ATM S 587: Fundamentals of Climate Change

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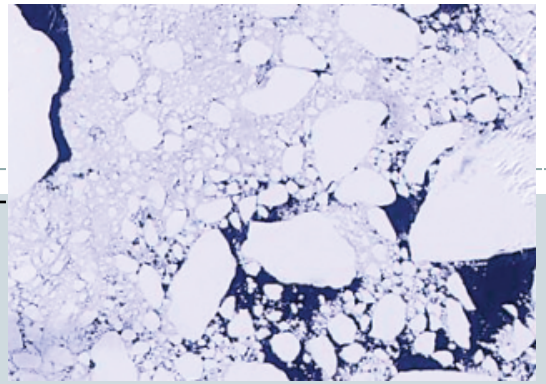
11/20/2013

*The **cryosphere***

sea ice

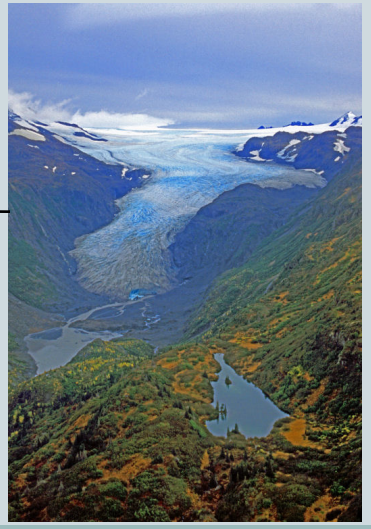


continental ice sheets

ice caps

permafrost

mountain glaciers



snow cover

The Cryosphere in Present Day

- Cryosphere: frozen water in the climate
  - **Mountain glaciers**: permanent ice on top of mountains
  - **Ice sheets**: glaciers that cover a large amount of land
    - Currently only Greenland and Antarctica
  - **Seasonal snow cover**
  - **Sea ice**: frozen ocean water floating
  - **Permafrost**: frozen soil

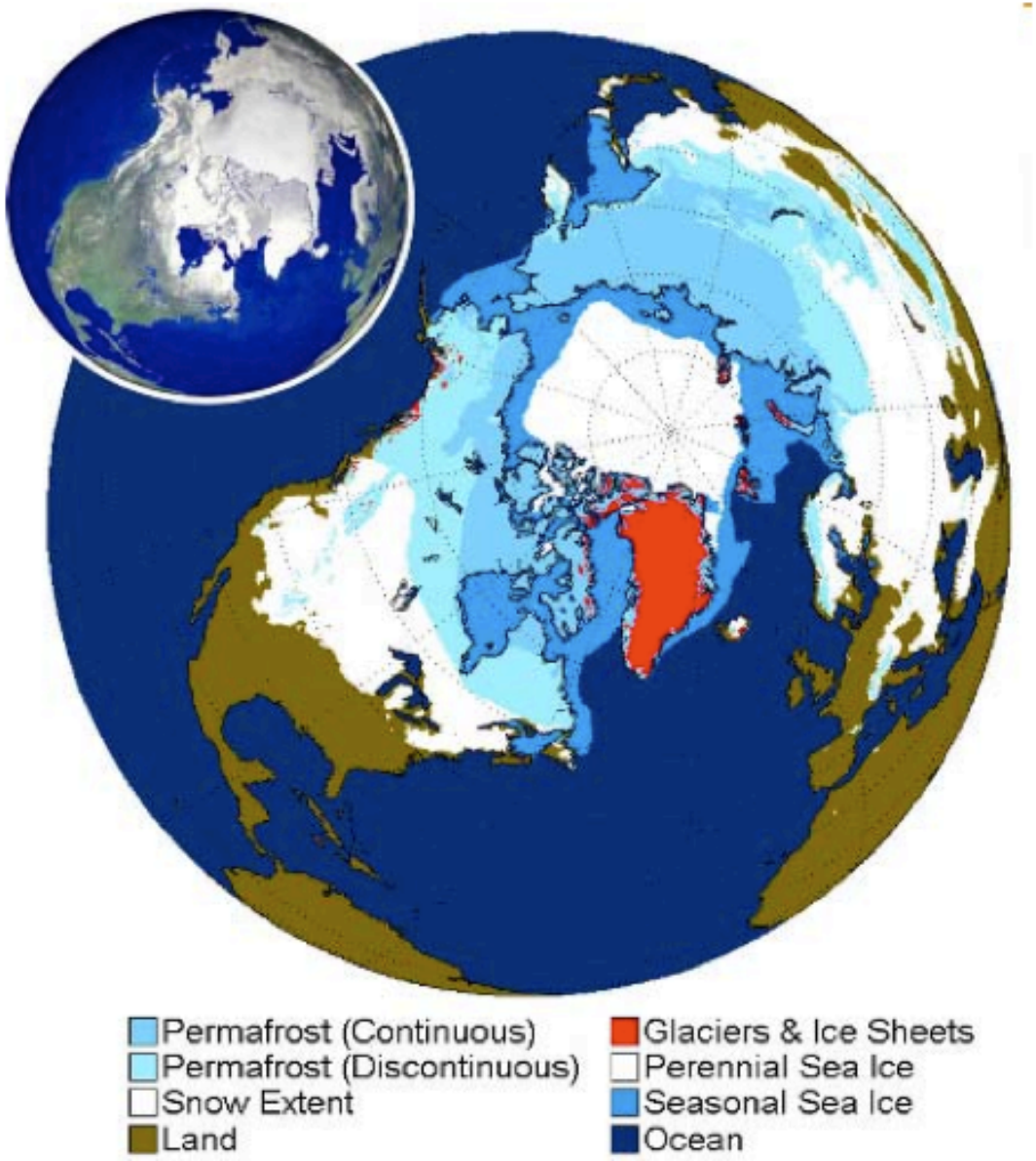
Relative Sizes of Cryosphere

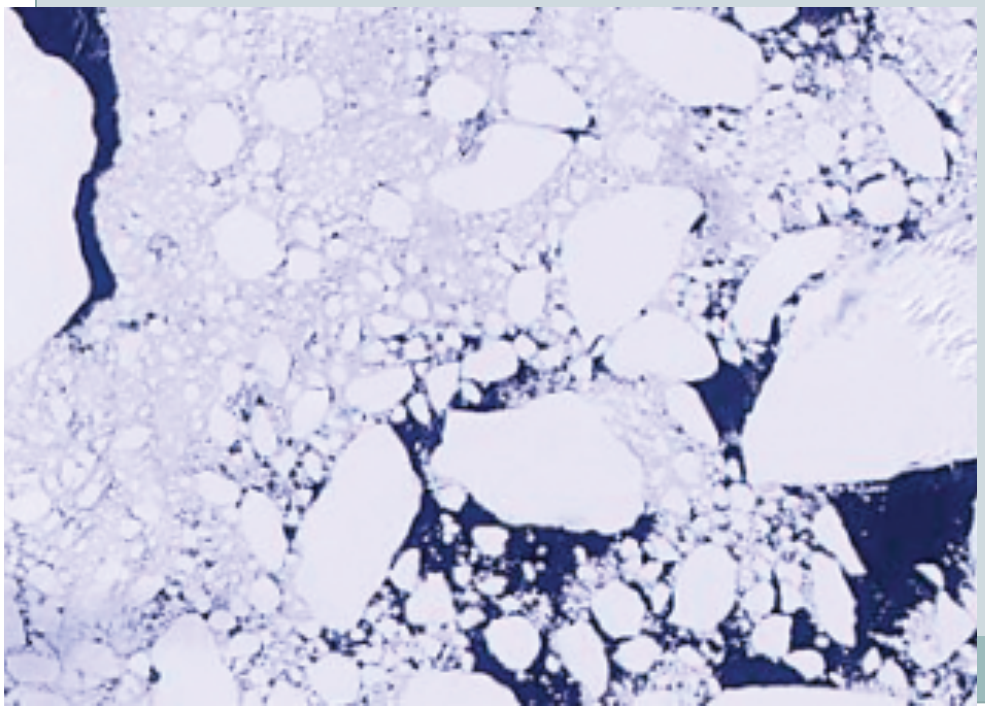
- Cryospheric components:
  - In terms of **coverage area** (percent of Earth surface area) and **volume** (how much sea level rise (SLR) would result from melting it all)
  - Antarctic ice sheet: 2.7% of Earth surface area, **61.1 meters** of sea level rise (SLR) if melted
  - Greenland ice sheet: 0.35% of area, **7.2 meters** of SLR
  - Alpine glaciers: 0.01% of area, 0.2 m of SLR
  - Seasonal snow cover: 9% of area (maximum), <0.01 m of SLR
  - Permafrost: 5% of area, 1 m of SLR
  - Sea ice: 7% of area (in season of maximum extent), 0.01 m of equivalent mass, (no sea level rise when sea ice melts)

Northern Hemisphere Cryosphere

- Maximum extent of ice types in NH:

(snow extent here is where snow coverage is > 50% during month with max coverage)

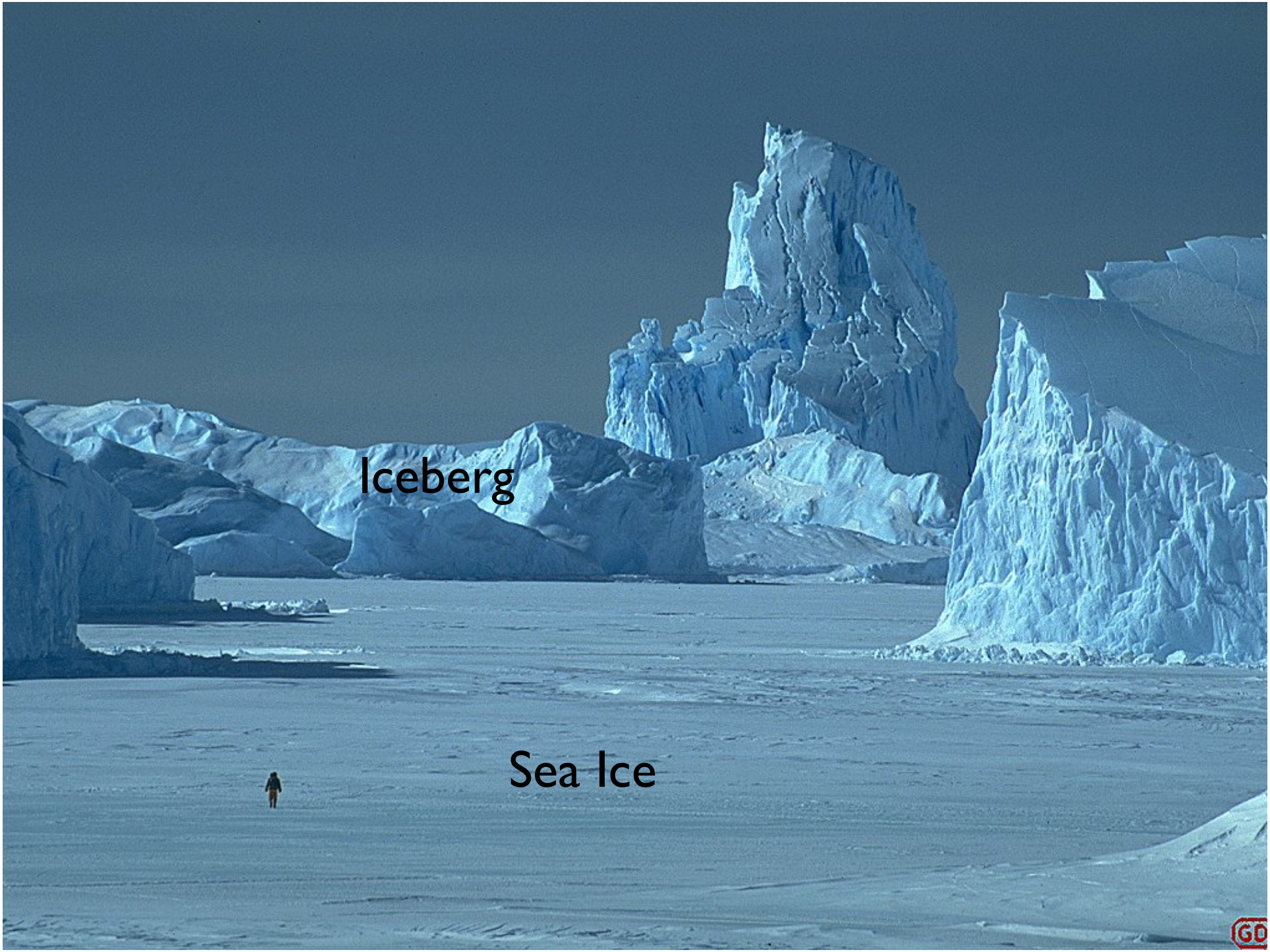




Sea ice

Sea Ice

- Forms from **frozen ocean water**
  - *Not* the same as icebergs, which break off of land ice
- Floats on the ocean surface
- Grows over the winter, melts in the summer


Iceberg
Sea Ice

How thick is sea ice?

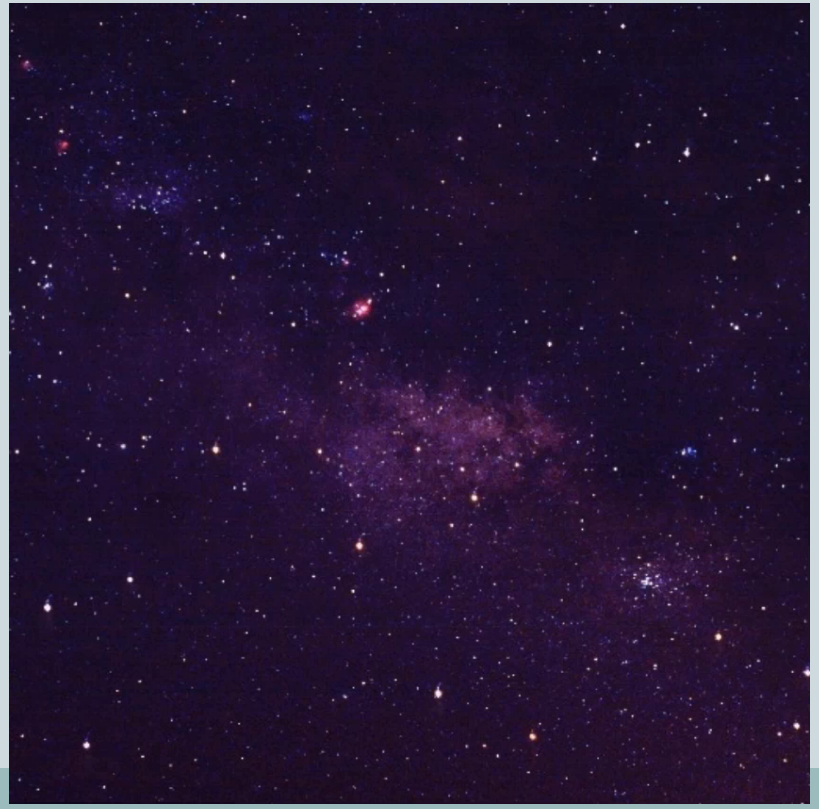
Arctic Sea Ice is typically 0.5 to 3 m thick

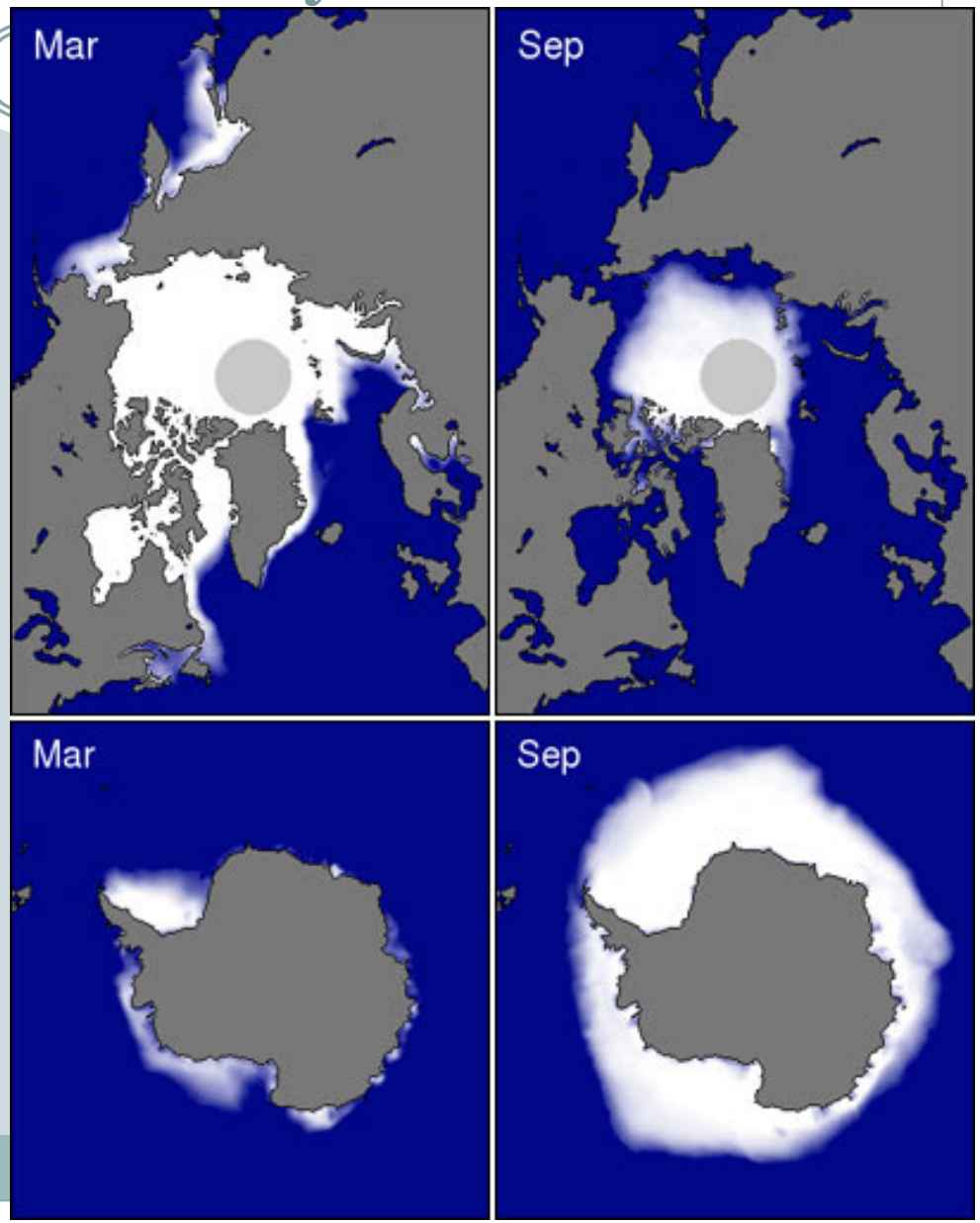
An exception is in *pressure ridges* which form when sea ice bumps into other sea ice. These can be 10-30 m thick


