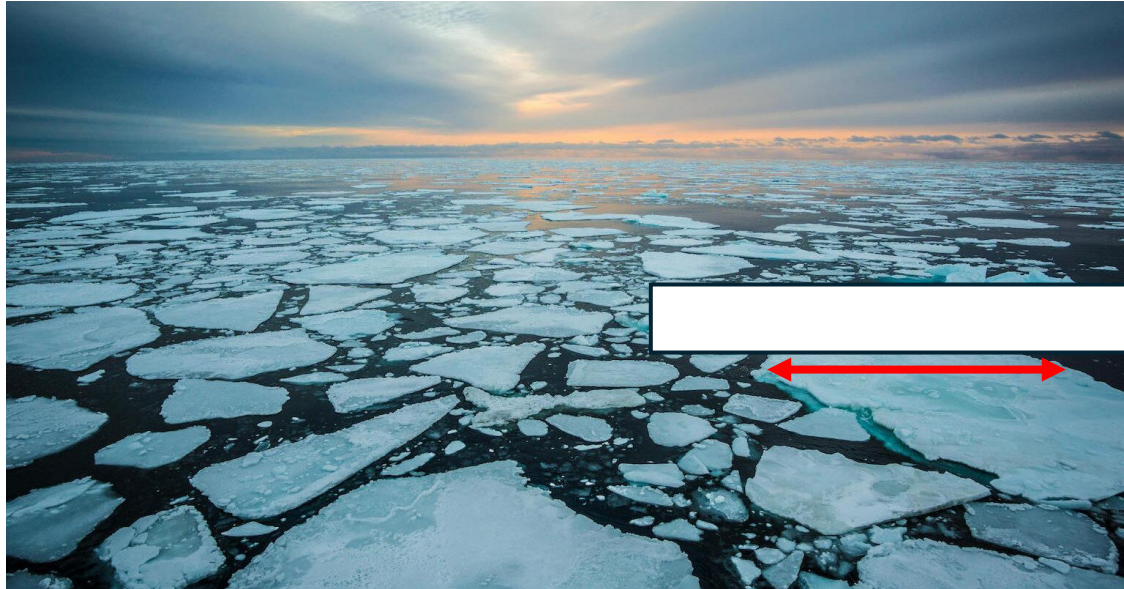
Recent and future cryospheric change : Glacier and Ice Sheet

