The Wedge, Grease and Heat: Why Ice Sheets Hate Water

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My Impressions

- “Include land ice component” is one of 6 Science Priorities
- CCSM is a very large community
- CCSM has lots of young people

- Ice sheet inclusion assigned to just two persons
- Polar continental-shelf oceanography seems to be missing

Ice-Sheet Surprises

- Ice shelf disintegrations
  - Suddenly unbuttressed land ice
- Summer acceleration of Greenland ice
- Accelerating outlet glaciers
  - Rapidly declining ice-sheet volume
- Subglacial water activity
- Tidal modulation of ice stream speed

Definitely NOT yo'Mama's ice sheets

Ice Sheets matter NOW:

Maldives

B. Richmond, USGS

London

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Table SPM-3. Projected globally averaged surface warming and sea level rise at the end of the 21st century. {10.5, 10.6, Table 10.7}

Case	Temperature Change (°C at 2090-2099 relative to 1980-1999) [a]		Sea Level Rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations [b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

maximum? **NO!**

"…but..flow rates could increase or decrease in the future."

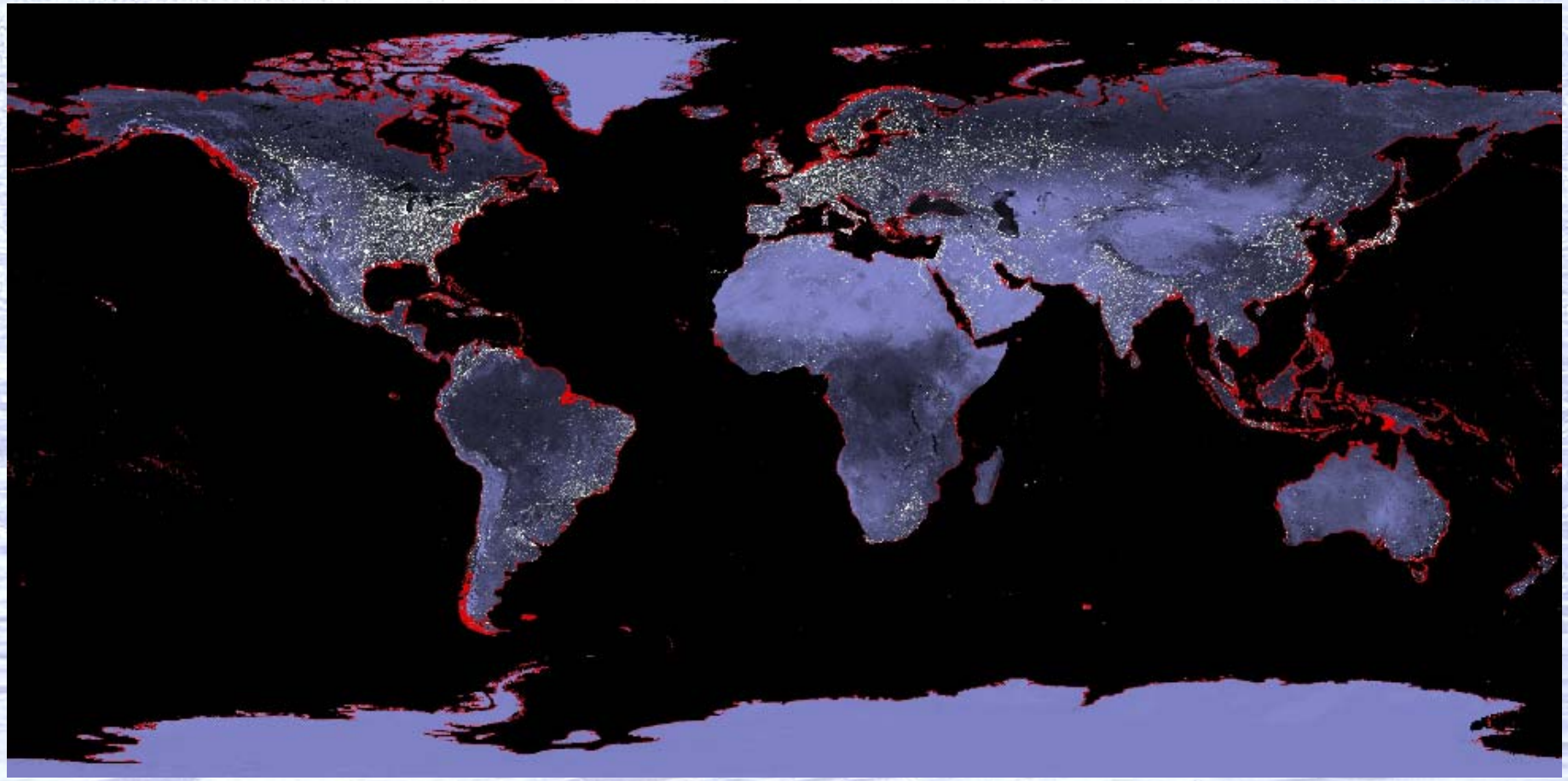
"Larger values cannot be excluded…"

"…understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise."

Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (a.k.a. NRC Decadal Survey)

Key Question #1 (of 6):
"Will there be catastrophic collapse of the major ice sheets, including Greenland and West Antarctica and, if so, how rapidly will this occur? What will be the time patterns of sea level rise as a result?"

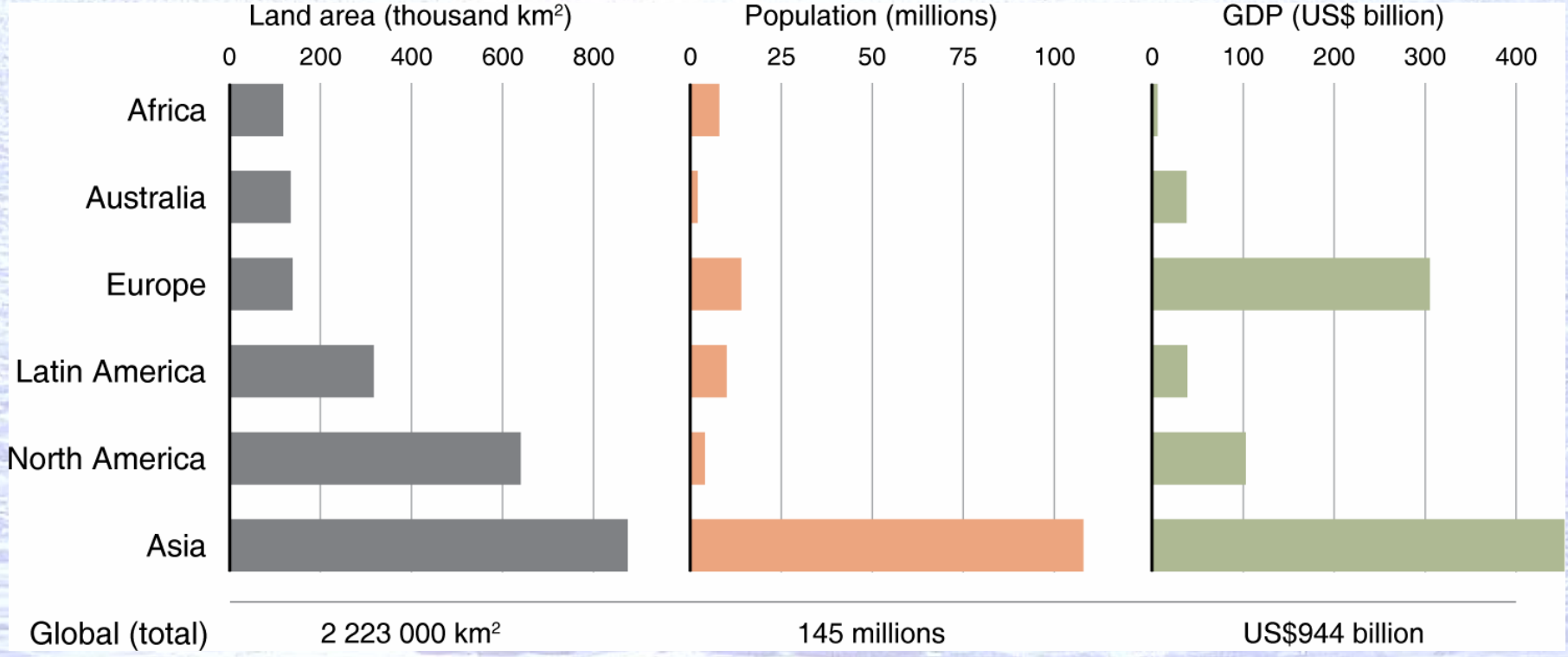
Ice Sheets matter Globally



Source: CReSIS and NASA

Land area lost by 1-meter rise in sea level

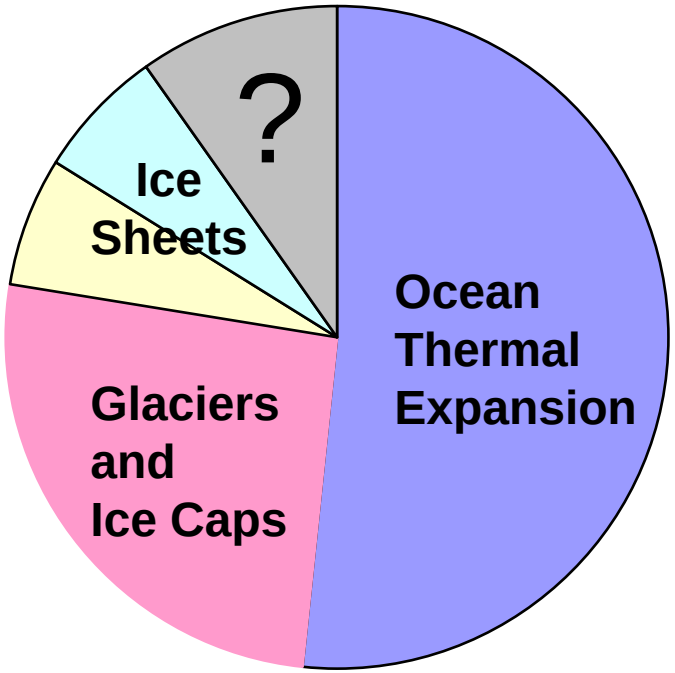
Impact of 1-meter sea level rise:



From Anthoff et al., 2006

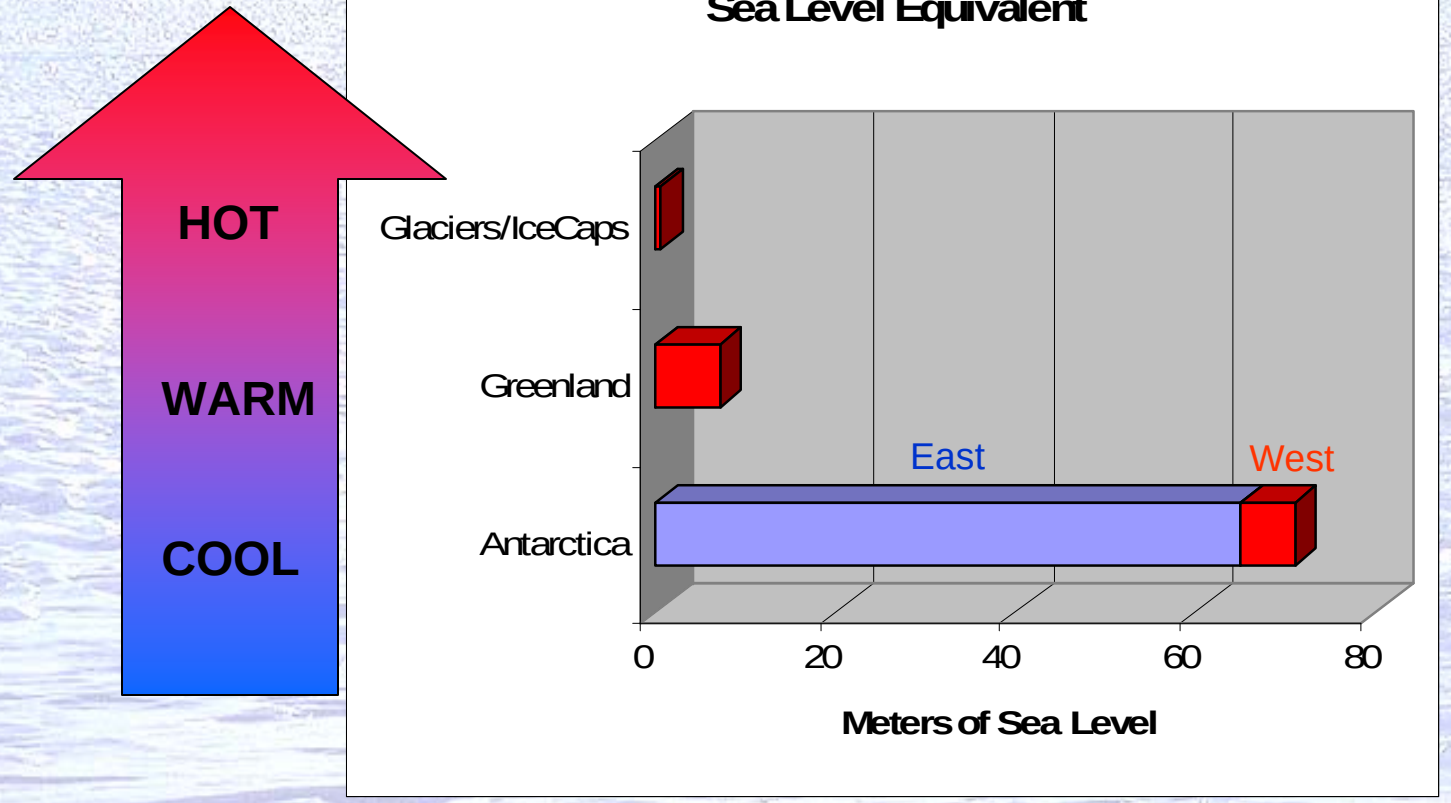
An immediate and significant impact on economies and ecosystems worldwide

Sea Level Rise Components

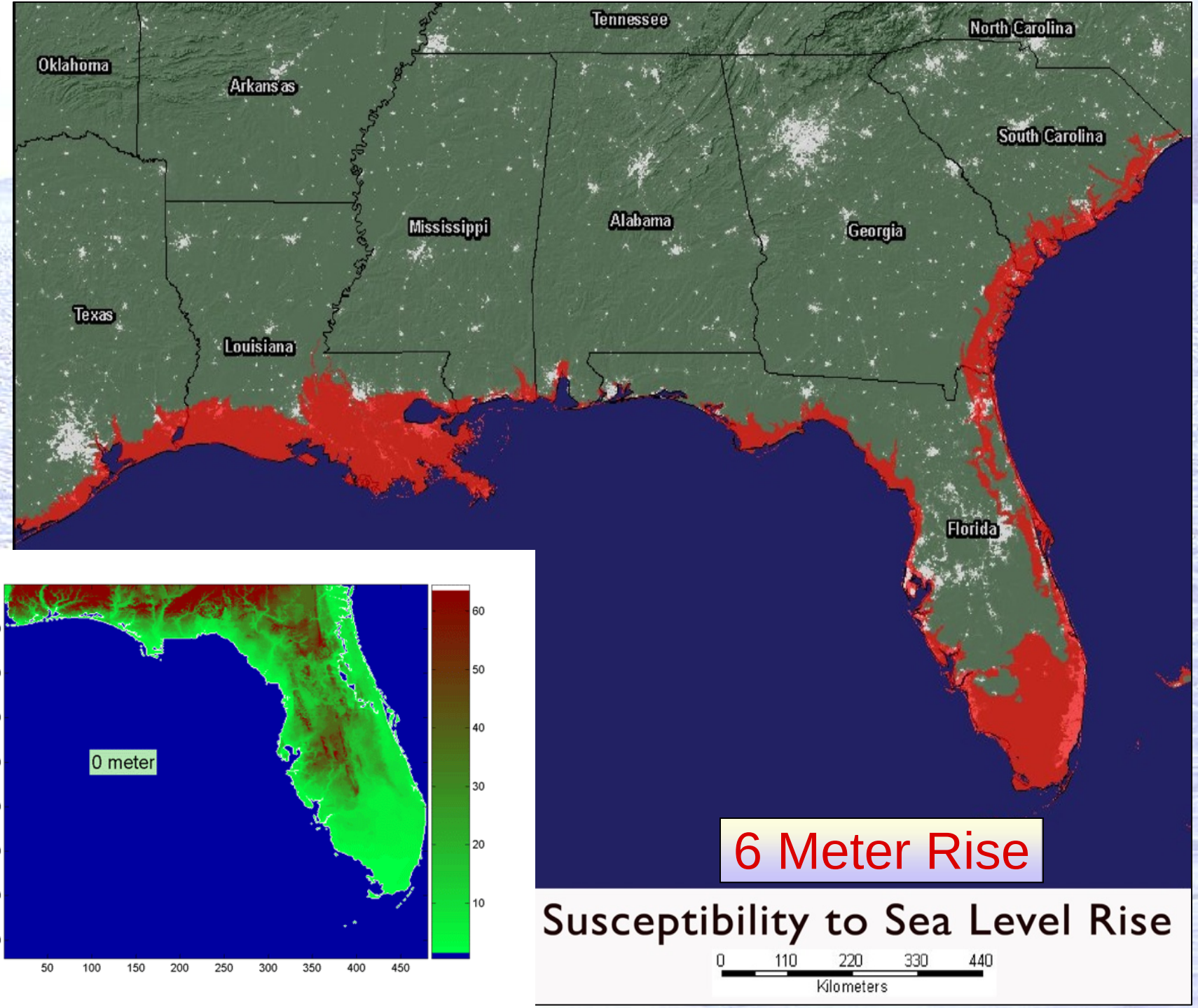


Source: IPCC FAR

Potential Sea Level



2-6% of all water on Earth
70-80% of all fresh water on Earth


Tennessee
North Carolina
Oklahoma
Arkansas
South Carolina
Mississippi
Alabama
Georgia
Texas
Louisiana
Florida
0 meter
50
100
150
200
250
300
350
400
50
100
150
200
250
300
350
400
450
60
50
40
30
20
10
6 Meter Rise
Susceptibility to Sea Level Rise
0
110
220
330
440
Kilometers