A scientific research team on sea ice

Sea Ice Seasonal Cycle

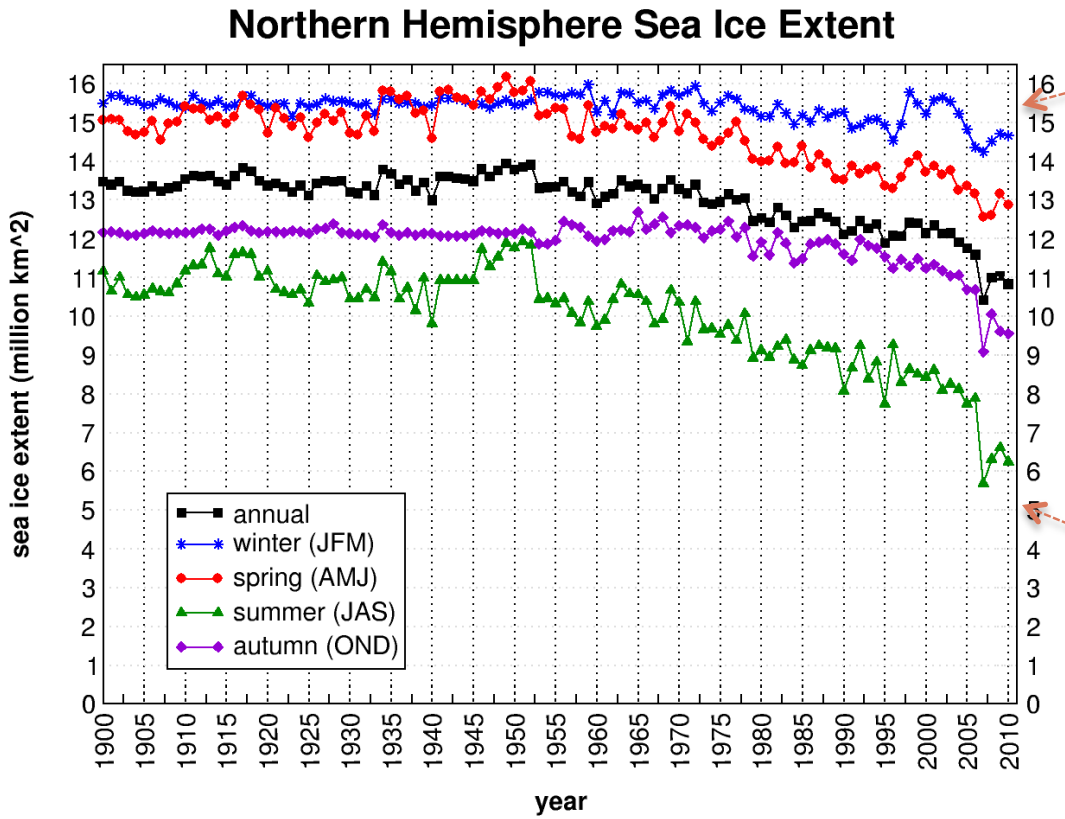
- NH and SH seasonal cycles





Melting Sea Ice

- Recent summer Arctic sea ice coverage is **30% lower** than 30 years ago



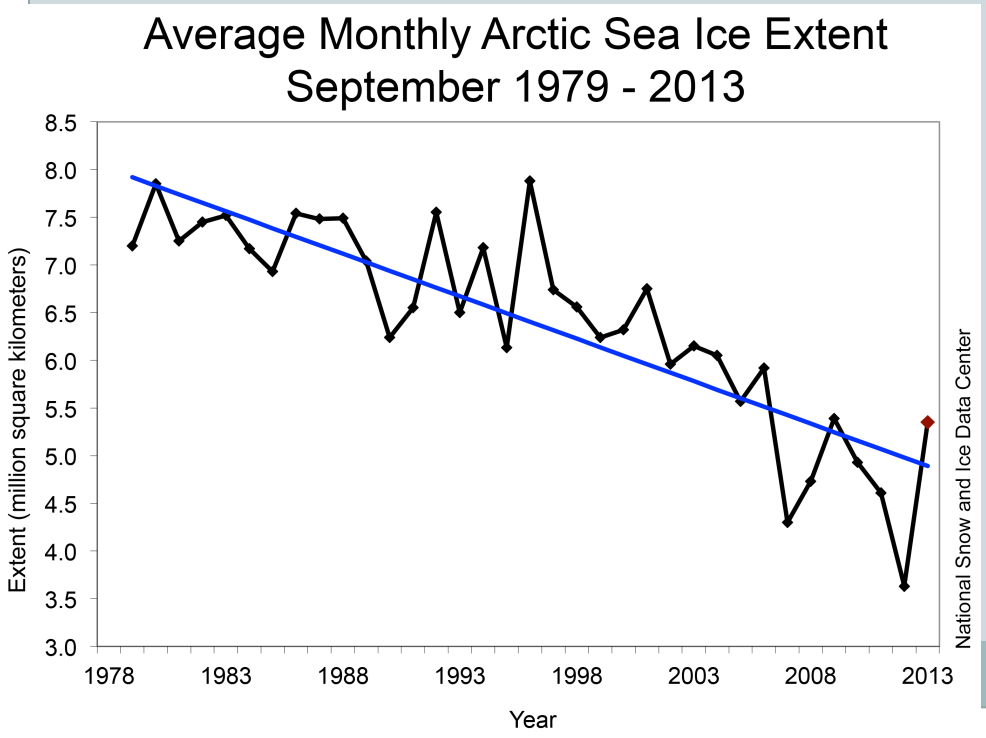
Ice always grows back in the **winter** (when there's no sunlight and it's extremely cold)

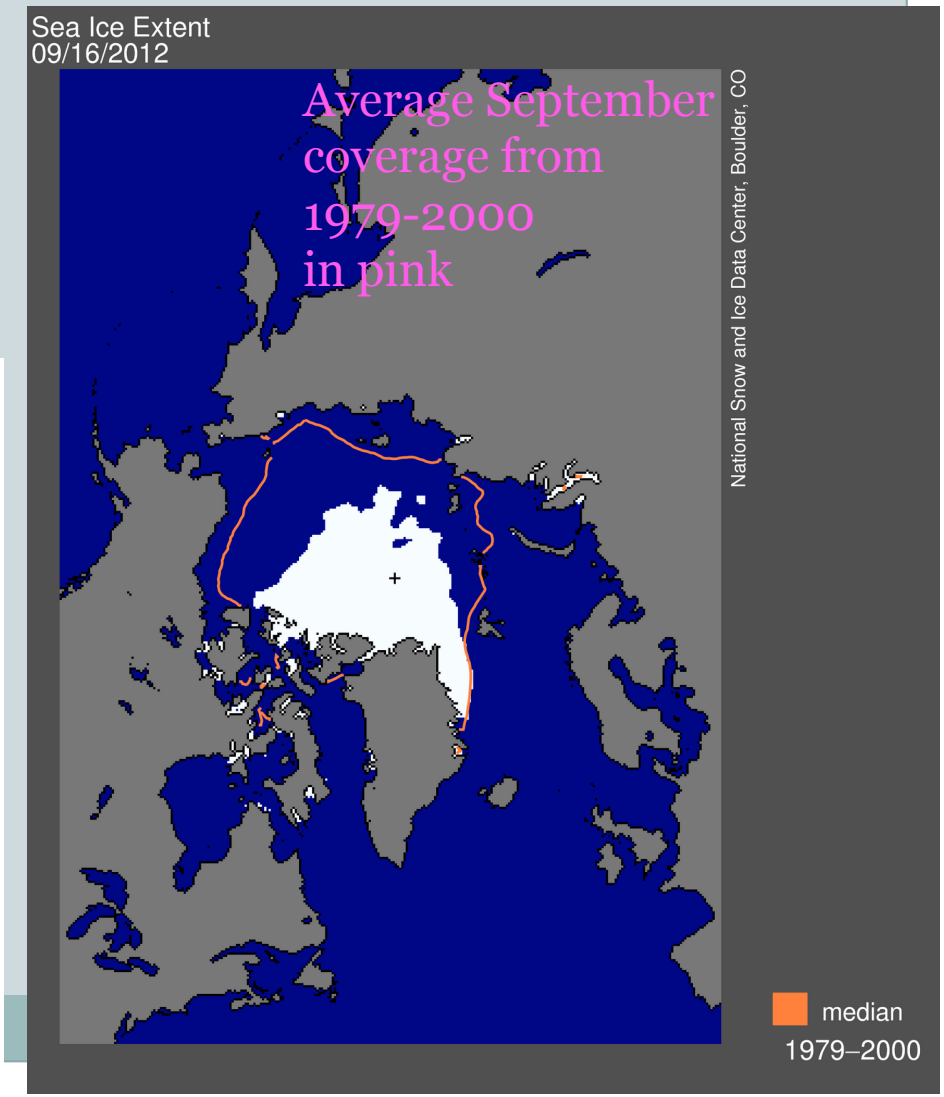
Minimum ice coverage occurs in September

Especially **2007** was an extremely anomalous year, as was 2012 (not plotted)

September Minimum Ice Extent

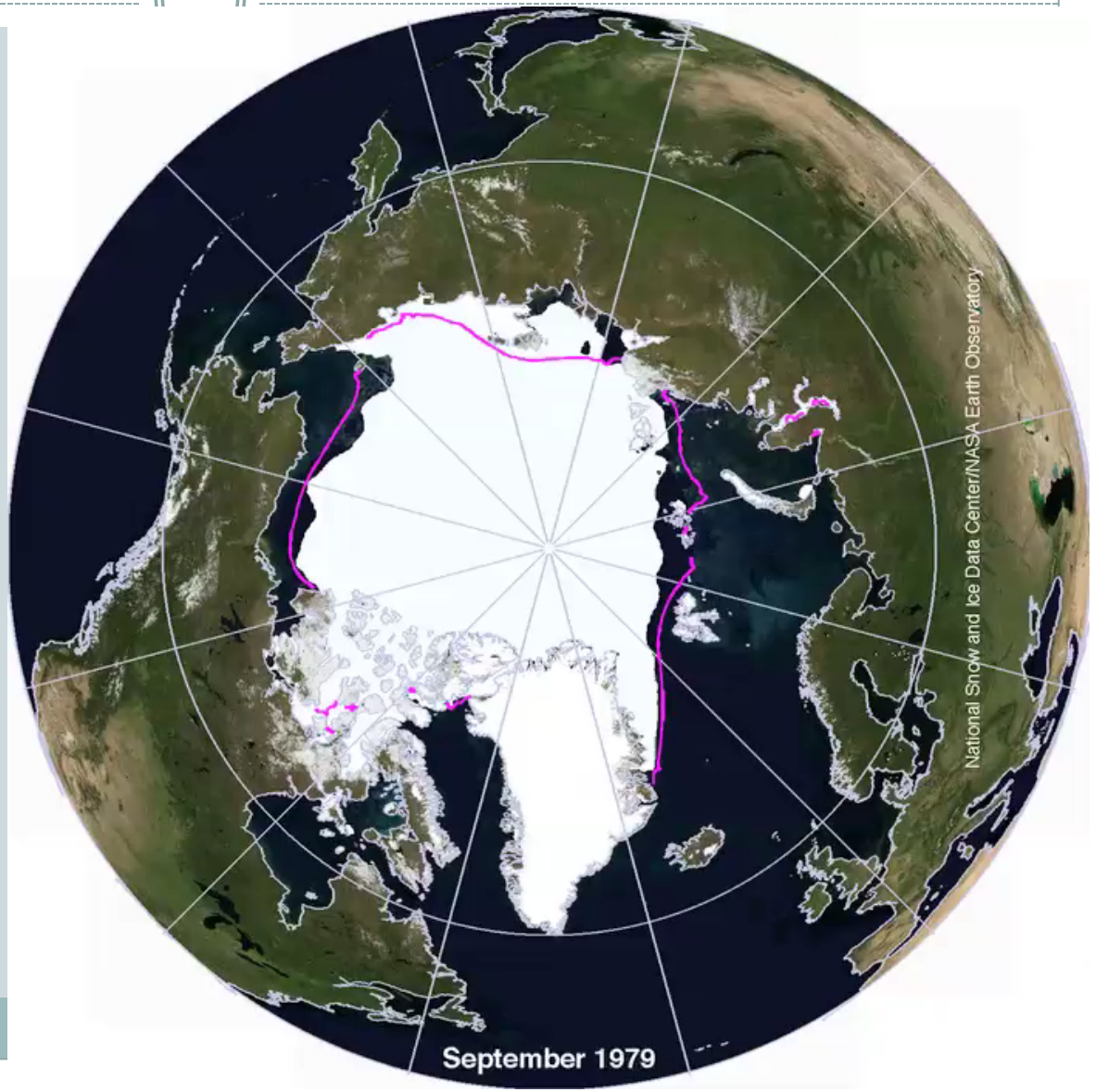
- Last 7 yrs: seven lowest years in Arctic sea ice extent





Animation of September Sea Ice Coverage

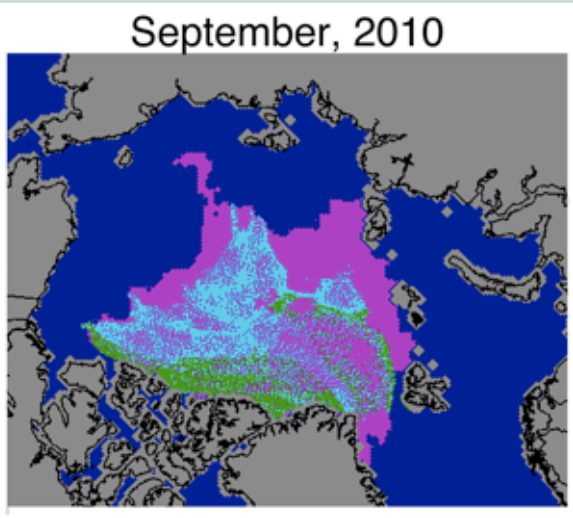
- Each year's minimum sea ice extent since 1979

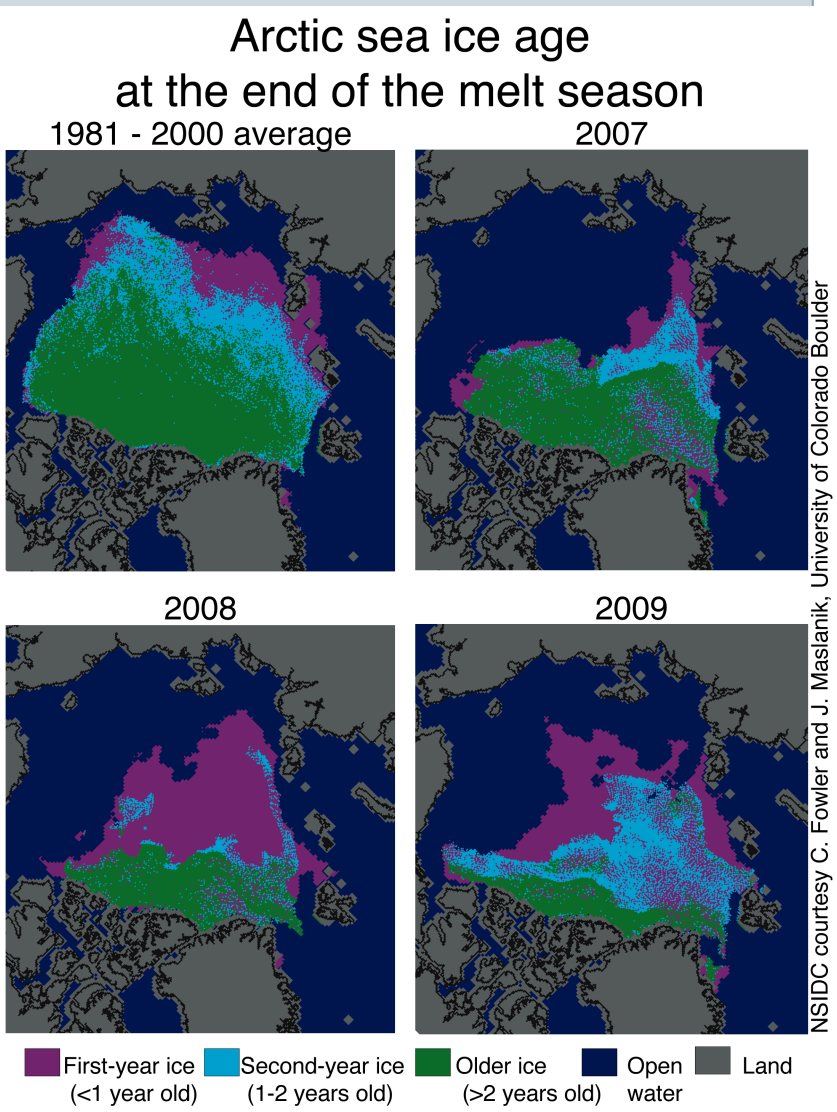


Winter Sea Ice

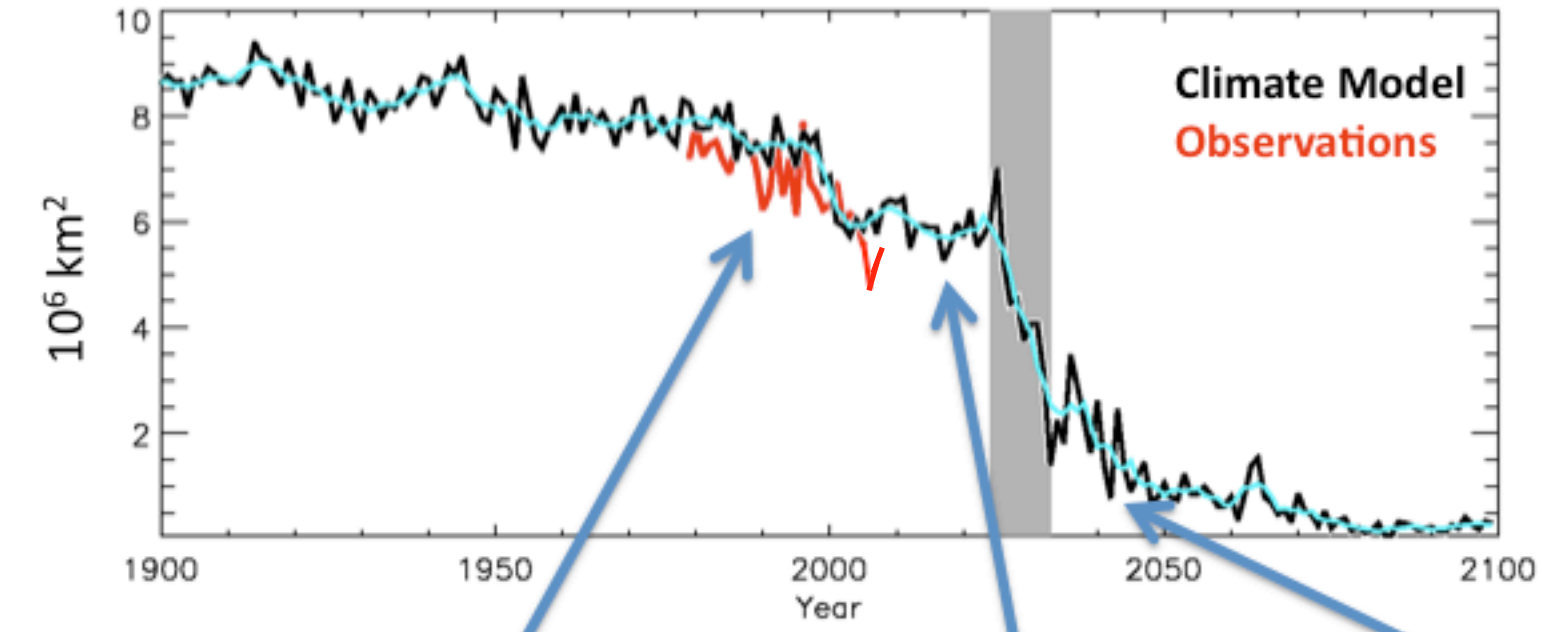
- Sea ice is getting **younger** → and **thinner** as well
  - Almost no ice is left that's over two years old

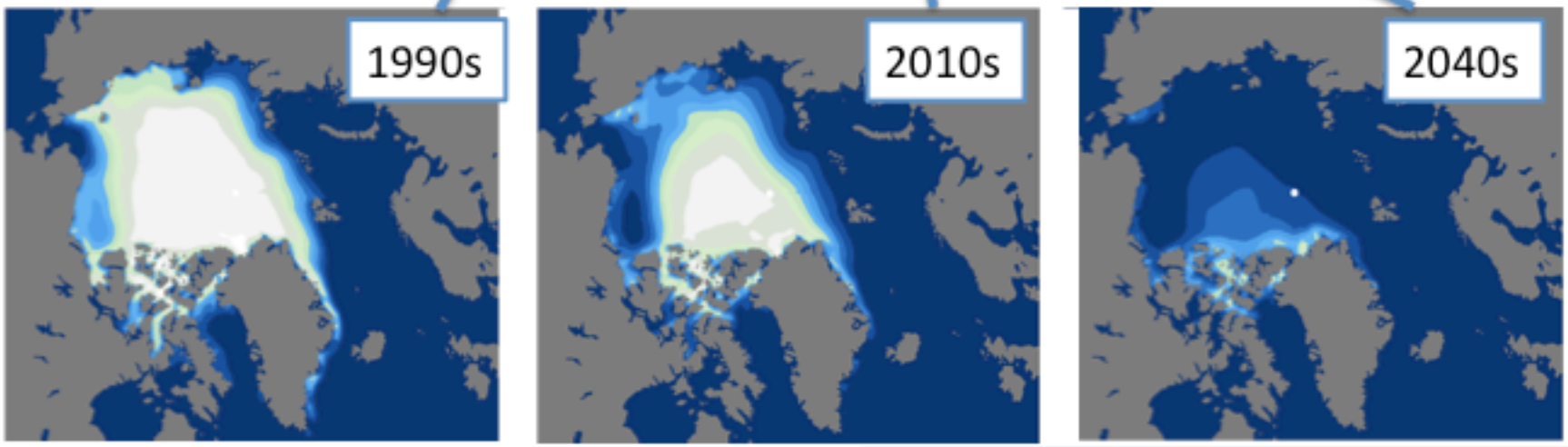
What do climate models say about the future of sea ice?