Mar 7, 2002



Recent and future cryospheric change

: Sea Ice



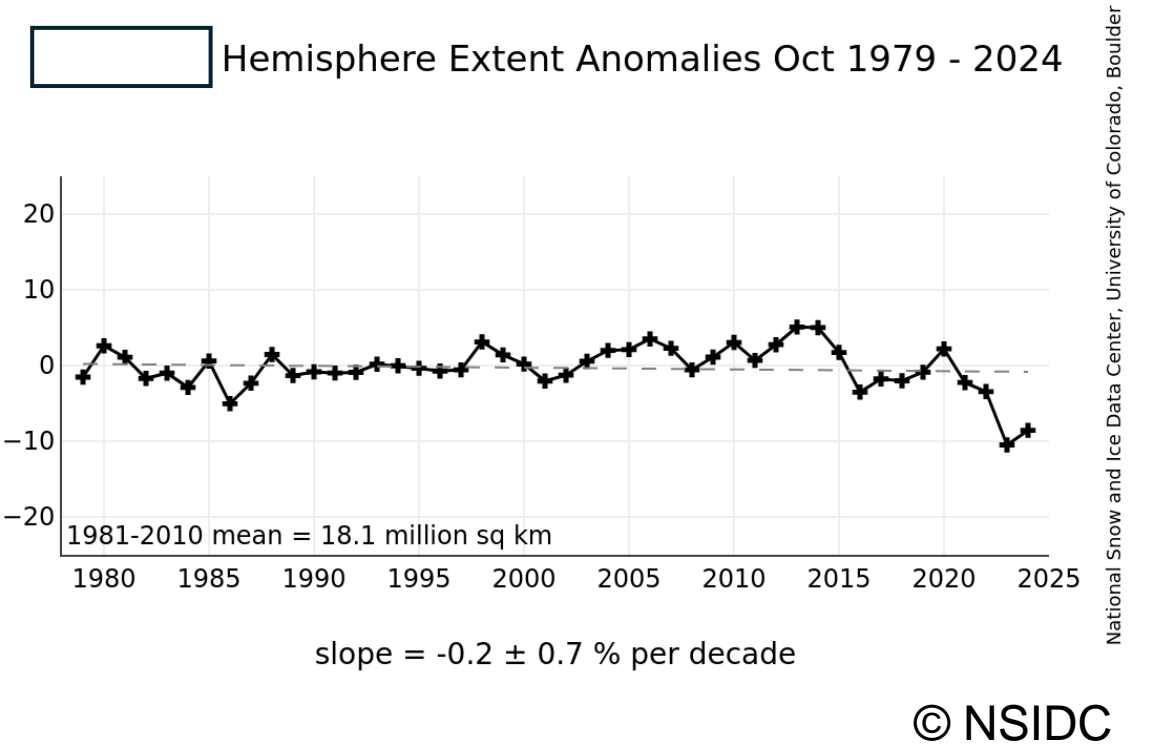
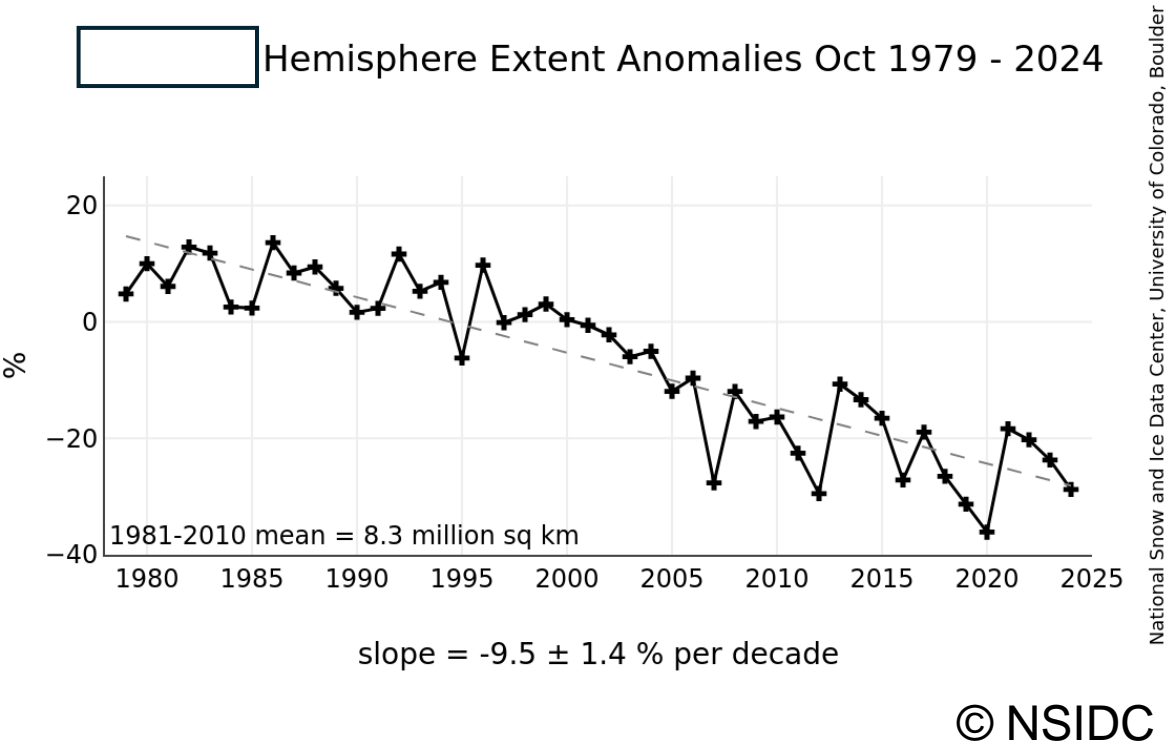
Sea ice has both horizontal and vertical dimension!

