XVI. Warming and the cryosphere

review

- temperature from thermometers, satellites, glacier lengths and boreholes all show significant warming in the 20th C+

- reconstruction of past temperatures from corals, tree rings, and ice cores indicate that the magnitude and rate of 20th C+ warming is *anomalous* in the last 1000 years

clicker question

comparison of the global temperature response to natural changes in radiative forcing with actual temperature reconstructions (from tree rings, corals, ice cores and thermometers) tells us

a) 20th C+ warming is simply the result of natural variability in radiative forcing from volcanoes and the sun

b) the additional (and increasing) radiative forcing from GHG's is needed to explain 20th C+ warming

c) the concept of radiative forcing provides a robust basis for estimating future temperature change

d) both a) and c)

e) <u>both b) and c)</u>

clicker question

negative radiative forcing associated with aerosols (sulfate etc.) produced during fossil fuel burning

a) partly offsets warming from GHGs

b) enhances warming from GHGs

c) will likely diminish in response to societal demands for cleaner air

d) both a) and b)

e) <u>both a) and c)</u>

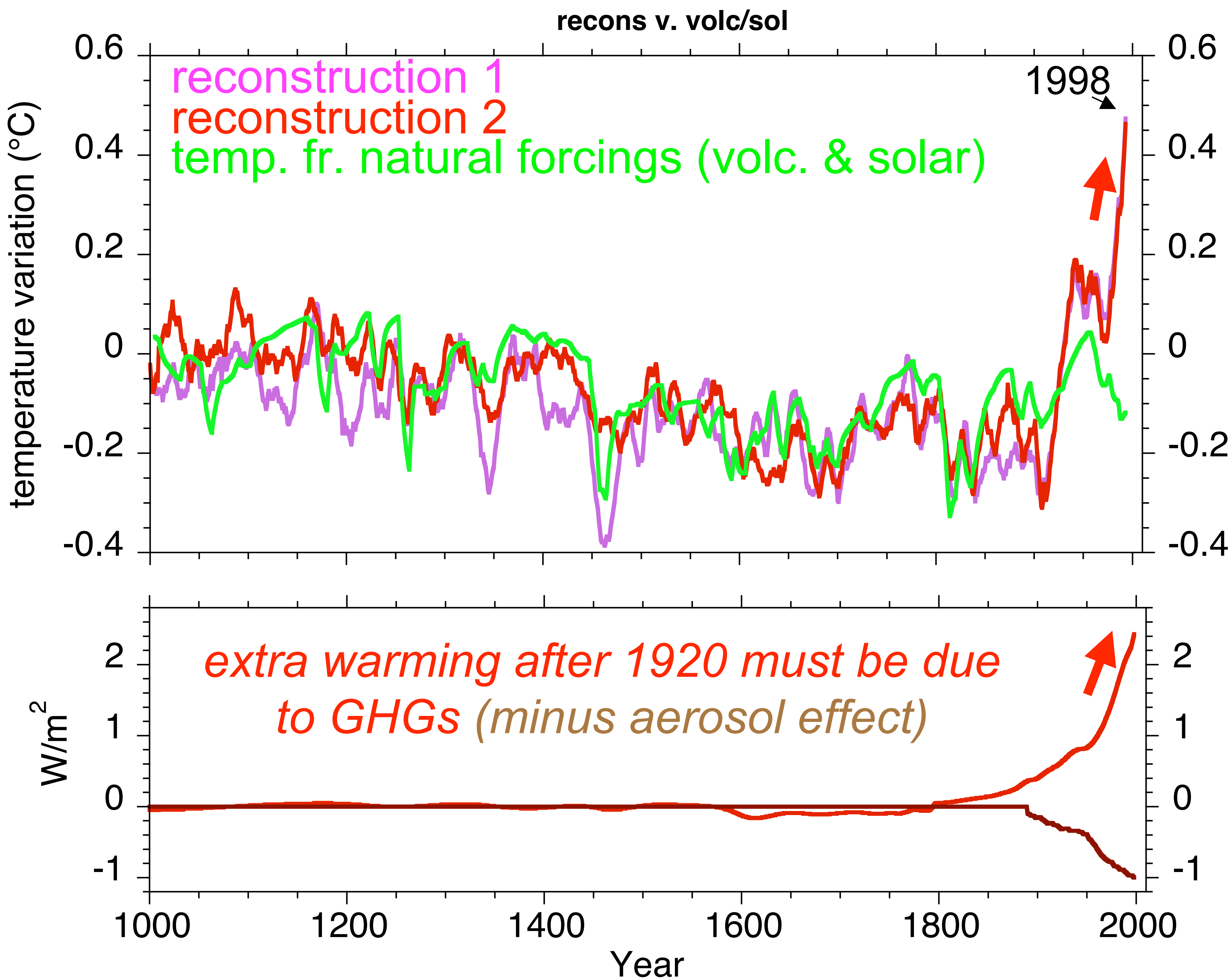
(man-made aerosols have been our "deal with the devil"!)

review

- natural variation in estimated *radiative forcing* from solar changes and volcanoes explains much of the variability in reconstructed temperature prior to ~1900

- after ~1900, *radiative forcing* from increasing GHG's is required to explain observed temperatures

- we have already reached the point where radiative forcing from GHGs (minus that from aerosols) is larger than any natural variation in radiative forcing during the past millennium



after Crowley '00

role and response of the cryosphere

- sea ice
  - formation and seasonal distribution
  - role in the climate system
  - warming and sea-ice amount
- Greenland and Antarctic Ice Sheets
  - increasing surface melt
  - acceleration of flow at margins
- global “small” glaciers
  - mass loss and warming
- polar amplification
- contributions to global sea level change (next class)

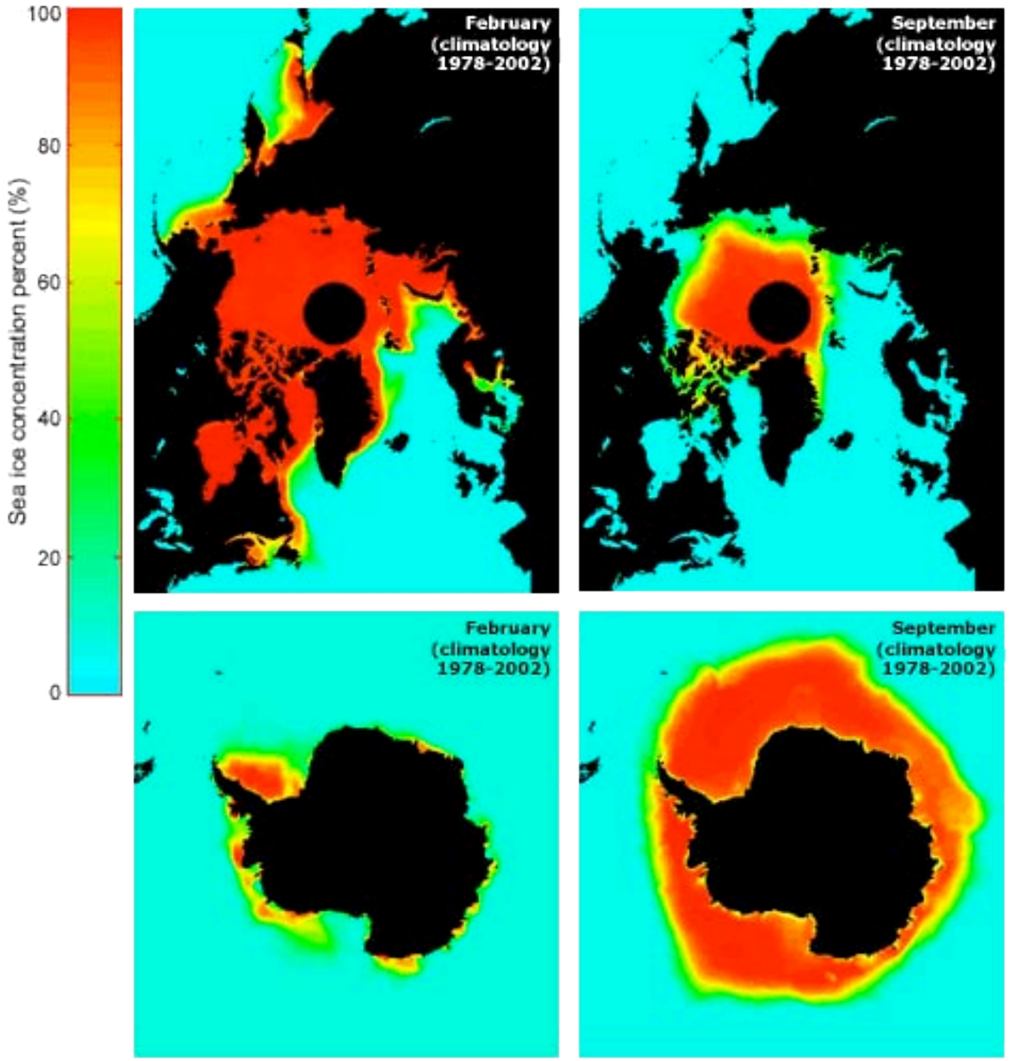
sea ice formation

forms small splinters which collect at the surface

gels together into small "pancakes" and then as consolidated sheets

sheets collide to produce ice ridges with deep keels

seasonal variation in sea ice

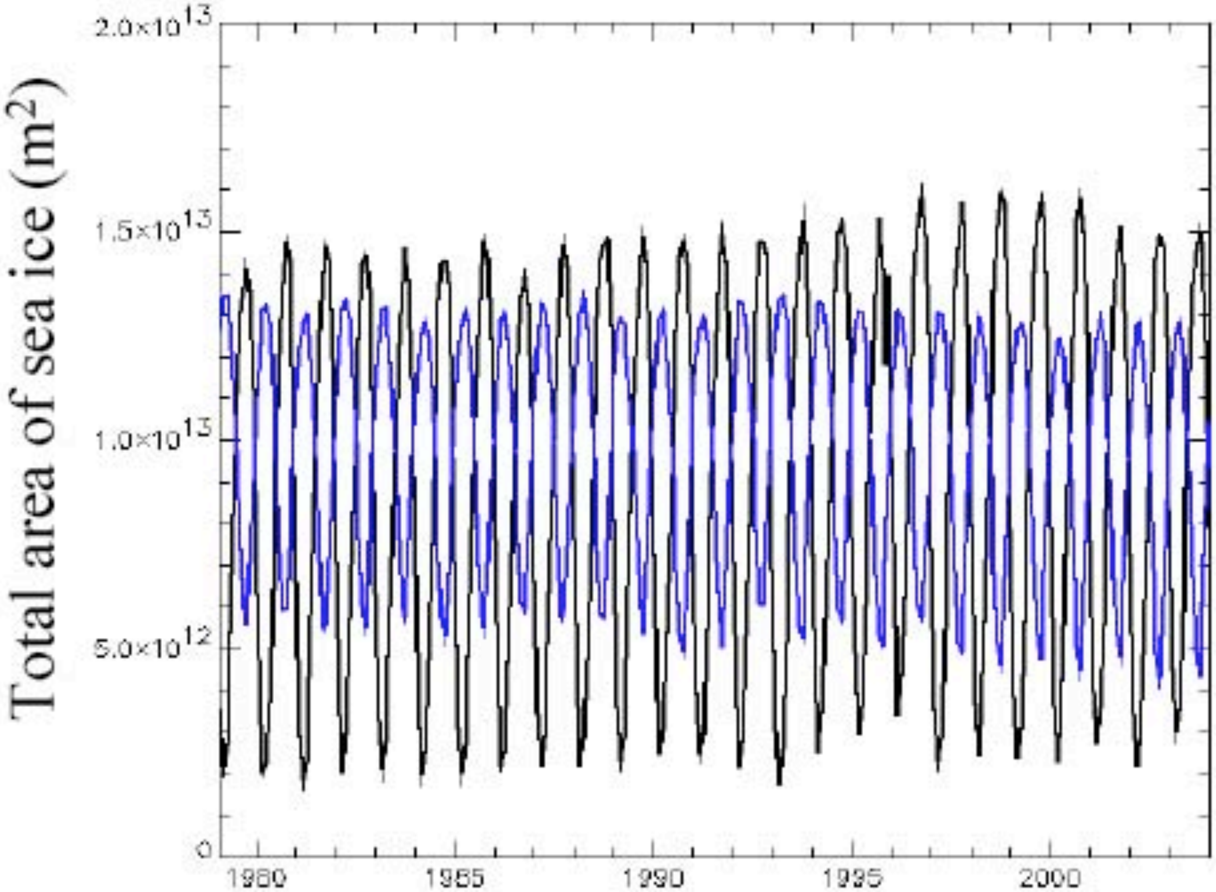


Arctic sea ice distribution is partly constrained by surrounding land mass, *can* have multi-year ice

Antarctic sea ice distribution is constrained by winds and sea surface temp., w/ a larger seasonal range & little or no multi-year ice

seasonal variation in sea ice

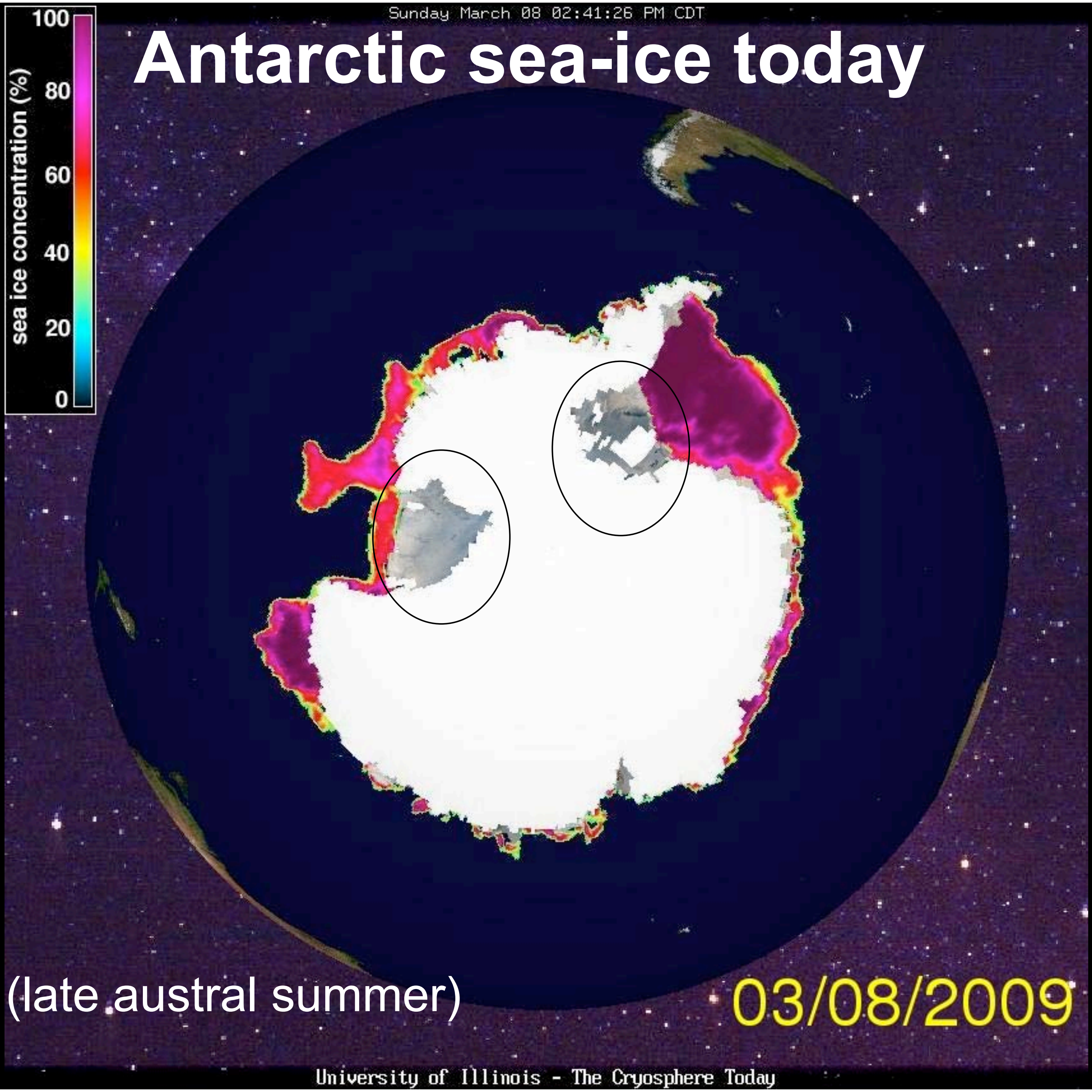
Northern Hemisphere v. Southern Hemisphere



Arctic sea ice extent restricted by land, but significant amounts remain in summer (allowing fmtn. of multi-year ice?)