September Sea Ice Extent





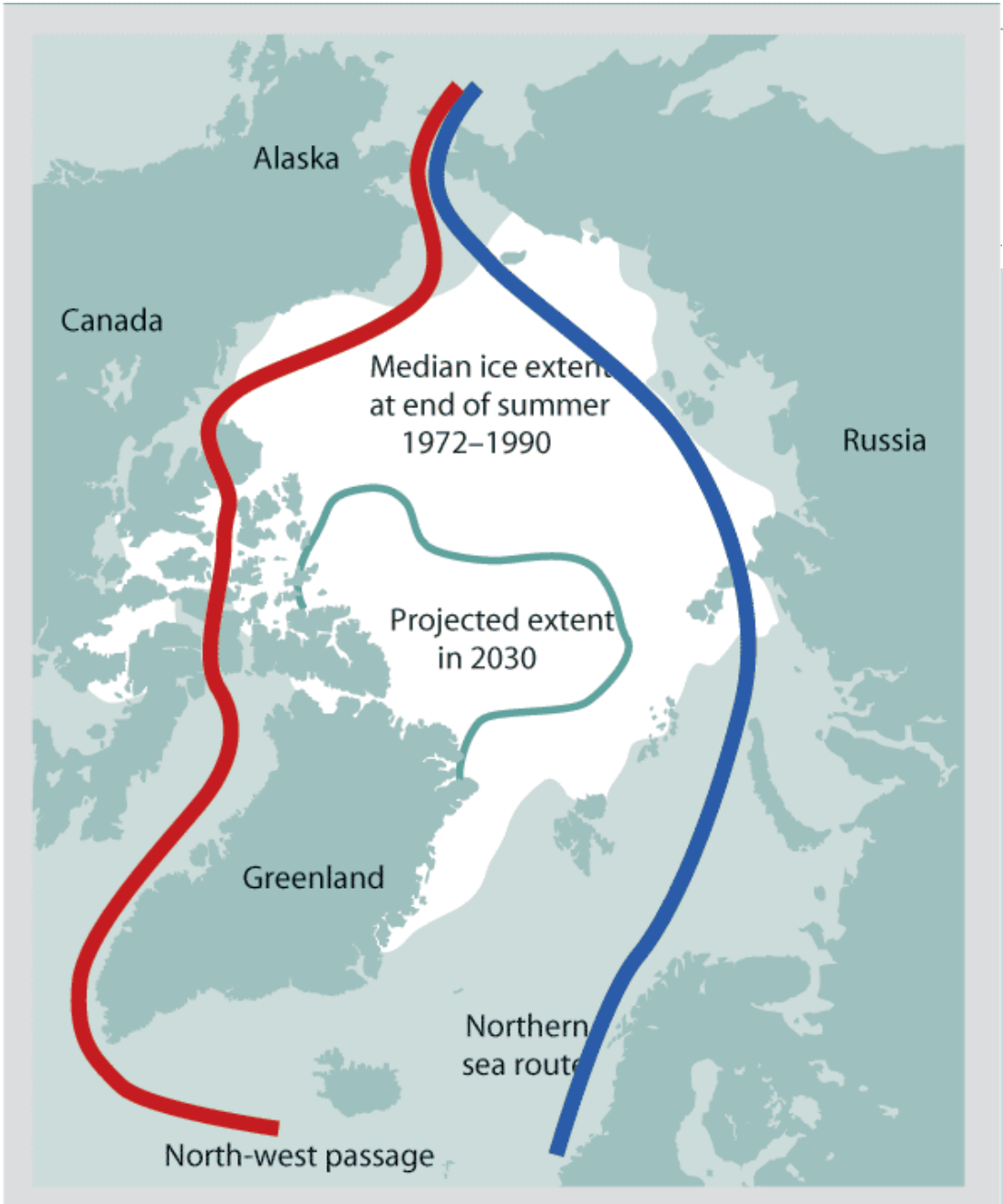
UW Research (Prof. Cecilia Bitz)

Holland, Bitz, and Tremblay, 2006

Future of Arctic Sea Ice

- Ice is getting younger and thinner
- Many models predict disappearance of summer ice by 2060
  - Previous slide's research of Prof. Bitz
- What will the impacts of the sea ice loss be?

UW Prof Cecilia Bitz



Projected summer shipping routes

THE HOT ZONE

The oil-rich waters around the Arctic Circle are heating up — and are up for grabs. A look at some of the territorial battles ahead.

1 U.S. CONTINENTAL SHELF

If the U.S. ratified the **Law of the Sea** treaty, it could claim territory here roughly half the size of Alaska.

2 CHUKCHI SEA

Shell has plans to explore here. But since Russia is claiming nearly half the Arctic Ocean, it may run into trouble.

3 BEAUFORT SEA

A 100-square-mile area in this body of water is said to be rich with oil and gas, but it's in dispute — so no one has bid on a drilling lease offered by both Canada and the U.S.

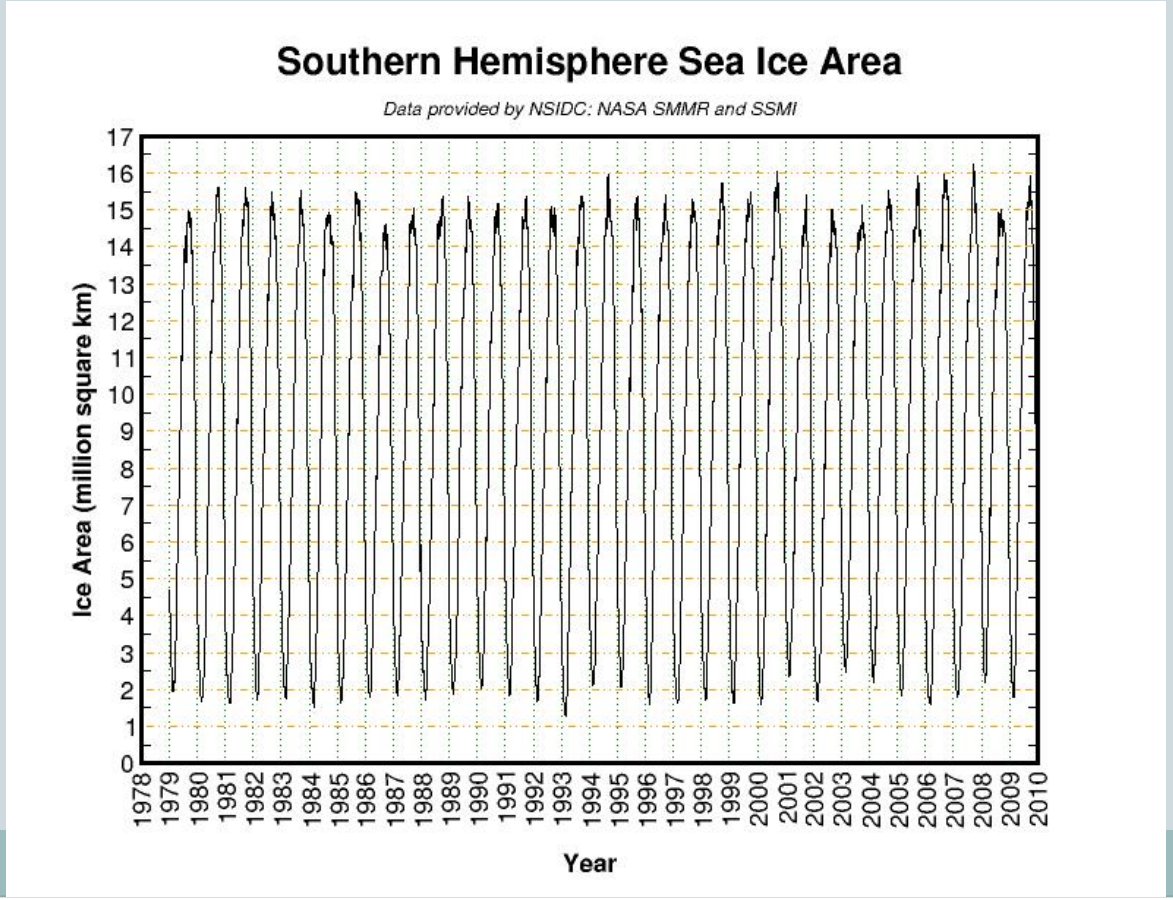
4 LOMONOSOV RIDGE

This giant undersea landmass extends from Russia to Greenland — and the two countries are fighting over it. In June, Russia said its scientists found evidence of a **70-billion-barrel deposit** and claimed rights to the whole ridge.

INTERNATIONAL MAPPING

Antarctic Sea Ice Trends

- Not much trend in S. Hem. (slight increase actually)
  - Related to ozone depletion? (Turner et al 2009)



How does sea ice loss affect **climate**?

- **Ice-albedo feedback** amplifies warming
- Warming reduces pole-to-equator temperature gradient, meaning heat is drawn less towards pole and **lower latitudes warm more too**

What are other **impacts** of sea ice loss?

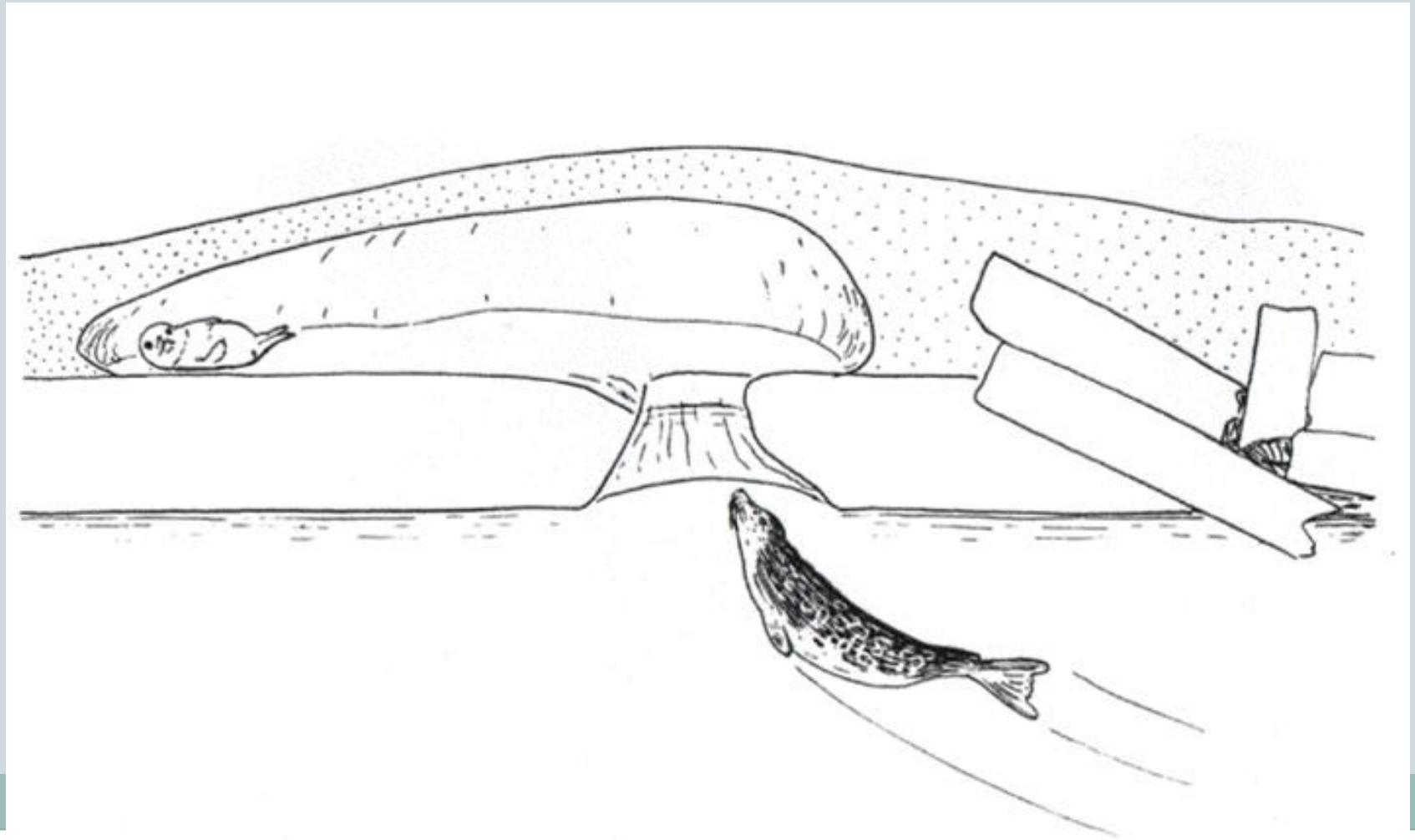
- **Erosion** if sea ice disappears (it damps waves)
  - Thawing **permafrost** also causes surfaces to soften
- Fragile and specialized **ecosystems**

drp_east_072808

June 2008

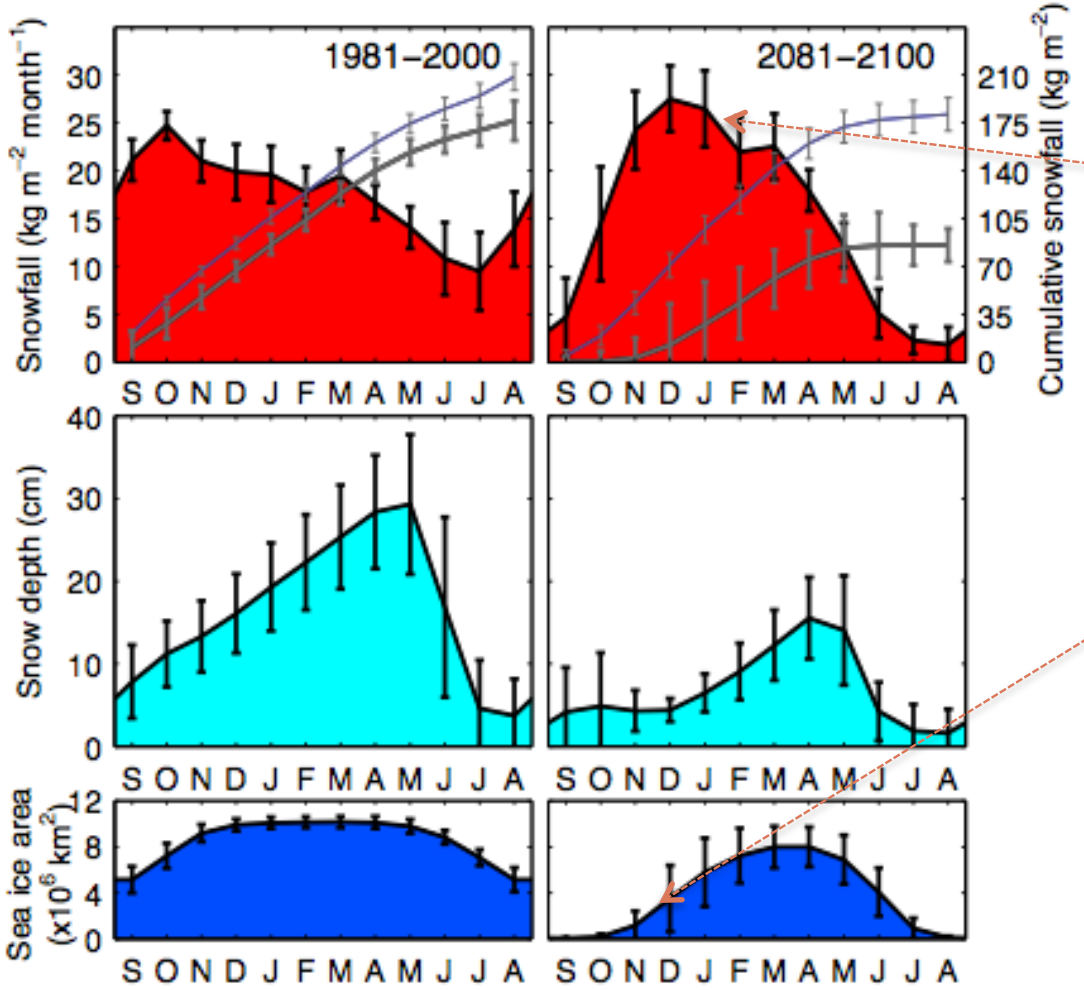
Ringed Seal Nests

- Need 50 cm of snow drifts to build nests for their young



Recent Study on **Snow on Sea Ice**

From new paper by Hezel, Zhang, Bitz and Kelly



More snowfall in winter in the future

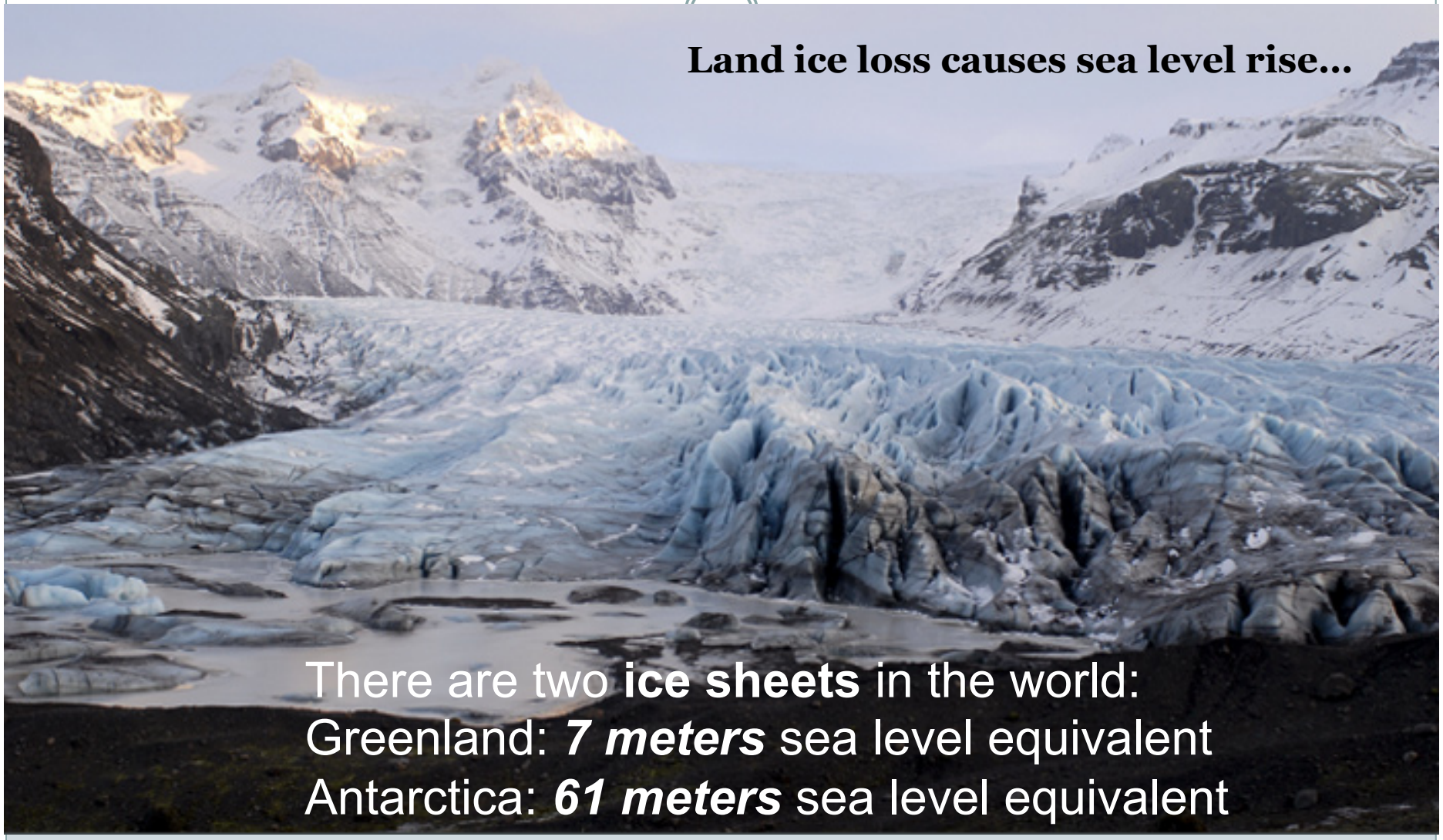
But **shorter-lived sea ice** leads to **less snow depth** on ice

Bad news for seals…

Summary of Sea Ice

- Sea ice is melting rapidly in the Arctic
- Dangerous for animal habitats there
  - Polar bears
  - Ringed seals
- Coastal erosion enhanced nearby
- On the plus side, if the climate stops warming, sea ice stops receding
- And sea ice melting **doesn't** lead to sea level rise
  - **Land ice** melting does affect sea level – let's discuss that next

What about land ice?