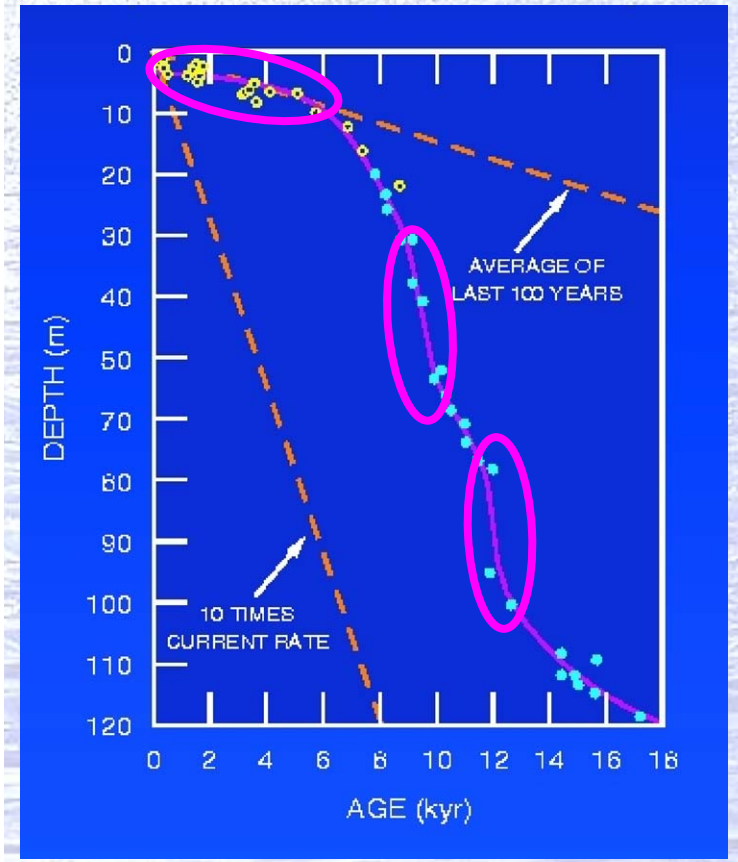
In a Warming Climate

- Warmer air temperatures should lead to increased snowfall
  - ➔ slow ice-sheet growth right away
- Warmer air temperatures should melt ice faster
  - ➔ slow ice-sheet shrinkage right away
- Warmer ice deforms and flows slighter faster
  - ➔ smaller ice sheets after a long time
- Changes in boundary conditions at base or ice front might accelerate ice flow significantly
  - ➔ much smaller ice sheets almost right away

Changes in ice flow may dominate near-term sea level change

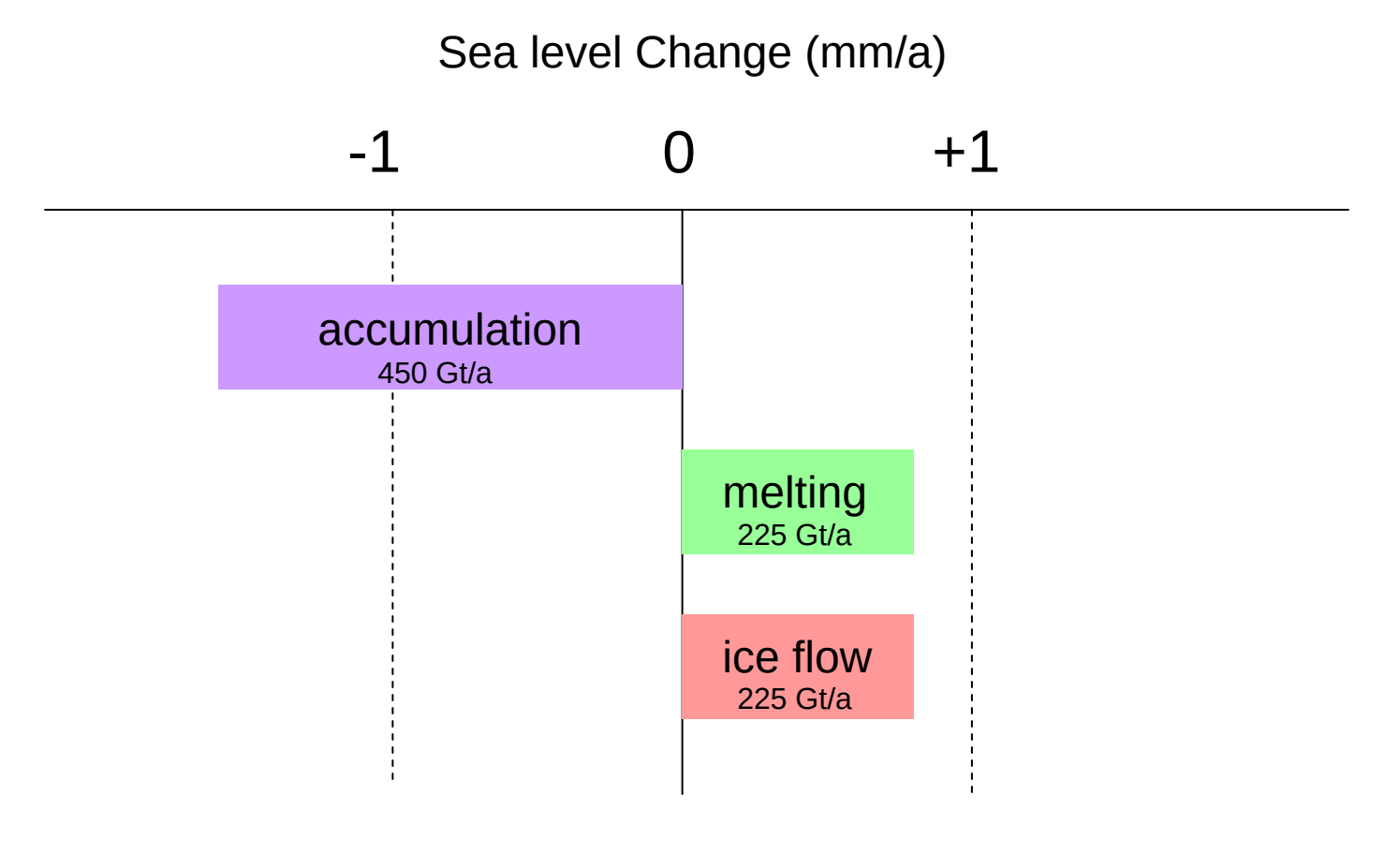
Sea-Level History Lessons

- Warmer climates always lead to less ice and higher sea level
- Sea level rises much faster than it falls
- Sea level has risen 20x the present rate
- Humans have never dealt with rapid sea level rise



Source: Fairbanks, 1989

“Old” Greenland Ice Sheet

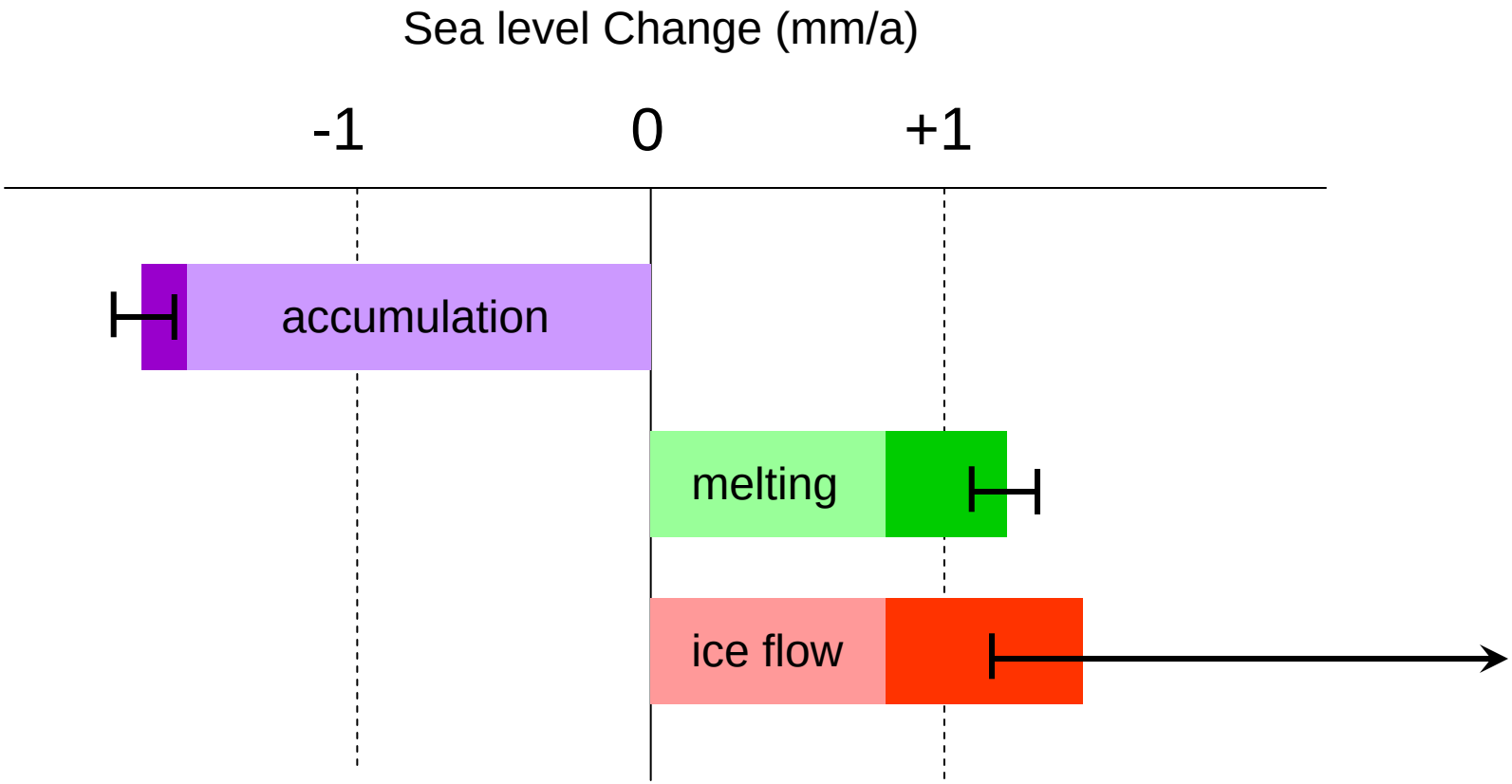


Approximately in “mass balance”

Observations

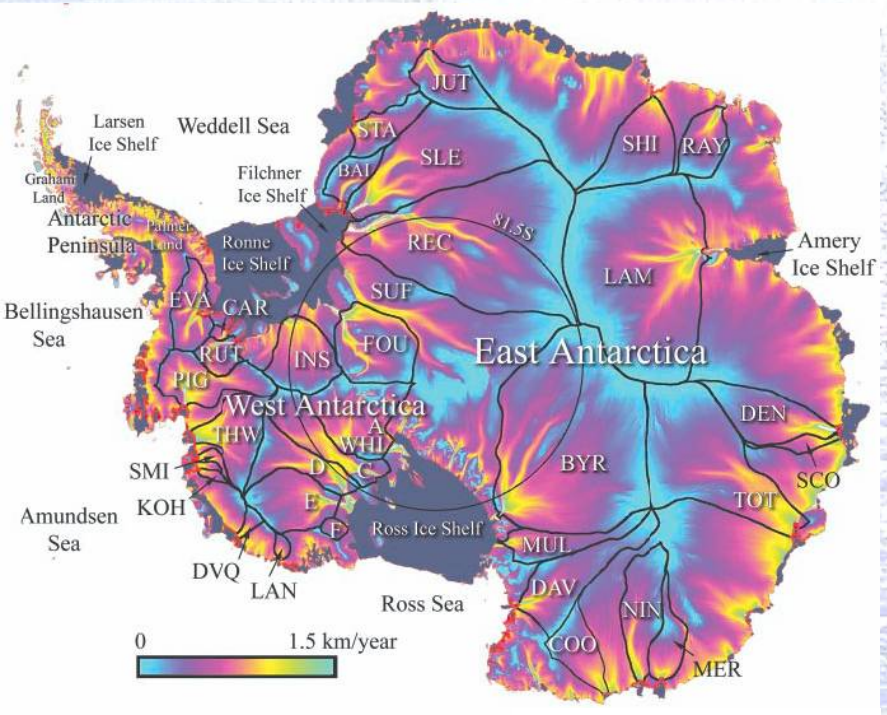
- Thickening in the high elevation interior of Greenland
  - Big change can be 10%
  - Climate models get this about right
- Increase in surface melting around perimeter
  - Big change can be 50%
  - Climate models also get this about right
- Large acceleration, retreat and thinning of outlet glaciers
  - Big change can be 100's%
  - 500% observed already
  - Ice flow models can't get this right

Tomorrow's Greenland Ice Sheet

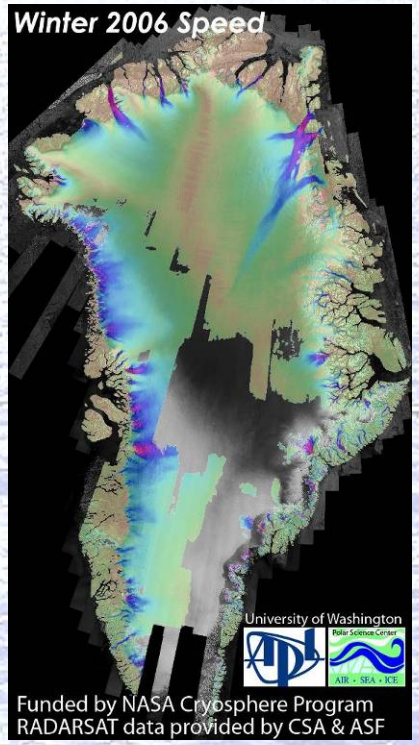


Things could get a little better or a lot worse
Increased ice flow will dominate the future rate of change

Fastest Flow at the Edges



Source: Rignot and Thomas



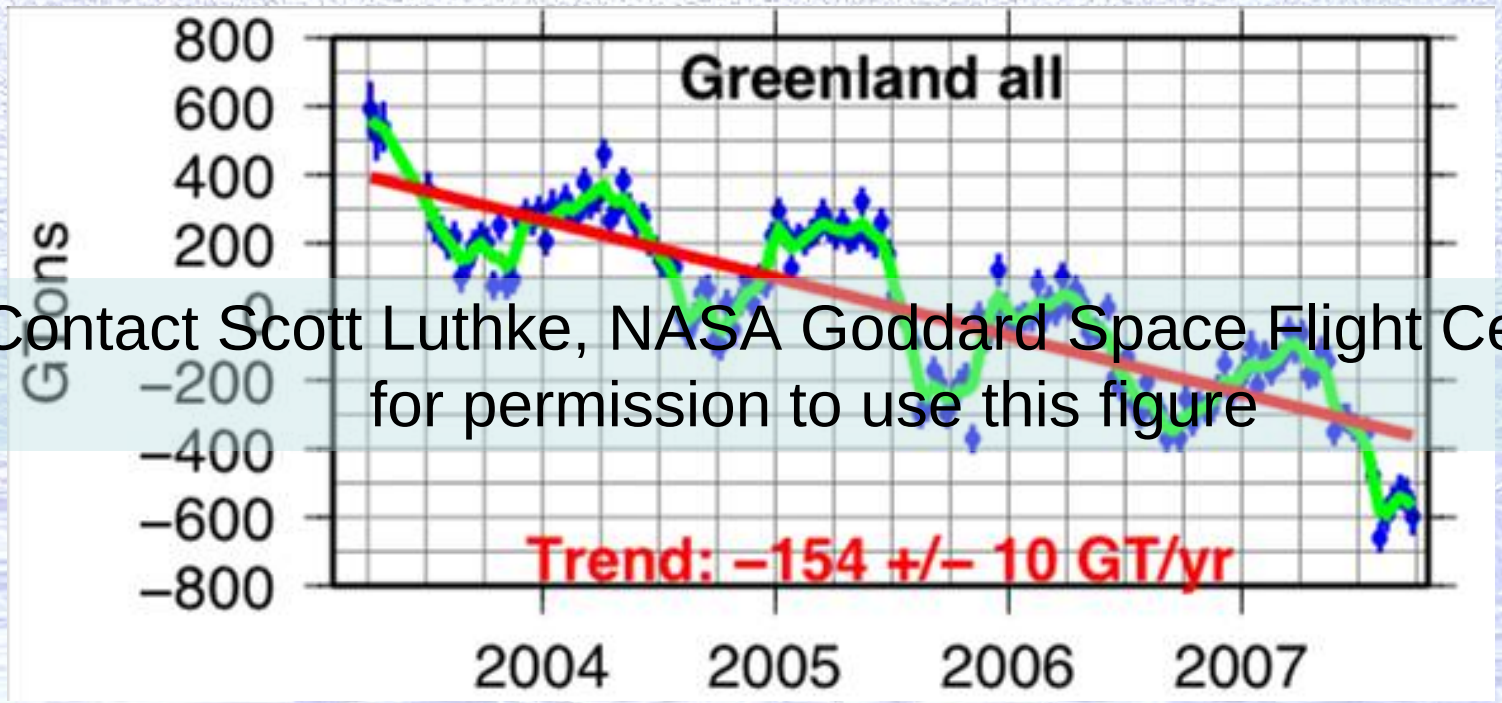
Source: Joughin

Interior: 1000's meters thick and slow

Perimeter: 100's meters thick and fast

Response time and speed of perturbation propagation are tied directly to ice flow speed