Antarctic sea ice extent restricted only by sea surface temperature and winds, but disappears almost entirely in summer

Antarctic sea-ice today

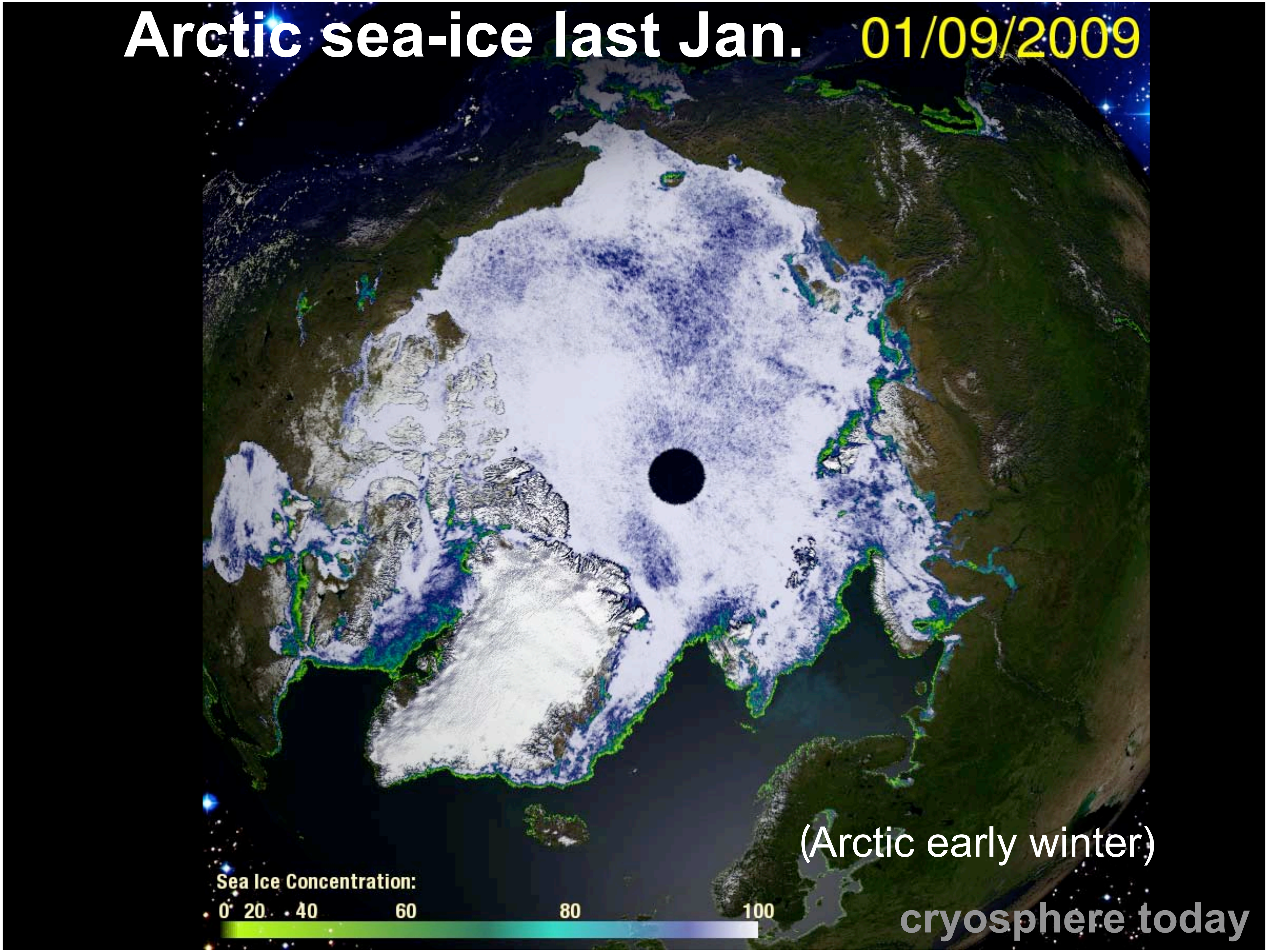


(late austral summer)

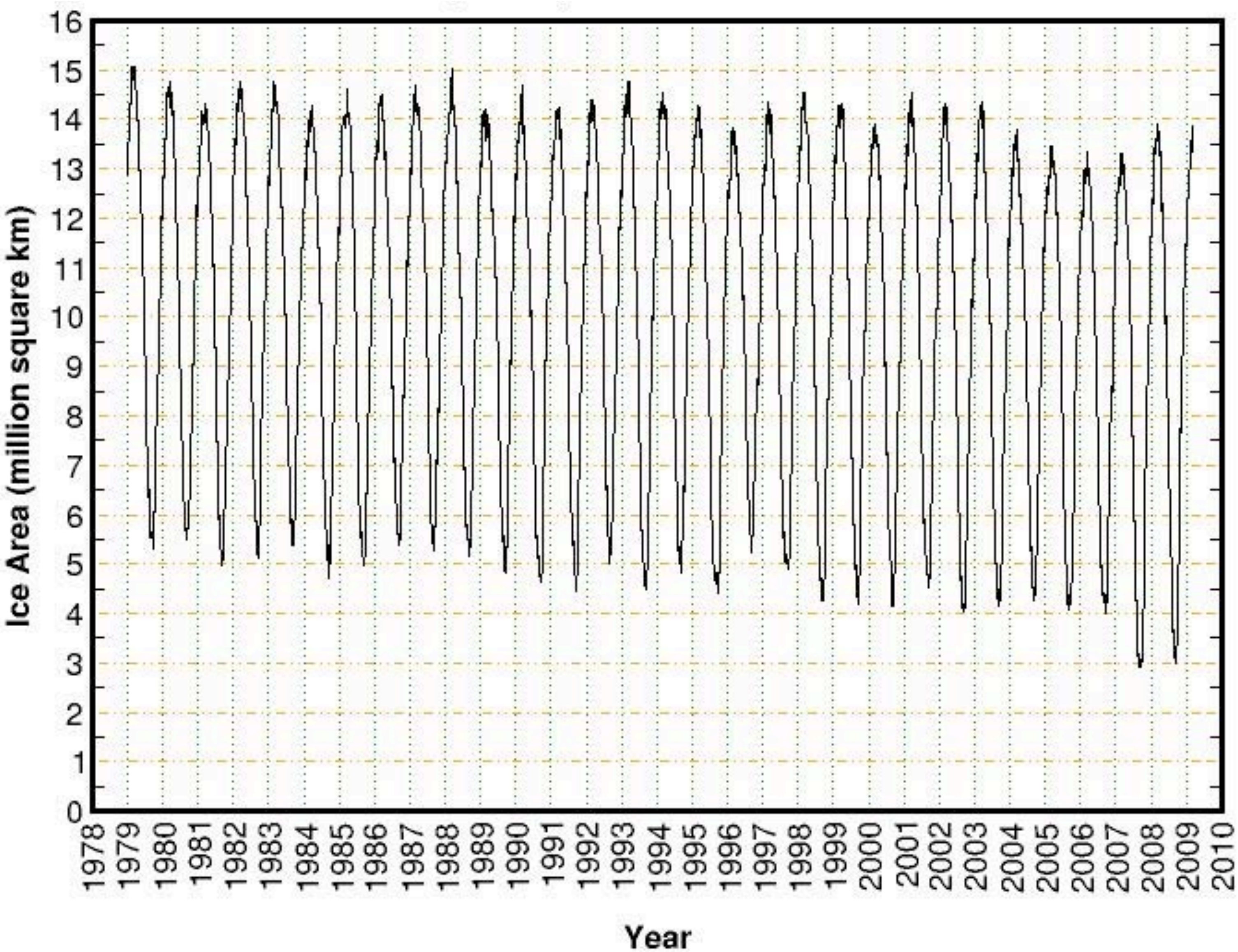
Arctic sea-ice today 03/06/2009

(Arctic late winter)

cryosphere today

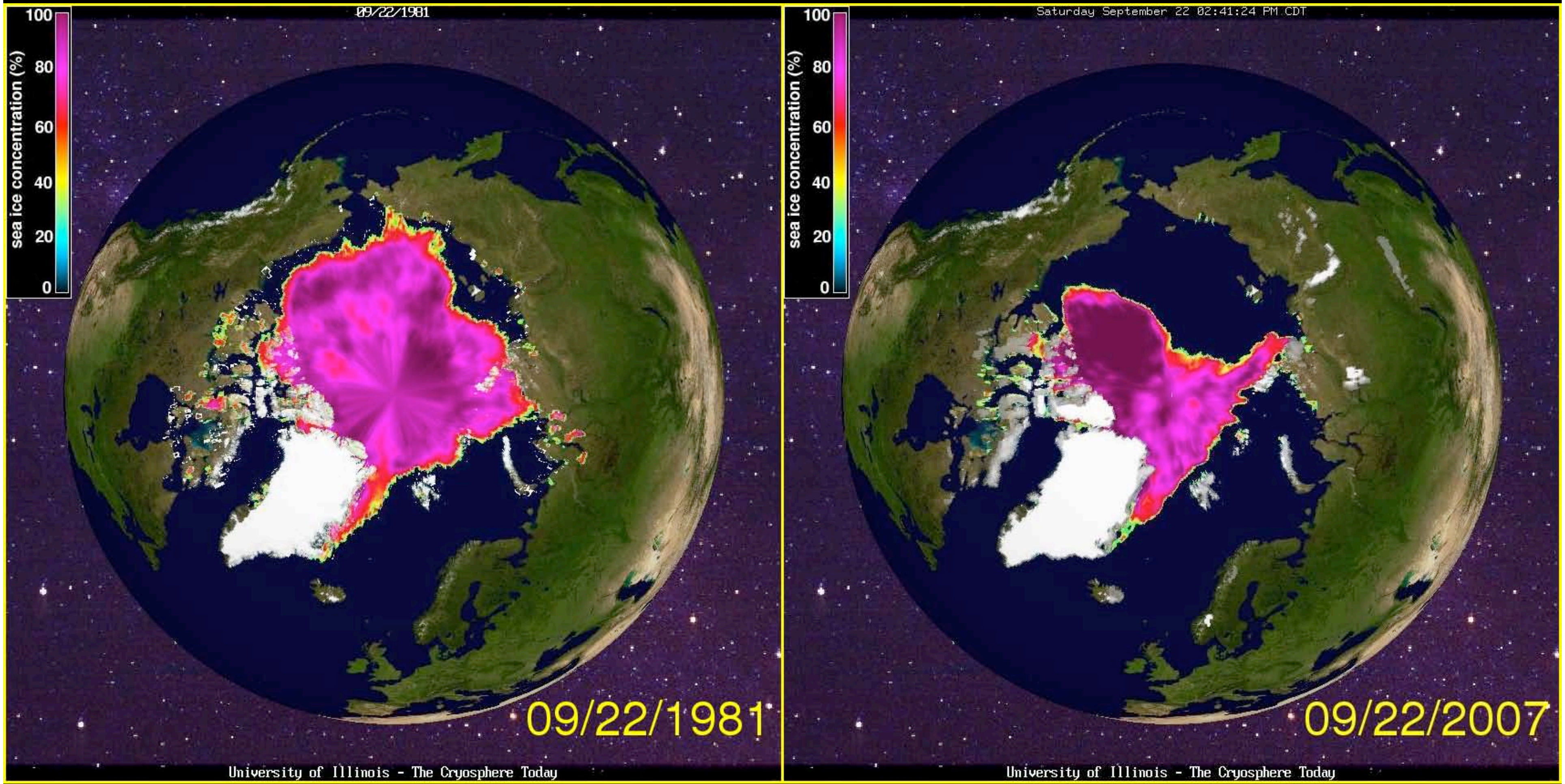

Arctic sea-ice last Jan.
01/09/2009
(Arctic early winter)
Sea Ice Concentration:
0 20 40 60 80 100
cryosphere today