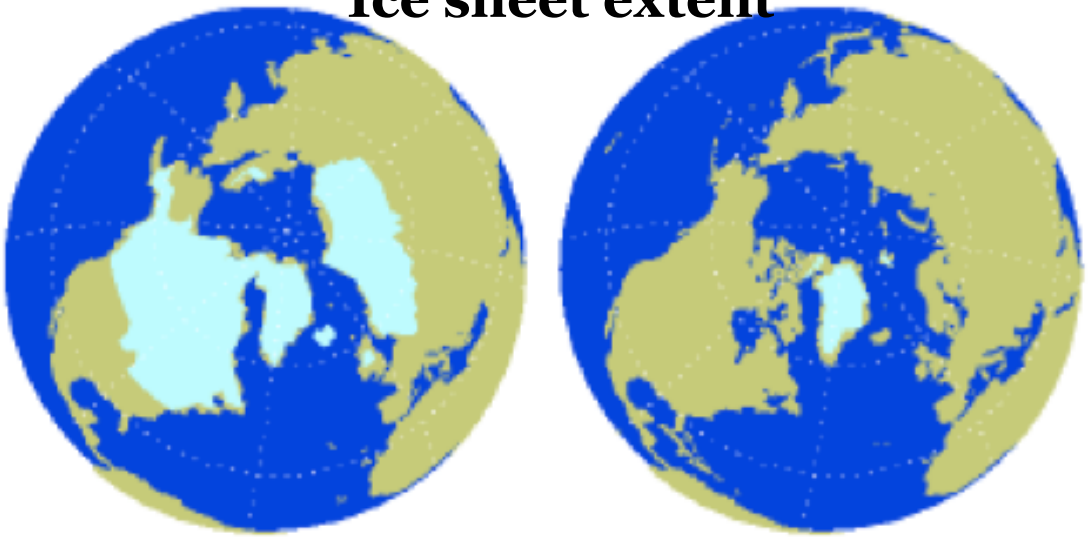


The Arctic is changing most rapidly, so let's start with Greenland…

Sea Level of the Past

- **Last Glacial Maximum** (15,000 yrs ago): **120 meters** lower sea level!
- **Cretaceous** (100 mil yrs ago): >100 meters higher!

Ice sheet extent

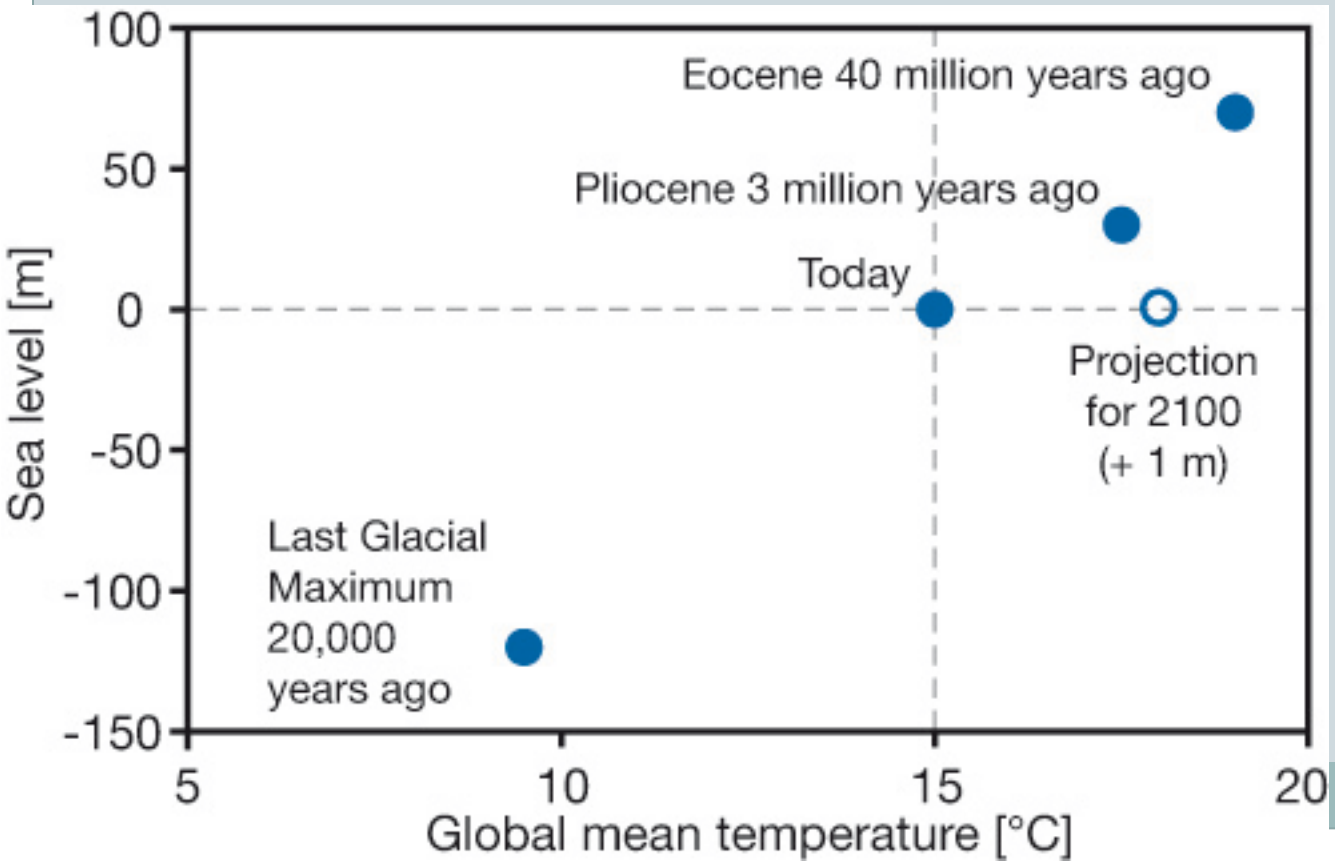


Last Glacial Maximum **Present**

The Cretaceous Seaway

Predictions of Sea Level Rise vs Past Changes

- Last time the temperature was 3° C warmer, sea level was **30 meters** higher…



Sea levels have varied a huge amount in the past!

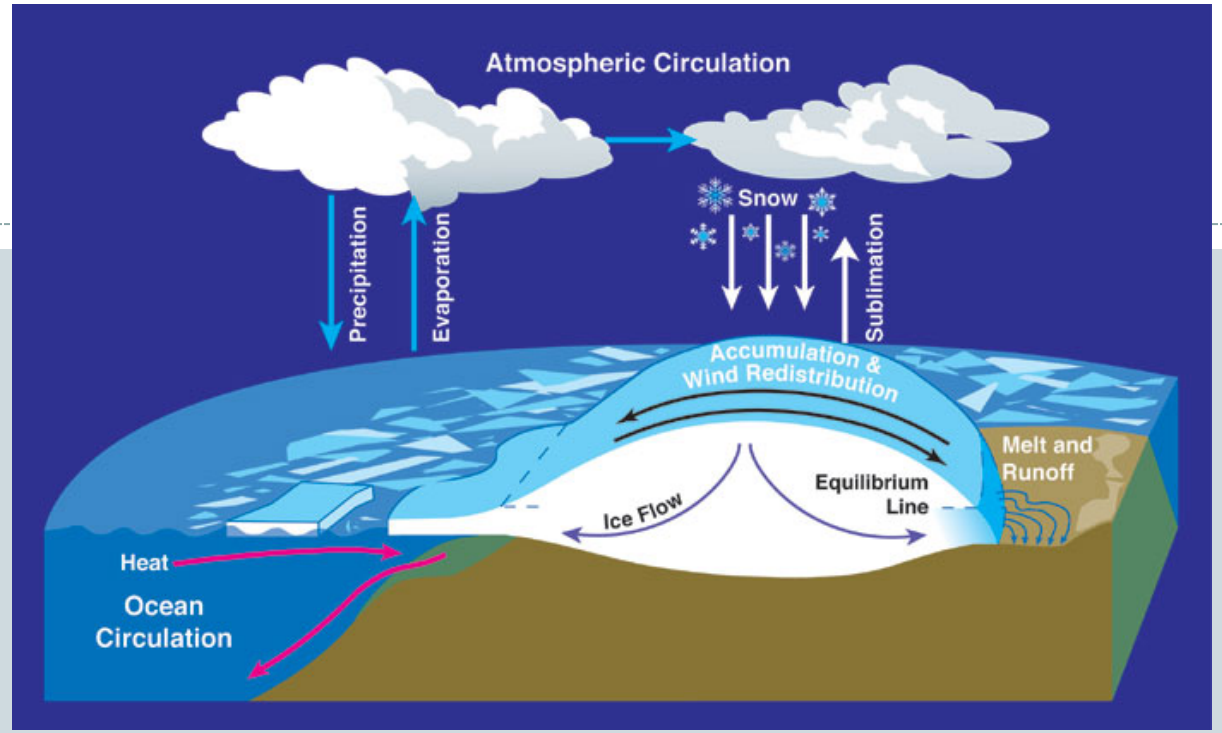
This is **not even close** to what's predicted though

We'll talk about why, and whether more extreme changes are possible

Greenland Ice Sheet

- Greenland: ice is ~100,000 yrs old
  - Surface is depressed to approximately sea level in the middle, mountains on the perimeter
  - Loses mass from sublimation, calving of icebergs away from edges, & running off of meltwater
  - Gains mass by snowfall
  - Large temperature rise in Arctic means melting has outweighed increased snowfall recently

Greenland summit is approximately height of Mount Baker



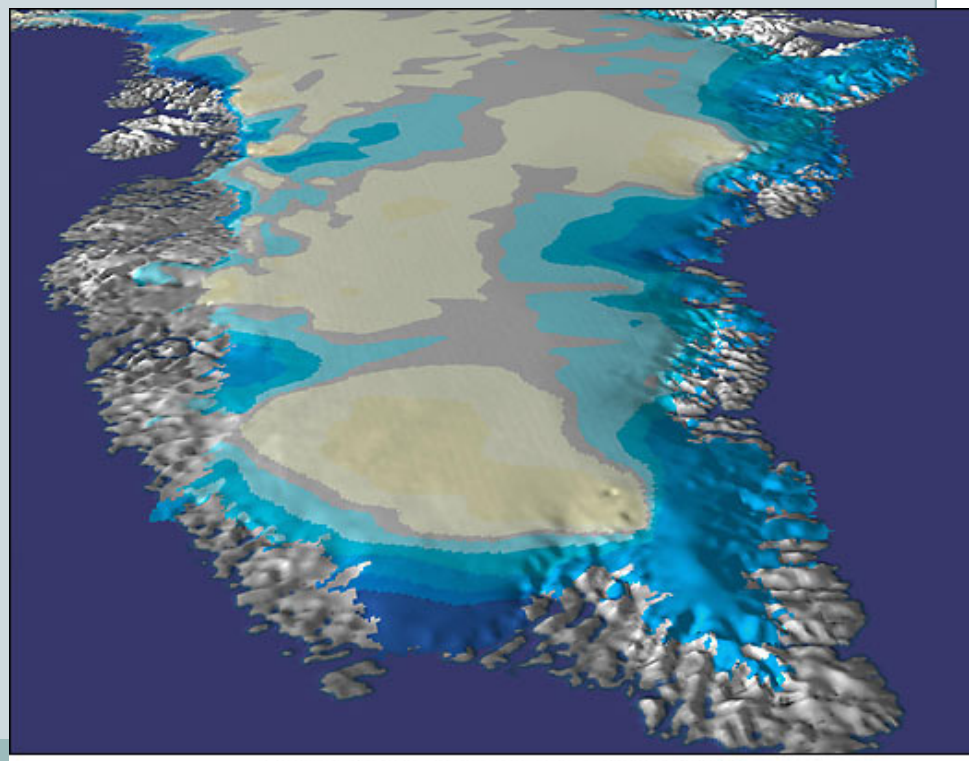
Mass balance of an ice sheet

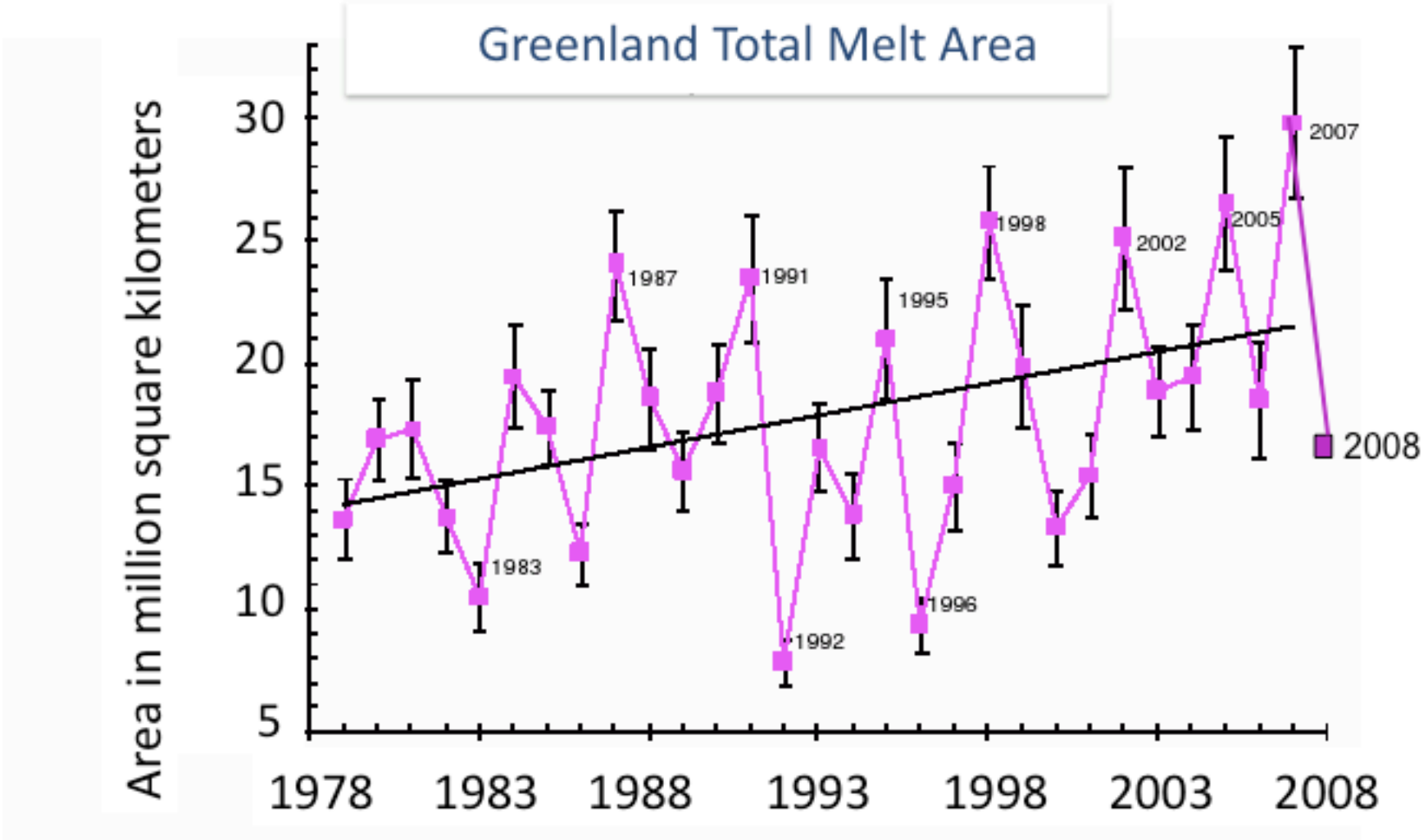
Gains mass from **snow** on top
Loses mass from **melting** and **calving** of **icebergs**

Both **loss** and **gain** are **increasing** (increased precipitation at high latitudes)
Greenland is losing mass though (losses are bigger than gains)…

Future of Greenland Ice Sheet

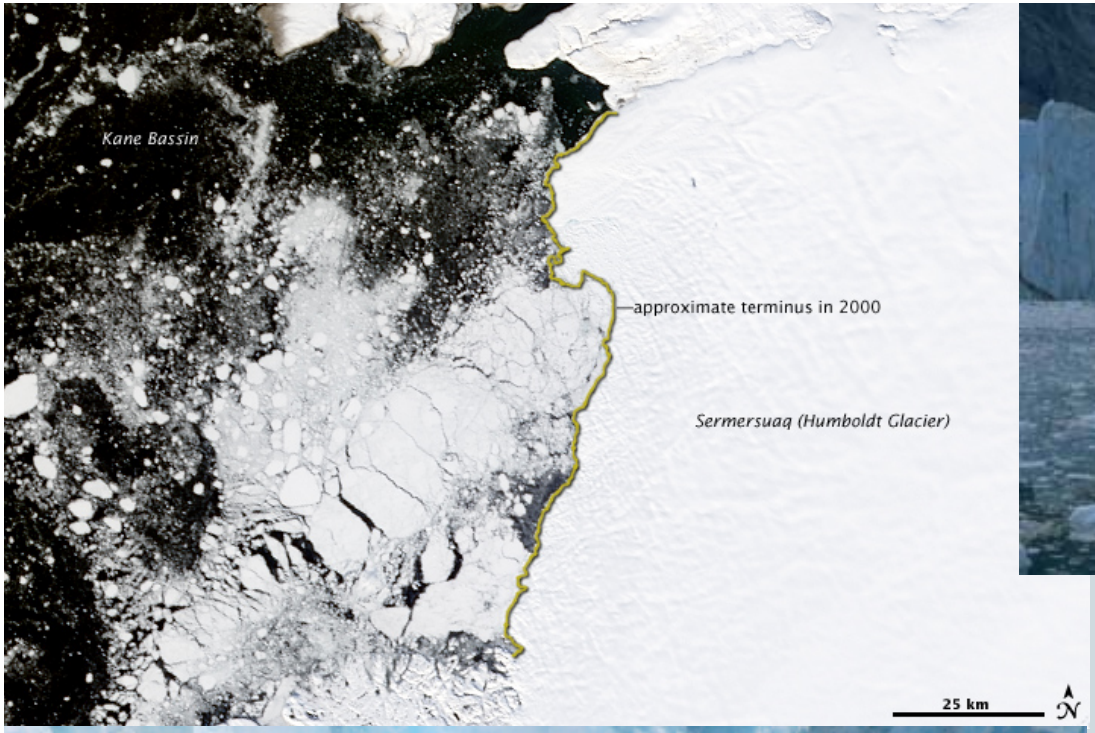
- Arctic is ground zero for global warming – what will happen to Greenland ice sheet?
  - Melt area has been expanding in recent years
  - Ice sheet models indicate 3 C warming would lead to 1 m sea level rise over 1000 yrs





Melting has increased since we've been measuring

Steffan and Huff, CU



Glacier **calving**: breaking of ice to form icebergs

A natural process but terminus of many glaciers is retreating

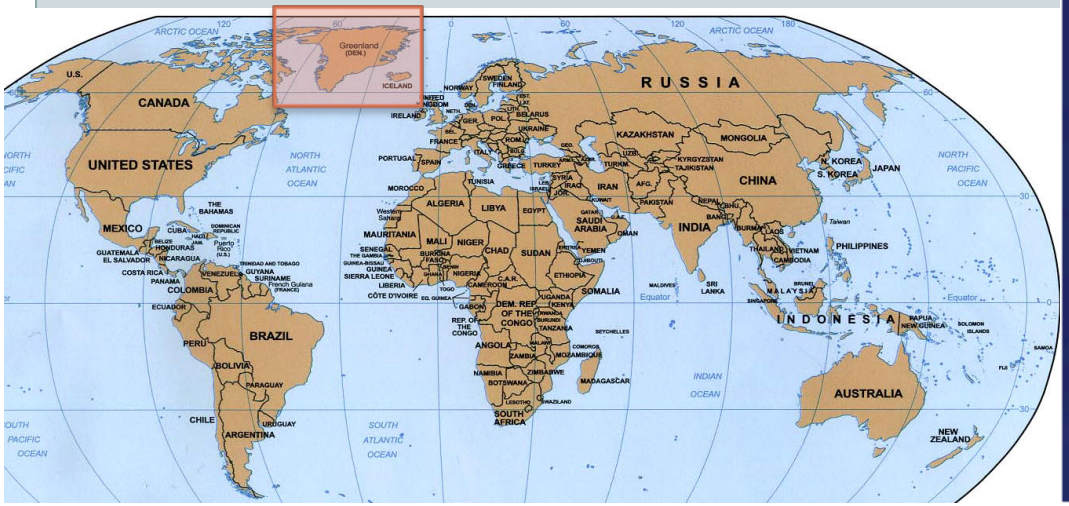
Where in Greenland does most of the **calving** of **icebergs** occur?

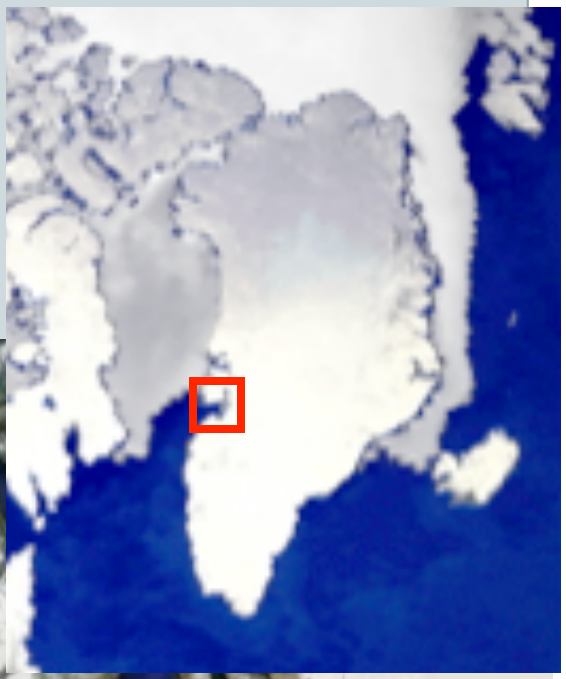
Greenland is surrounded by fjords filled with **ice streams** (fast flowing ice)

Many icebergs calve within these streams

Greenland Ice Loss from Calving

- 10% of Greenland icebergs calve from Jakobshavn Isbrae
  - You might know it as Sermeq Kujalleq
  - Don't confuse with Kangerdlugssuaq
  - Near town of Qeqertarsuaq
  - In Qaasuitsup municipality
    - North of Qeqqata municipality





Jakobshavn drains 6.5% of Greenland ice and makes the most icebergs in the N. Atlantic.