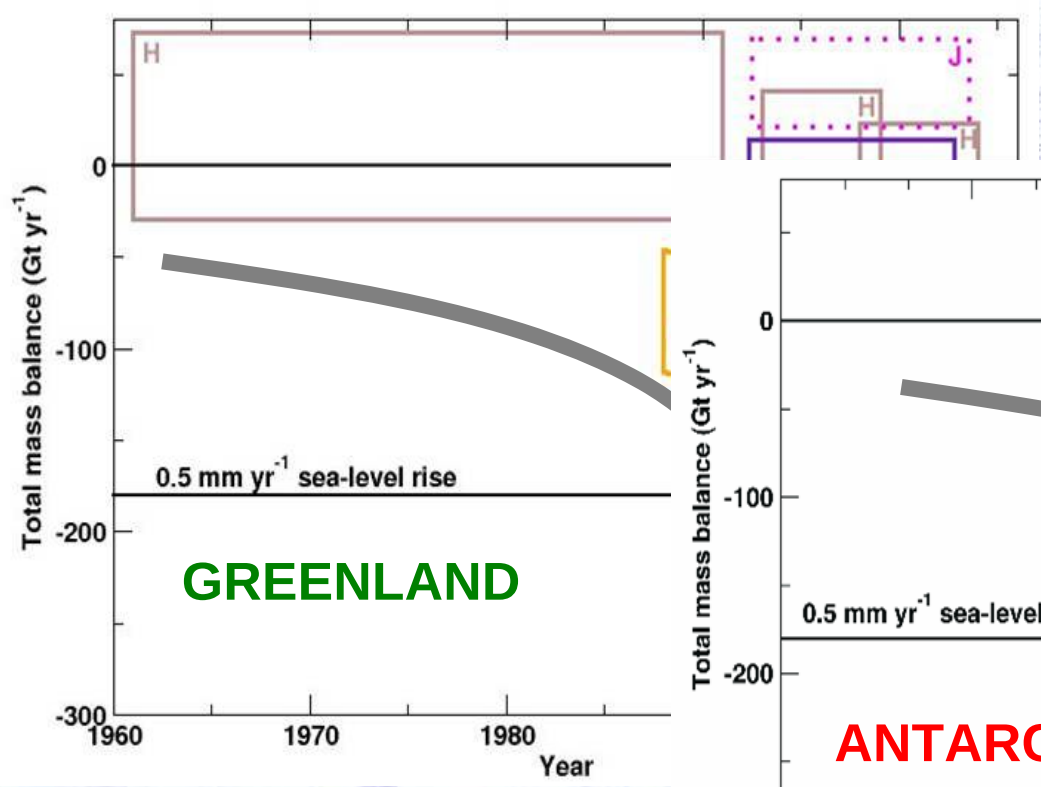
Declining “Health” of Greenland

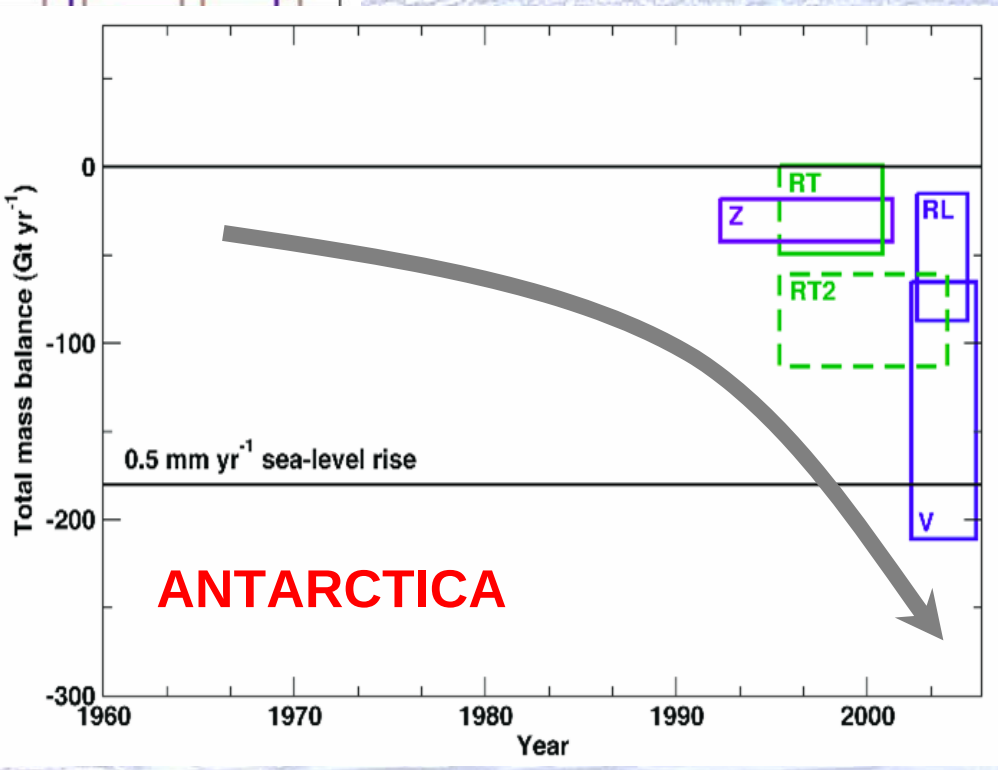


Contact Scott Luthke, NASA Goddard Space Flight Center for permission to use this figure

(Source: Luthcke et al., unpub.)

Mass Balance Results





Ice-Sheet Surprises

- Ice shelf disintegrations
  - Suddenly unbuttressed land ice
- Summer acceleration of Greenland ice sheet
- Accelerating outlet glaciers
  - Rapidly declining ice-sheet volume
- Subglacial water activity
- Tidal modulation of ice stream speed

All caused by Water

- Ice shelf disintegrations
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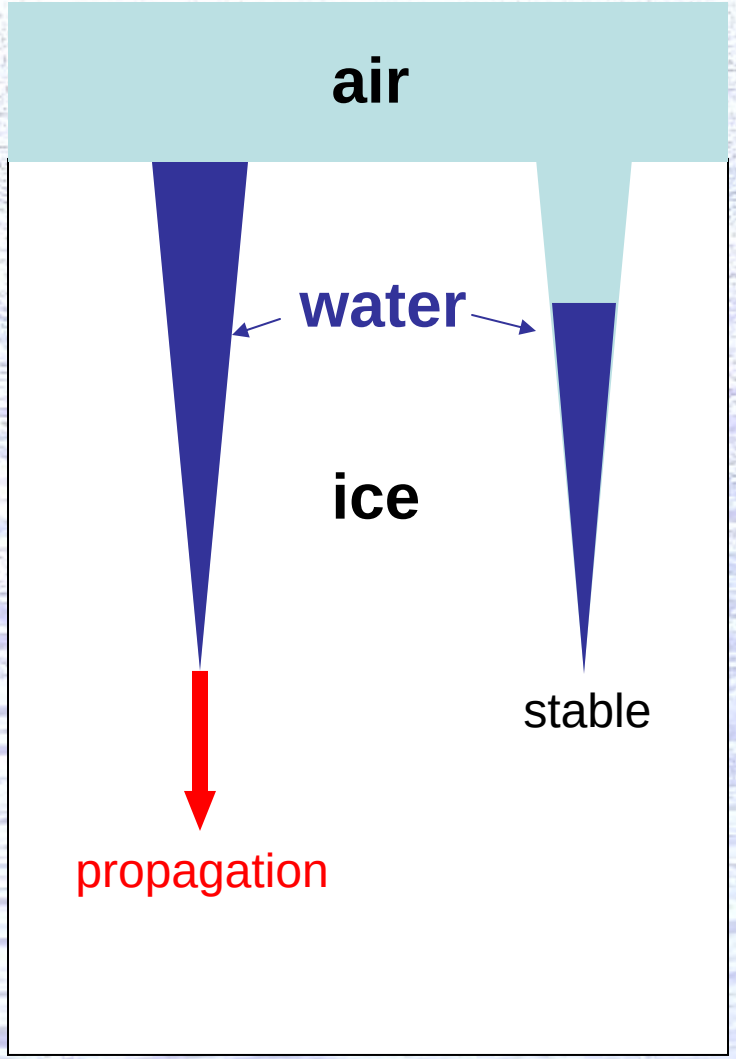
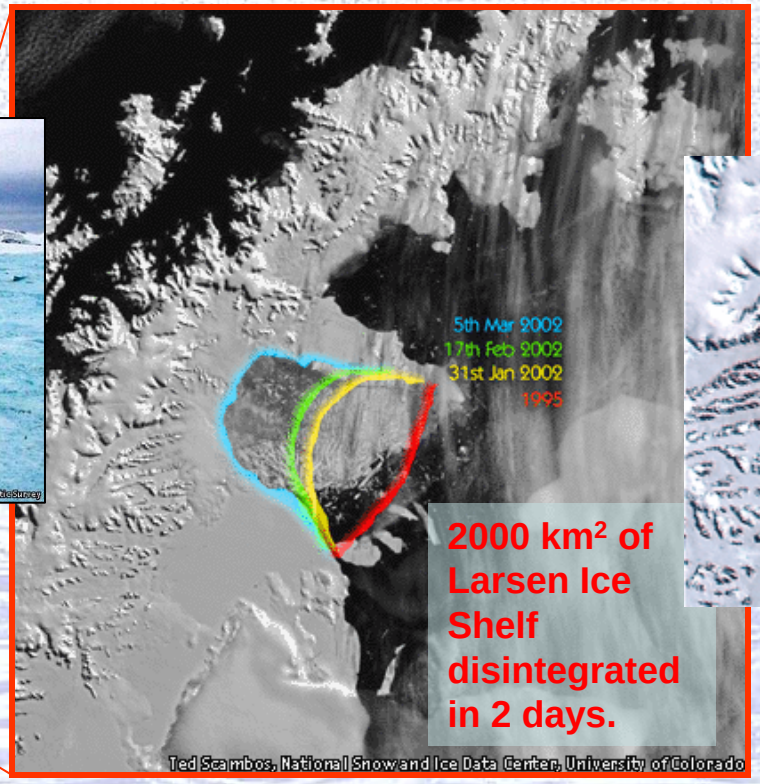
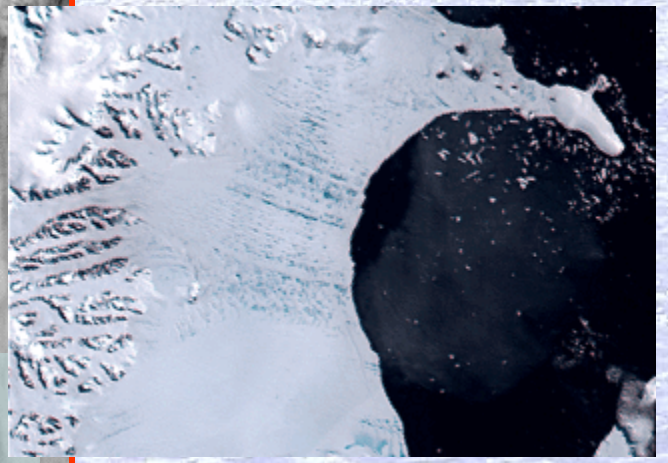
The most sophisticated ice-flow models can’t reproduce recent ice-sheet behavior

Water as The Wedge

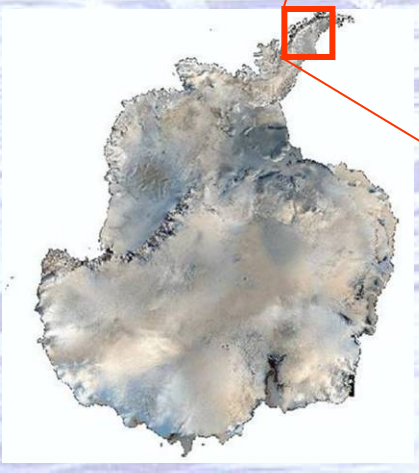


Disintegrating Ice Shelves





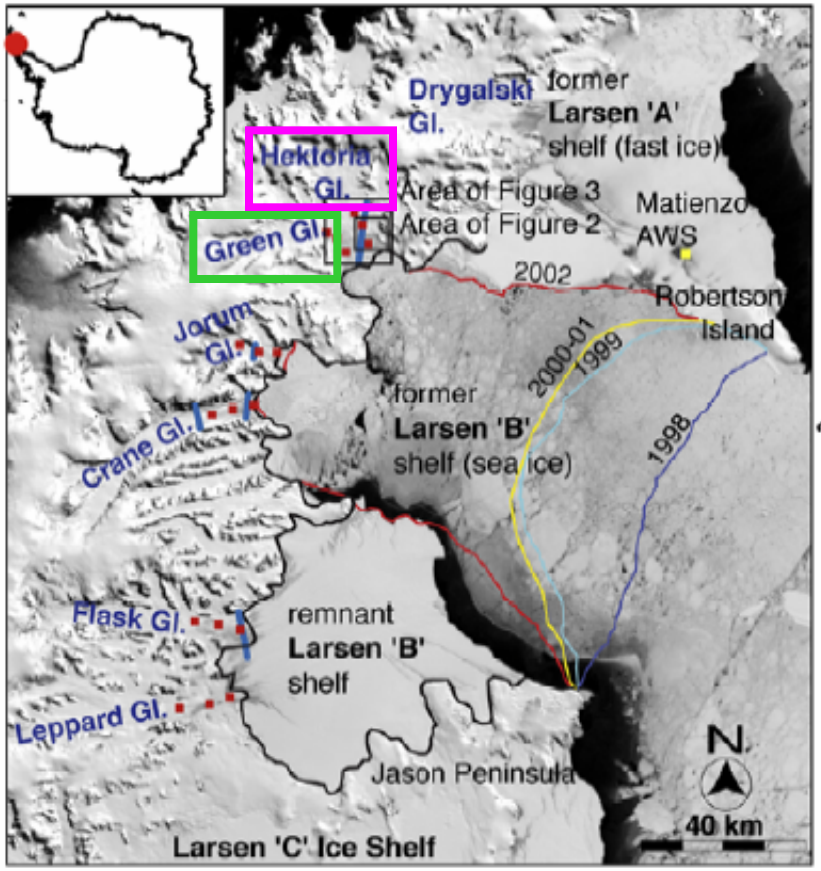
Source: T. Scambos



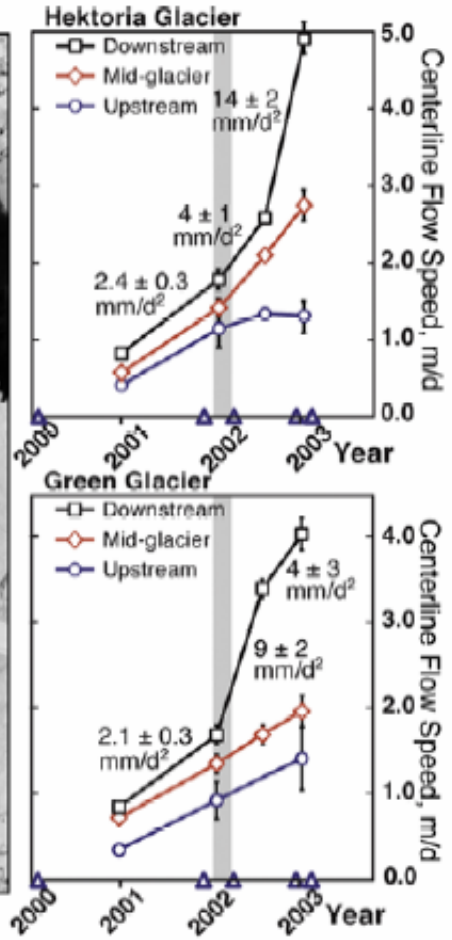
Require >10,000 years to form

Disintegrate in weeks

Consequence of Ice Shelf Loss



(Scambos et al., 2004)