NH sea ice area



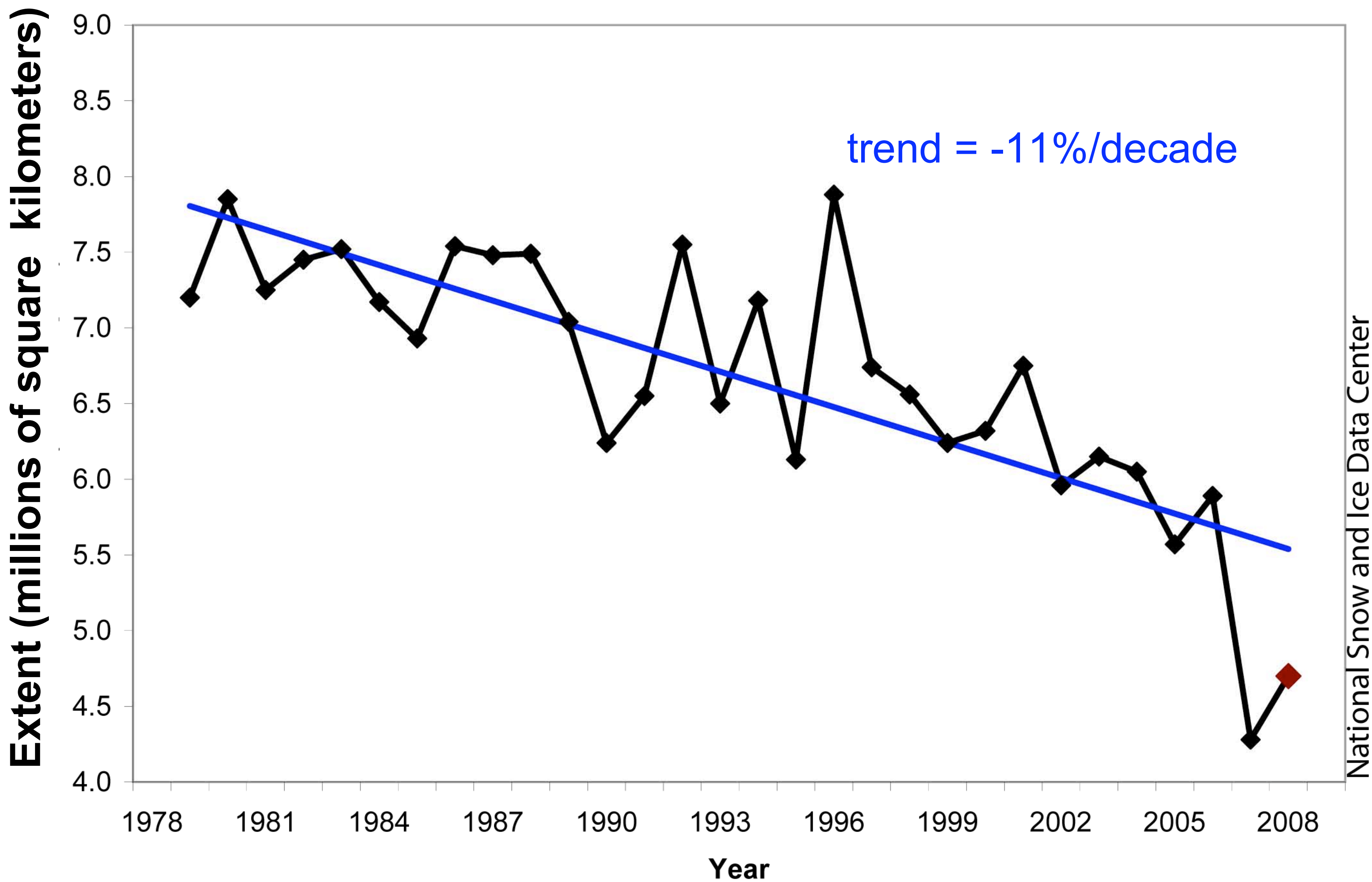
CU-NSIDC

end-of-summer sea ice extent
1981 v. 2007



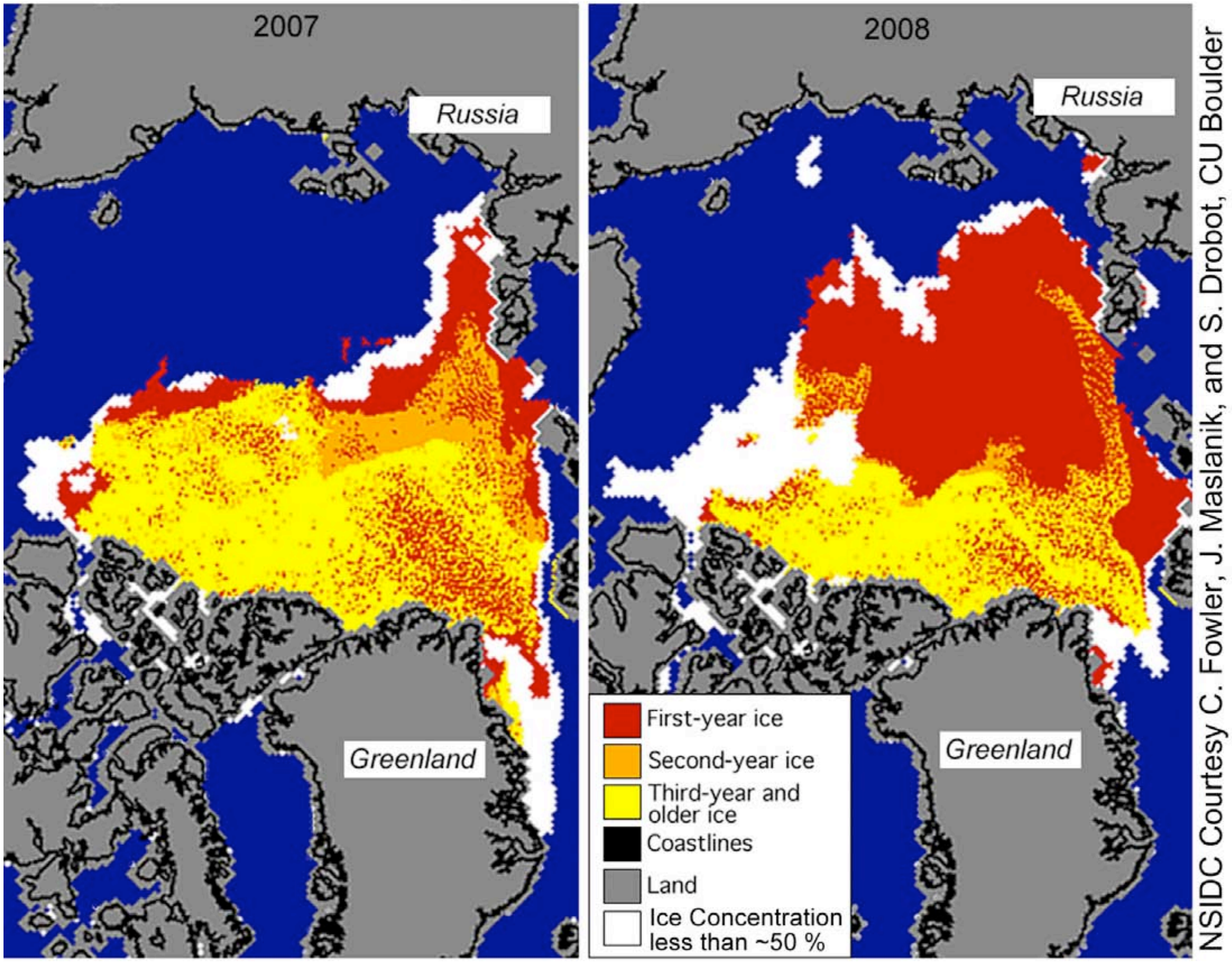
cryosphere today

Sep Arctic Sea Ice Extent '79 - '07



CU-NSIDC

Arctic sea ice age 2007 & 2008



There is less multi-year ice. First year ice is thinner and more vulnerable to complete melt……

sea ice and energy fluxes

consider surface w/ ice compared to open water:

- albedo of ice higher
  - *less short wave radiation absorbed*
- temperature of ice lower than liquid ocean
  - *less energy as radiation going up*
  - *less sensible heat going up (i.e., less conduction)*
- less evaporation (much more energy is required to convert ice to vapor than water to vapor)
  - *less latent heat going up*

sea ice and energy fluxes

- *conclude sea ice acts to insulate atmosphere from ocean*
- recall there is a poleward transport of heat by the atmosphere and ocean- sea ice stops that ocean heat from entering the polar atmosphere
- ***so when there is sea ice the Arctic stays cold, when there is no sea ice the Arctic can warm substantially***

clicker question

the couplings between sea-ice cover, ocean-atmosphere heat flux, and temperature are

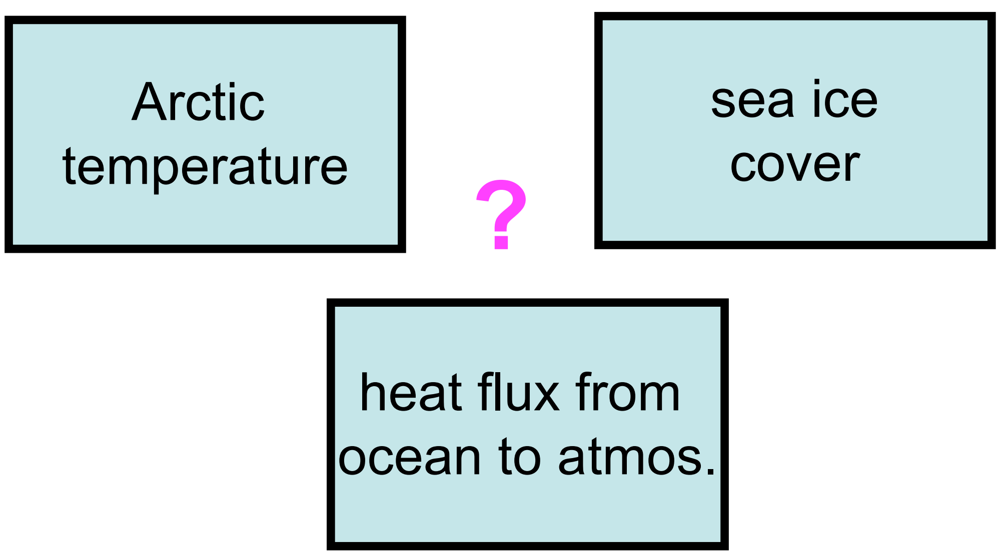
a) all negative couplings

b) all positive couplings

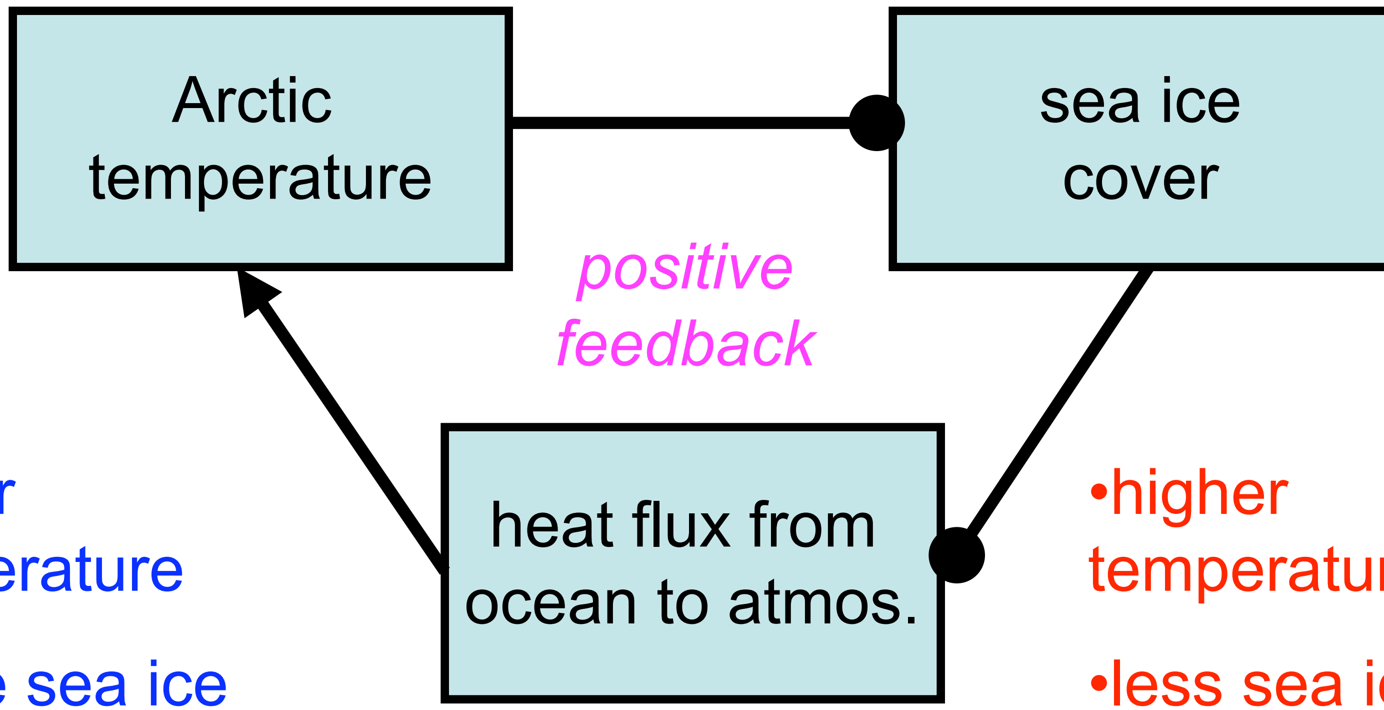
c) represent net negative feedback loop

d) <u>represent a net positive feedback loop</u>

e) none of the above



sea ice - temperature feedback

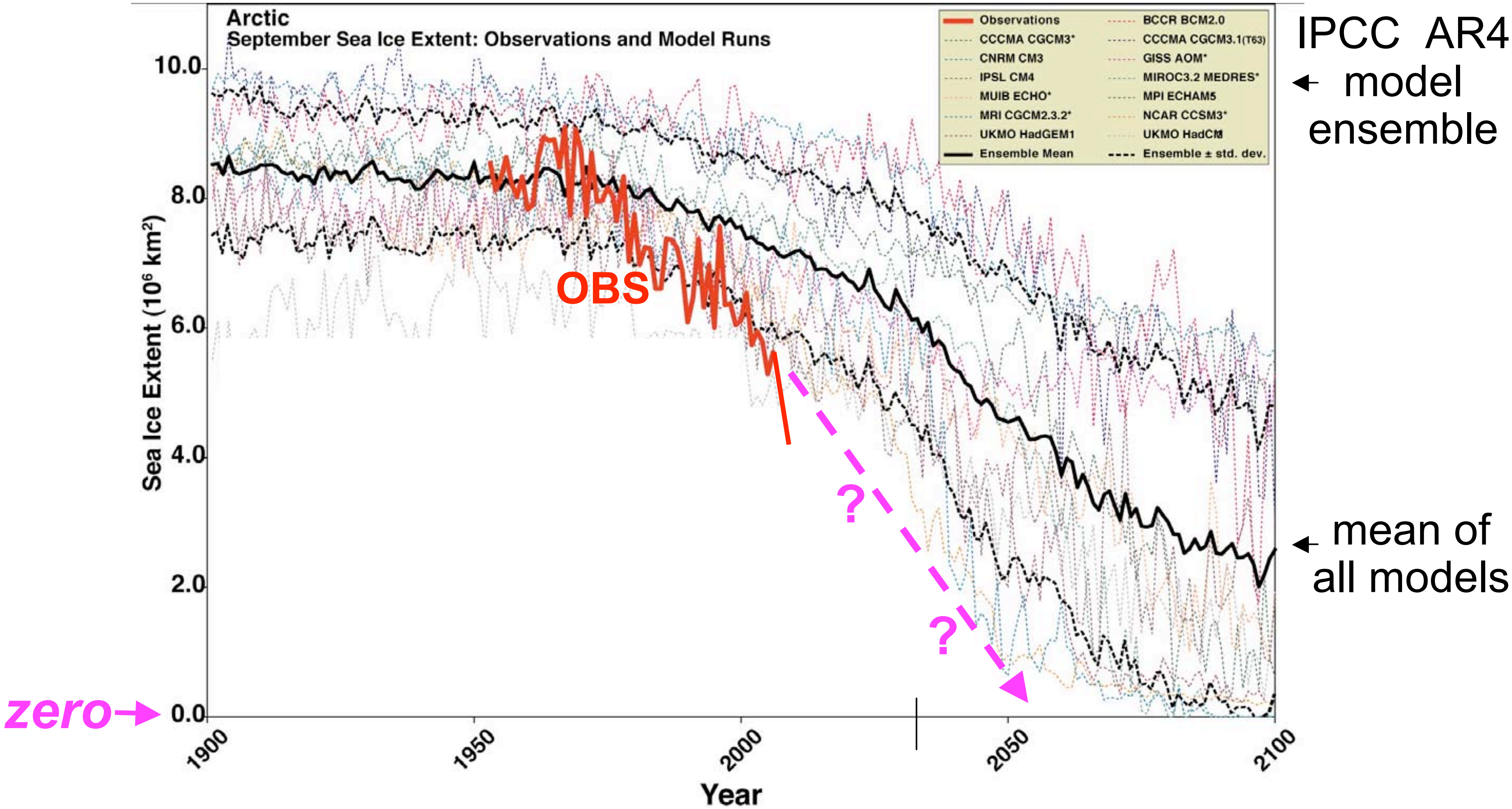


- lower temperature
- more sea ice
- lower O-A heat flux
- lower temperature.....

this feedback largely explains observed Arctic amplification of warming

- higher temperature
- less sea ice
- greater O-A heat flux
- higher temperature.....

observations vs. models



observed sea ice decline is >50 years ahead of expectation from models forced by GHG's (and other human and natural radiative forcings discussed earlier) suggesting models do not capture all relevant interactions

Stroeve et al., '07 NSIDC

“A linear increase in heat in the Arctic will lead to a non-linear, and accelerating, loss of ice”

Norbert Untersteiner, Professor Emeritus, Univ. of Washington, 2006

impacts of a summer-ice free Arctic ?

- sharply warmer Arctic Autumn and Winter from increased O-A heat fluxes (*polar amplification of warming*)
- local ecological and human impacts
- altered weather patterns outside the Arctic (due to altered large scale patterns of heating and pressure)
- altered salinity and ocean circulation

no evidence of summer-ice free Arctic in last million years

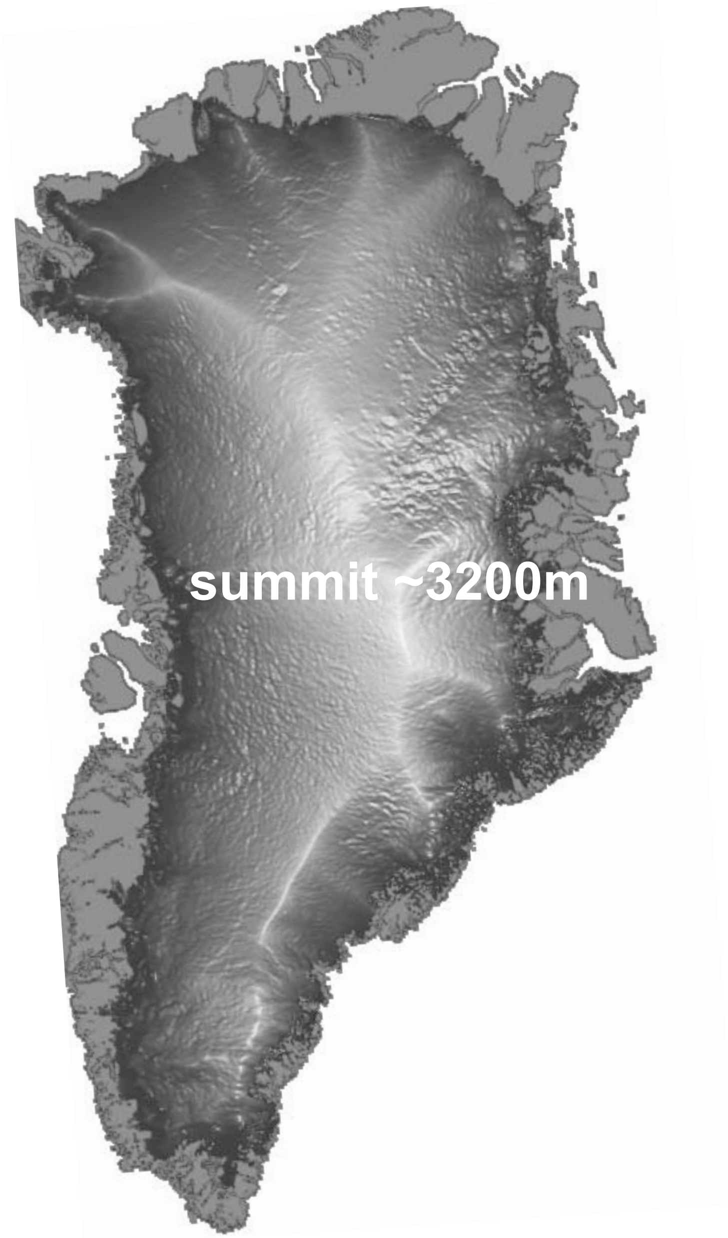
polar bears *require* sea ice

US listed as threatened under Endangered Species Act due to habitat (sea ice) loss resulting from high latitude warming?