Ocean surface



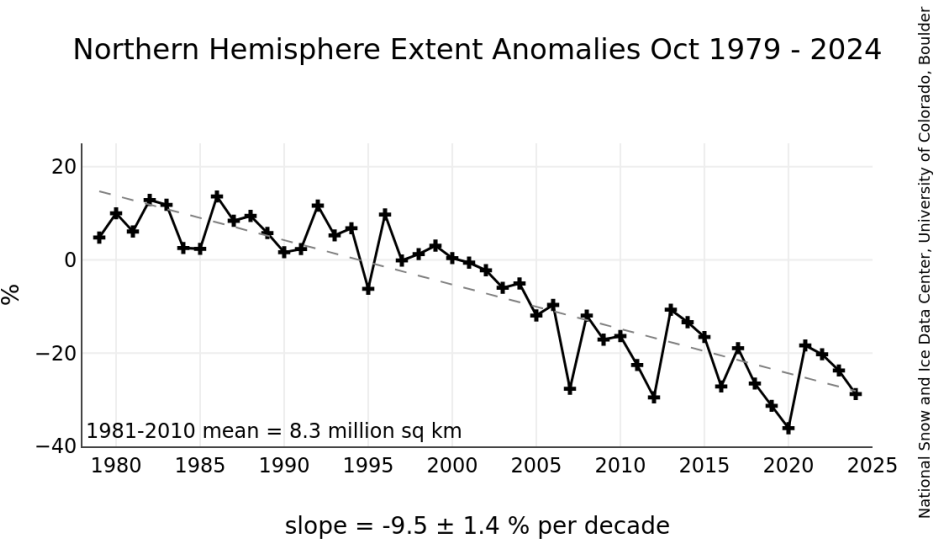
Recent and future cryospheric change

: Sea Ice

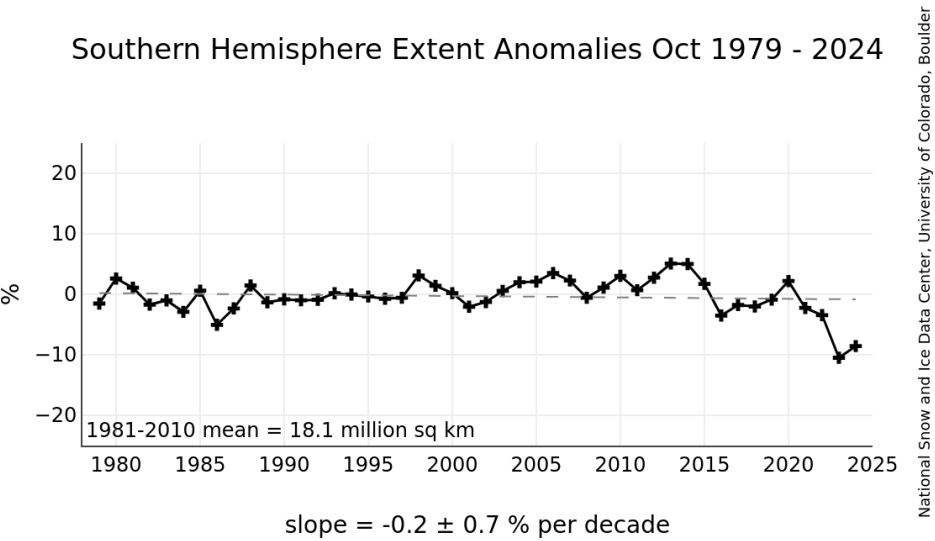


Recent and future cryospheric change