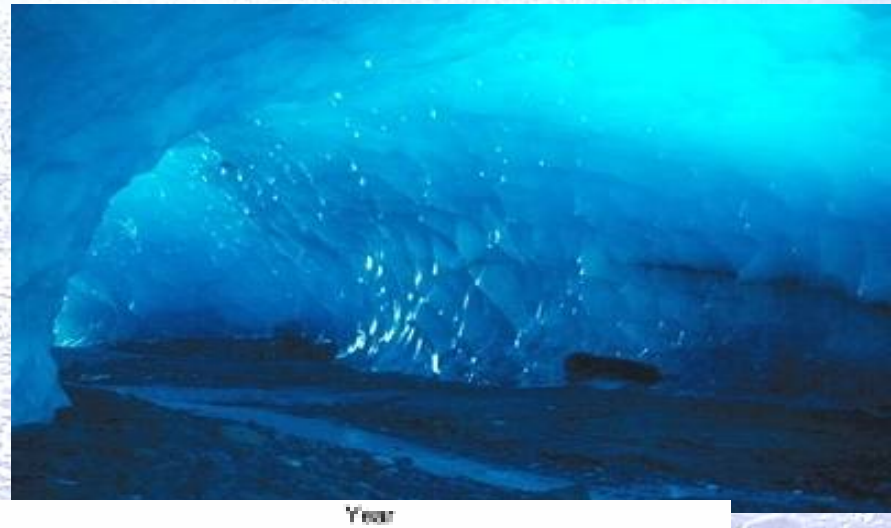
up to 510% faster in 2 years

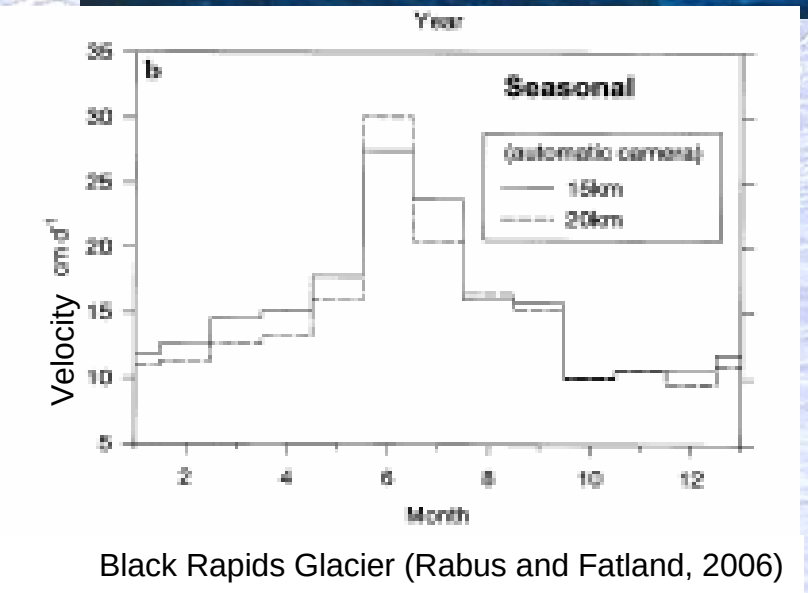
up to 400% faster in 2 years

Formerly buttressed glaciers accelerate

Water as Grease

well understood for mountain glaciers

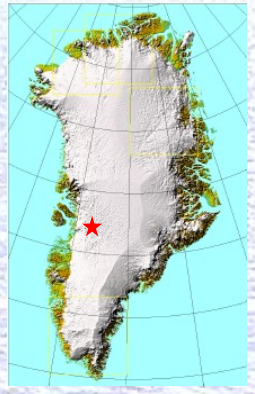


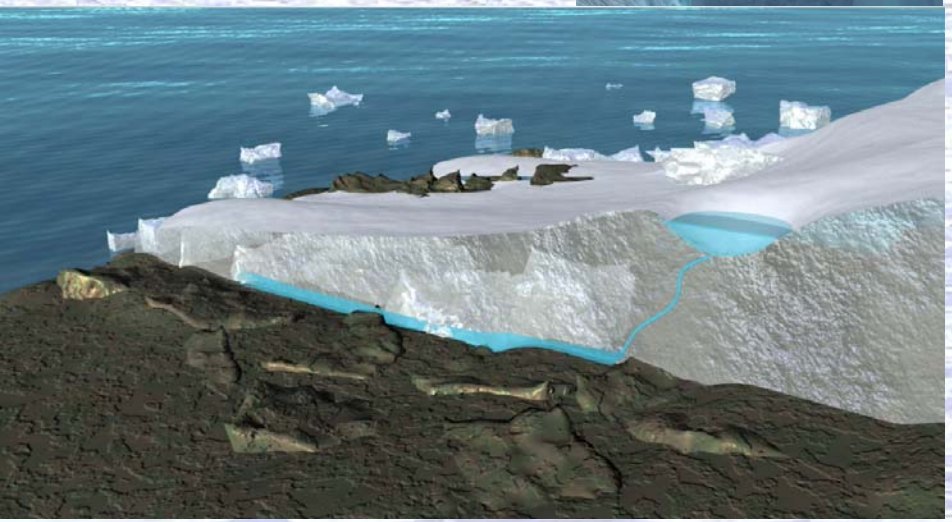


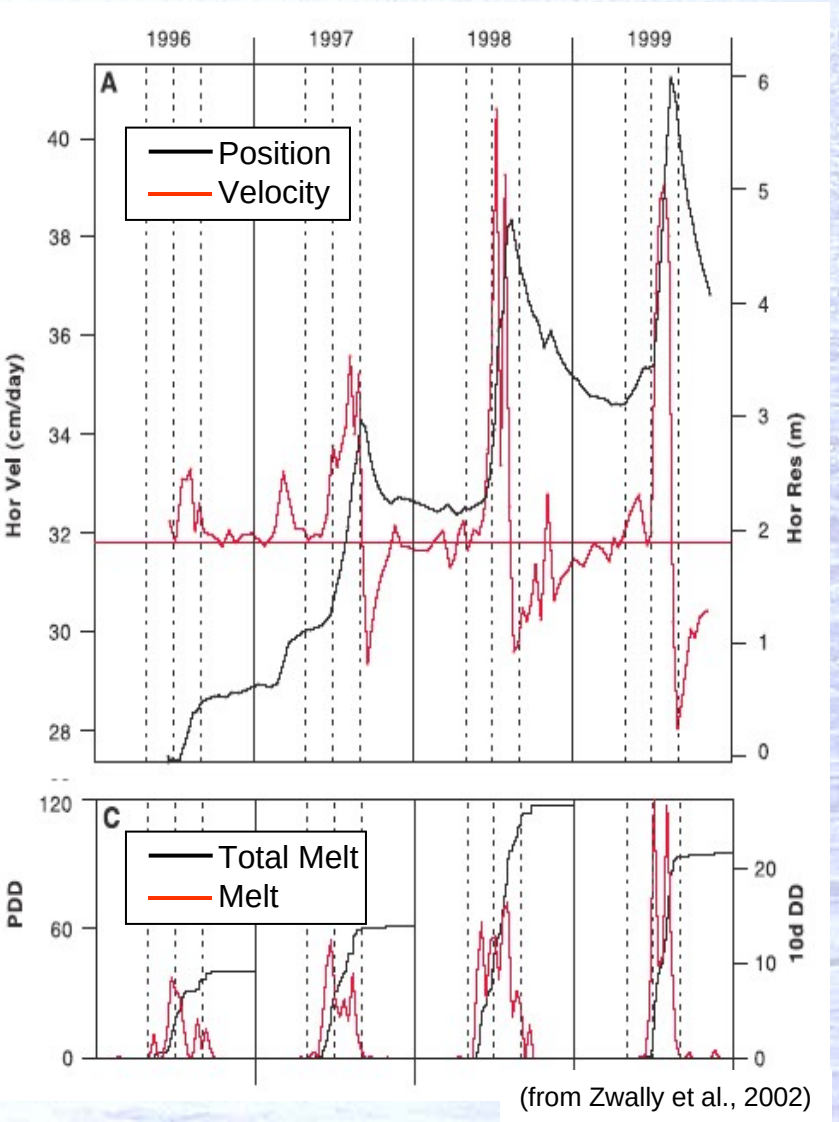
Black Rapids Glacier (Rabus and Fatland, 2006)

Summer meltwater penetrates to glacier bed reducing basal friction

Summer acceleration of Greenland's margins





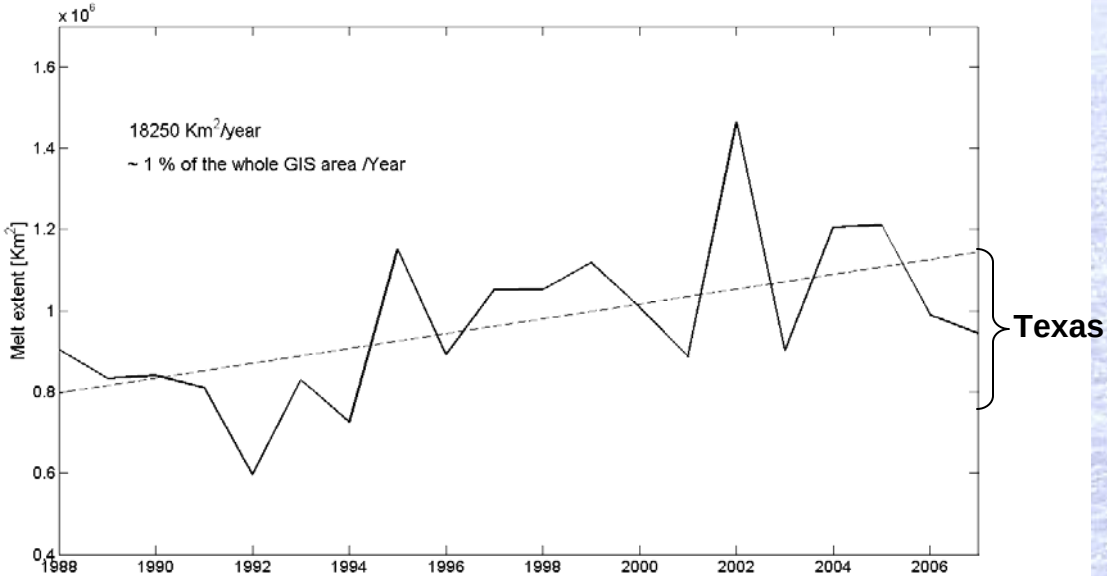


Glacier flow increases 10-15%
Slower ice increases up to 70%

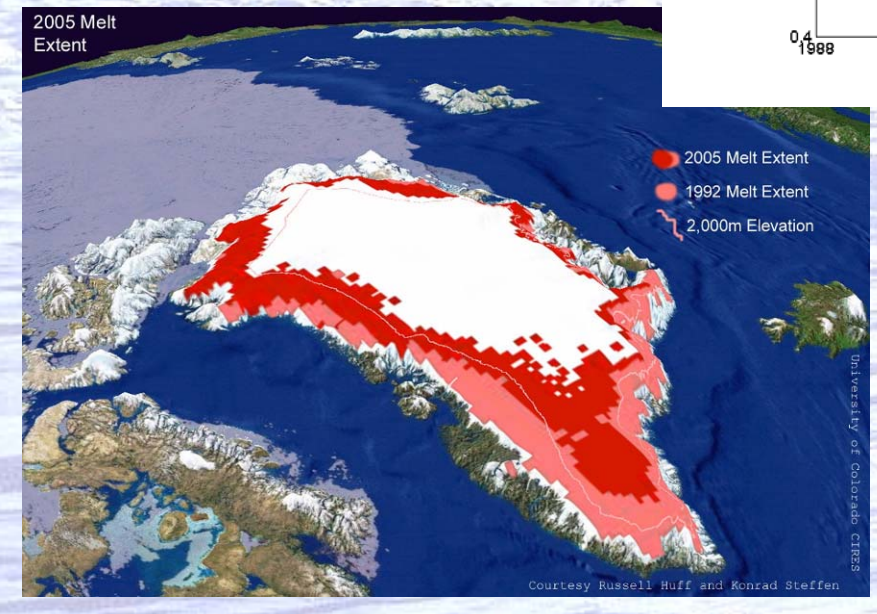
(from Joughin et al., 2008)

(from Zwally et al., 2002)

More Melt = More Lubrication = Faster Flow

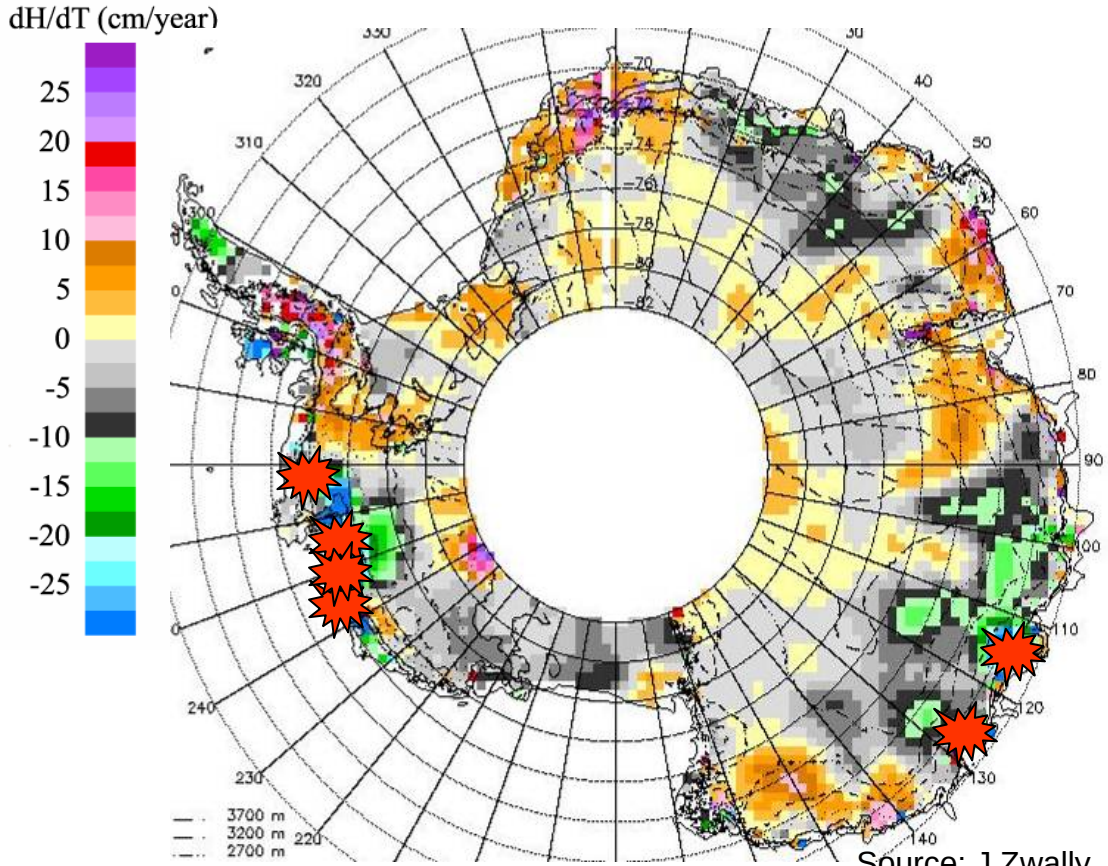


(Source: M. Tedesco)