Retreated significantly since 1990

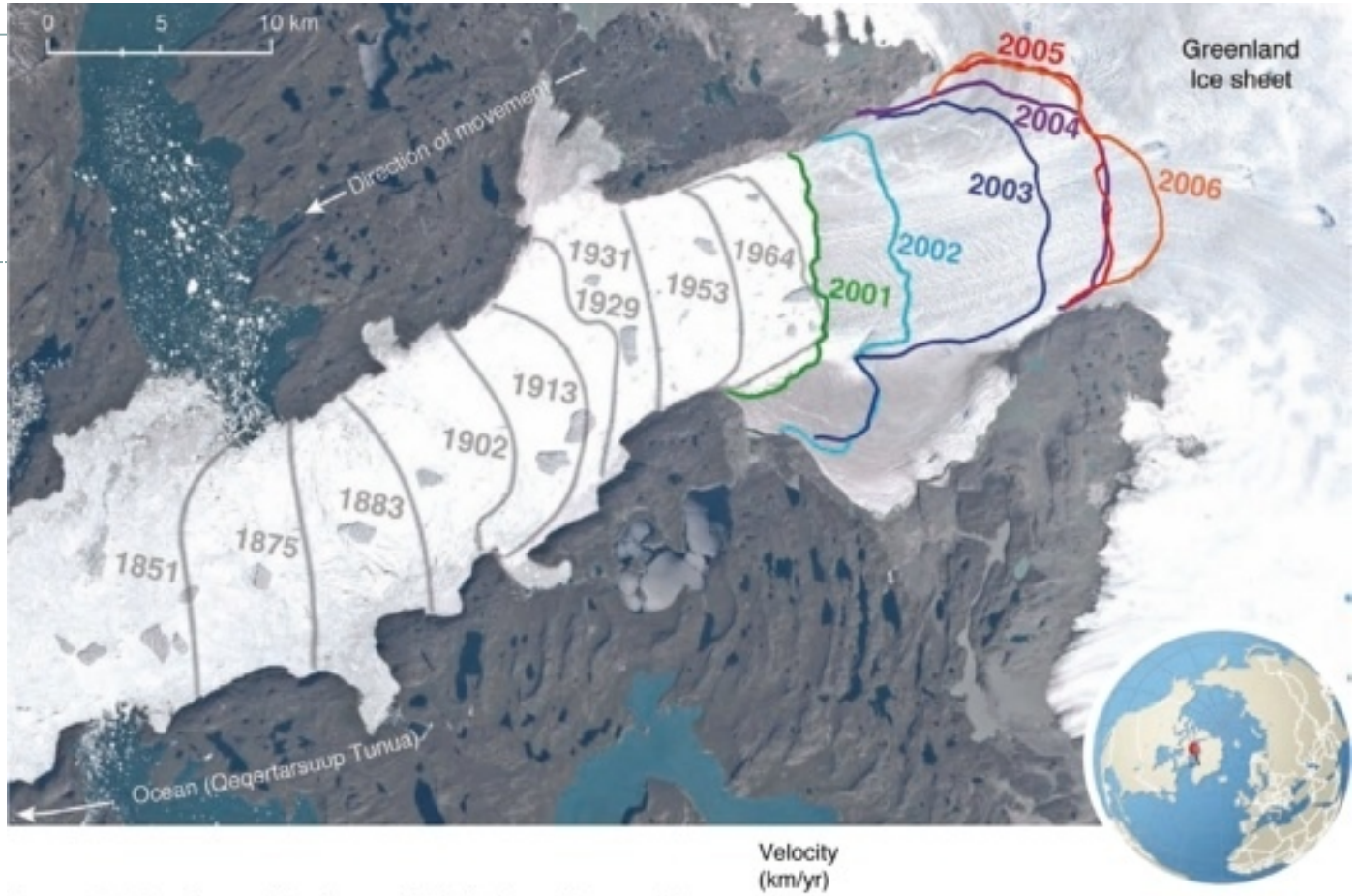
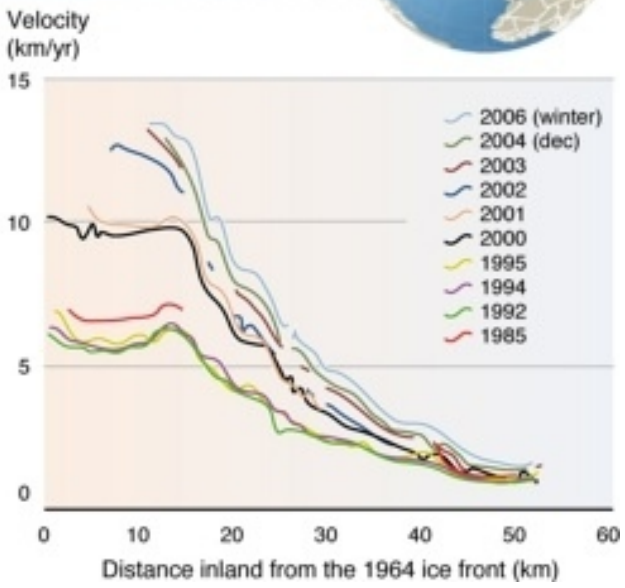


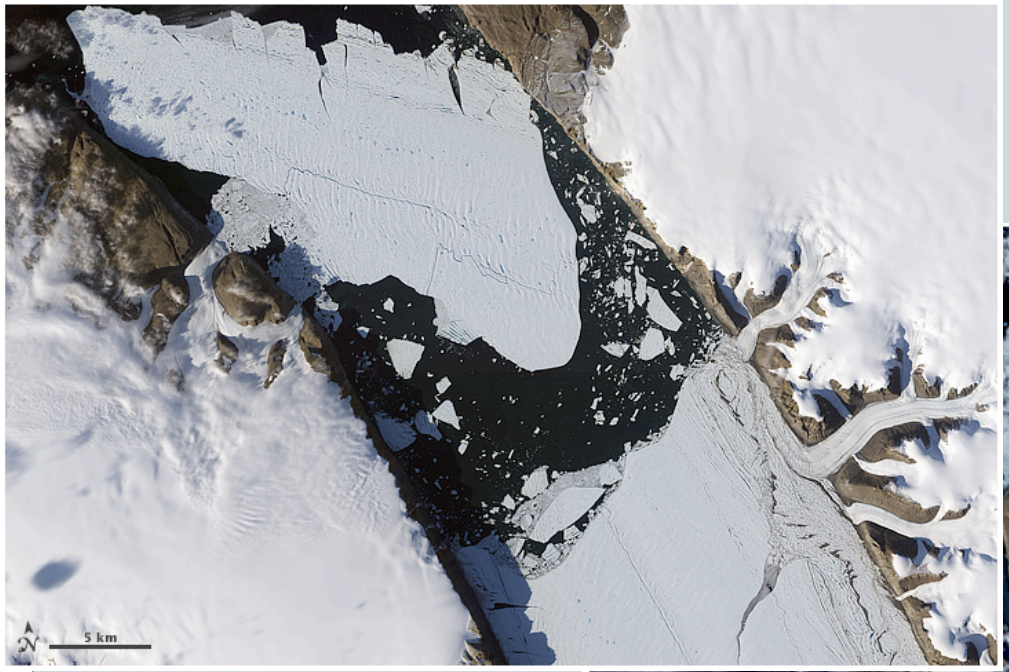
Figure 6A.6: Landsat satellite image of Jakobshavn Isbrae and its fjord, showing locations of the calving ice front in years from 1851 to 2006. The glacier extends through the Illulisat Icefjord, surrounded by mountains. Icebergs calve off from the main glacier, pile up and block the fjord before being released into Qeqertarsuup Tunua (Disko) Bay and Davis Strait. The whiter areas in the fjord are piled-up icebergs and the "real" glacier ends where the greyish striped section ends – showing that this image is from 2001.
The graph shows glacier-velocity profiles for 1985 to 2006. During this period Jakobshavn Isbrae, already the world's fastest glacier, doubled its speed to almost 14 km per year[28,29] after rapid thinning and break up of its floating ice tongue[31].

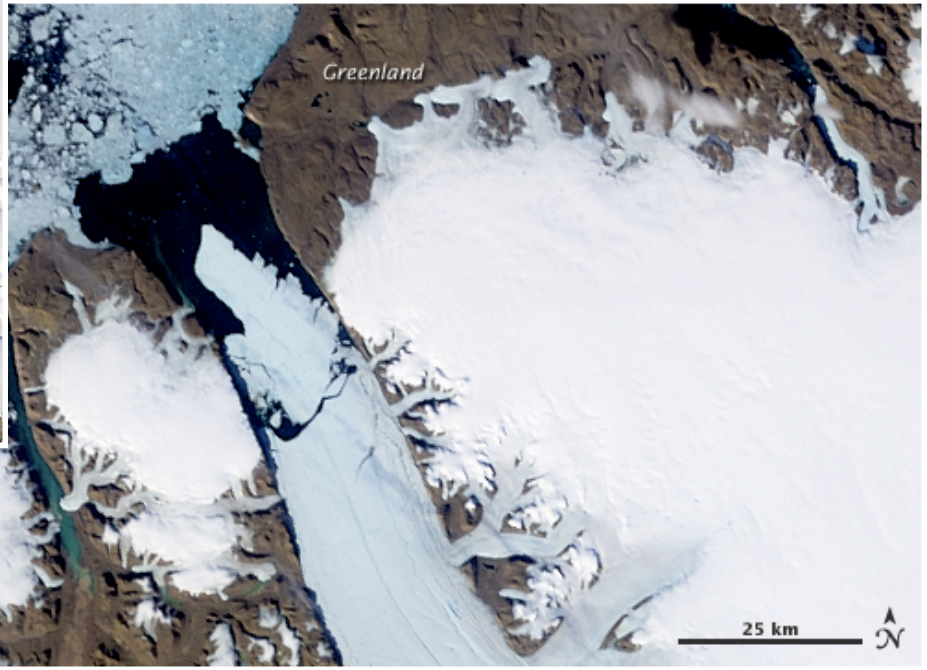
Sources: NASA/Goddard Space Flight Center Scientific Visualization Studio. Historic calving front locations courtesy of Anker Weidick and Ole Bennike
Source: based on Howatt and others 2007



Recent Calving Event in NW Greenland

- August 5, 2010: biggest iceberg in nearly 50 years broke off from Petermann Glacier





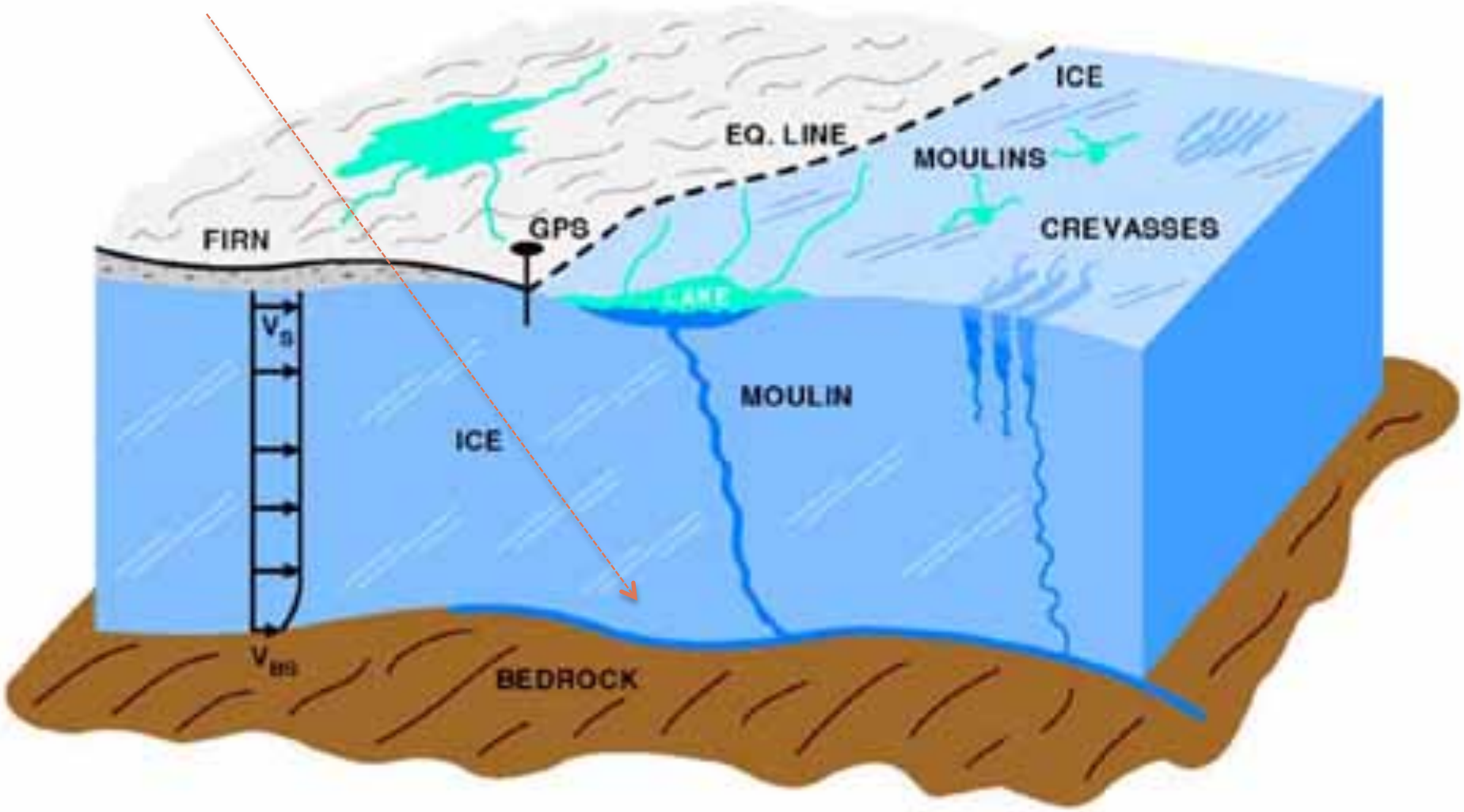
Greenland Mass Balance

- Overall, losses are exceeding gains in Greenland
  - Also losses from calving have accelerated in the last 10 yrs
- Greenland is **very** big though
  - It took tens of thousands of years to grow
  - At current rates it would take many **thousands** of years to melt
  - Now it's contributing less than 10% of sea level rise
- Could Greenland ice loss accelerate in the future?

Could Greenland Ice Loss Accelerate?

- **Maybe**. Here's one way it might:
  - **More melting** causes larger melt ponds
  - Meltwater can fall through cracks & make it to the bedrock below

Water dripping through could cause it to stick to the bottom less & flow faster



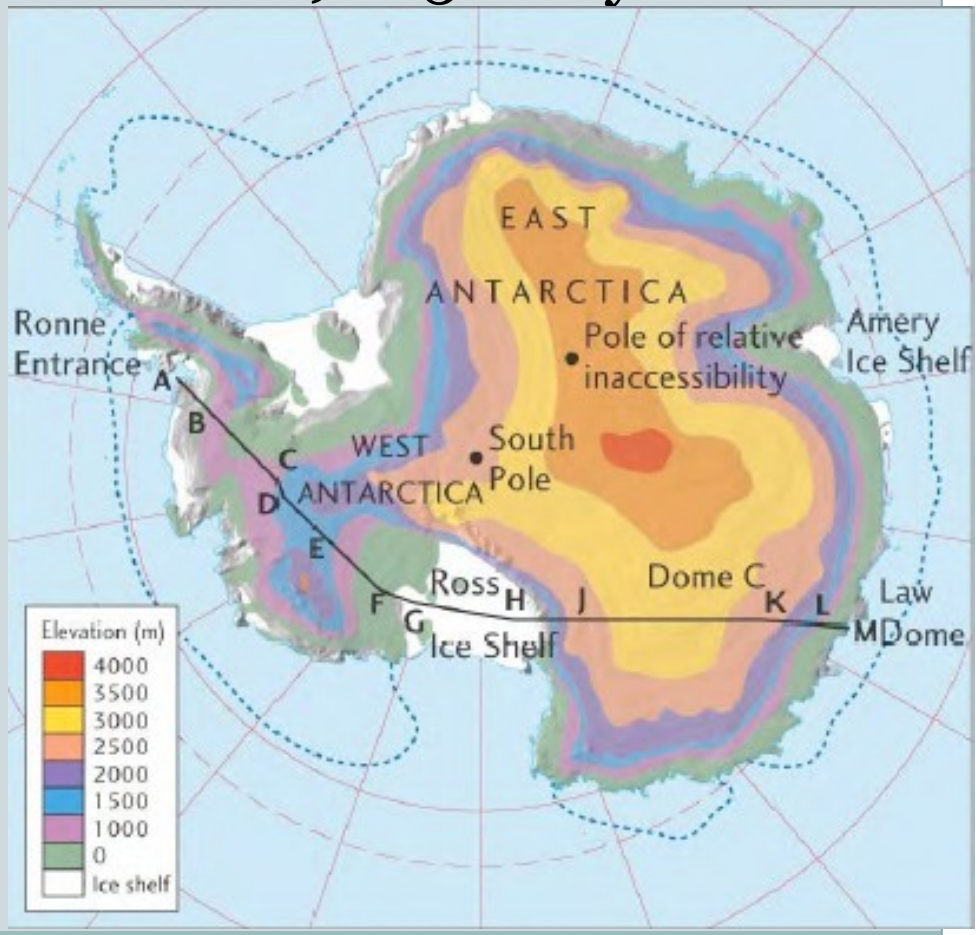
It's still unclear how relevant this is in causing recent accelerations of calving

Future of Greenland

- A 3° C temperature rise would almost certainly melt Greenland (eventually)
  - This would likely take many centuries though
- Currently, Greenland melting is a small contribution to sea level rise
  - This is likely to become a larger percentage in the future though

Antarctic Ice Sheet

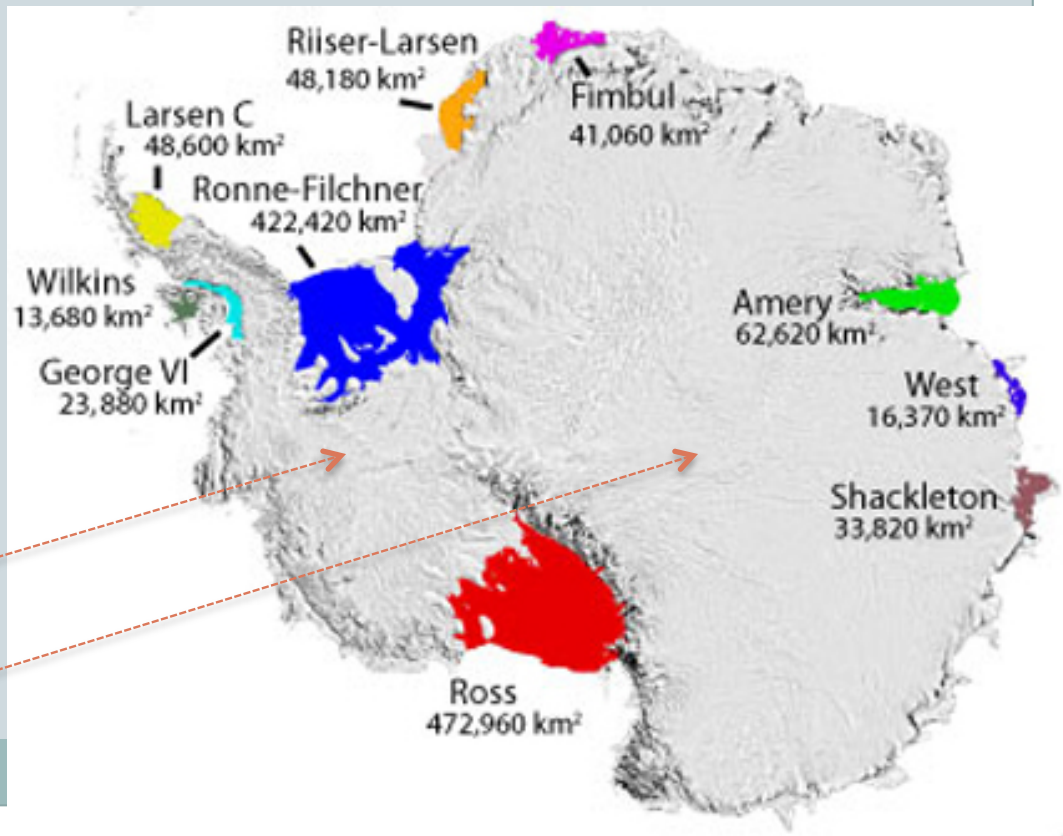
- Antarctic ice sheets (East and West): ~500k yrs old
  - East sheet: 90% of mass
  - West sheet: 10% of mass
  - Ice shelves (Ross, Amory): when ice flows from sheet onto the ocean