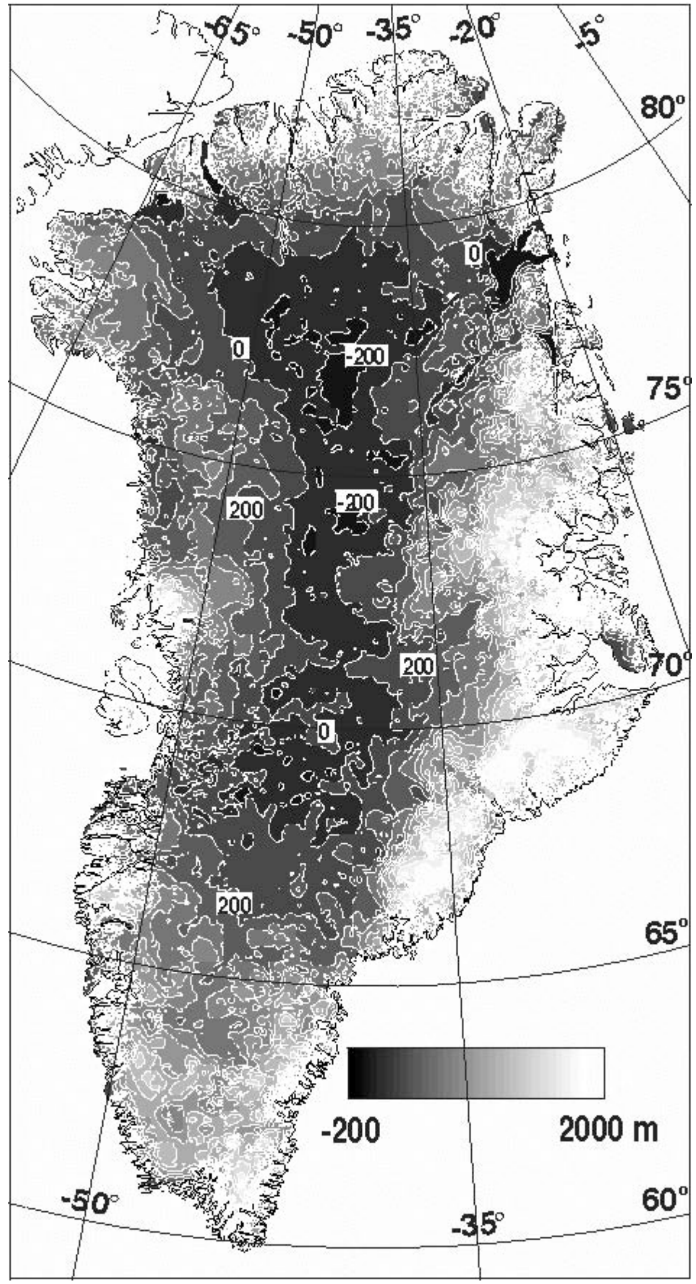
sea ice summary

- sea ice cover varies extensively by season
- in the Arctic, considerable ice remains in summer (*until recently*), leading to formation of thick (~5 m) multi-year ice
- in Antarctica, nearly all the new ice melts each year
- sea ice cover regulates the exchange of energy between the ocean and atmosphere
- i.e., sea ice acts as an *insulator*
- sea ice can amplify Arctic climate change thru a *temperature- sea ice - heat flux feedback* (a more complete description of the *ice-albedo feedback* over water)
- Arctic sea ice cover has declined over the last 25 yrs of observations, most dramatically since 2000
- a simple projection of current trends suggests the Arctic will be ice free by 2050 (and likely before)

Greenland Ice Sheet

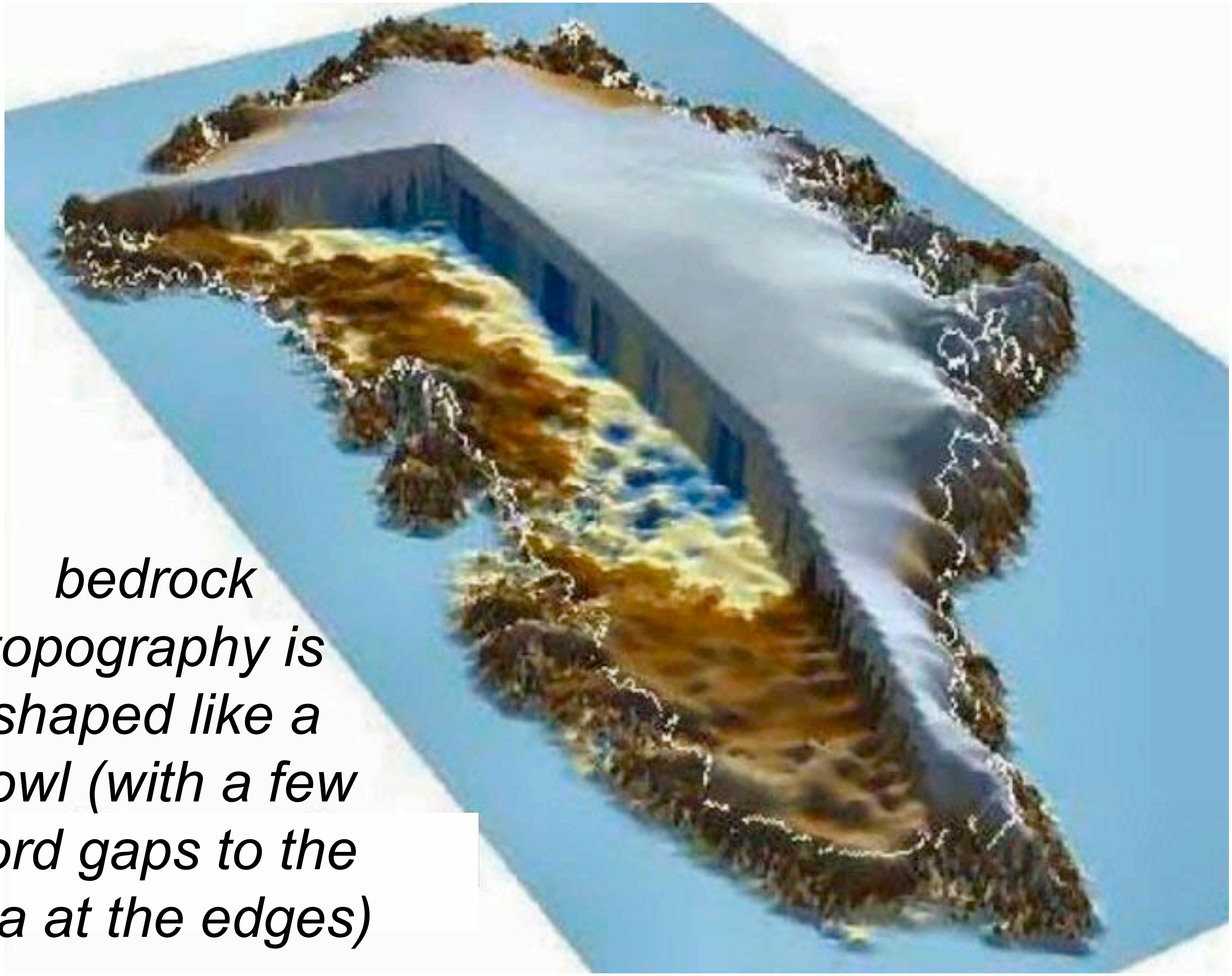


with ice



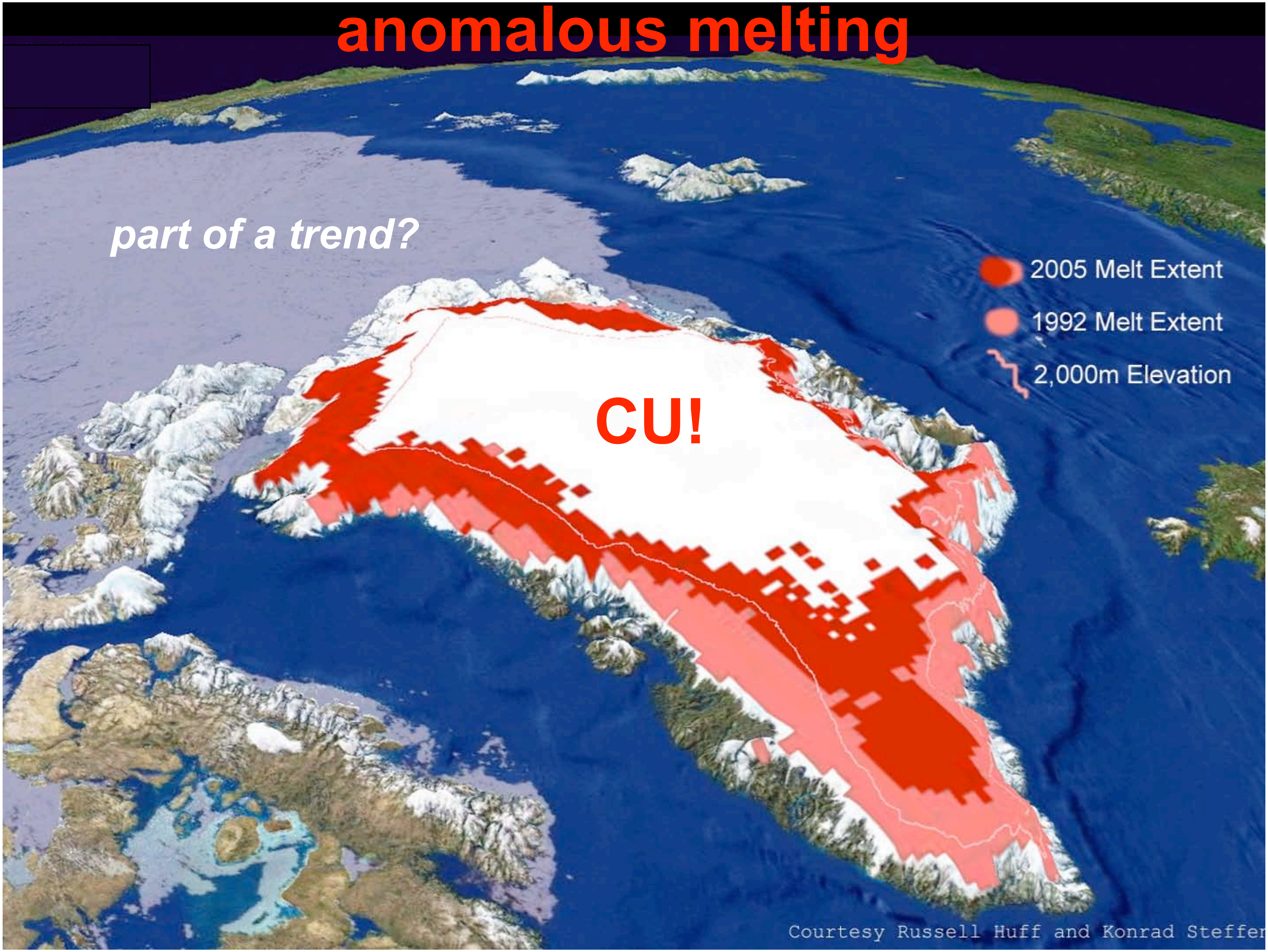
without (interior depressed below sea level)

Greenland Ice Sheet

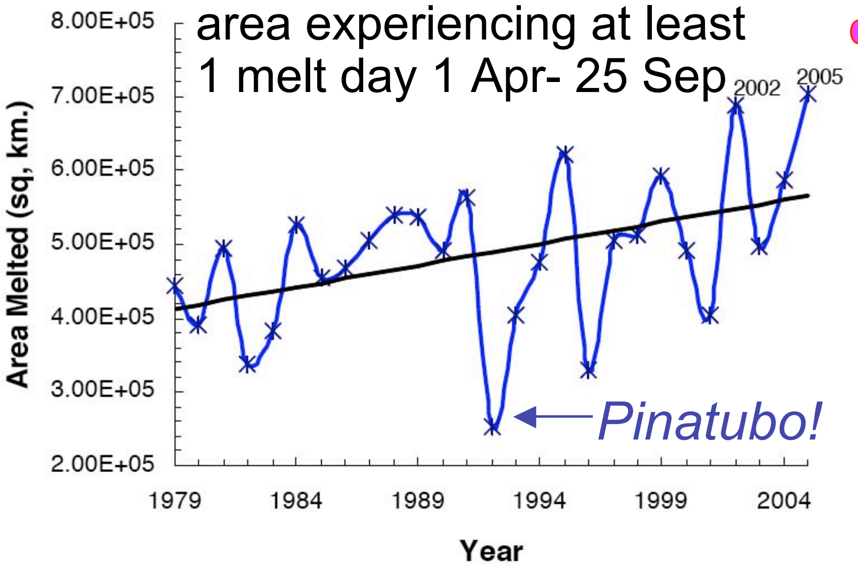


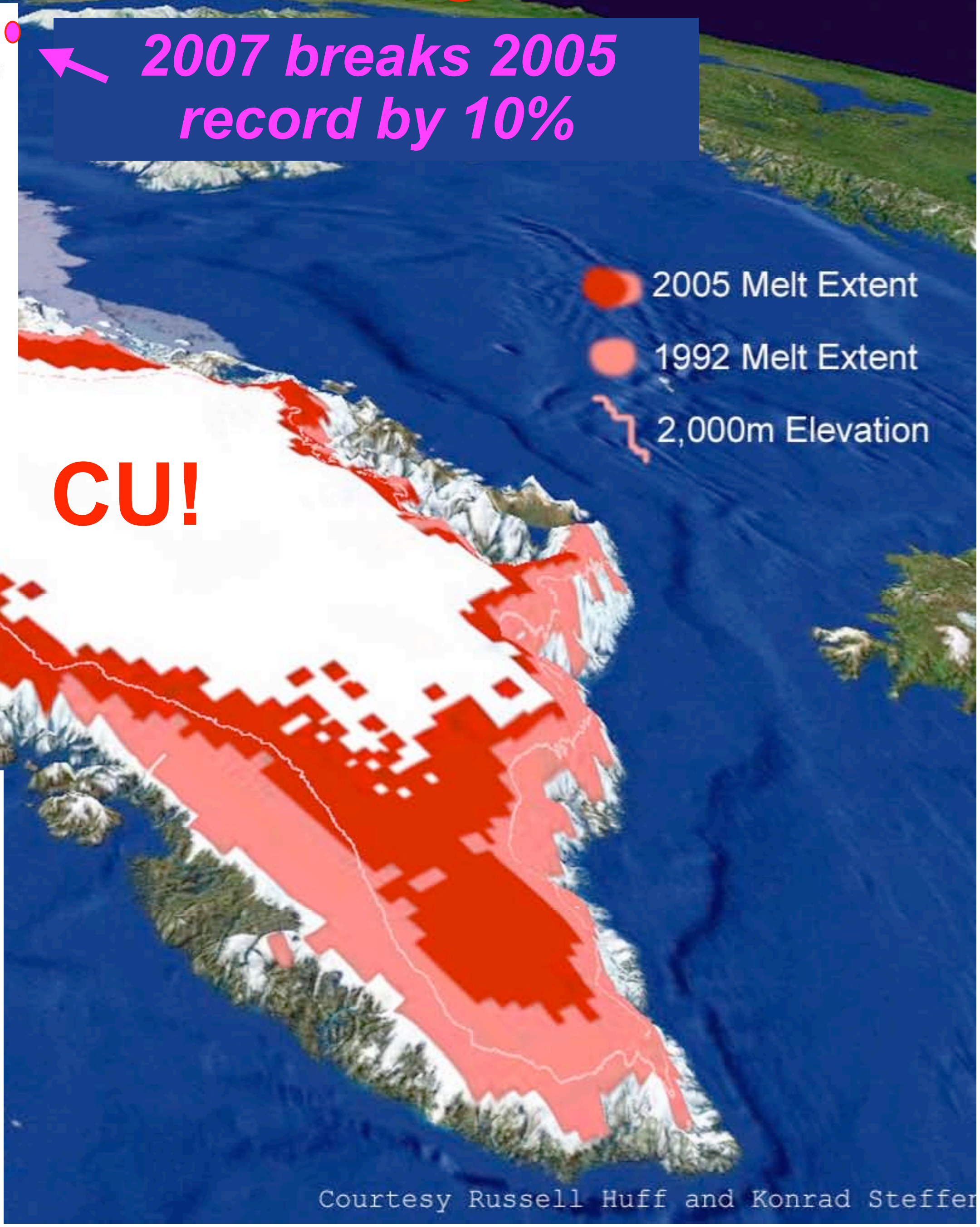
bedrock topography is shaped like a bowl (with a few fjord gaps to the sea at the edges)