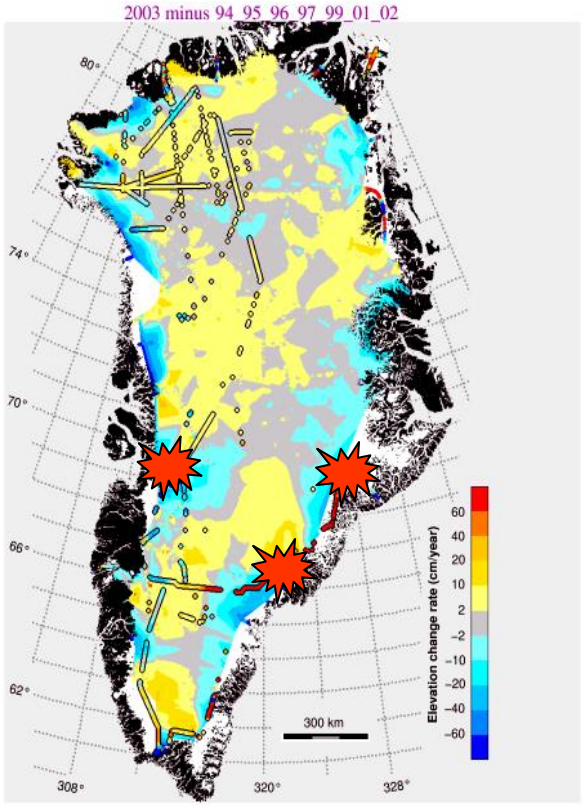


Flow increase is proportional to amount of melt

Water as Heat



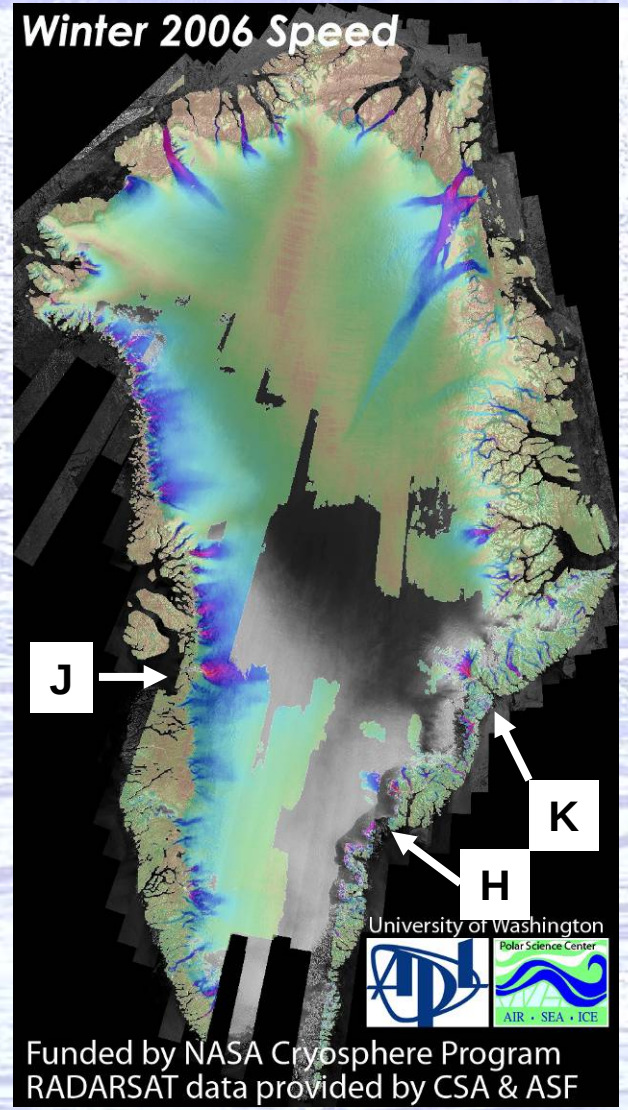
Source: J.Zwally



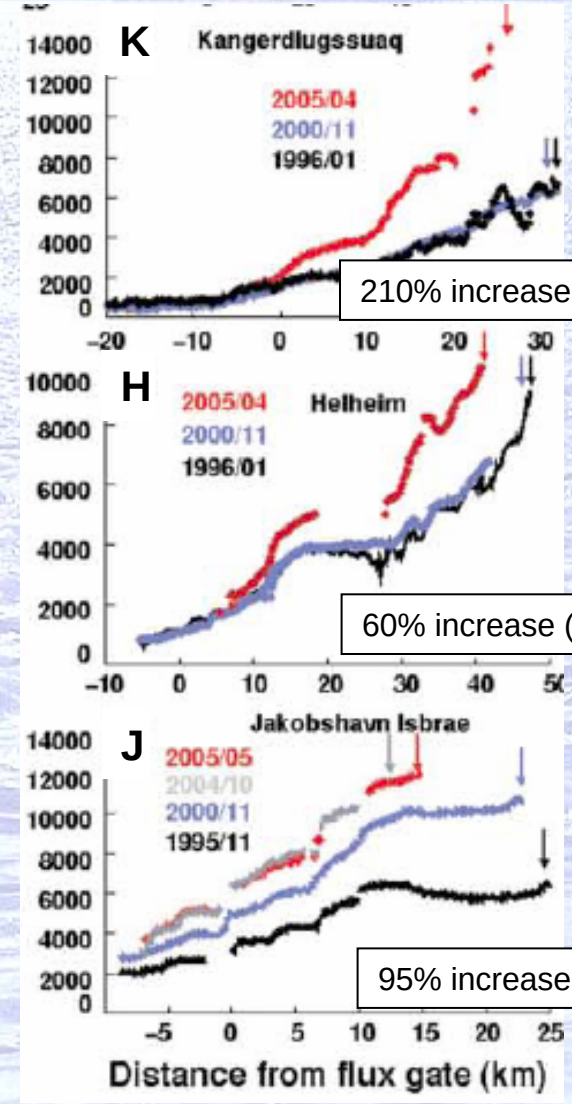
Source: W. Krabill

The deepest outlet glaciers exiting into the ocean are responding most. WHY?

Accelerating Outlet Glaciers



(Source: I. Joughin)



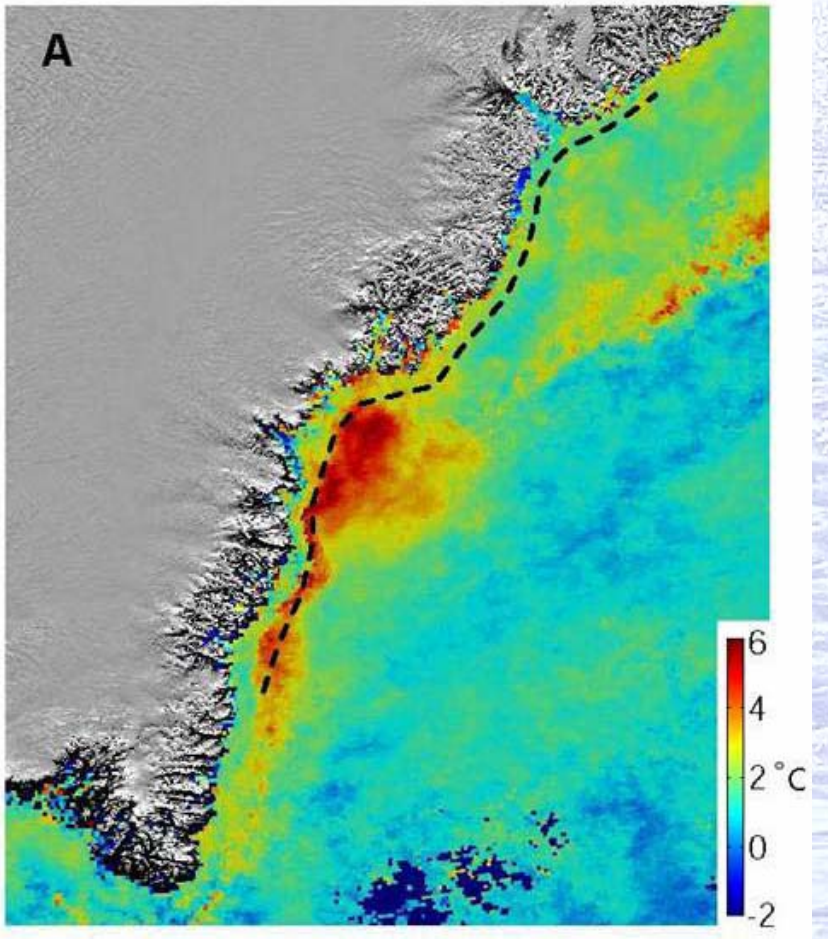
210% increase (2000-2005)

60% increase (2000-2005)

95% increase (1996-2005)

(Rignot and Kanagaratnam, 2006)

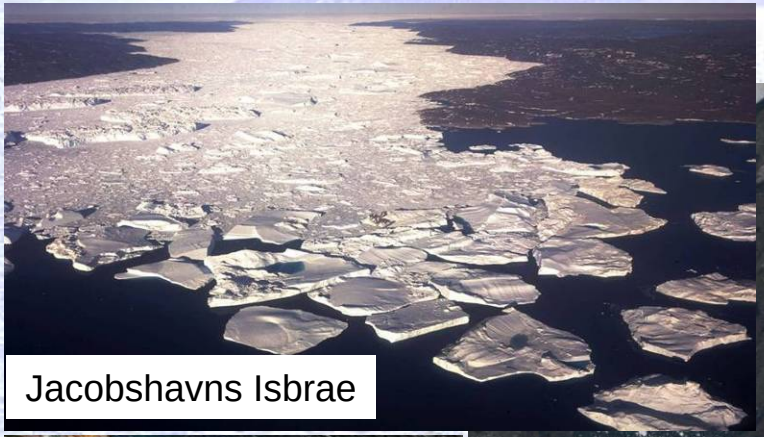
Warm Water Spotted Offshore



(Source: Howat et al., submitted)

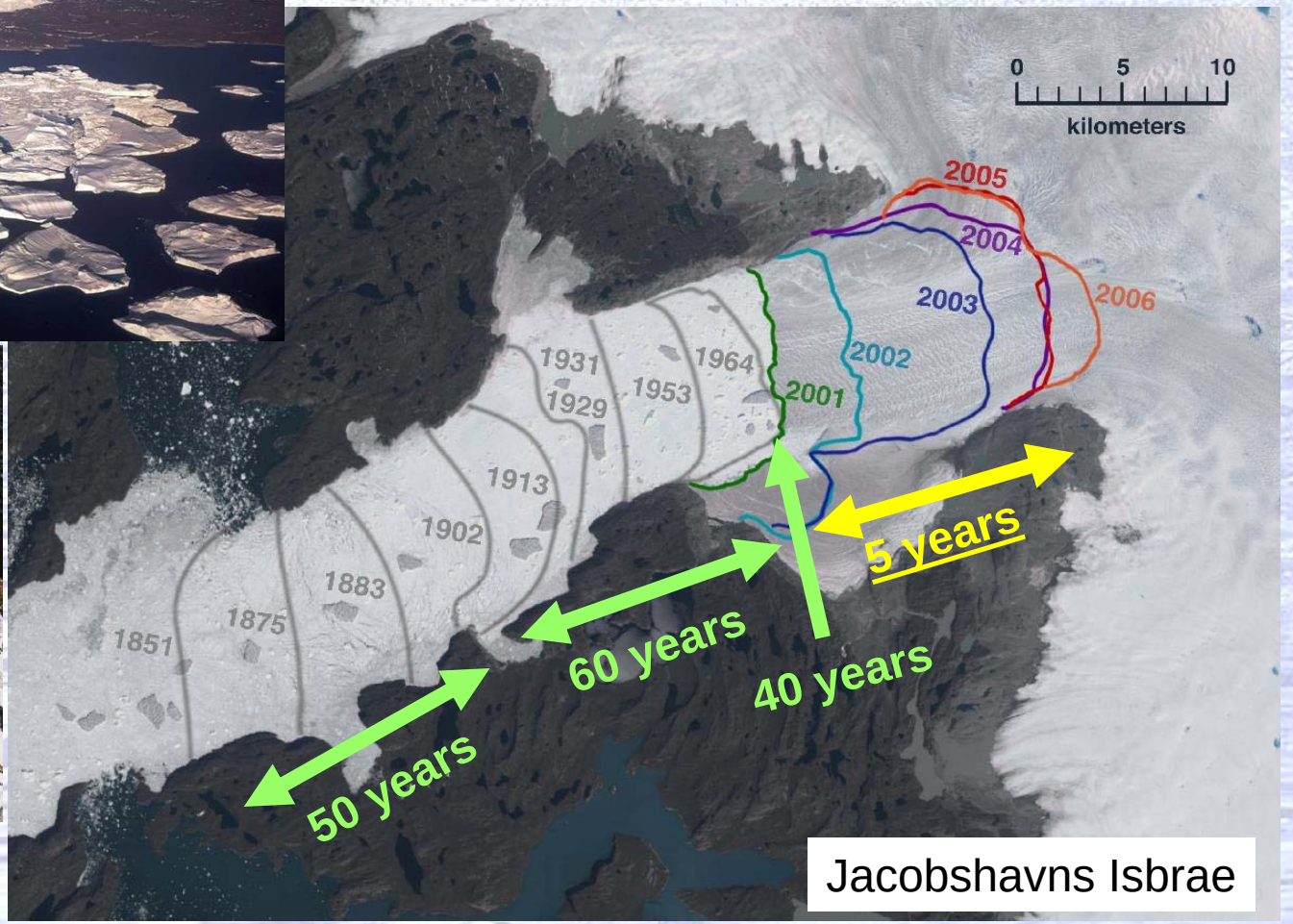
Sea surface temperature anomaly for August 2003