Max thickness is ~300 m taller than Mt Rainier

Antarctica

- Has two giant and many smaller **ice shelves** (in colors below)
  - Remember ice shelves float but are connected to the sheet
- Acceleration of melt has occurred in W. Antarctica recently
  - Even more acceleration than in Greenland



West Antarctica

East Antarctica

Antarctic Temperature Changes

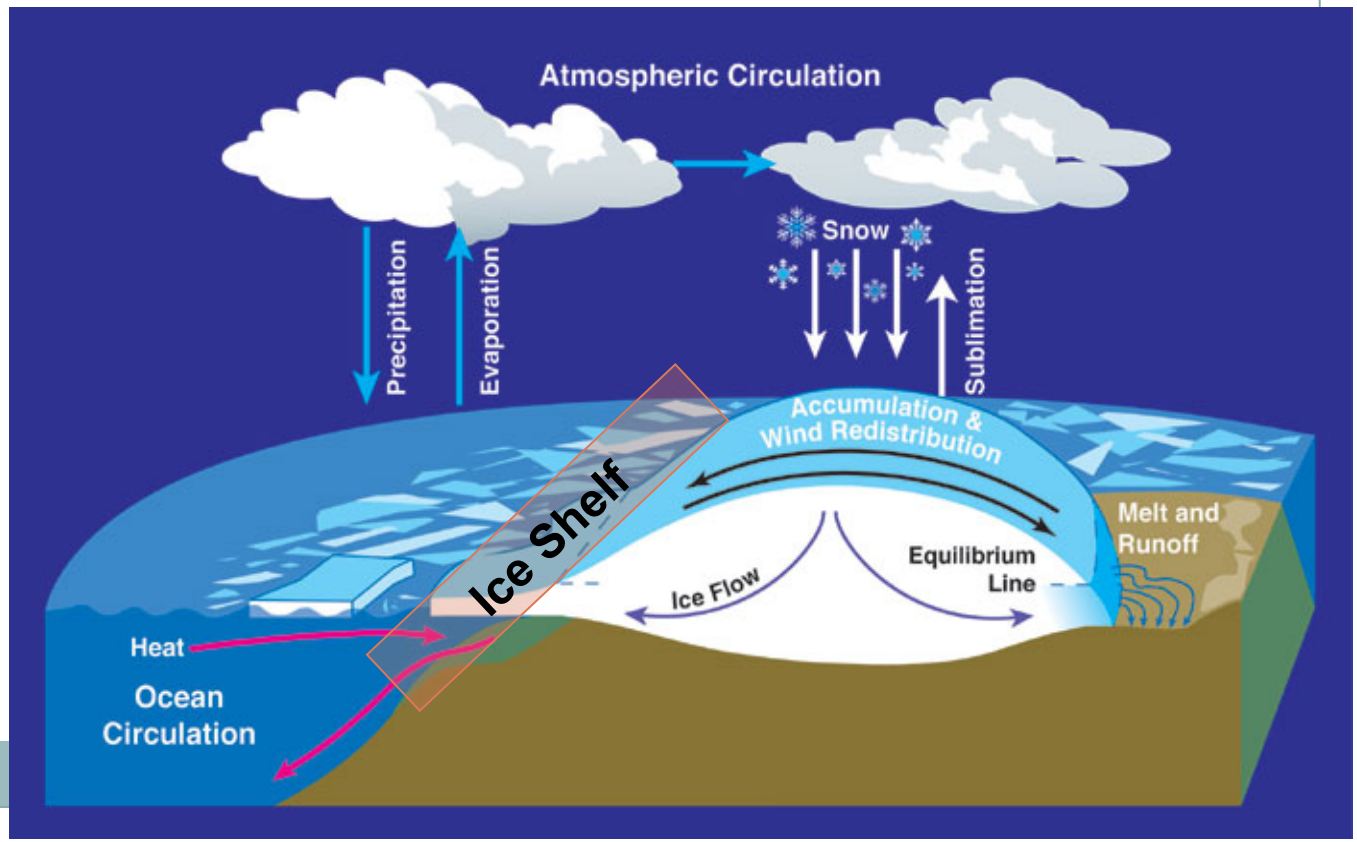
- Antarctica has experienced relatively small warming to this point
  - This was long ago forecast by climate models
  - Strong jet stream keeps warmer air out of high latitudes
  - Also ocean nearby takes up a lot of heat
  - **No sea ice decrease** has happened in Antarctica either
    - Although nearly all Antarctic sea ice melts each summer anyway
- East Antarctica is not warming, West Antarctica is warming

Antarctica Facts

Ice shelves reduce calving (by buttressing the ice)

Antarctica's icy surfaces are very cold, but warming in the **surrounding ocean** is a problem for the shelf base

Ice shelf collapse can then lead to acceleration of calving




Antarctic ice shelf
© www.virtualantarc


Icebergs

Future of Antarctic Melting

- Antarctica has the most land ice (61 meters of potential sea level rise)
  - But East Antarctica (the big part) is thought to be safe
    - It's really cold there…
  - West Antarctica is potentially dangerous: 5 m of sea level rise
    - Much of the West Antarctic Ice Sheet is *under sea level* so warmer ocean water could get in and melt much more after melting starts

Summary of Land Ice

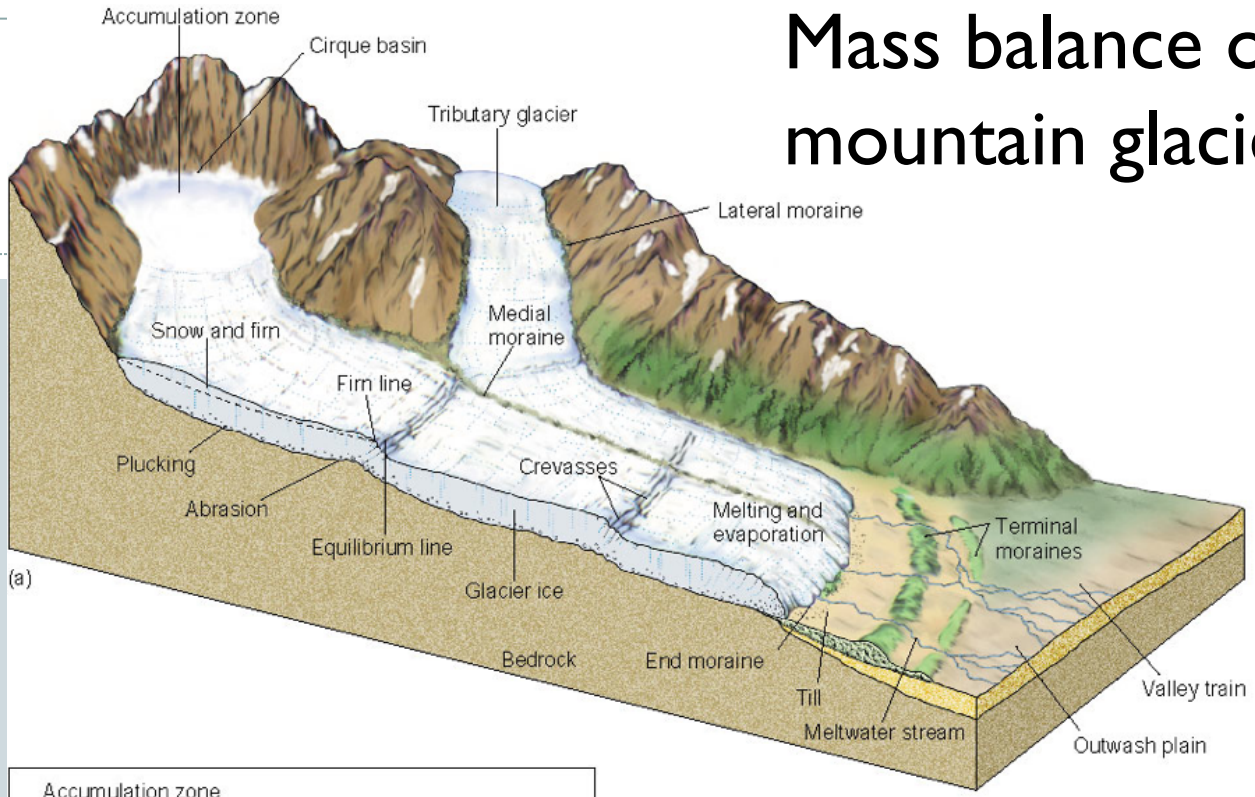
- Both Greenland (7 m) and West Antarctica (5 m) could experience some significant melting/calving by 2100
  - Enough to contribute 30 cm to 1.5 m worth of sea level rise
- In the long term, land ice will be the big contributor
  - Even if global warming stopped, melting would likely continue for many 100s of years
  - Over 2^{0} C global temperature rise would almost certainly melt Greenland completely

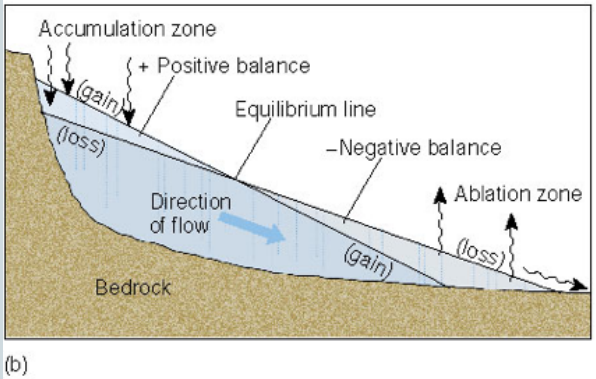
Mountain Glaciers

Presently **melting mountain glaciers** are contributing more to sea level rise than Greenland and Antarctica **combined**.

This probably won't be the case in 50 years (the ice sheets are so much bigger…)

Mass balance of a mountain glacier





(b)

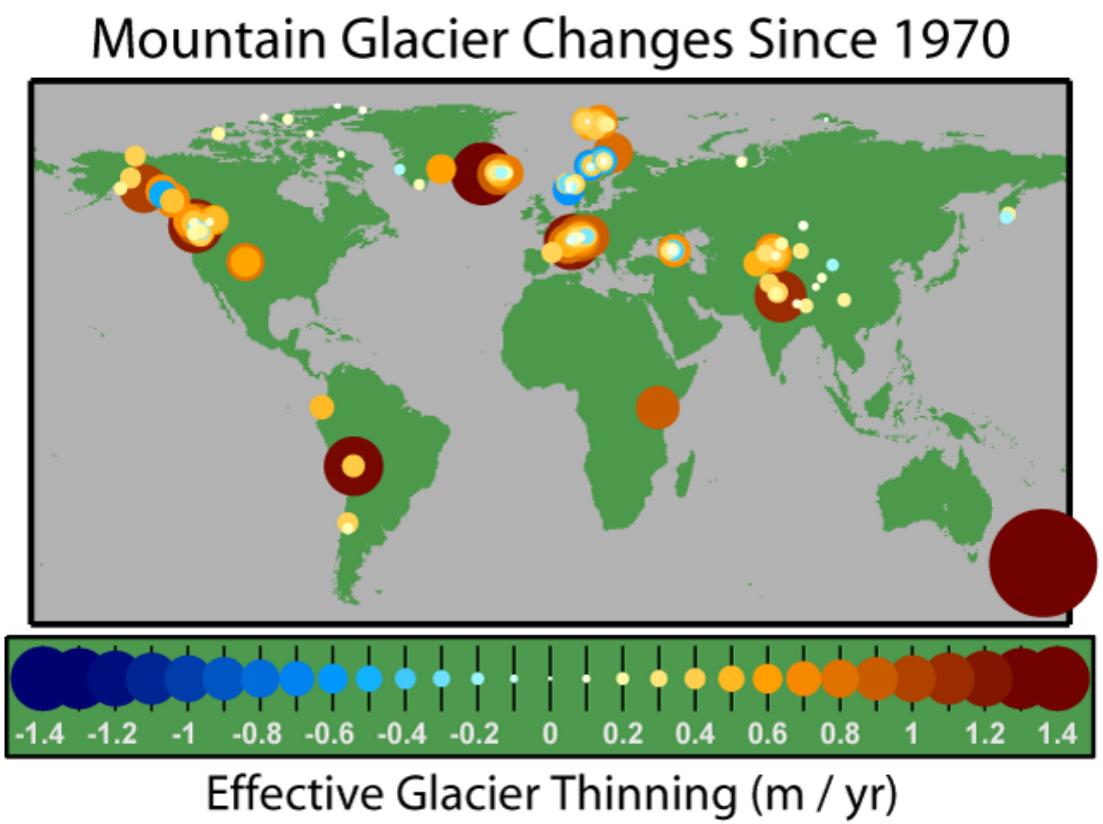
Gain due to snowfall

Loss due to melting, sublimation

Mountain glaciers don't lose mass due to breaking off chunks into the sea

Mountain Glacier Mass Balance

- Mountain glaciers are rapidly losing mass in most places
  - Increased melt is outpacing snowfall in all but a few places