anomalous melting



anomalous melting



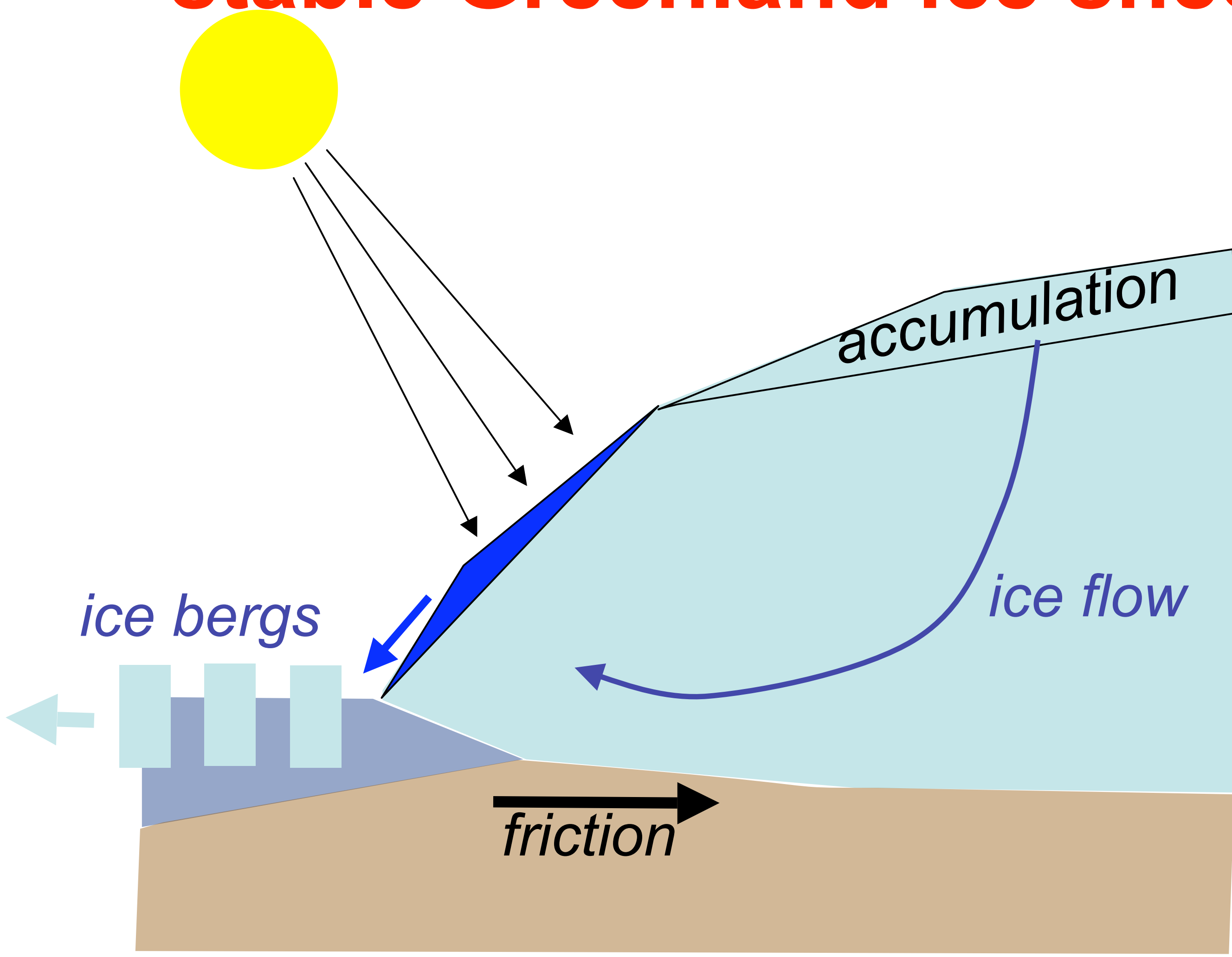


~30% increase in melt area since 1979

total Apr-Sep melt area shows similar trend (~+30% since 1979)

response to 1991 eruption of Mt. Pinatubo consistent with melt response to temperature, now dominated by increasing radiative forcing from GHGs

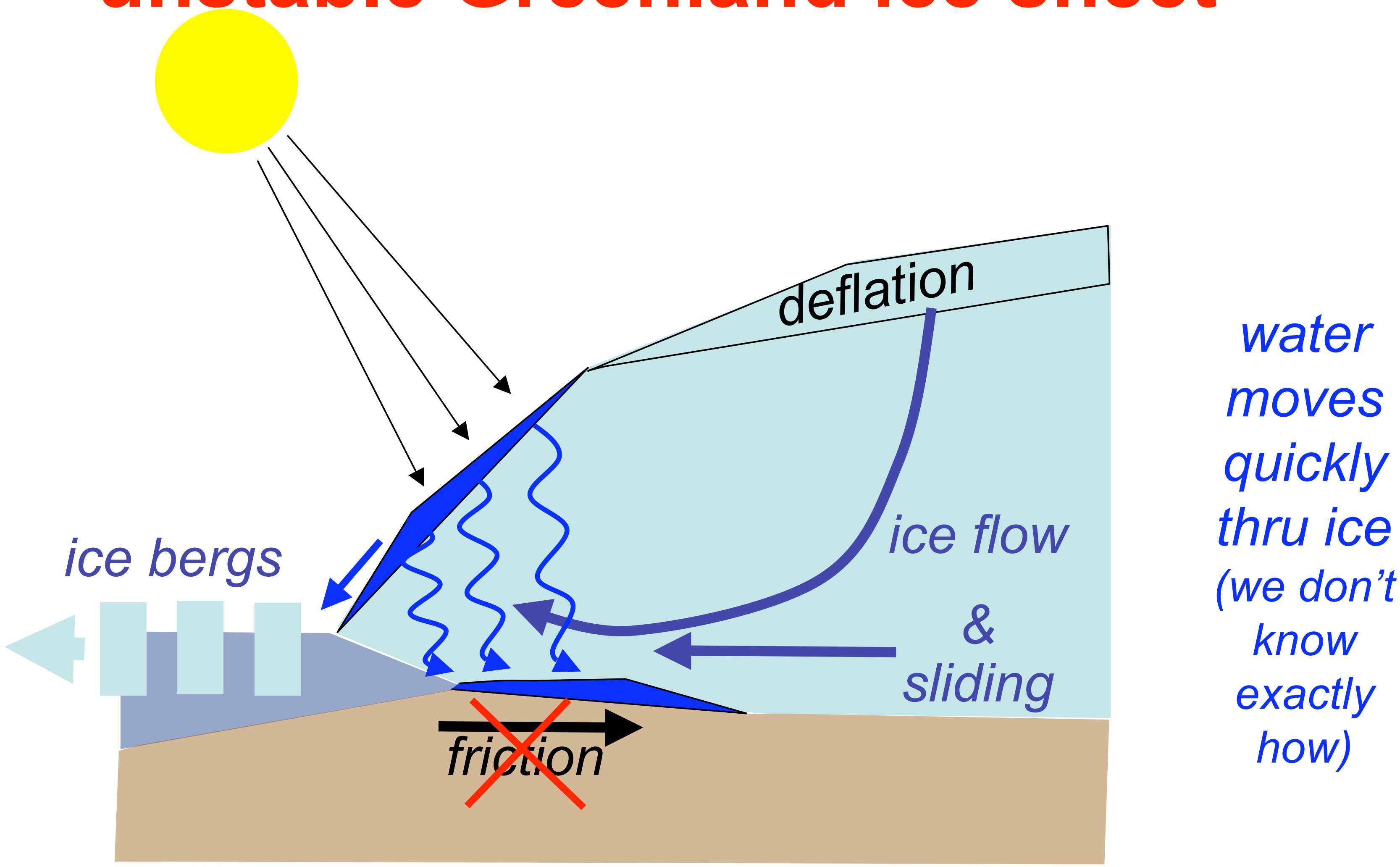
stable Greenland ice sheet



heat
diffuses
slowly
thru ice

at steady state ice gain is matched by ice loss from
melting and ice berg calving at ice streams
melting is a slow process
friction limits flow through ice streams

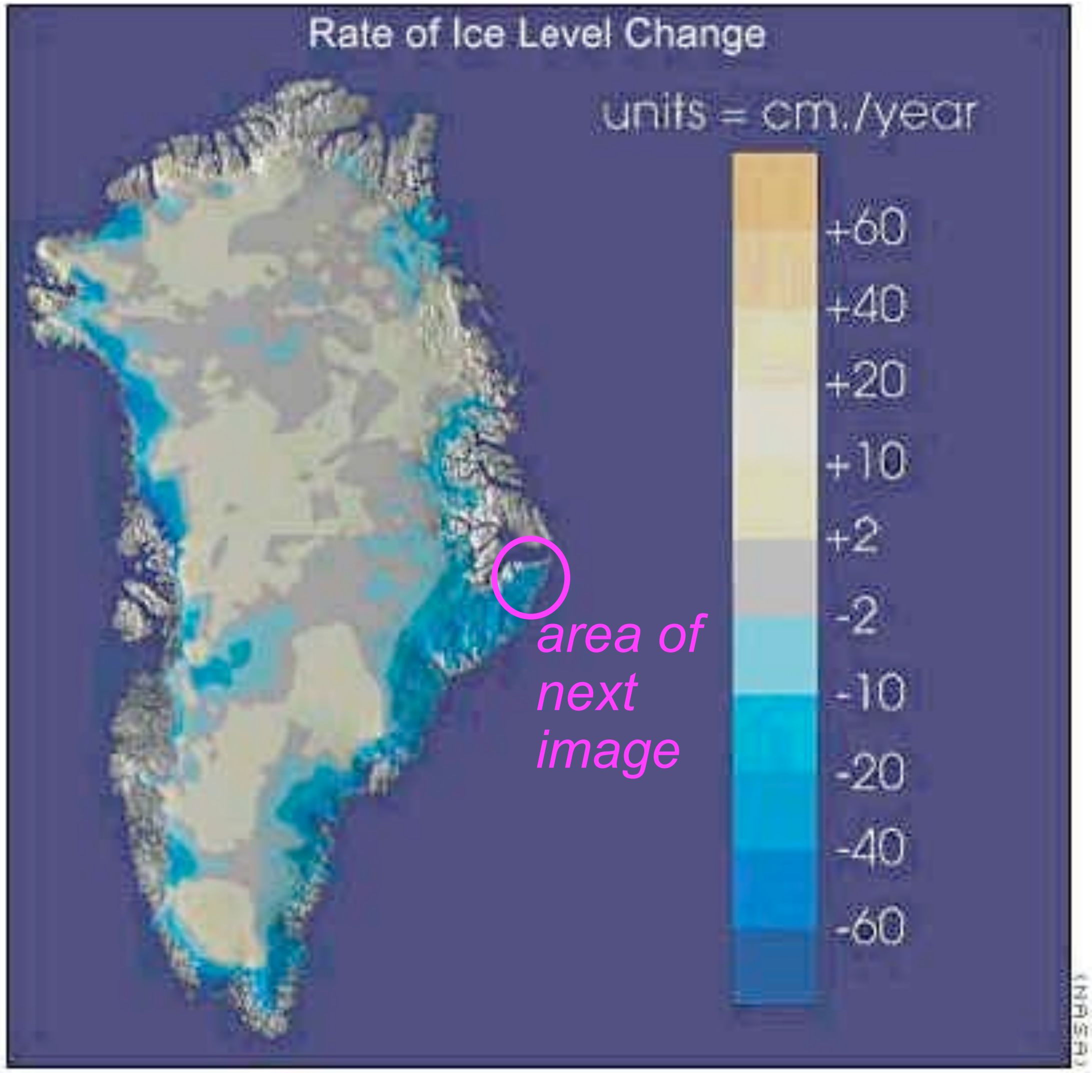
unstable Greenland ice sheet



melt water reaches the ice sheet bed, greatly reducing friction and permitting accelerated sliding and flow through ice streams, increased ice berg calving and ice sheet thinning

marginal thinning

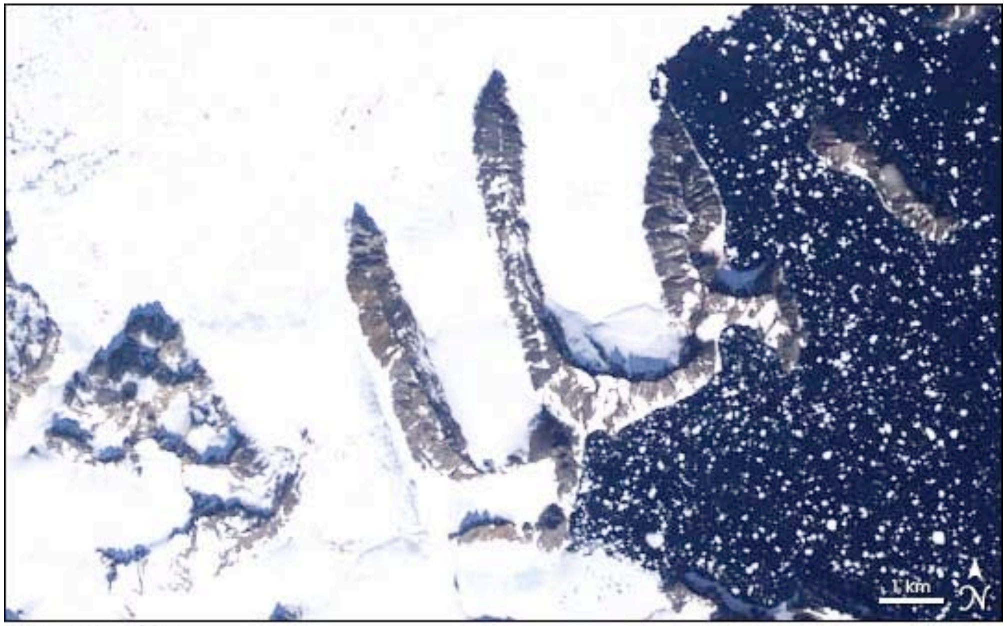
thickness change from satellite altimetry