Rapid Retreat

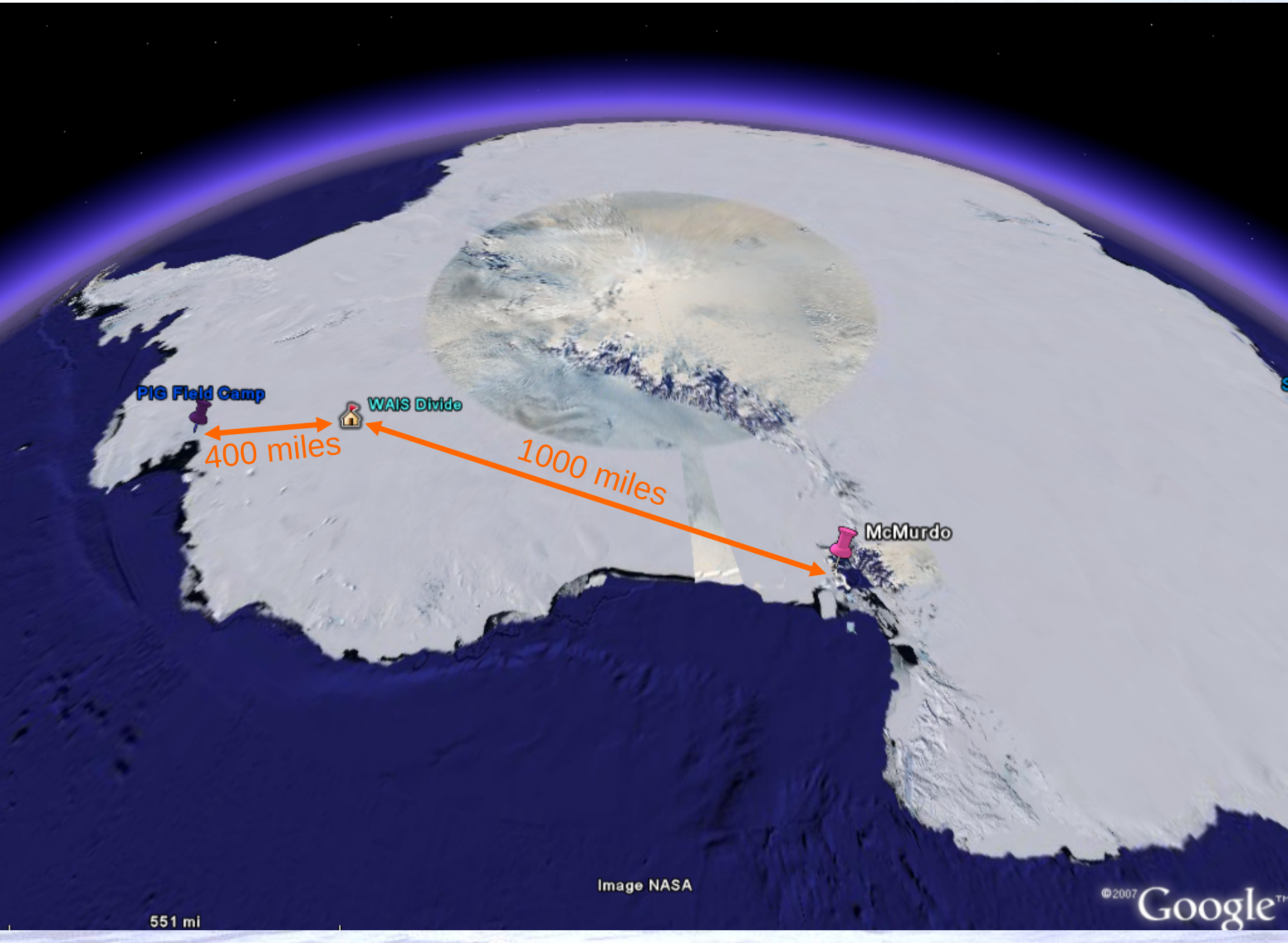


Jacobshavns Isbrae

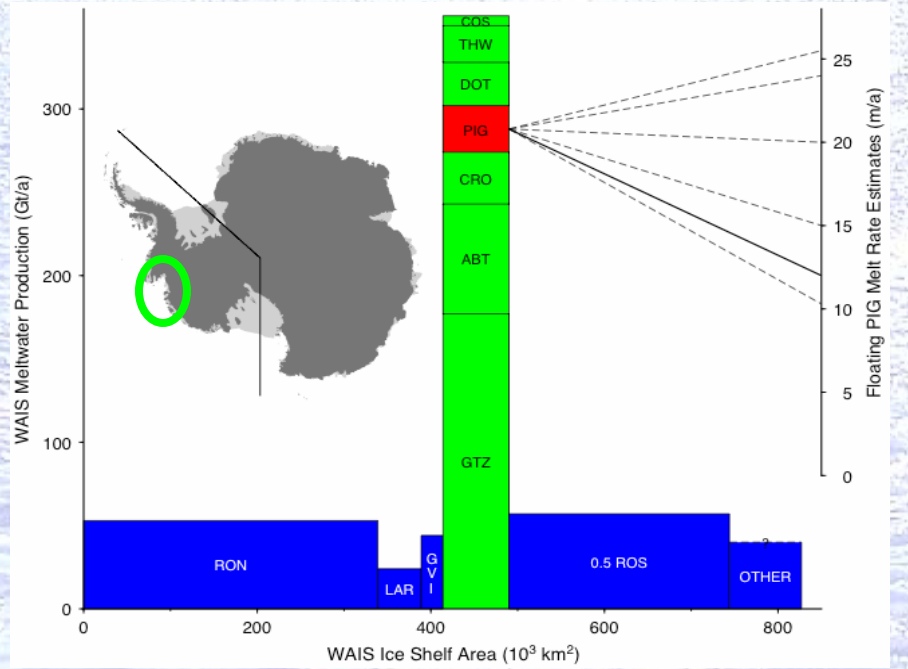
Kangerdlugssuaq Glacier

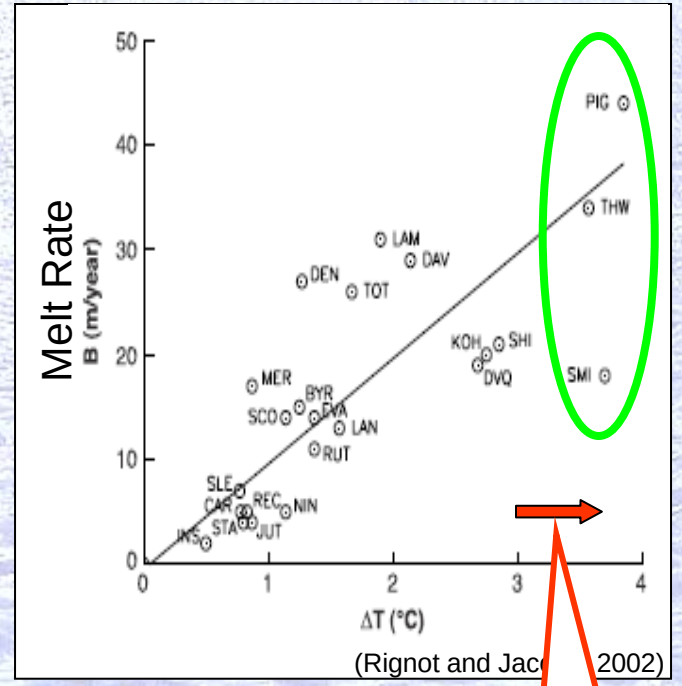


Jacobshavns Isbrae


PIG Field Camp
WAIS Divide
400 miles
1000 miles
McMurdo
Image NASA
©2007 Google
551 mi

Extreme Sub-Ice-Shelf Melt Rates





(Rignot and Jac 2002)

10 m/a melt per 1K temperature difference

freezing point depression due to 1000-m thick ice

National Aeronautics and Space Administration

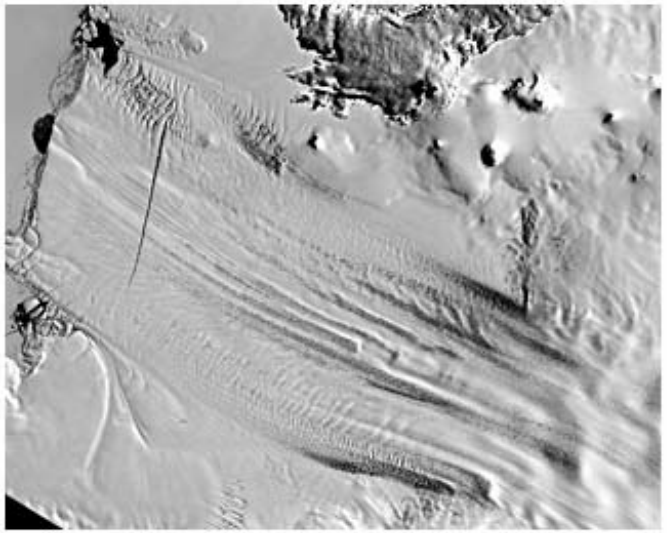
National Science Foundation

pine island glacier ice shelf

home
who
what
where
why
how
when
blogs

Pine Island Glacier (PIG) Ice Shelf

This project's official title is "Ocean-Ice Interaction in the Amundsen Sea: the Keystone to Ice-Sheet Stability". A real mouthful, but it captures the essence of what we intend to do, where we will do it and why we feel it is important to do it. Various other measurements have captured the West Antarctic ice sheet changing very rapidly in the region where it flows into the Amundsen Sea, one of the sectors of the Southern Ocean. The spatial pattern strongly suggests that the cause of this change is weaker ice shelves, the floating apron of ice that fringe the perimeter of the ice sheet. Our hypothesis is that warm water is melting the undersides of these ice shelves decreasing the "back pressure" from the ice shelves to help hold the ice sheet. Less backpressure means the ice sheet can flow faster. Faster flow-smaller ice sheet-higher sea levels-slow motion coastal flooding worldwide.



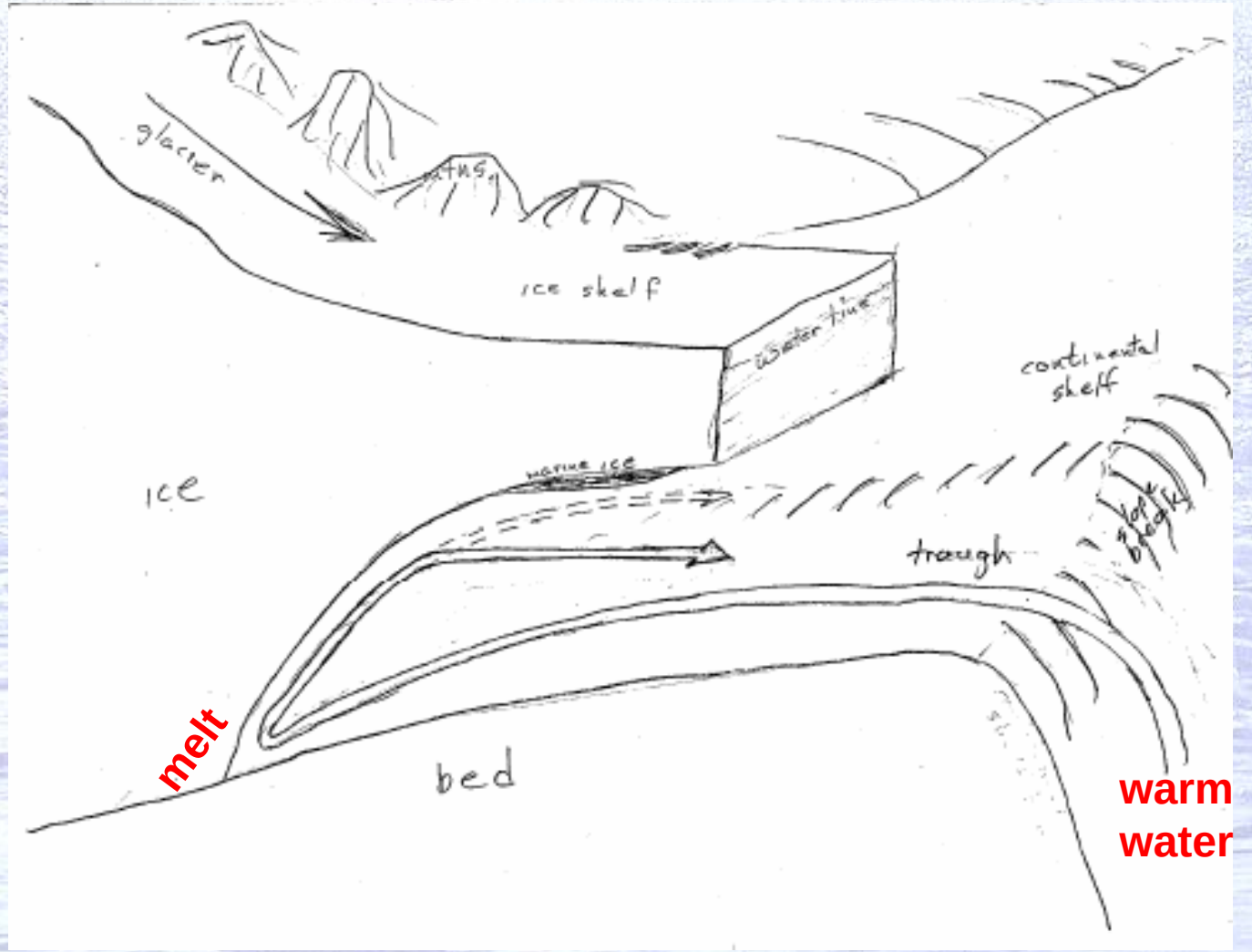
Landsat image - January 2001
High- Resolution Image *1785x1683 pixels, 1.1MB*

Doubled speed
in 20 years

Now moving
<u>One foot per hour</u>!

http://pigiceshelf.nasa.gov

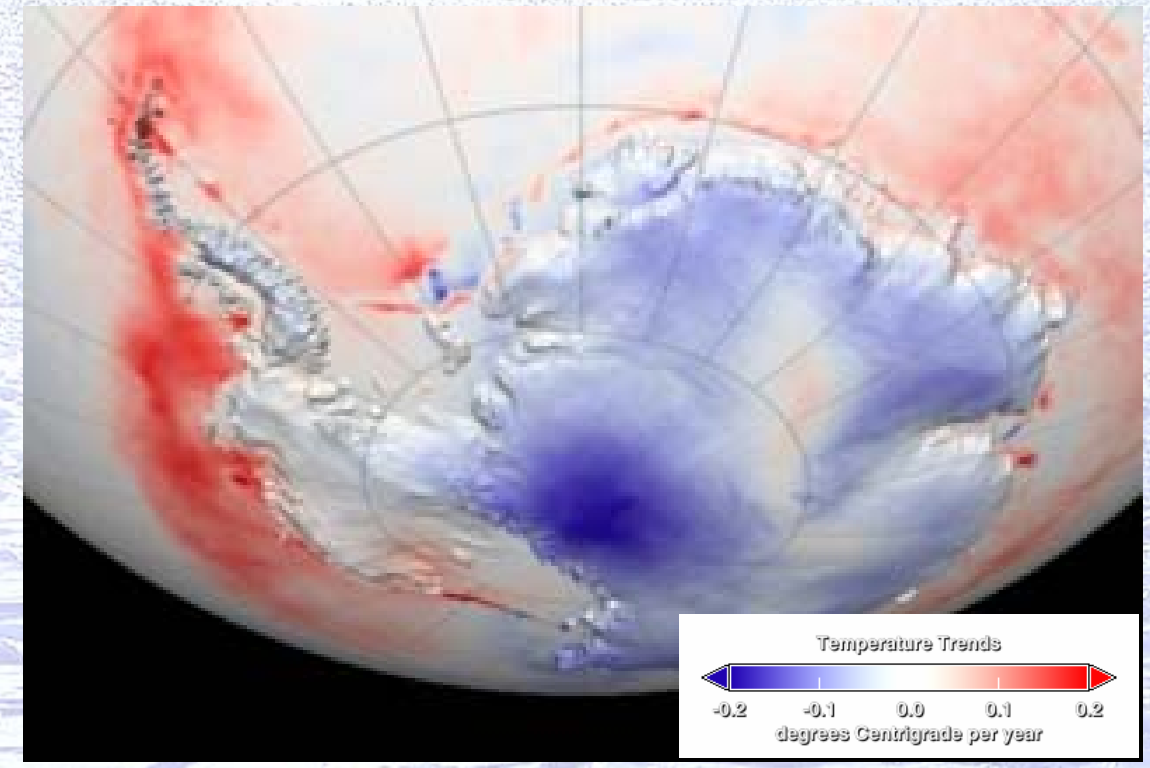
Our Hypothesis



Ice Shelf Sensitivity

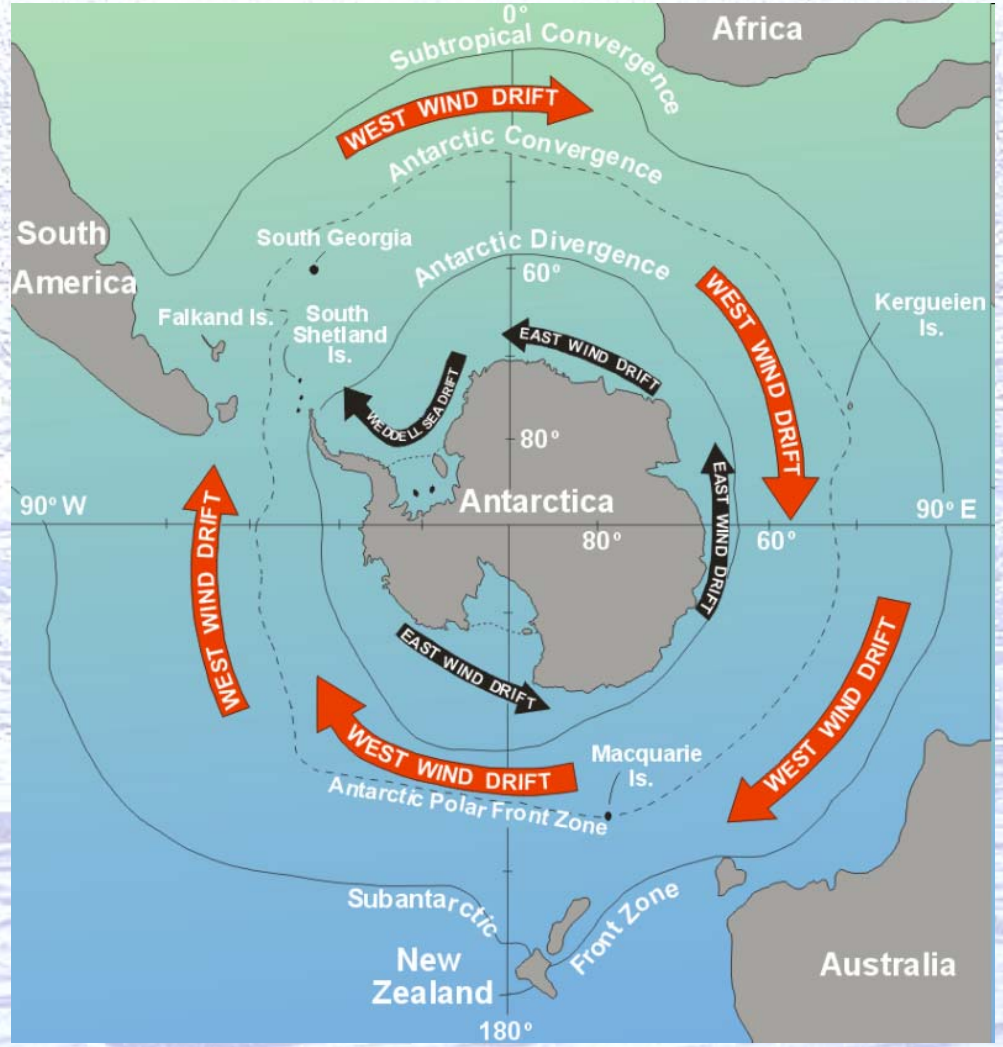
- Thinning
  - reduces buttressing (recall Larsen-B)
- Grounding line retreat replaces friction controlled flow (slow) with stretching flow (fast)
  - Speed of floating ice controlled by “creep thinning”, goes as (ice thickness)^3