: Sea Ice



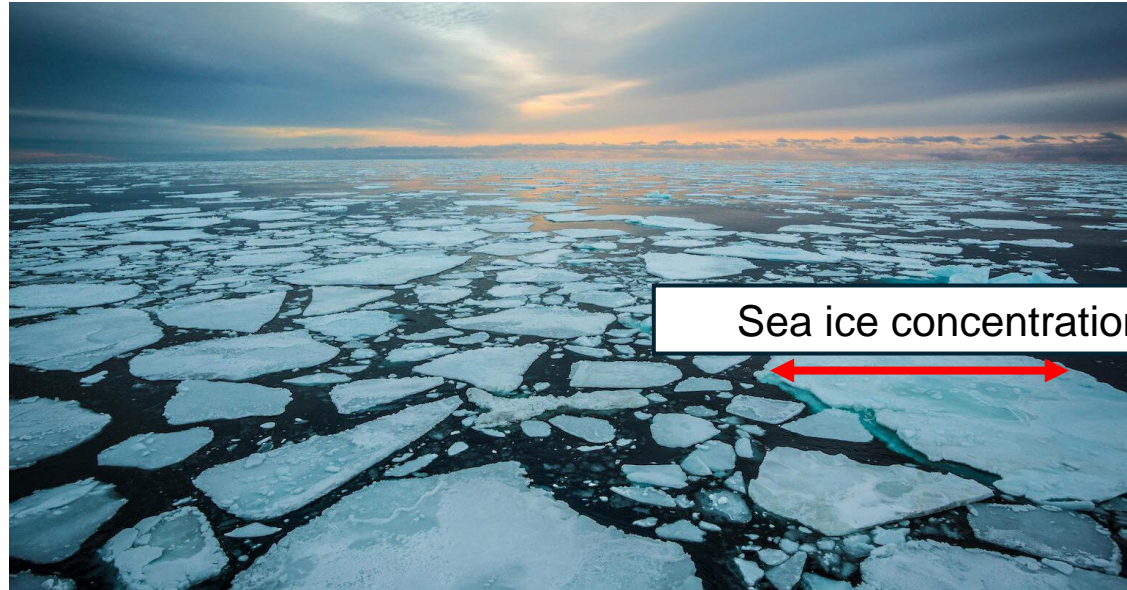
AT5. What mechanism caused the difference in trend between the two hemispheres?



How are these observations (since 1970s) obtained?