Global Warming Art Project

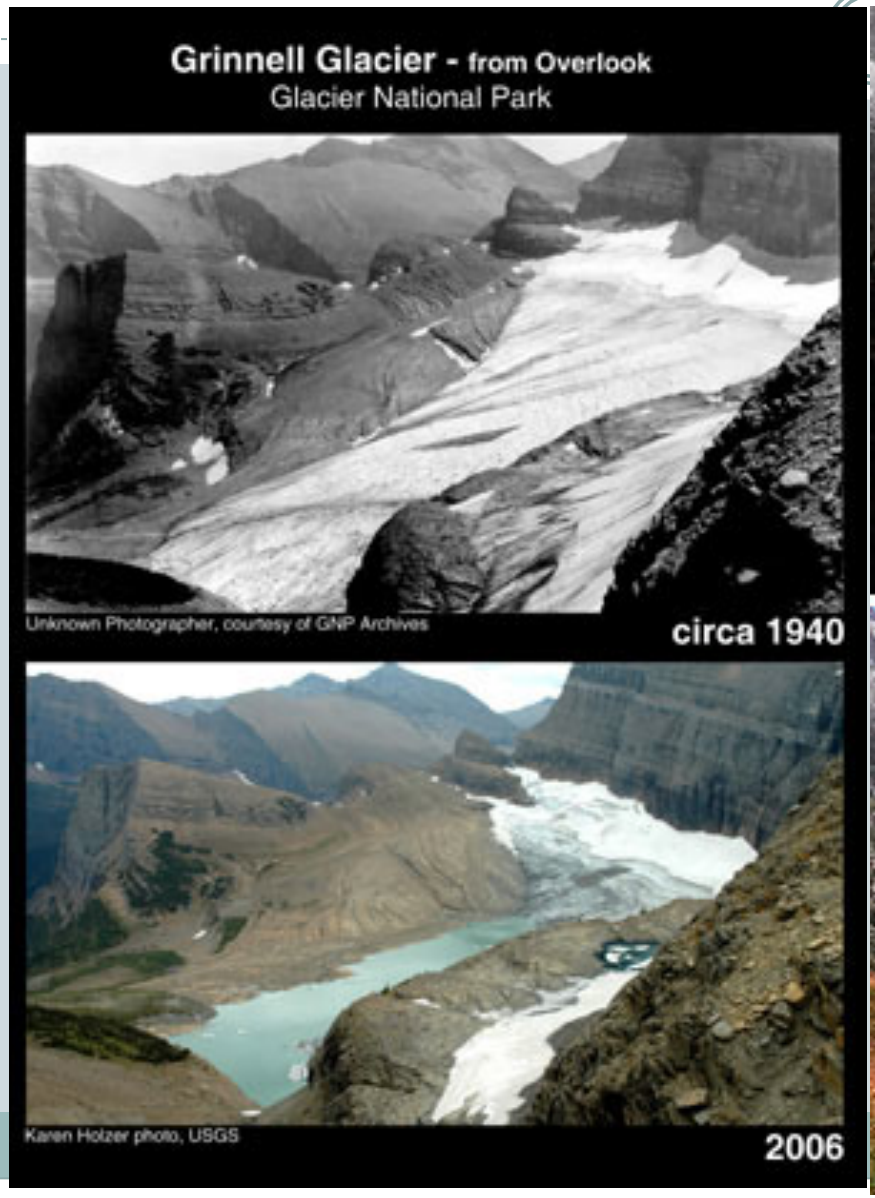
Mountain glaciers

We don't have to go far to see the retreat of mountain glaciers…

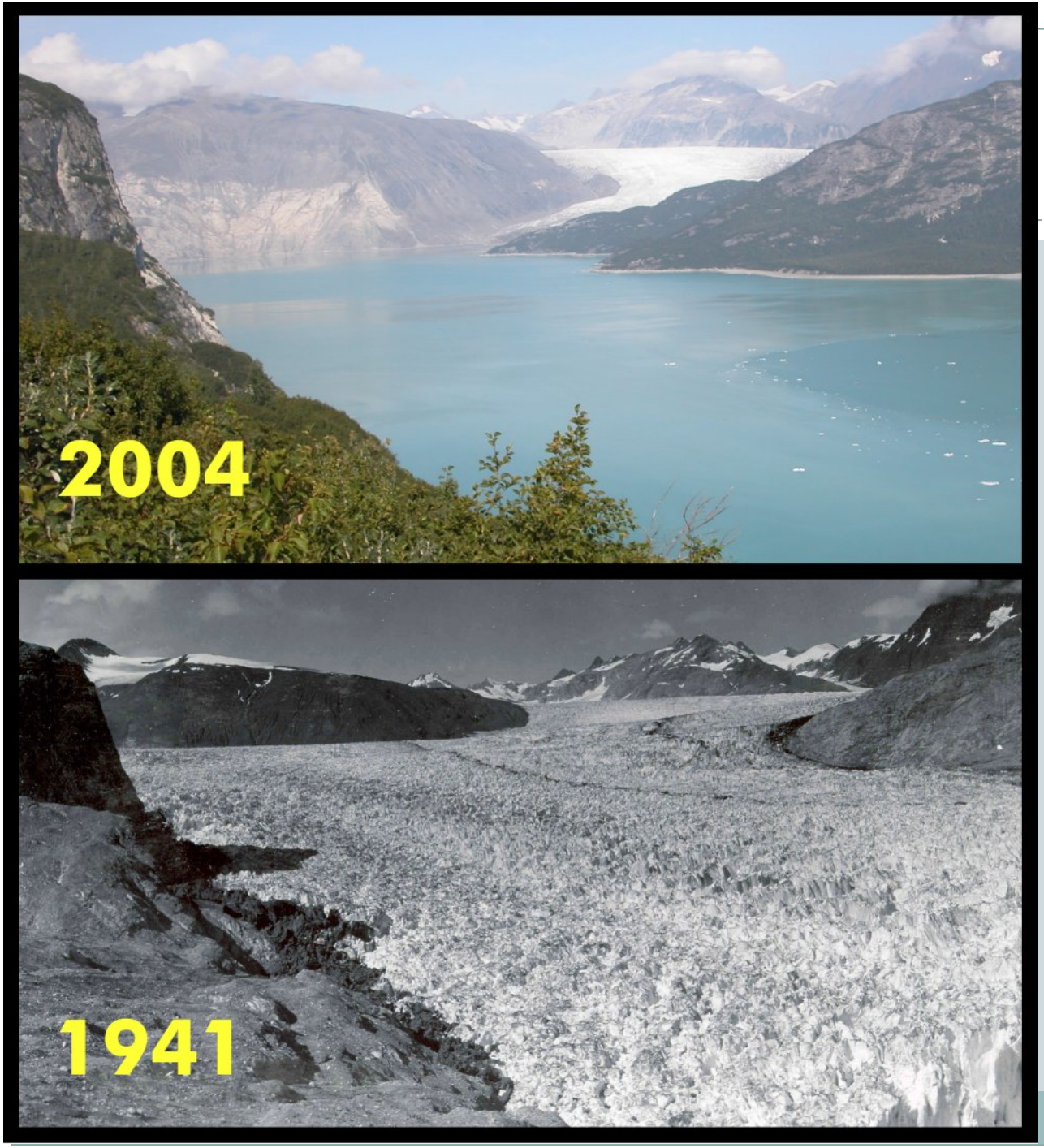
White Chuck glacier
North Cascades

Deglaciation

~~Glacier~~ Park, Montana



Switzerland

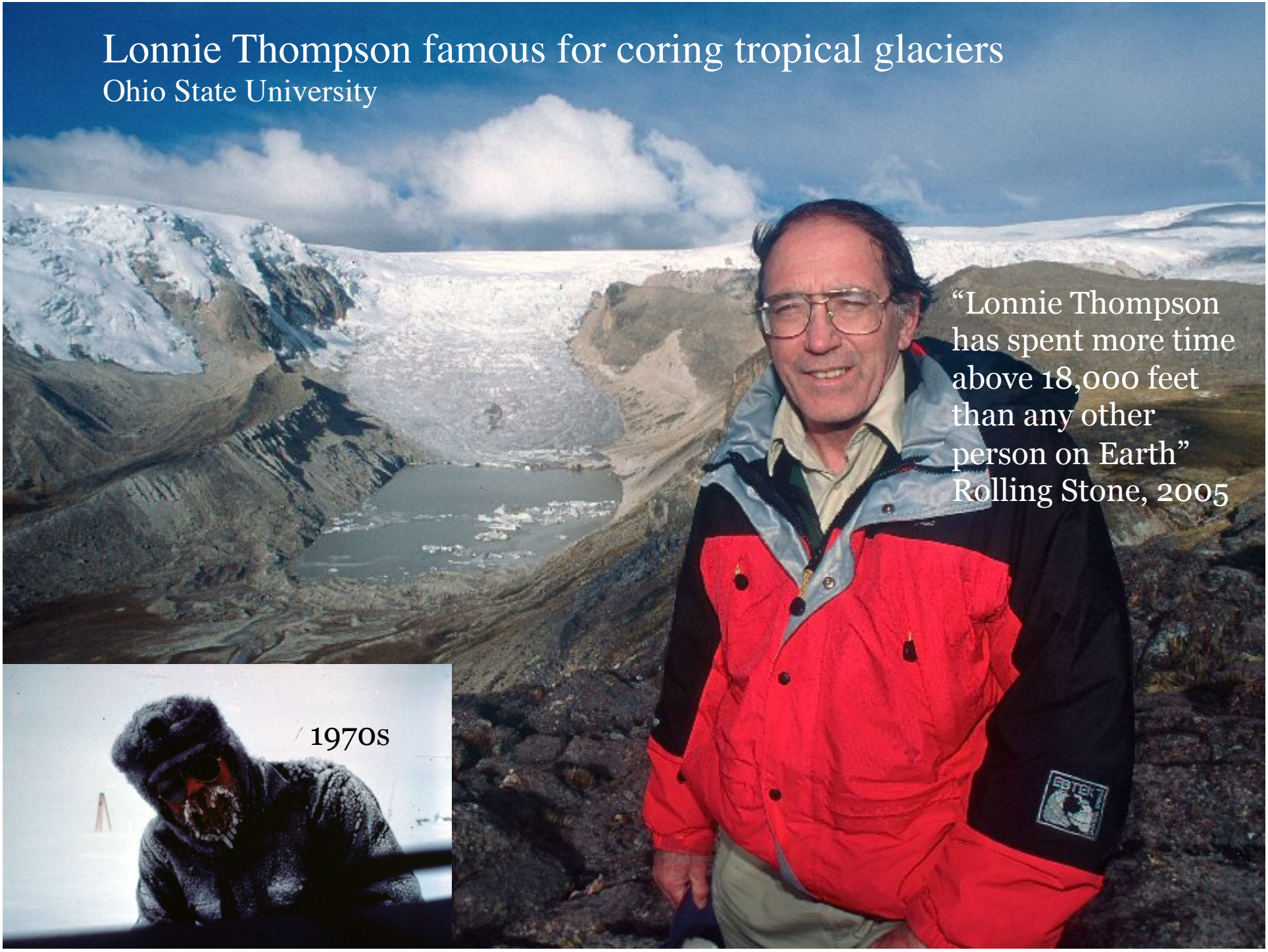


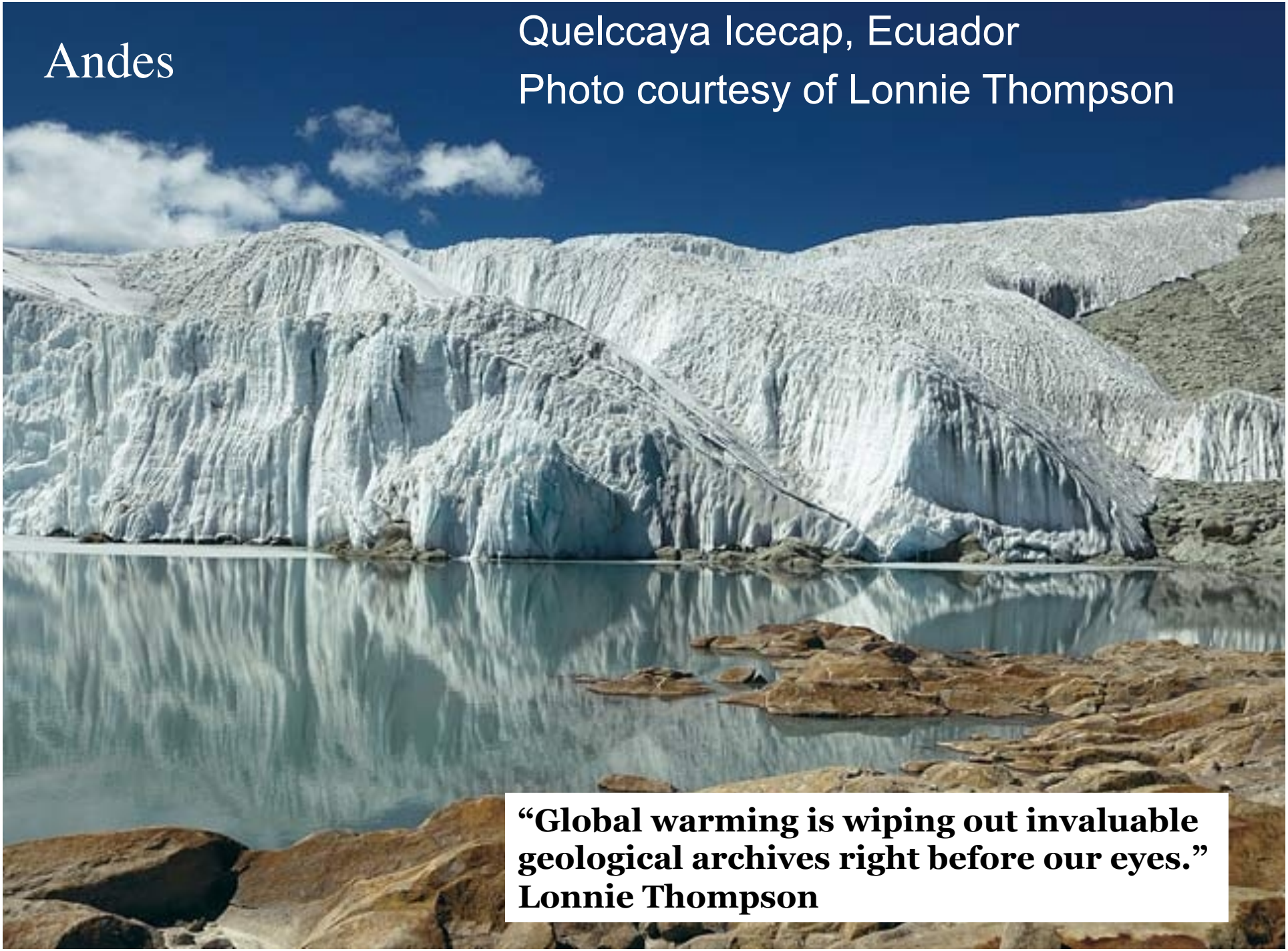
Glacier Bay Alaska

Himalayan glaciers may be melting from black carbon deposition too

Lonnie Thompson famous for coring tropical glaciers

Ohio State University



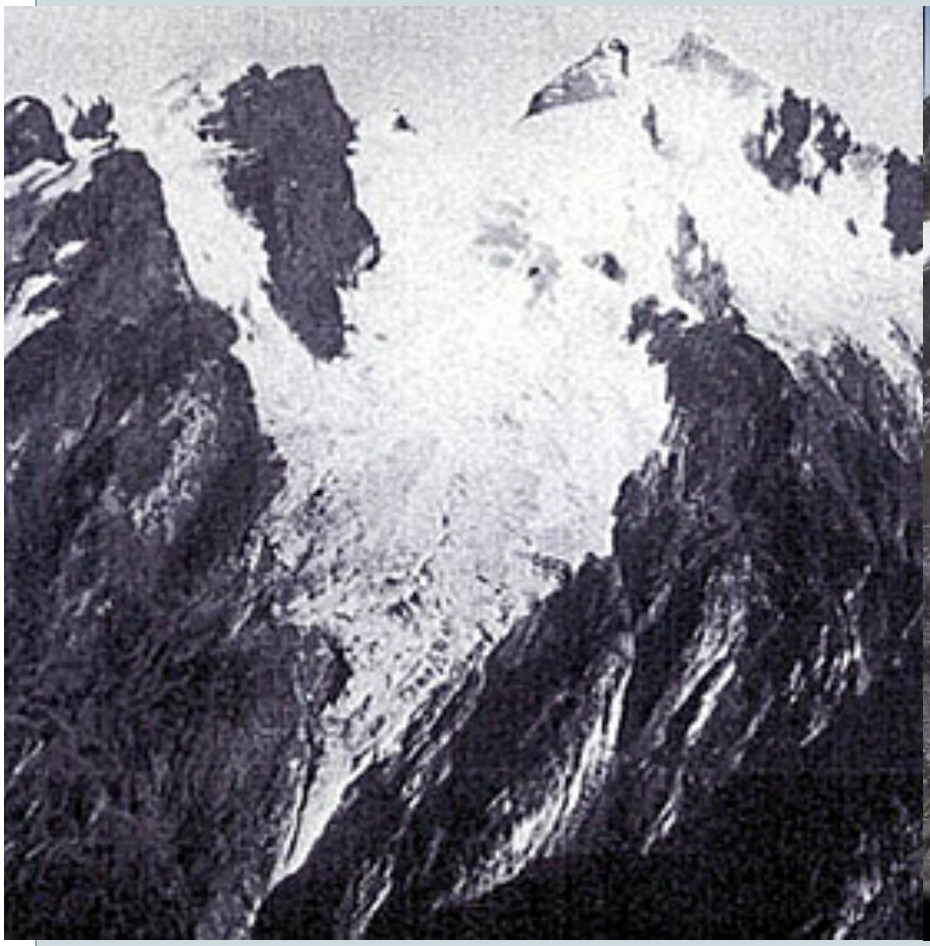

Andes
Quelccaya Icecap, Ecuador
Photo courtesy of Lonnie Thompson
“Global warming is wiping out invaluable geological archives right before our eyes.”
Lonnie Thompson

Melting Glaciers are Revealing Ancient Treasures!

- Much of the snow on glaciers fell a long time ago
- Recent NYT article (Jan 15, 2011) on melting glaciers in the Andes & elsewhere uncovering stuff
  - Melting has revealed:
    - Inca mummies
    - A 550 year old iceman
    - Planes from WWI and WWII
    - A British plane from the 1940s that was rumored to have gold in its cargo (with no gold though…)

Tropical glaciers

Ruwenzori
Uganda



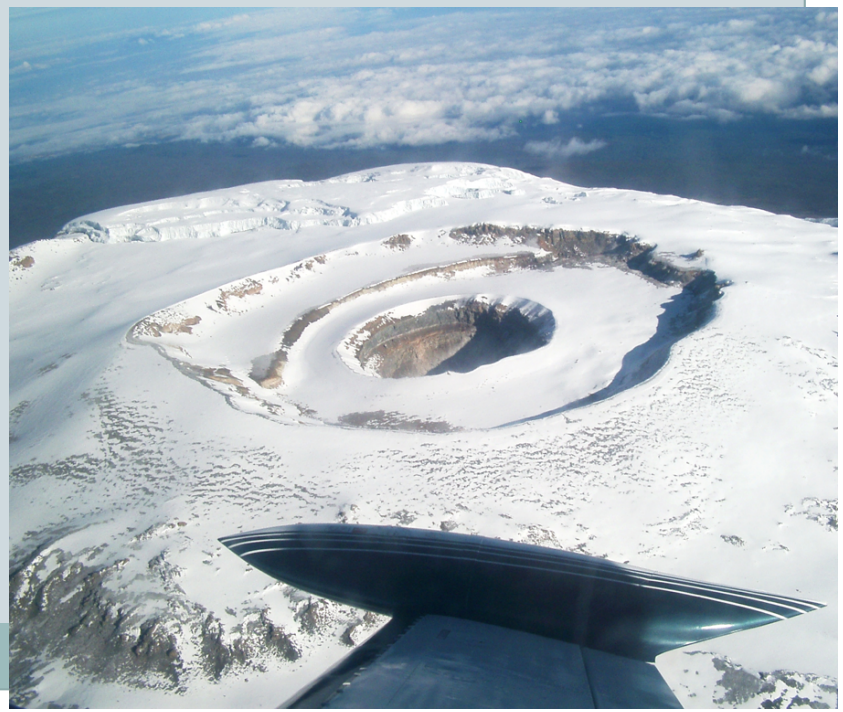
1906

present day

Kilimanjaro

Kilimanjaro snow is disappearing from **sublimation** because the atmosphere there is **drier** now.

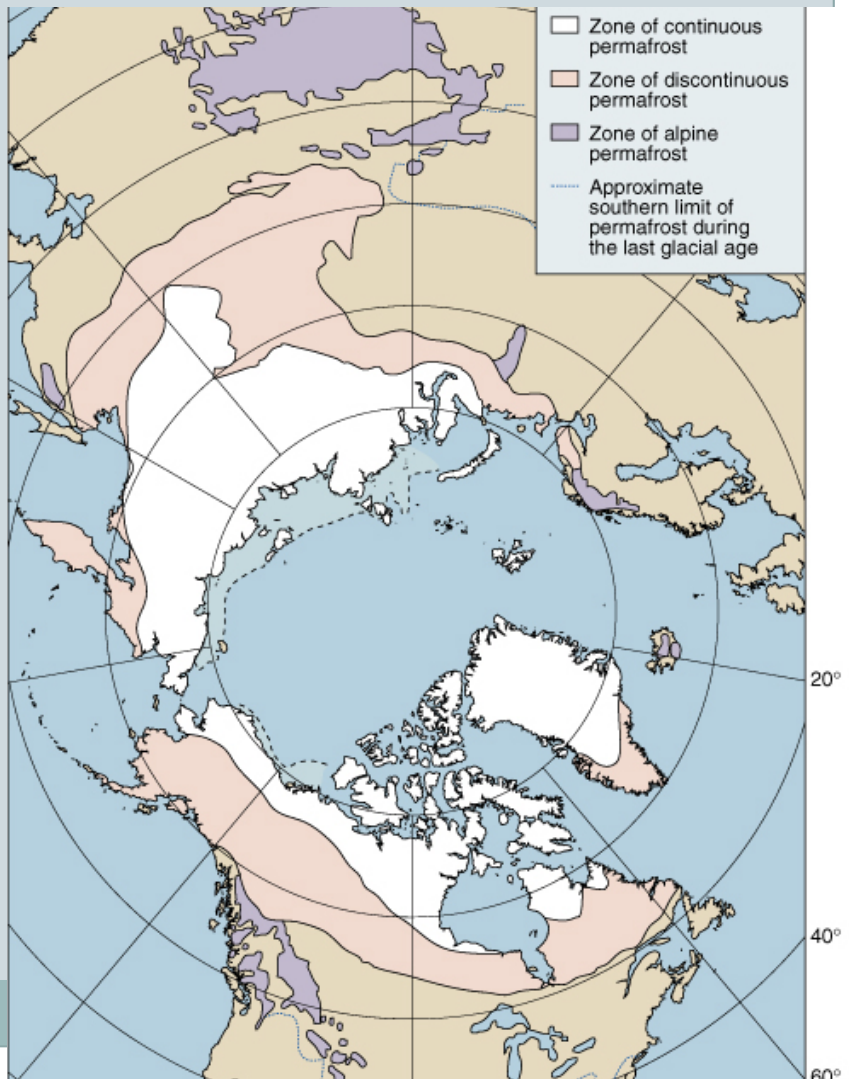
May still be caused by humans, but not directly by warming.



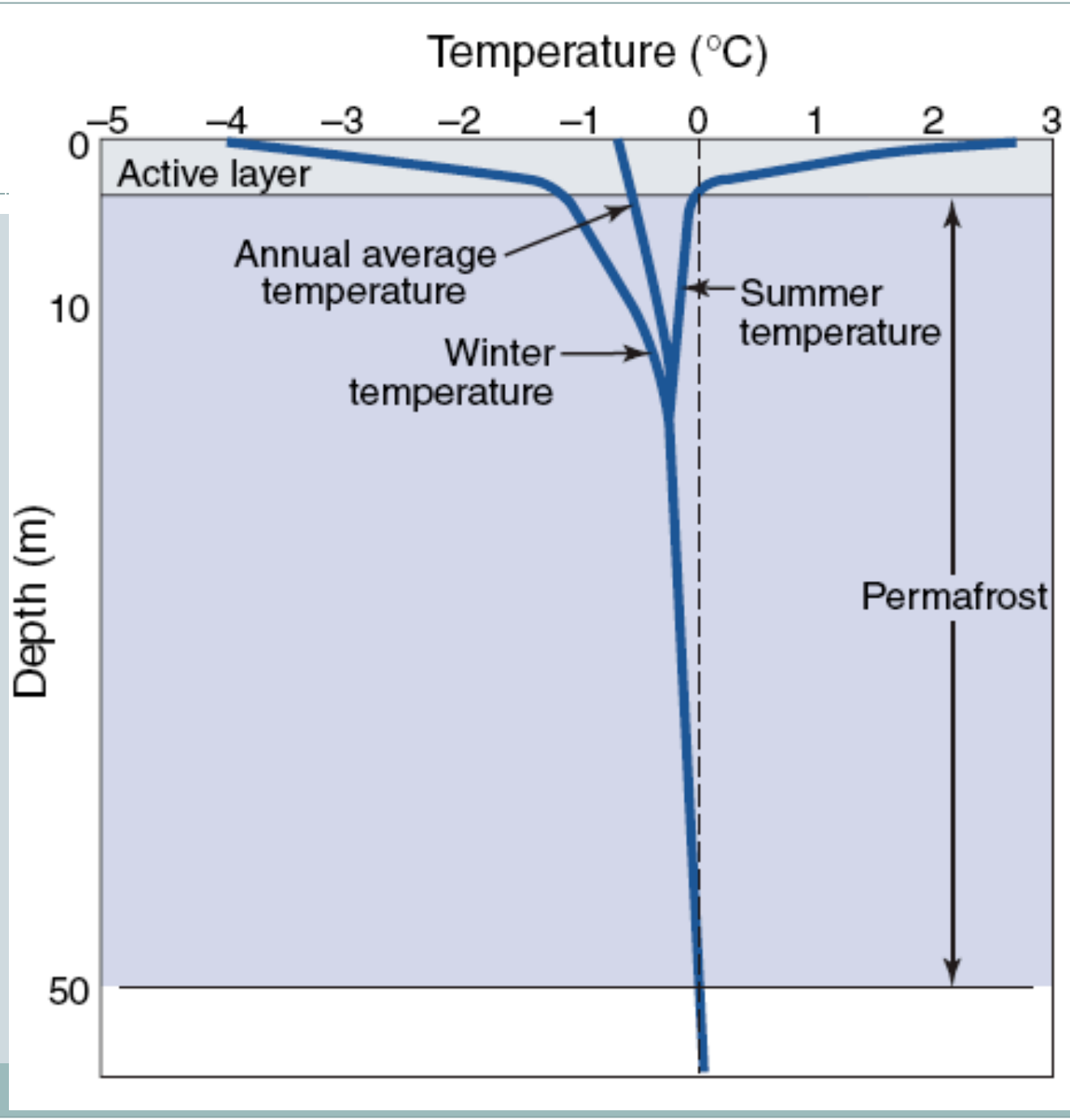
Permafrost

- **Permafrost**: ground that's frozen year-round
  - Extent at present →

- Typically has a thin layer on top that thaws in the summer: the "**active layer**"

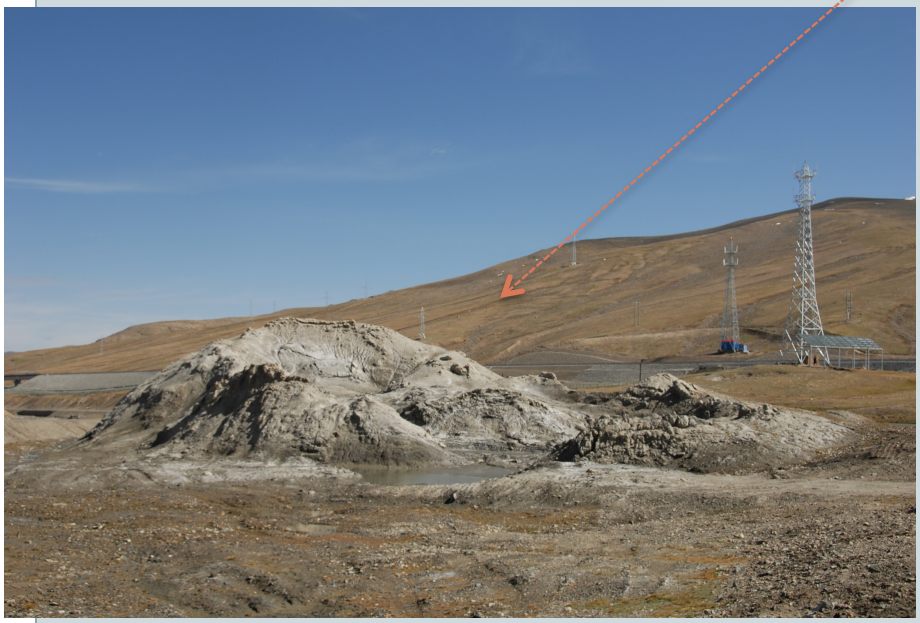


Ice is usually underground. Can be visible at river channel. This picture shows ice massive (the blue stuff) and active layer (grey above).