anomalous melting and sliding has led to widespread thinning of the margin

from W. Krabill NASA

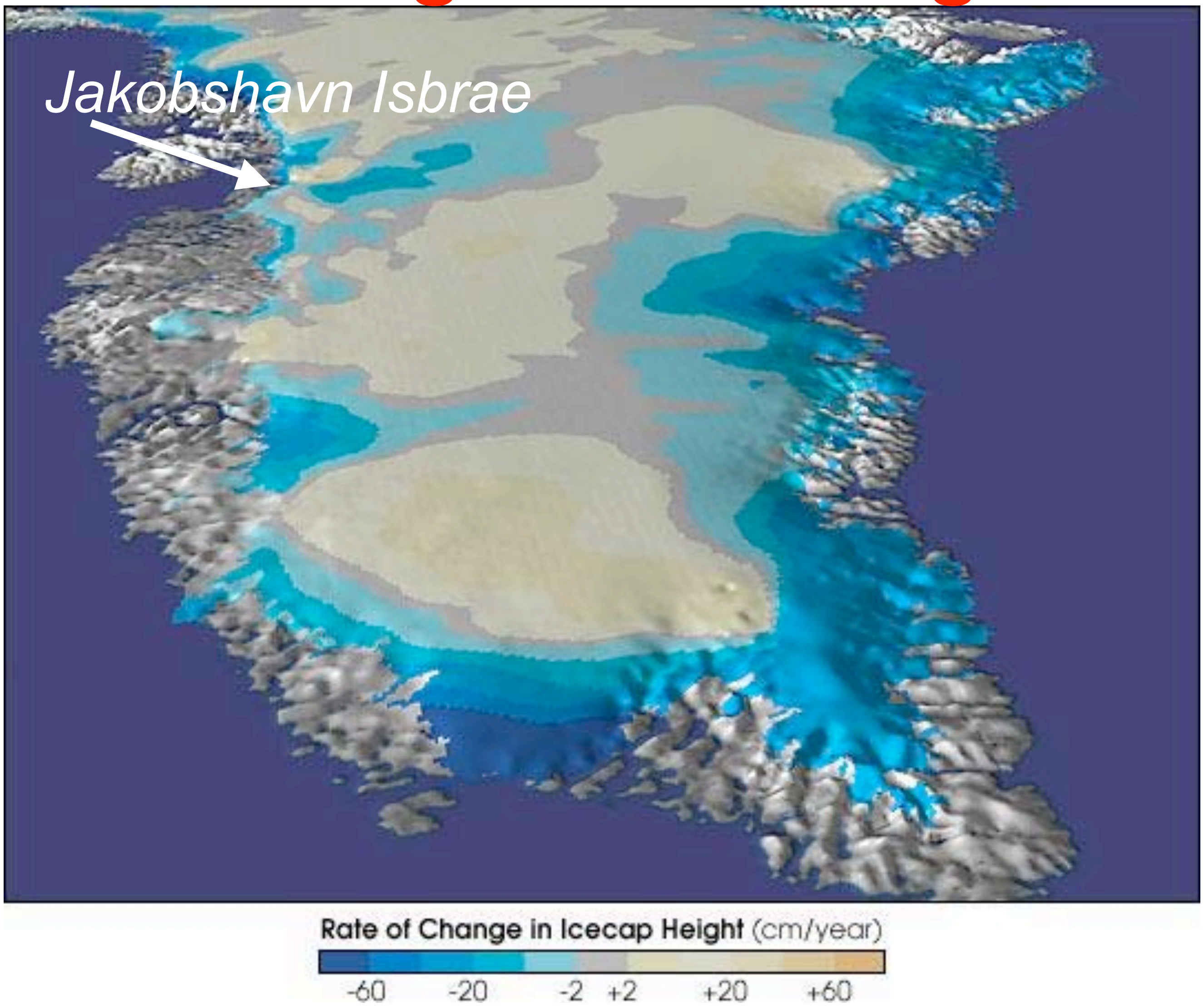
but is it real?



August 11, 1985

September 5, 2002

marginal thinning



deflation is greatest at and upstream of fjord gaps where ice streams pull ice out of the interior

- Jakobs
- http://ip
/m0000

NASA AND THE INTERNATIONAL POLAR YEAR

NASA POLAR EXPRESS

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+ EDUCATORS
+ MUSEUMS
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- EVENTS

MULTIMEDIA

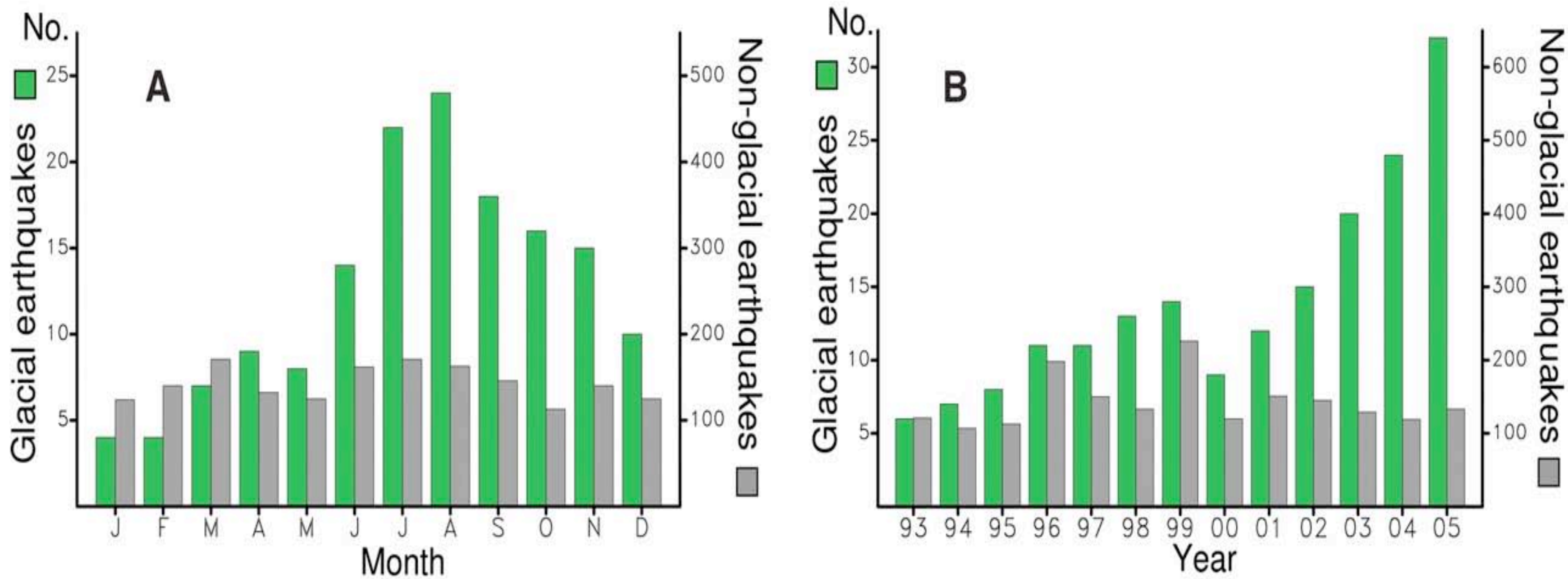
Fastest Glacier in Greenland Doubles Speed

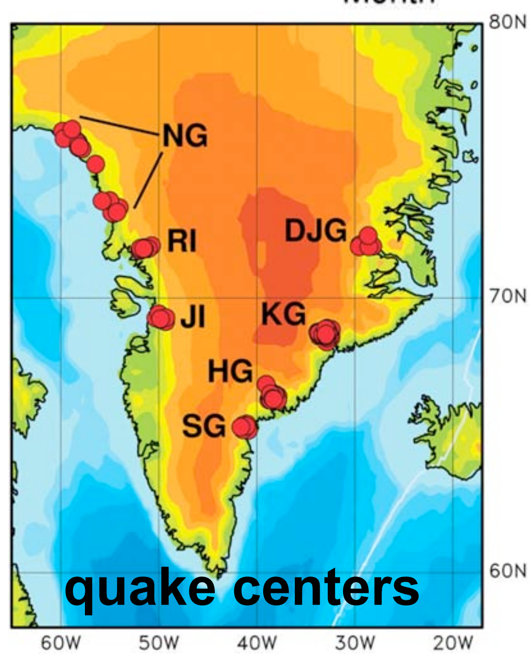
Scientists who study Earth's ice and the flow of glaciers have been surprised to find that the world's fastest glacier in Greenland doubled its speed between 1997 and 2003.

Jakobshavn Glacier Retreat 2001-2003: Jakobshavn Isbrae holds the record as Greenland's fastest moving glacier and major contributor to the mass balance of the continental ice sheet. Starting in late 2000, following a period of slowing down in the mid-1990s, the glacier showed significant acceleration and nearly doubled its discharge of ice. The following imagery from the Landsat satellite shows the retreat of Jakobshavn's calving front from 2001 to 2003. (An update of the glacier's retreat through 2006 has been added.)

As more ice moves from glaciers on land into the ocean, it raises sea levels. Jakobshavn Isbrae is Greenland's largest outlet glacier, draining 6.5 percent of Greenland's ice sheet area. The ice stream's speed-up and near-doubling of ice flow from land into the ocean has increased the rate of sea-level rise by about .06 millimeters (.002 inches) per year, or roughly 4 percent of the 20th century rate of sea-level increase.

ice sheet quakes!





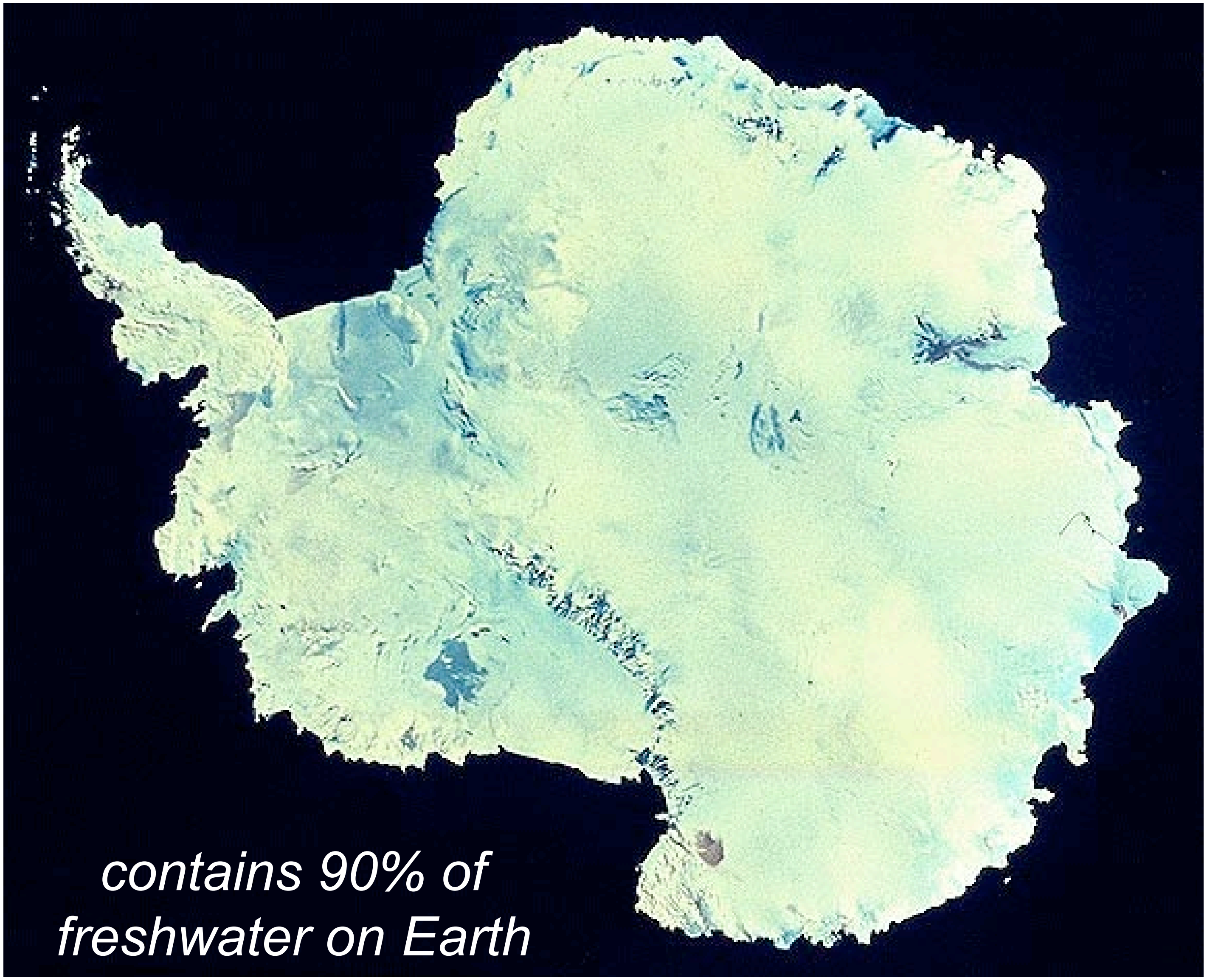
Lurching of Greenland ice streams creates tremors that are recorded world wide. They occur more frequently in warm months (due to melt lubrication). Their annual occurrence has doubled in the last 5 years!

Ekstrom et al., ‘06

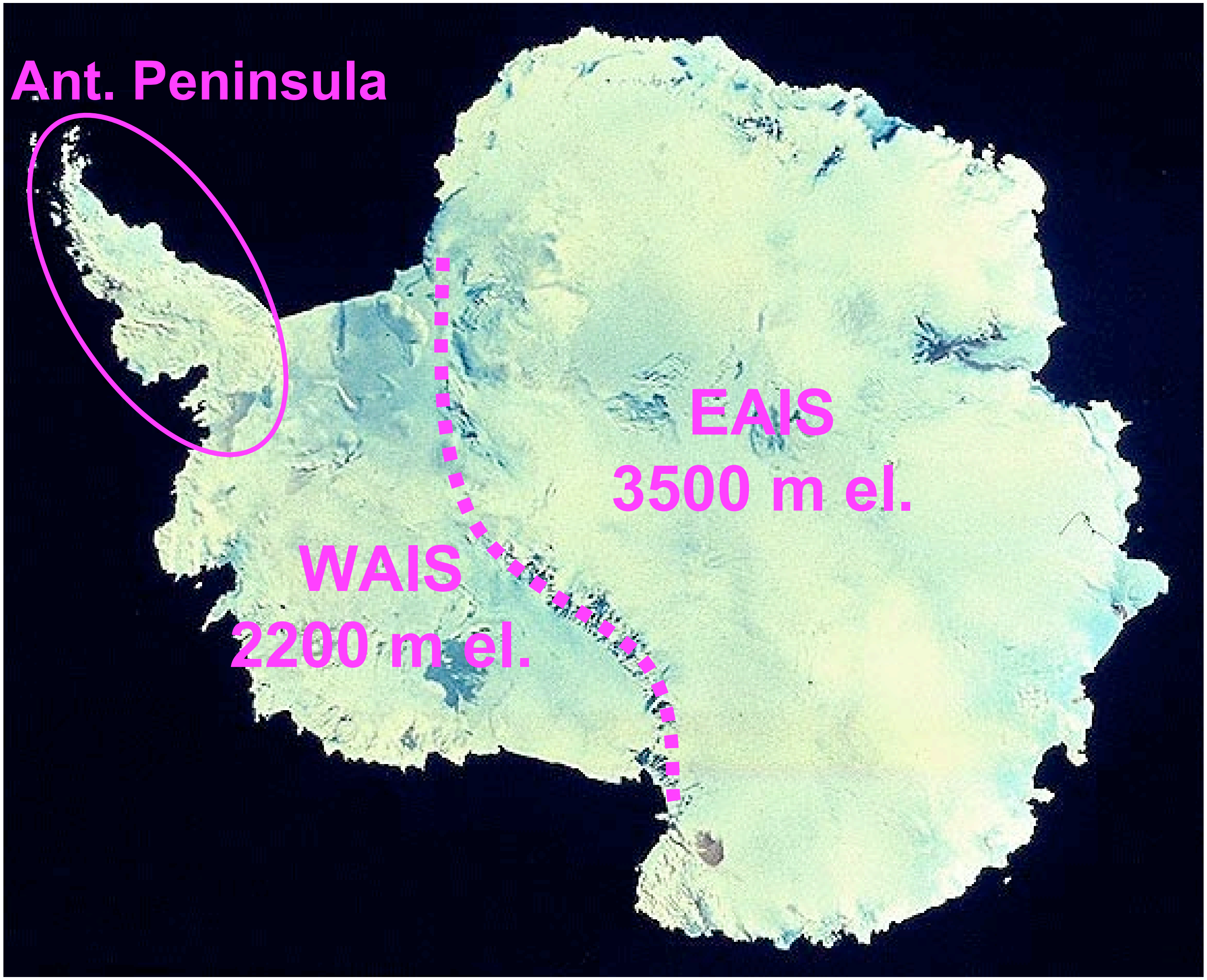
GIS summary

- satellite observations indicate that Greenland melt area is increasing in assoc. with Arctic and global warming
- meltwater appears to be lubricating the base of the ice sheet, increasing sliding through ice streams
- satellite altimetry indicates that the margin of the ice sheet is thinning
- ice flow through ice streams terminating in the sea has increased as indicated by direct measurements and seismic activity within the ice
- *these are signs of ice sheet instability that may lead to an irreversible loss of ice (and sea level rise)*