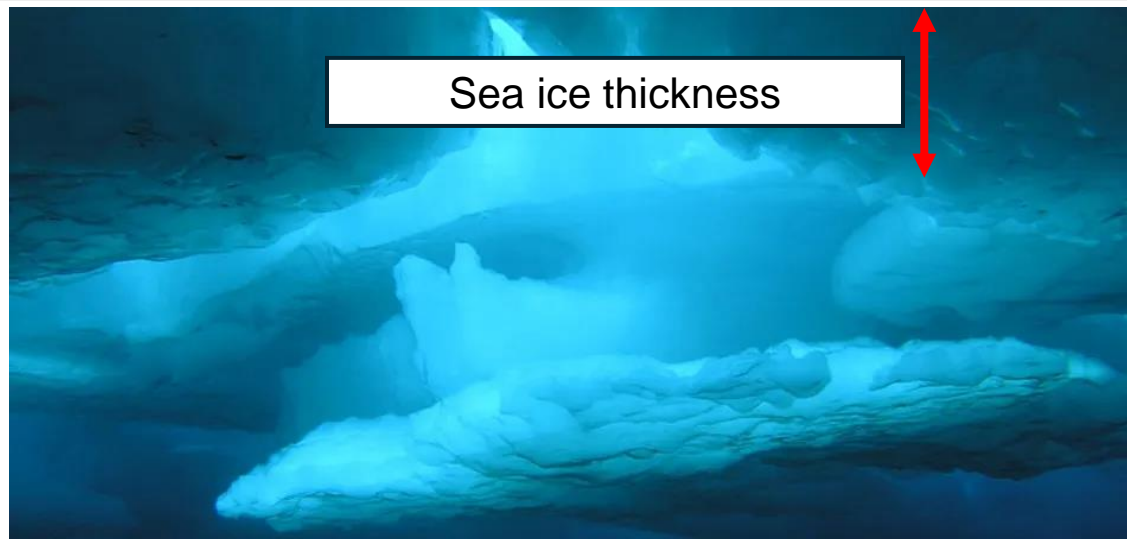
Recent and future cryospheric change

: Sea Ice



Sea ice has both horizontal and vertical dimension!

Ocean surface

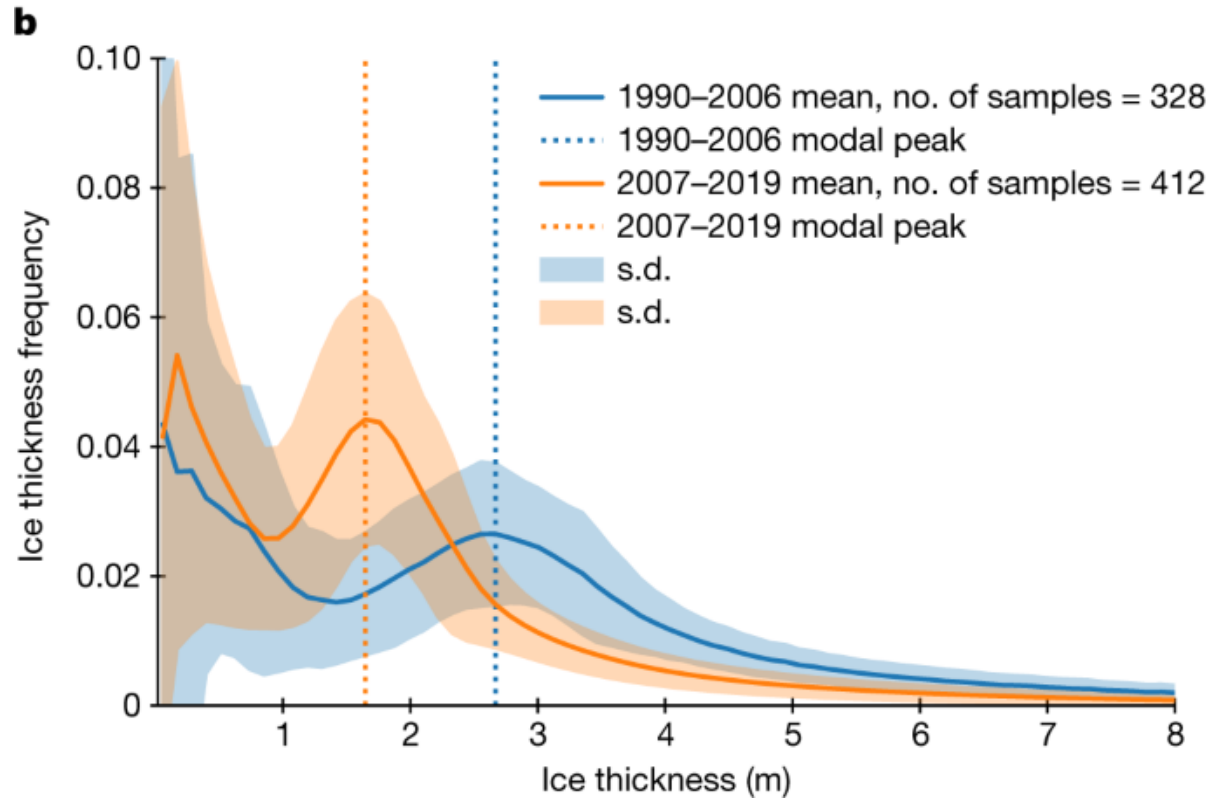


Recent and future cryospheric change : Sea Ice

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-

Search

Reset

N:90, S:-90, E:180, W:-180

From to

Storage Location

☐ In Earthdata Cloud (1)