Start in the Atmosphere

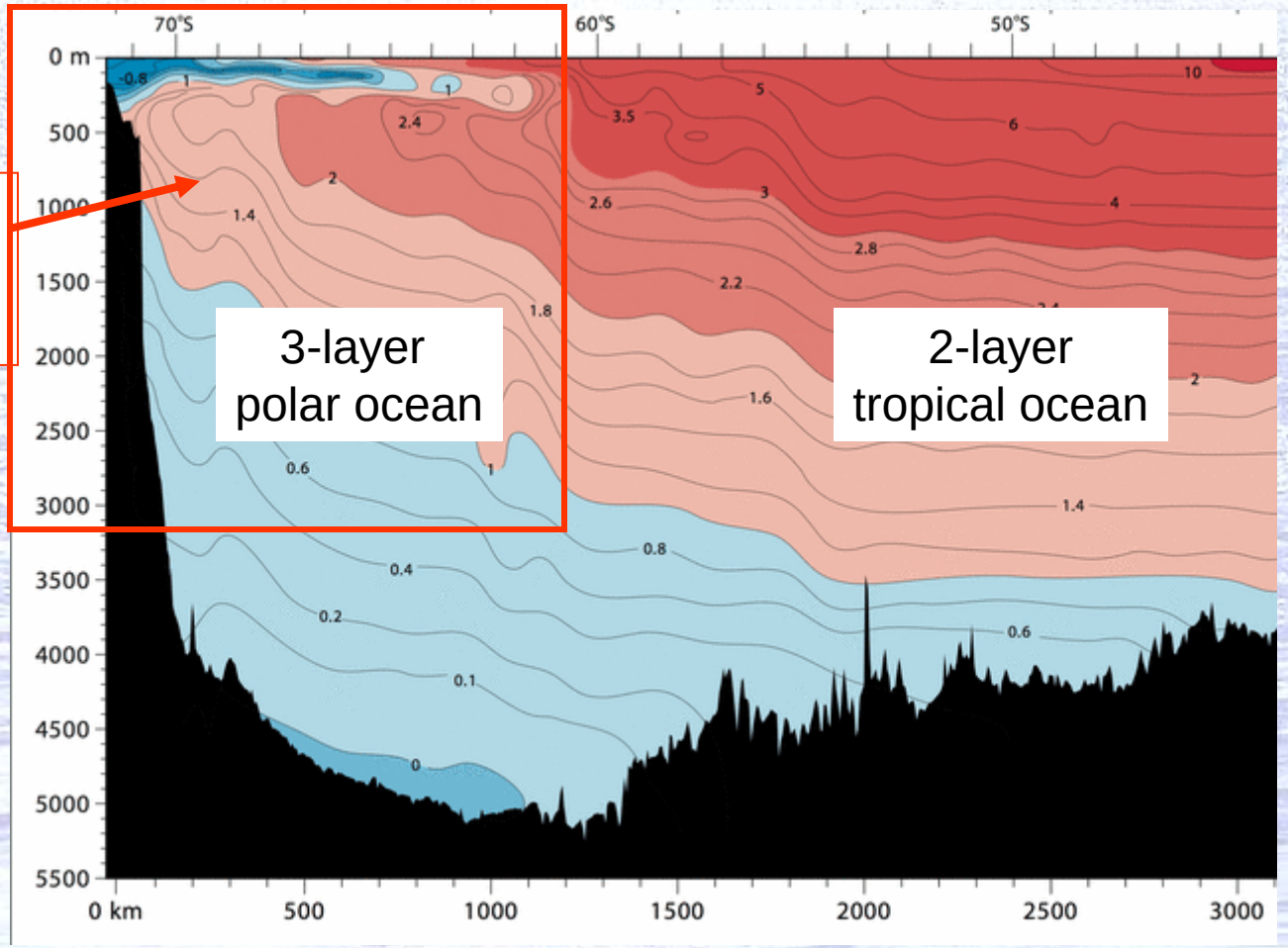


Increased temperature gradient increases circumpolar winds

Now Some Oceanography

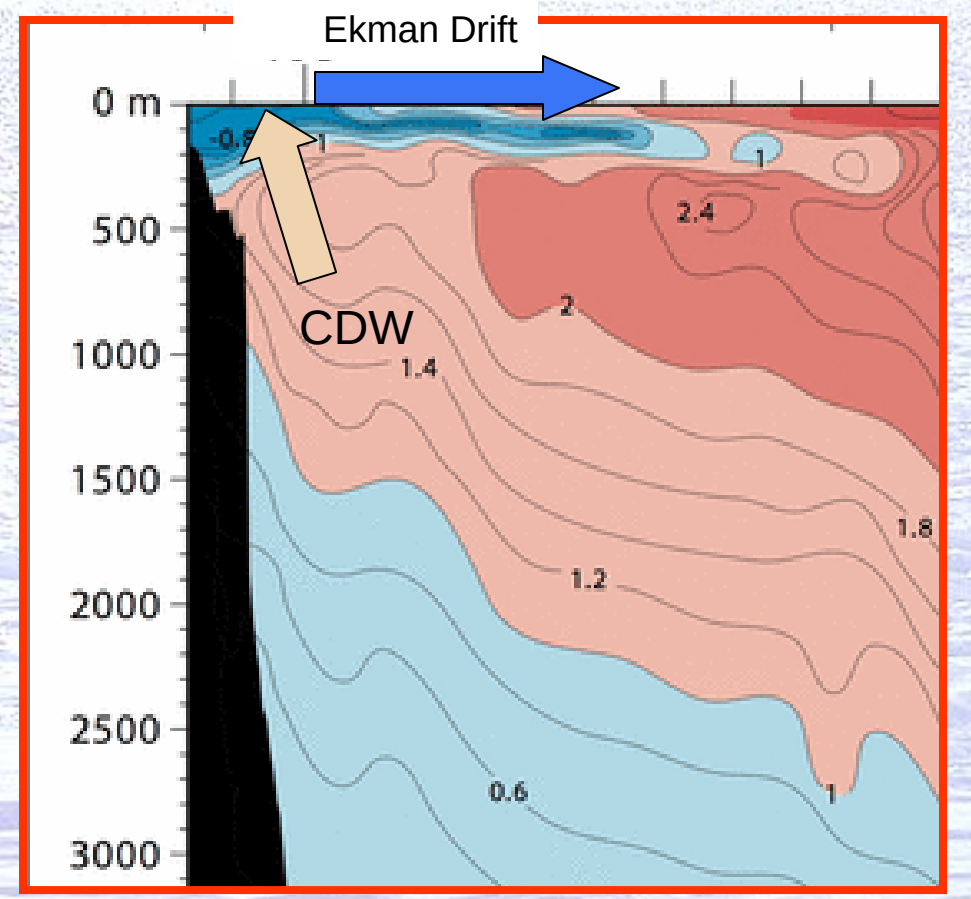


Some More Oceanography

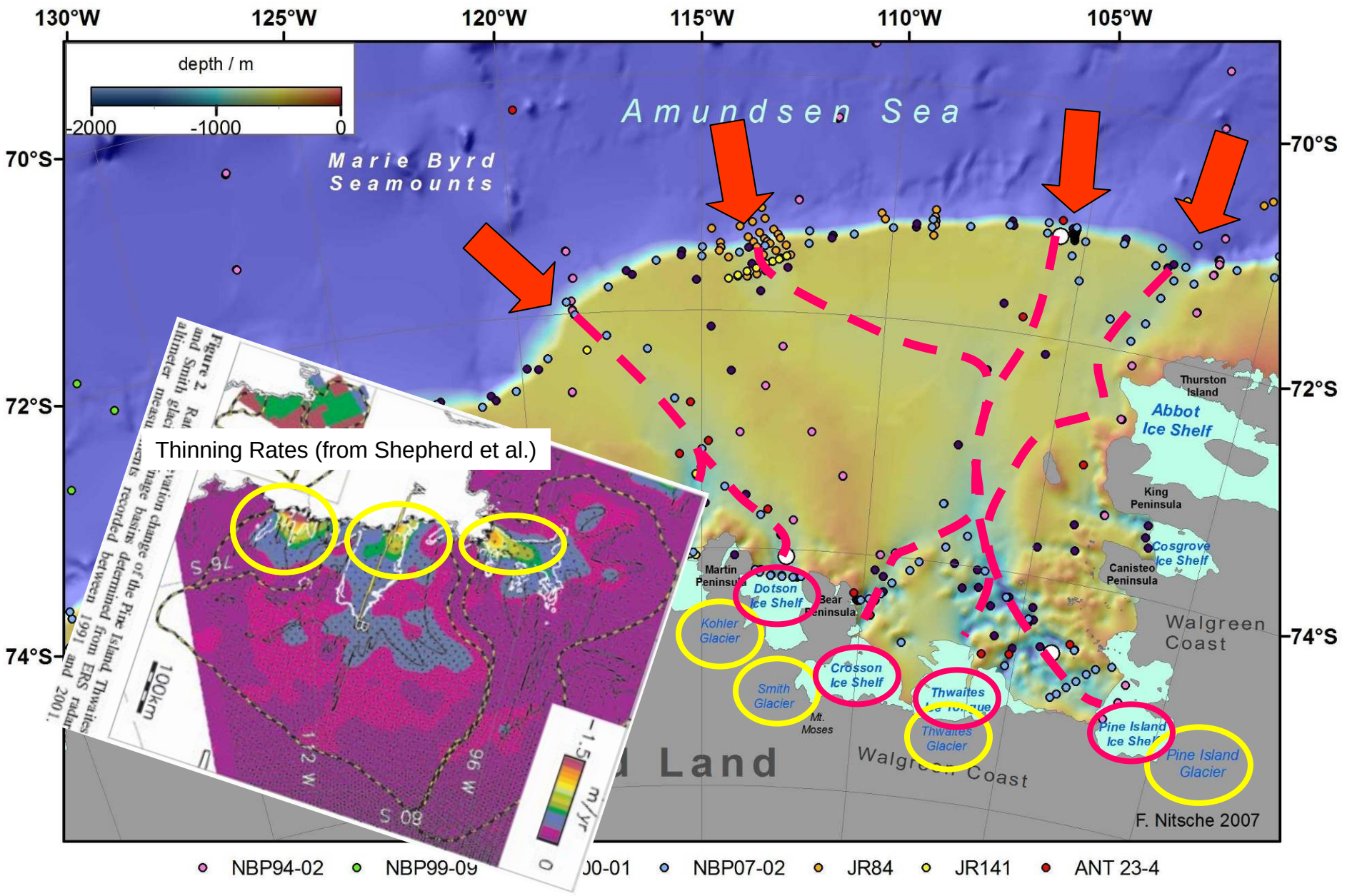


Source: S. Jacobs

Upwelling of CDW

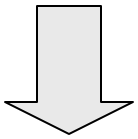


Getting Hot Water (CDW) to the Glaciers

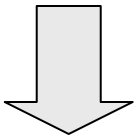


An Interdisciplinary Process

Meteorology



Oceanography



Marine Geophysics

Glaciology

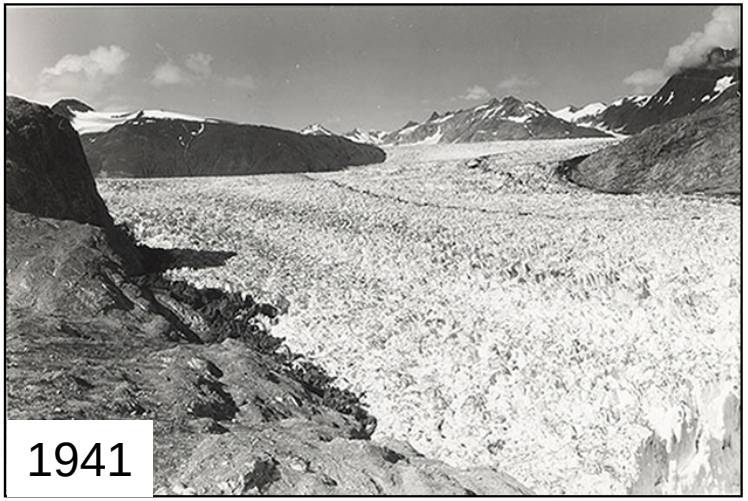
- Ozone hole causes stratospheric cooling and tropospheric warming
- Southern Ocean westerlies intensify
- Circumpolar Current increases
- Ekman transport cause upwelling of Circumpolar Deep Water (CDW)
- CDW brings heat onto Amundsen Sea continental shelf
- Glacially eroded troughs funnel warm water toward outlet glaciers
- Increased basal melt of ice shelves results in ice acceleration