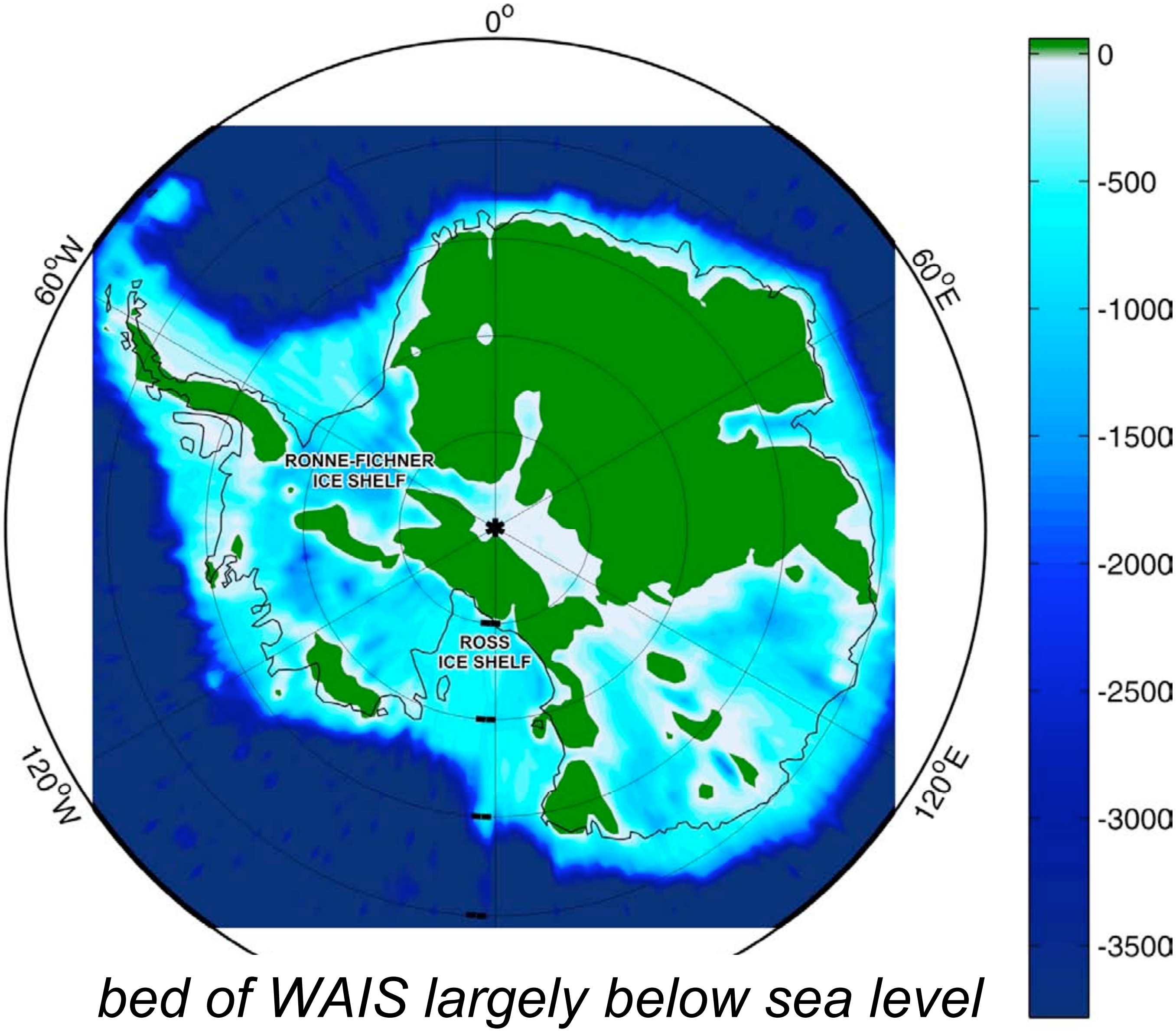
W & E Antarctic Ice Sheets



W & E Antarctic Ice Sheets



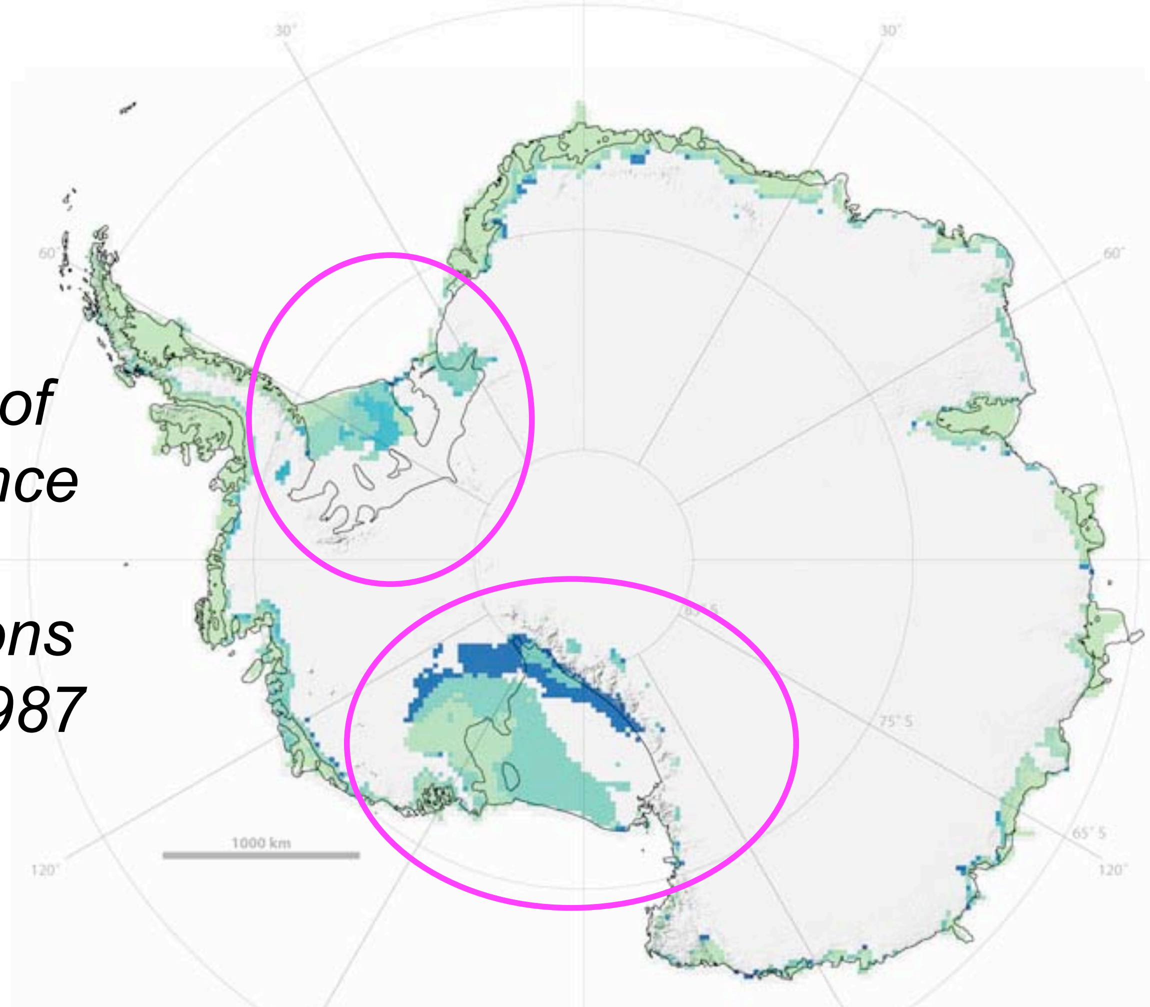
Antarctic topography beneath ice



bed of WAIS largely below sea level
(more on vulnerability next lecture)

melt creep

first year of melting since satellite observations begin in 1987

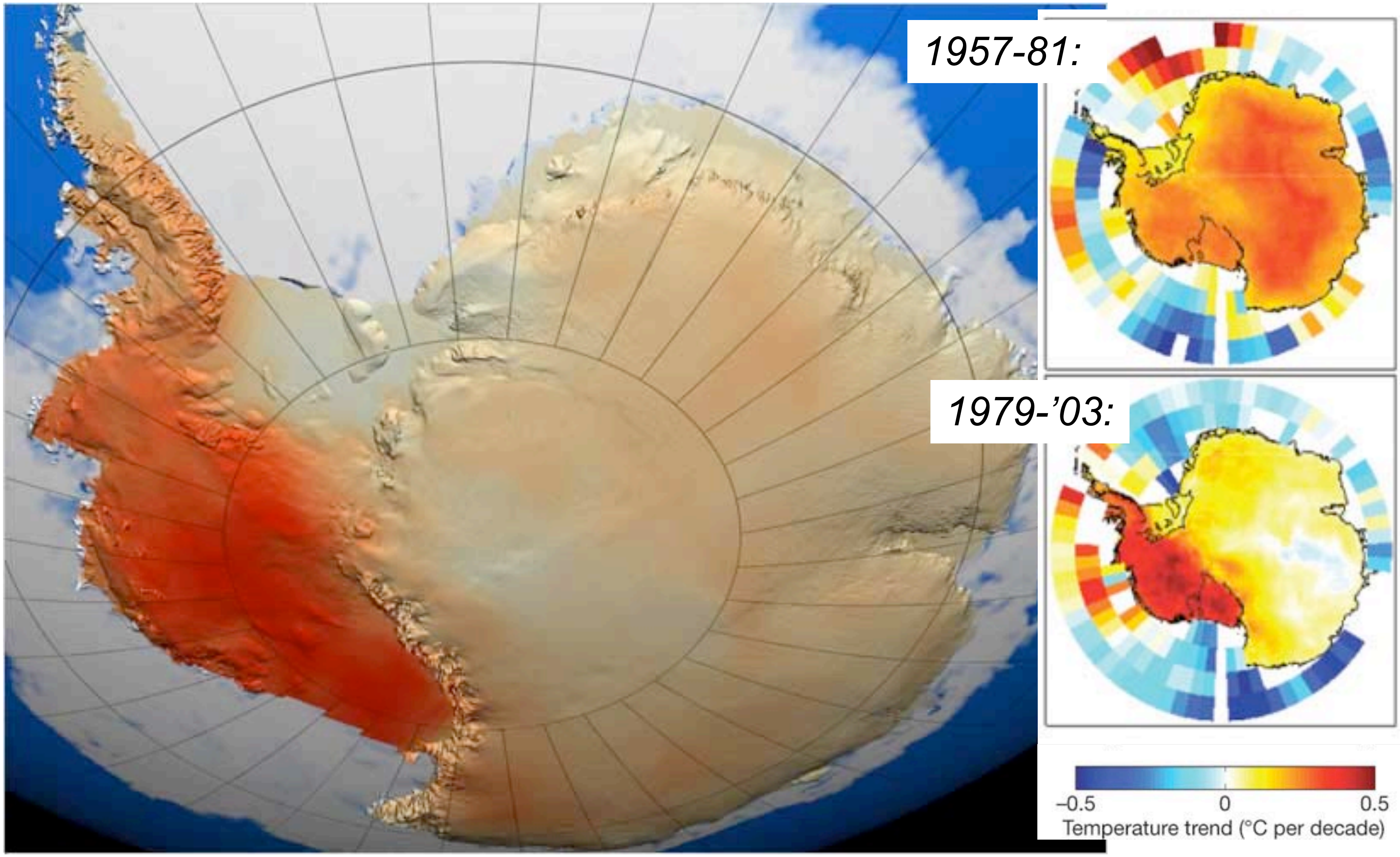


areas of floating glacier ice (ice shelves) that buttress inland

these are also melting at the btm.!

first year of melting

News Flash!: Antarctica is warming



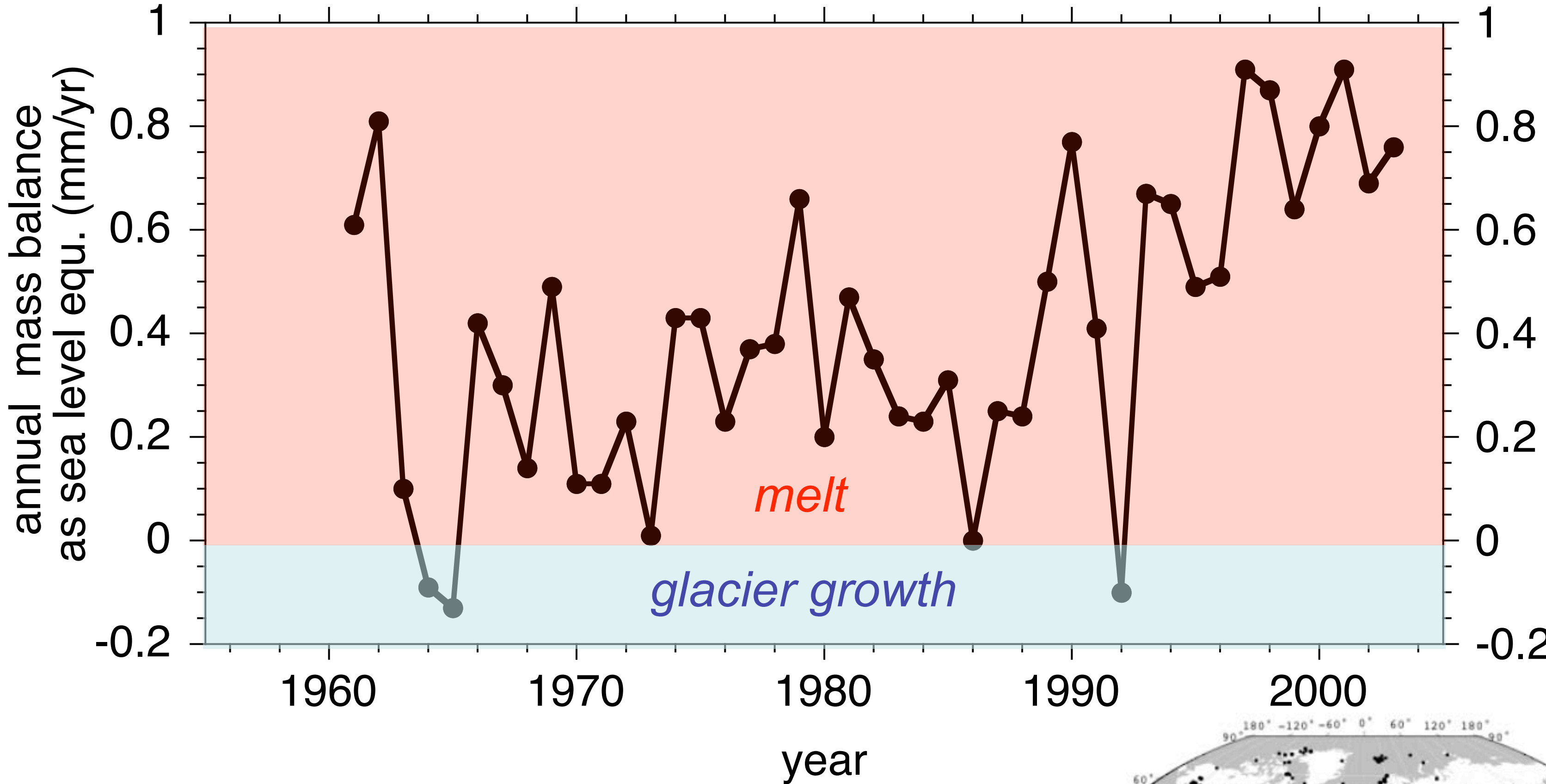
Antarctic is warming, most dramatically at lower elevations

Steig et al. '09

Antarctic Ice Sheet summary

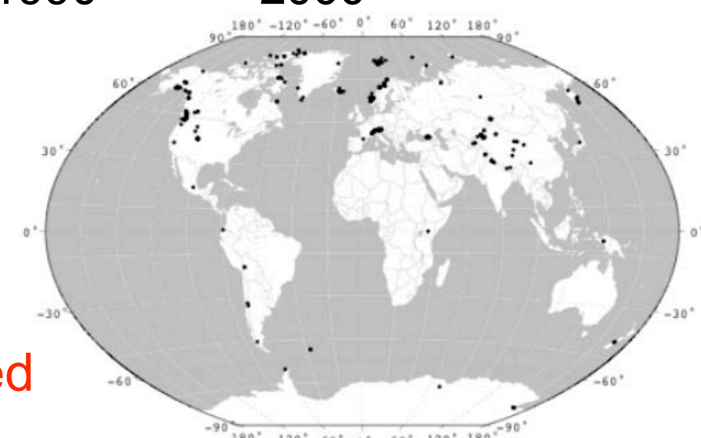
- two ice sheets (EAIS and WAIS) separated by Trans-Antarctic Mountains
- WAIS is lower in elevation and largely grounded below sea level (*making it inherently less stable, more on that next lecture*)
- satellite observations indicate that more and more low lying parts of the ice sheets are melting for the first time since obs began in late 1980's
- we now also know that the continent is warming, with most recent warming occurring in low lying areas (this is new!)