Spatial Coverage

☐ Show Global Only (5)

Parameter

☐ BASINS (1)

☐ BRIGHTNESS T... (1)

☐ COASTLINE (1)

☐ ELEVATION (4)

☐ FAST ICE (1)

☐ FREFROARD (1)

Showing 1-25 of 71 Data Sets

Sort by: Relevance (highest t... Per page: 25

MEaSUREs InSAR-Based Antarctica Ice Velocity Map

Temporal Coverage

1996-01-01 to 2016-12-31

Parameter

ICE VELOCITY

Data Format

NetCDF

Summary

This data set, part of the NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Program, provides the first comprehensive, high-res...

MEaSUREs Annual Greenland Outlet Glacier Terminus Positions from SAR Mosaics

Temporal Coverage

1972-09-16 to 2021-03-25

Parameter

GLACIER EXTENT

Data Format

Shapefile

Summary

This data set, part of the NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) program, consists of annual, digitized (polyline) ice fr...

Search

Reset

N:90, S:-90, E:180, W:-180

From to

Storage Location

☐ In Earthdata Cloud (35)

Spatial Coverage

☐ Show Global Only (39)

Parameter

☐ AEROSOL BAC... (2)

☐ AEROSOL EXTI... (1)

☐ AEROSOL OPTI... (1)

☐ AEROSOL PAR... (1)

☐ ANTICYCLONE... (1)

☐ ATTITUDE CHA... (1)

Showing 1-25 of 63 Data Sets

Sort by: Relevance (highest t... Per page: 25

ATLAS/ICESat-2 L3A Land Ice Height

Temporal Coverage

2018-10-14 to present

Parameter

GLACIER ELEVATION/ICE SHEET ELEVATION

Data Format

HDF5

Summary

This data set (ATL06) provides geolocated, land-ice surface heights (above the WGS 84 ellipsoid, ITRF2014 reference frame), plus ancillary parameters that can be used...

ATLAS/ICESat-2 L3A Sea Ice Height

Temporal Coverage

2018-10-14 to present

Parameter

SEA ICE ELEVATION

Data Format

HDF5

Summary

The data set (ATL07) contains along-track heights for sea ice and open water leads (at varying length scales) relative to the WGS84 ellipsoid (ITRF2014 reference frame) after e...

MOSAIC

Embark on the largest polar expedition in history: in September 2019, the German research icebreaker Polarstern set sail from Tromsø, Norway, to spend a year drifting through the Arctic Ocean - trapped in ice. The goal of the MOSAiC expedition was to take the closest look ever at the Arctic as the epicenter of global warming and to gain fundamental insights that are key to better understand global climate change. Hundreds of researchers from 20 countries were involved in this exceptional endeavour. Following in the footsteps of Fridtjof Nansen's ground-breaking expedition with his wooden sailing ship Fram in 1893-1896, the MOSAiC expedition brought a modern research icebreaker close to the north pole for a full year including for the first time in polar winter. The data gathered will be used by scientists around the globe to take climate research to a completely new level. Led by atmospheric scientist Markus Rex, and co-led by Klaus Dethloff and Matthew Shupe, MOSAiC is spearheaded by Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI).

See expedition

See science

Science & Data

IceBridge Data

Science Collaboration

Presentations

IceBridge Publications

Level 1 Science Requirements

IceBridge Data

During each campaign, Operation IceBridge collects large amounts of data on land and sea ice. This information, and that collected by IceBridge's partnering organizations, is made available to the public free of charge no more than six months after each campaign. This data is stored and managed by the National Snow and Ice Data Center via an online portal.

For an introduction on using the NSIDC data portal, go to the NSIDC Operation IceBridge Quick Start webpage, for a number of video tutorials.

We ask that you cite the use of this data in your work and inform the IceBridge Project Science Office when you publish a study using IceBridge data.