Temperature (°C)
–5
–4
–3
–2
–1
0
1
2
3
0
10
50
Depth (m)
Active layer
Annual average temperature
Winter temperature
Summer temperature
Permafrost

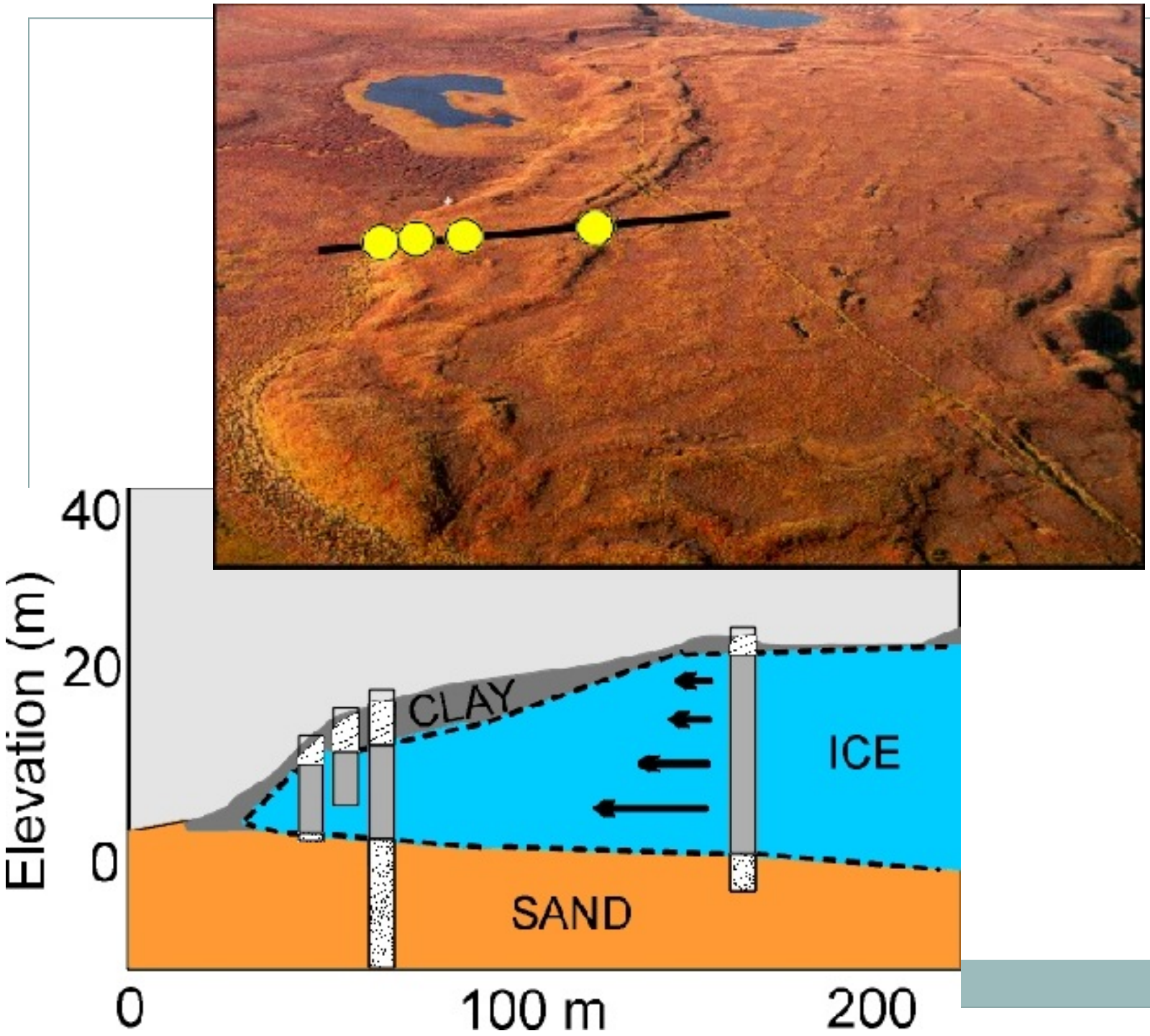
“Drunken Forest”

- Ice expands upon freezing
  - This causes potholes in roads in winter, etc
- Frozen ground causes weird formations



- When permafrost thaws, trees point in all directions!

“Drunken Forest”


40
20
0
Elevation (m)
CLAY
ICE
SAND
0
100 m
200

Thawing permafrost

widespread evidence of thaw

causing:

- damage to roads and buildings
- methane to be liberated
- vegetation to increase

to thaw all the permafrost will take centuries

permafrost thawing will be accelerated if summer sea ice continues to retreat

Will thawing permafrost release or take up greenhouse gases?

Snow-free season is short so plant growth rates are low. Plants are cold adapted, which is their strategy for survival. Not adapted for much competition. Likely more vegetation will come in after thaw.

Soils are very carbon rich (decaying plants & animals frozen into permafrost). Some fear **methane release** from thaw. Others say greater vegetation will draw down CO2.

Methane Hydrates

are water ice cages enclosing methane
(also known as methane clathrates)

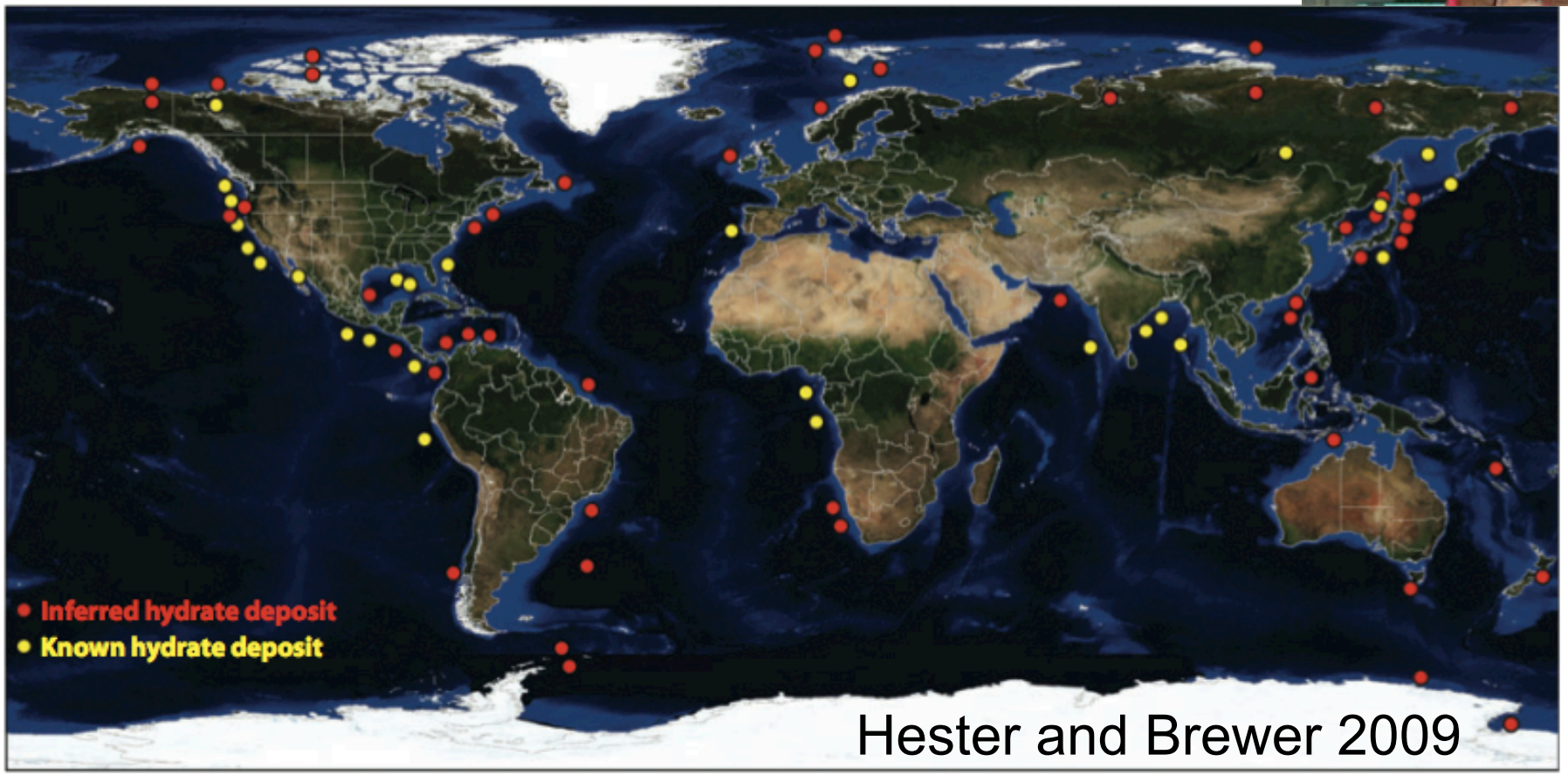


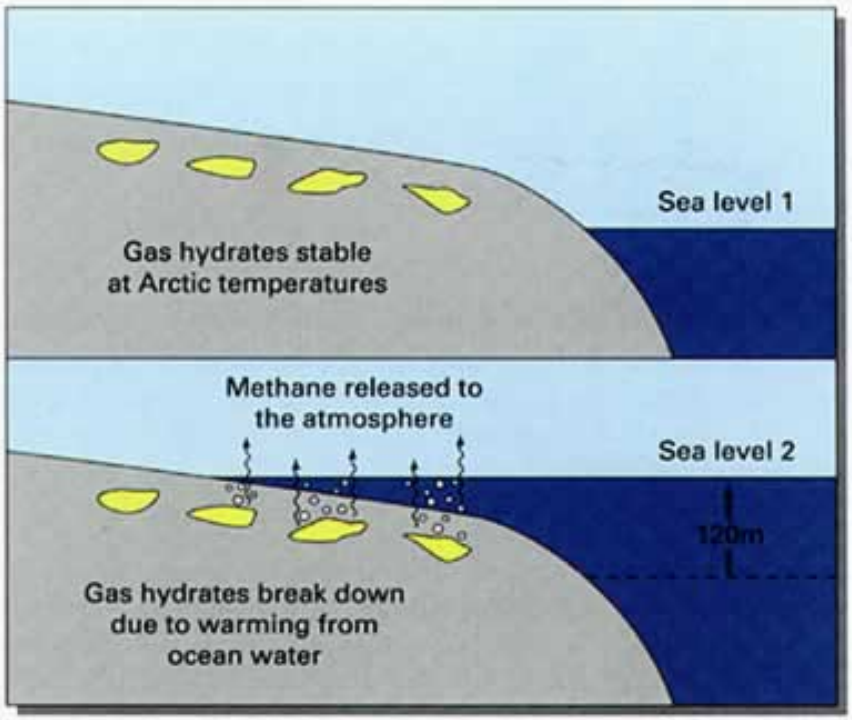
Figure 1

Worldwide map of more than 90 documented hydrate occurrences. Data from Kvenvolden & Lorenson (2001) and Milkov (2005).

Methane Hydrates

Carbon stored is 500-10,000 Gtons C (Coal is 3,200 Gtons C)

Need high pressure - under ice massive in permafrost
or ocean sediments



Sea-level rise causes relatively warm ocean water to cover cold Arctic strata. The resulting breakdown of stable gas hydrates within the sediment releases gas into the atmosphere.

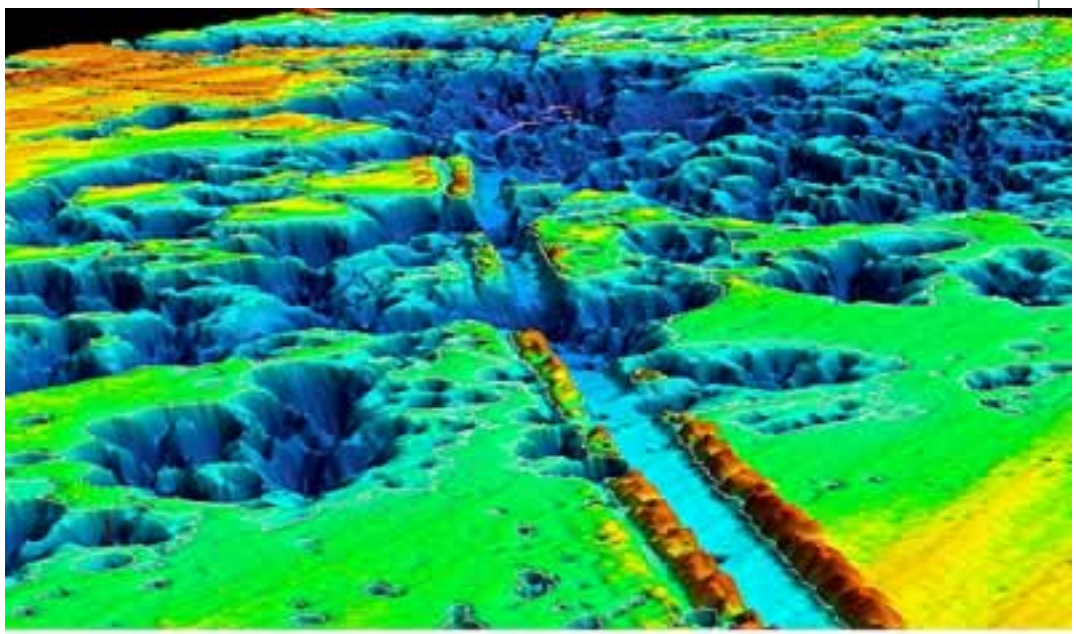
Methane ice diagram.
Source: http://marine.usgs.gov/fact-sheets/gas-hydrates/gas-hydrates-6.gif; accessed November 27, 2005.

The risk from them this century is speculative.

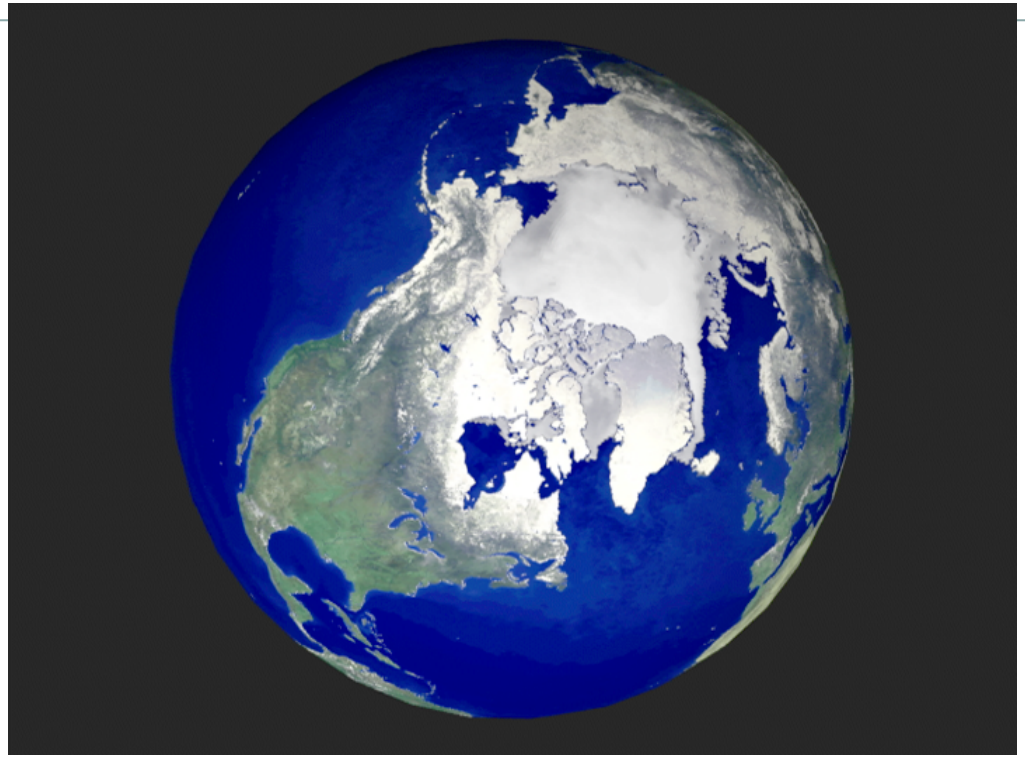
However their release would possibly create a positive feedback.

55 million years ago methane hydrates appear to have been released to the atmosphere at a time when the earth also warmed 2-3 C

There are pockmarks in ocean sediments as indication of past catastrophic release.



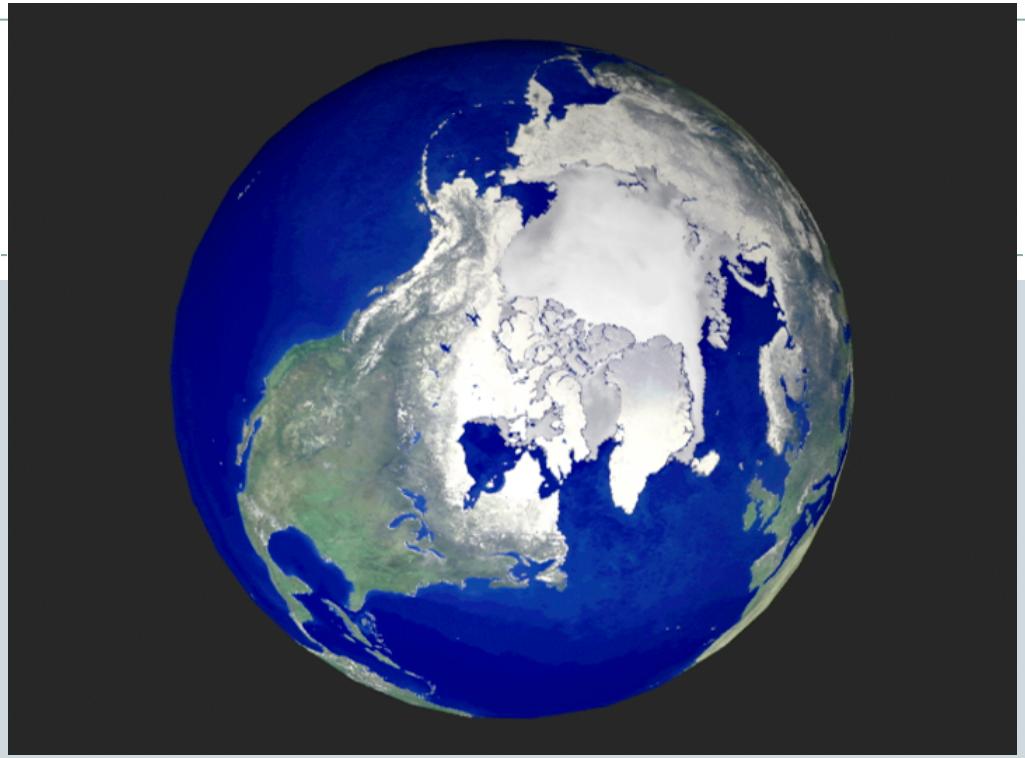
"Pockmarked" ocean floor suggesting shallow gas deposits; Canada's Beaufort Sea Geohazards Project.
Source: http://gom.nrcan.gc.ca/beaufort/images/pockmarksdem.jpg; accessed November 27, 2005.



Snow covered land is by far the largest **area** component of the cryosphere.

Snow is part of the positive ice-albedo feedback cycle, such that if snow melts earlier in spring, it causes spring warming and soil drying.

Snow is an important reservoir for water in some communities.



Precipitation is increasing in high latitudes with global warming

Snow covered season is shorter but depth may be greater

20,000 musk oxen die from Banks Island rain on snow

Rain falls onto snow, refreezes later & animals cannot graze

UW research: Rennert et al 2009 and many other studies