global "small" glaciers



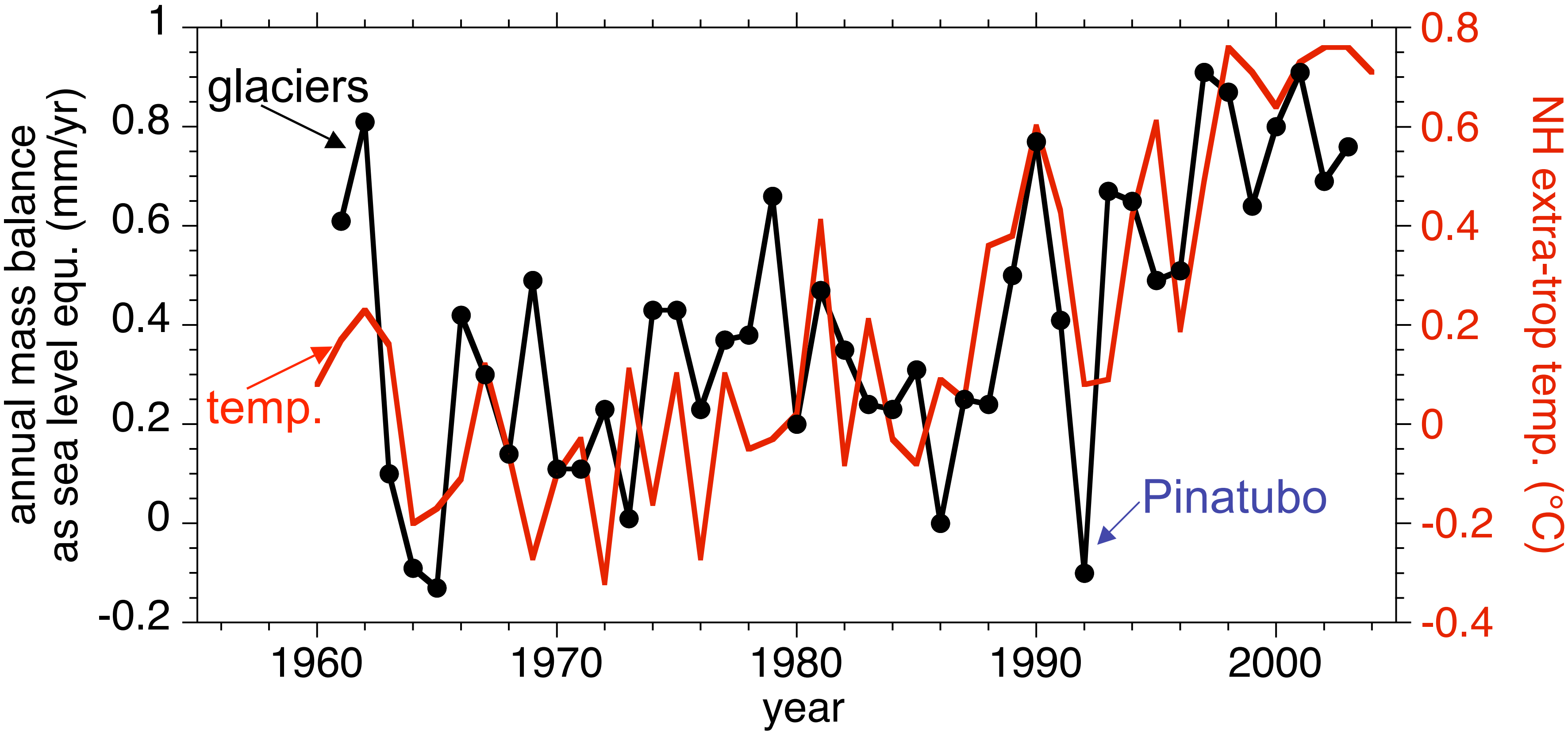
net mass balance (accumulation vs. melting) of hundreds of glaciers has been evaluated by CU's Mark Dyurgerov

annual global small glacier mass balance expressed in terms of contribution to global sea level



studied glacier systems

global“small” glaciers vs. temperature



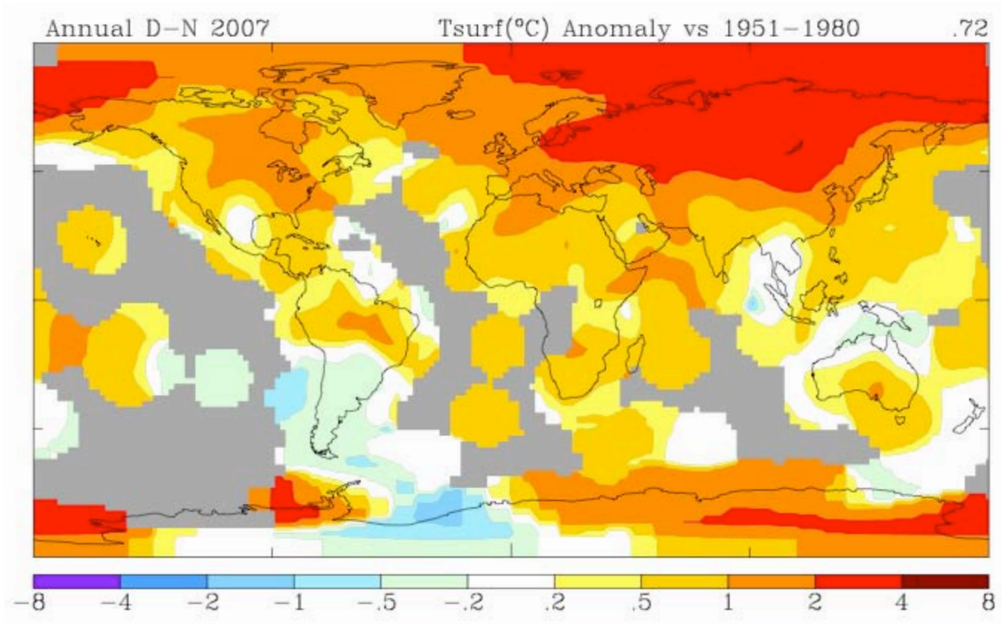
annual global small glacier melting (or growth), given here as equivalent annual change in sea-level, follows temperature change of extra-tropical NH (from GISS)

global glacier melting appears v. sensitive to warming

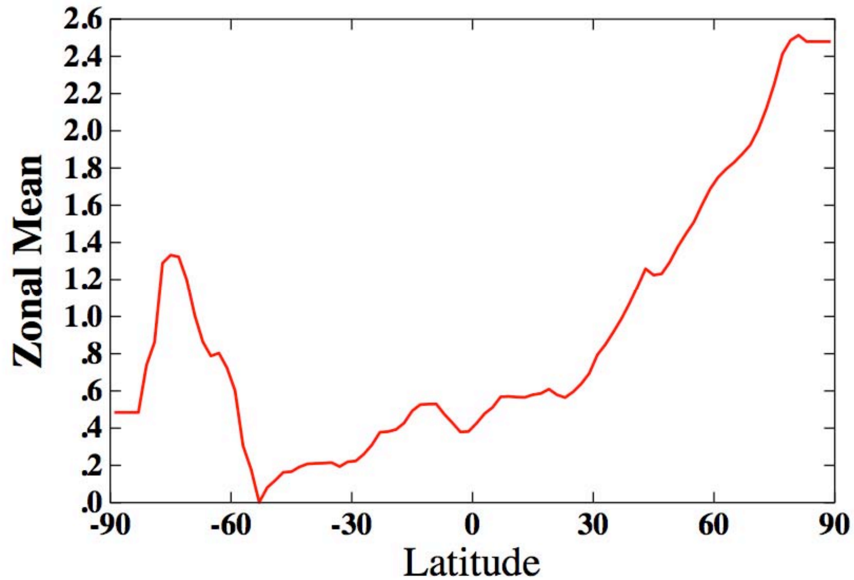
glacier data of Dyurgerov (CU), analysis of Lehman & Knutti

polar amplification

annual mean T anomaly 2007 vs 1951-80



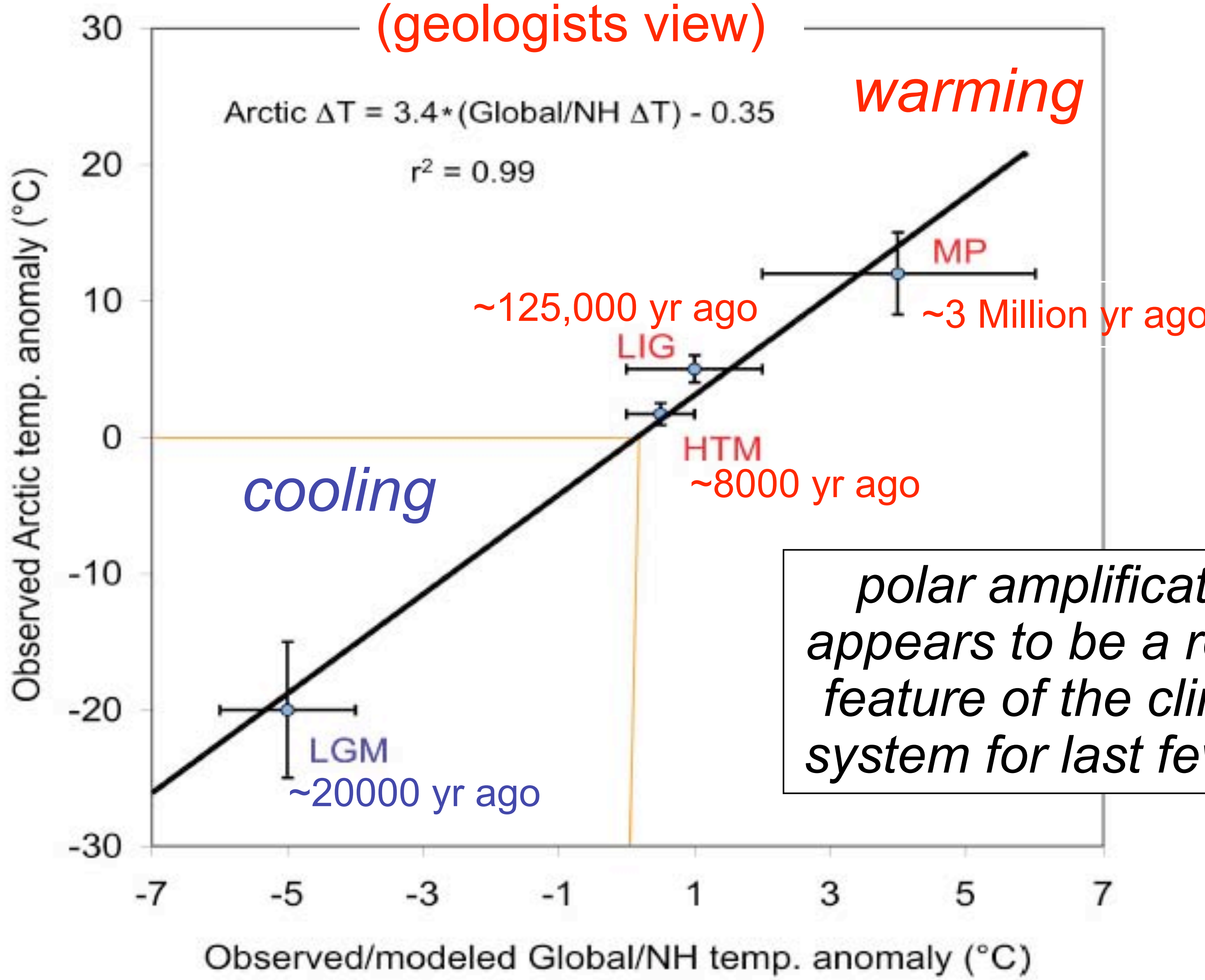
zonal mean T anomaly 2007 vs 1951-80



http://data.giss.nasa.gov/gistemp/maps/

polar amplification

(geologists view)



polar amplification appears to be a robust feature of the climate system for last few MY

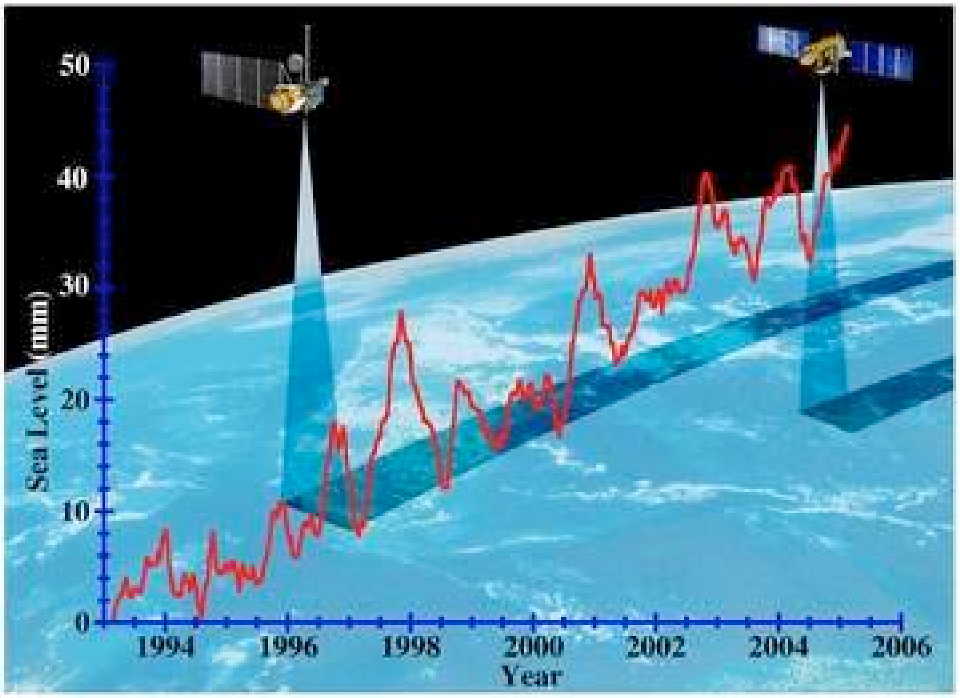
Miller and Brigham-Grette

key points

- the cryosphere is responding to warming not just in high latitudes but globally
- this response includes (but is not restricted to) loss of Arctic sea-ice, melting at the margin of the Greenland and Antarctic ice sheets, and melting of globally distributed “small” glaciers
- *temperature - sea ice - ocean heat flux feedback* and *temperature-albedo feedback* amplify temperature change in the Arctic
- sliding and thinning of the Greenland ice sheet margin may lead to irreversible ice loss
- melting of any ice that is not already floating contributes to rising sea level (*the subject of our next lecture!*)

next class

- sea level change



- no additional reading

lecture 17 learning goals

- be able to describe the role of sea ice in the climate system
- be able to describe the satellite-based record of sea ice extent in Arctic for the last ~25 yrs
- be able to describe the satellite-based record of melting around the margins of the Greenland Ice Sheet for the last ~25 years
- be able to describe the recent “mass balance” trends of small glaciers around the world
- consider the relationship of these various records to temperature changes over the same interval
- consider whether Antarctic is isolated from the rest of the global climate system (or not)
- consider the possible impacts of meltwater at the bed of the Greenland Ice Sheet on its overall stability

“dynamic instability”

- thinning of the GIS margin by melting is undoubtedly due to recent warming
- once there is sufficient thinning of the margins, however, the ice sheet profile is likely to adjust to the altered (and still changing) *force balance* within the ice sheet independently of climate
- this adjustment is a response to *positive feedbacks* involving melting, marginal thinning & sliding
- we might say that under certain conditions, the Greenland ice sheet may be “dynamically unstable”
- *understanding the complex feedbacks involved is essential to predicting the fate of the ice sheet and global sea level (new reason for glaciologists to “get out of bed in the morning”)*