Field studies of all three (and more) processes are underway

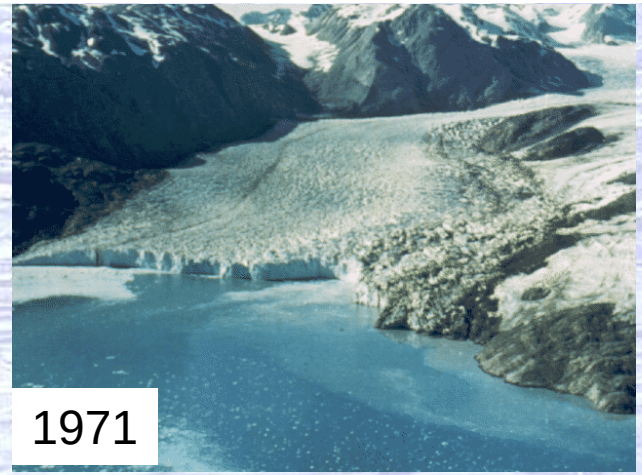
Meanwhile…

Tidewater glaciers are a good analogue to anticipate ice sheet future

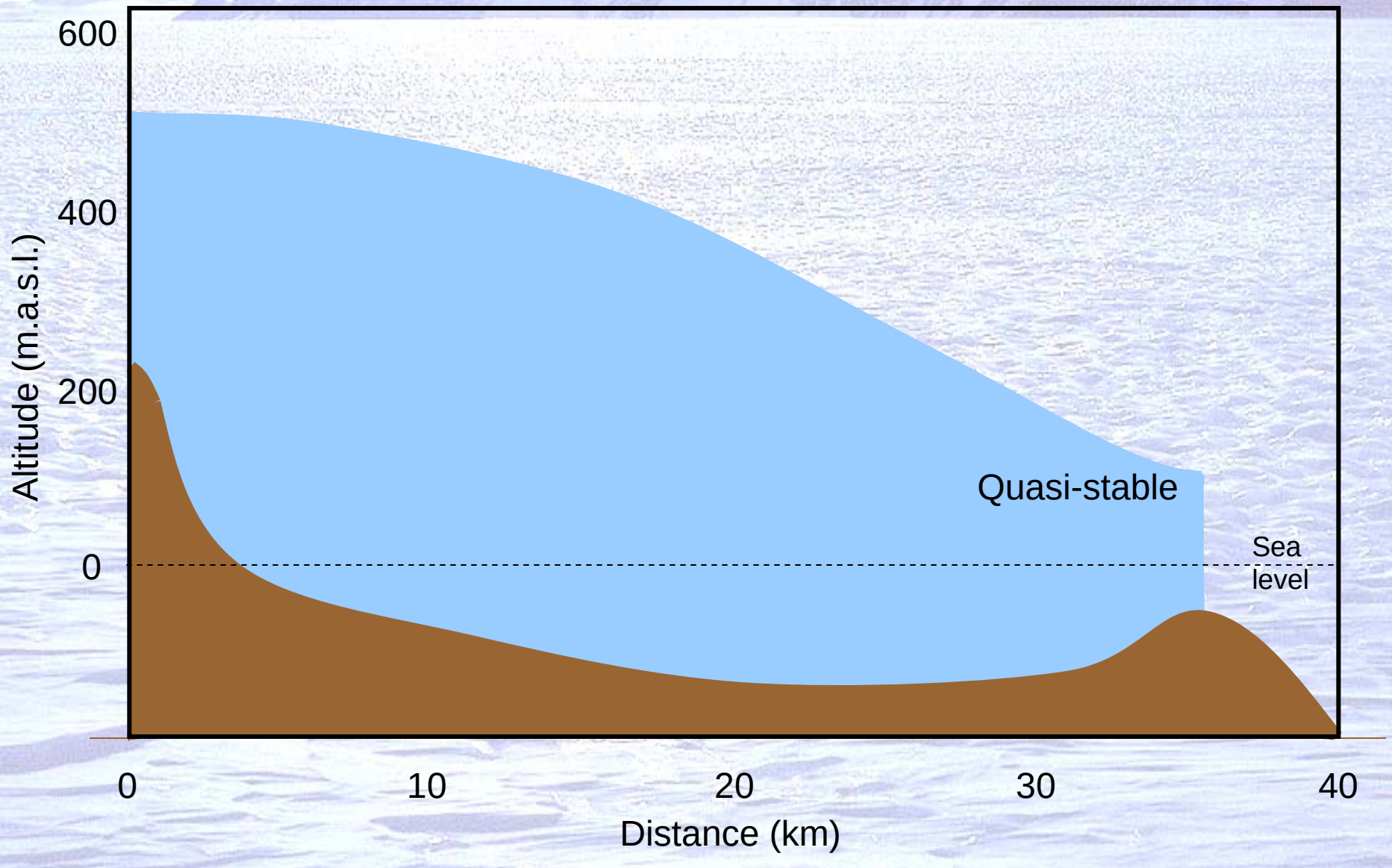
Muir Glacier, Alaska



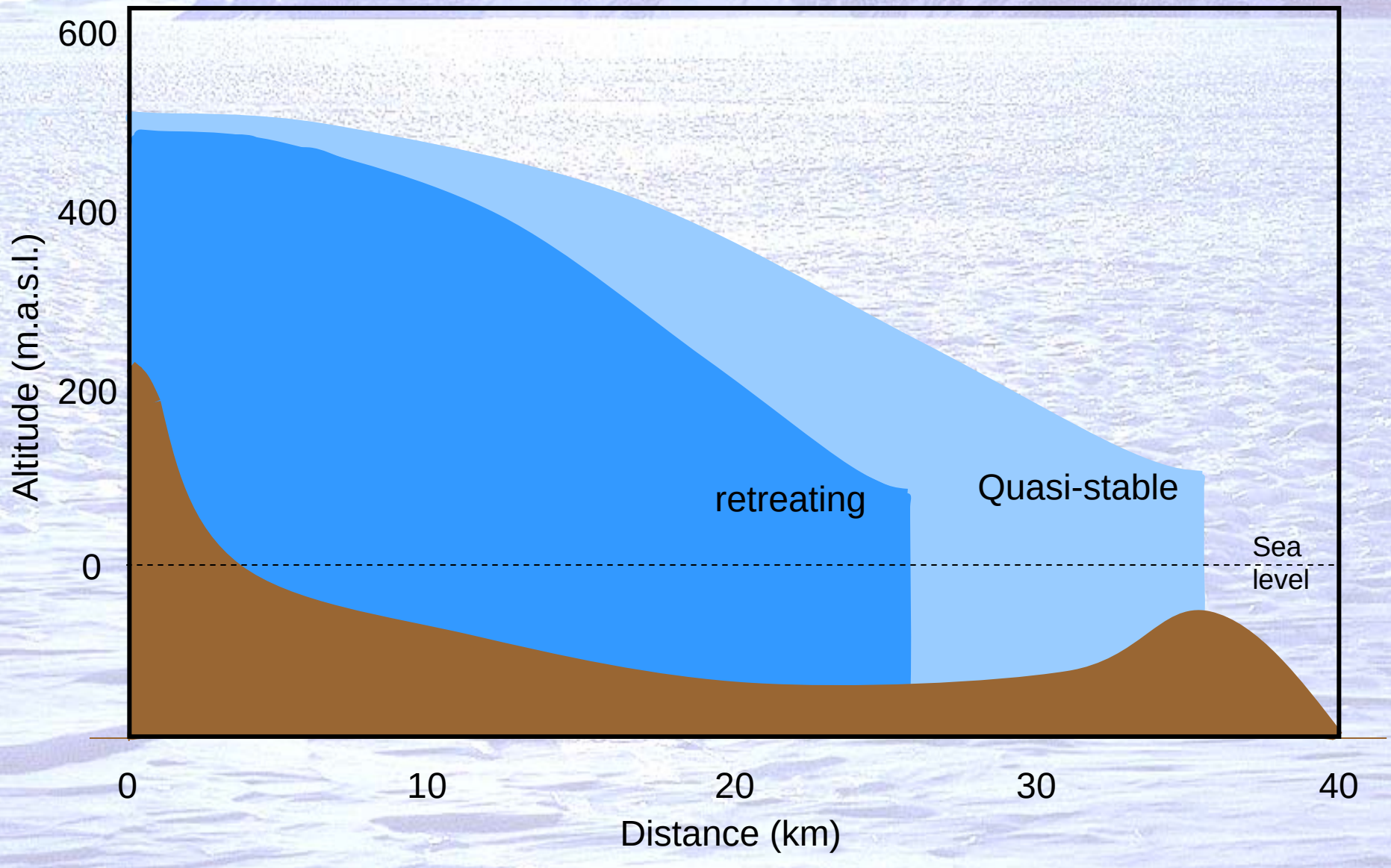
Large outlet glaciers are displaying classic “drastic retreat” traits similar to Alaskan tidewater glaciers



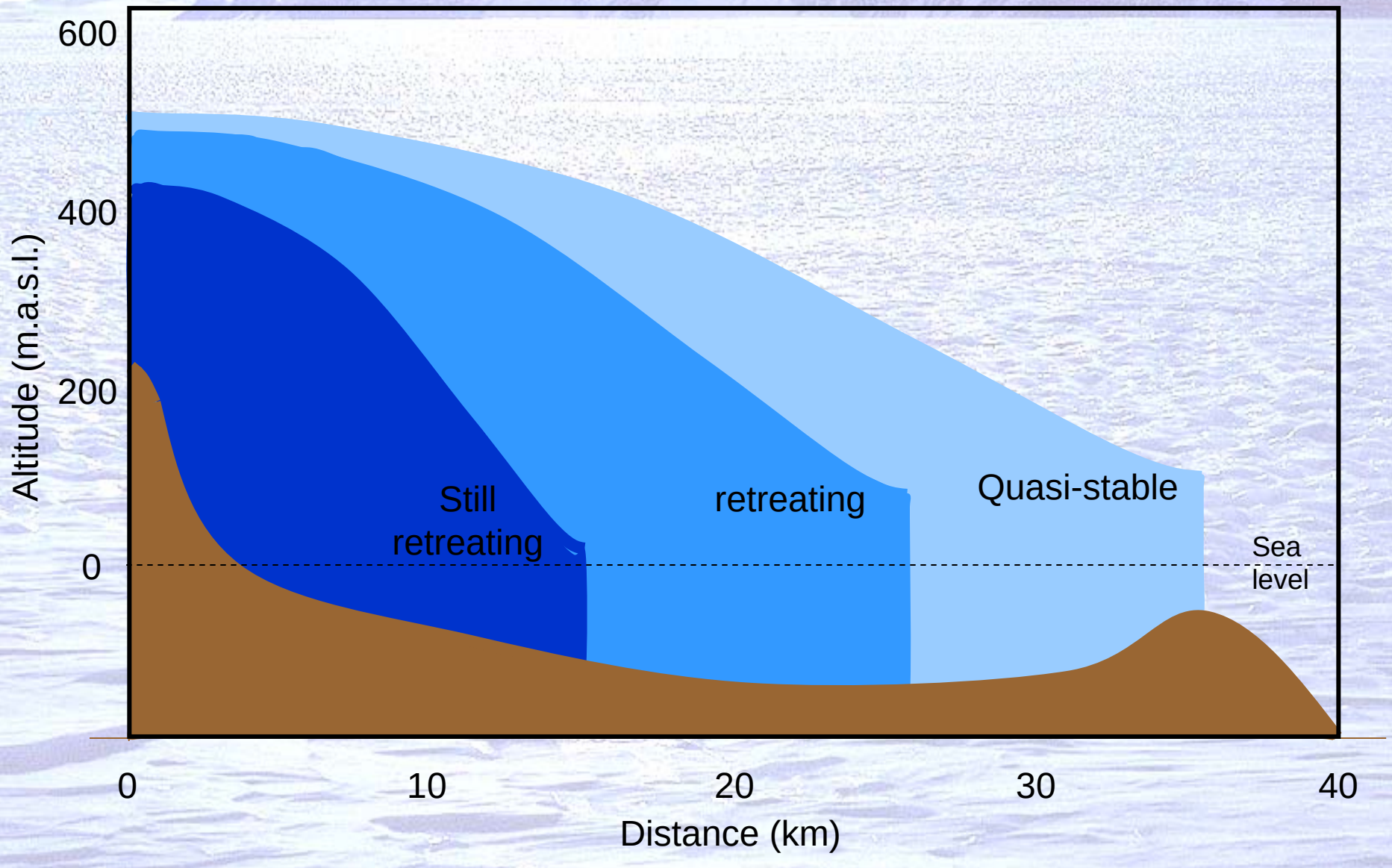
Tidewater Glacier “Drastic Retreat”



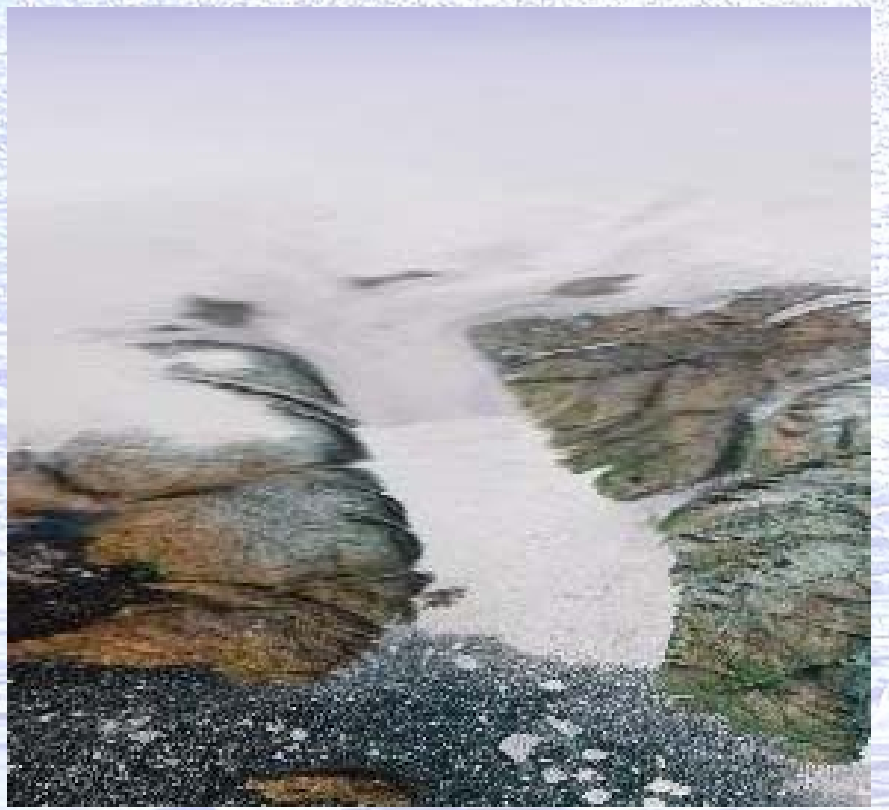
Tidewater Glacier “Drastic Retreat”



Tidewater Glacier “Drastic Retreat”

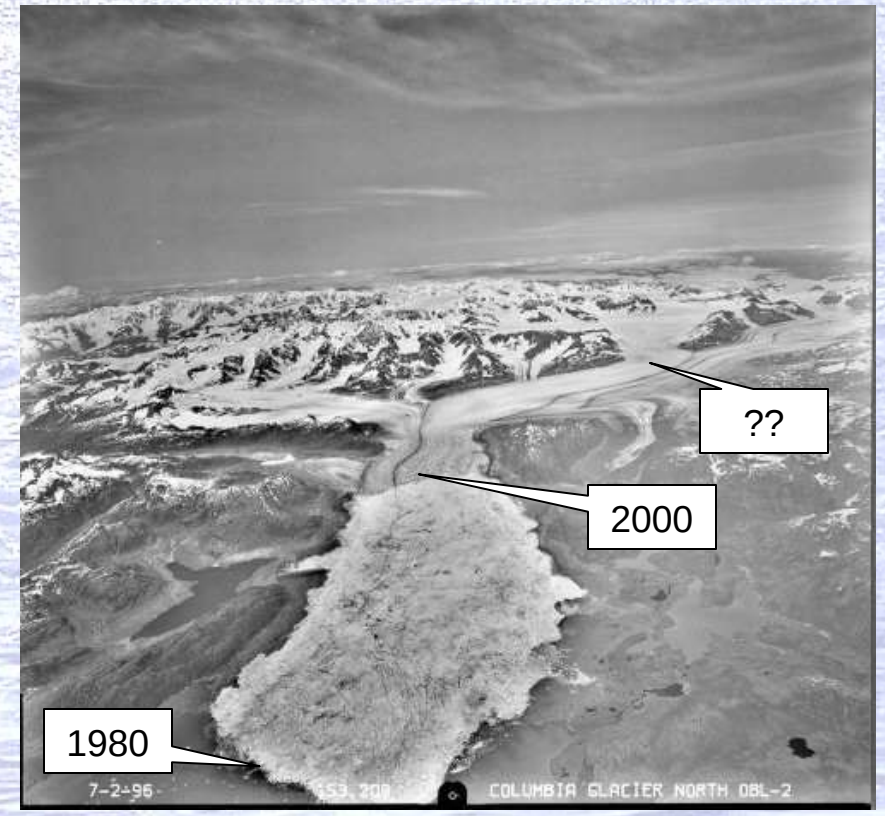


Helheim Glacier, Greenland



2007 image (GoogleEarth)

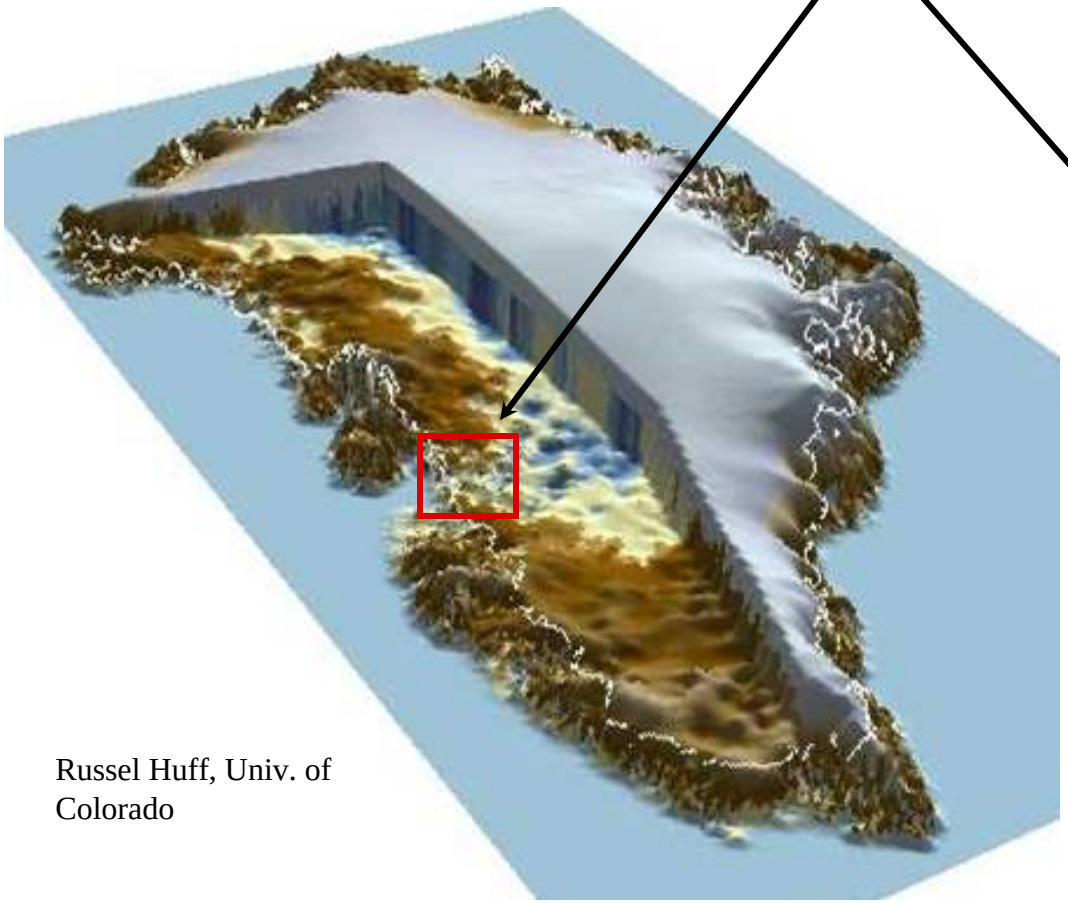
Columbia Glacier, Alaska

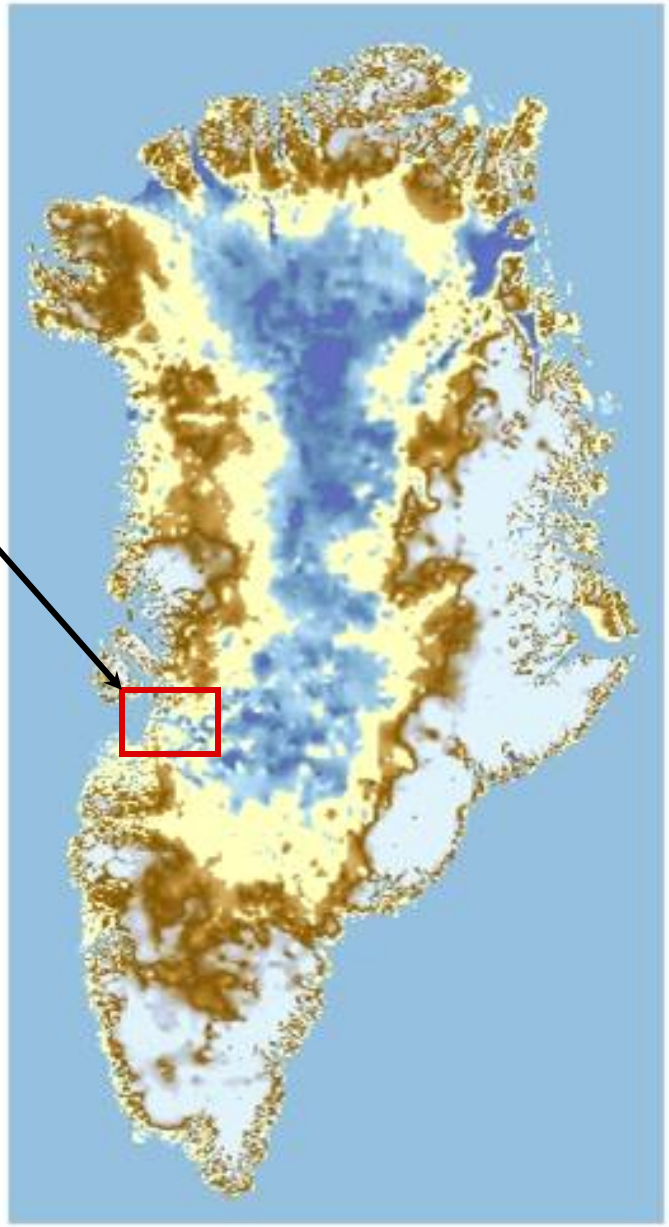


Source: USGS

1996 aerial photograph

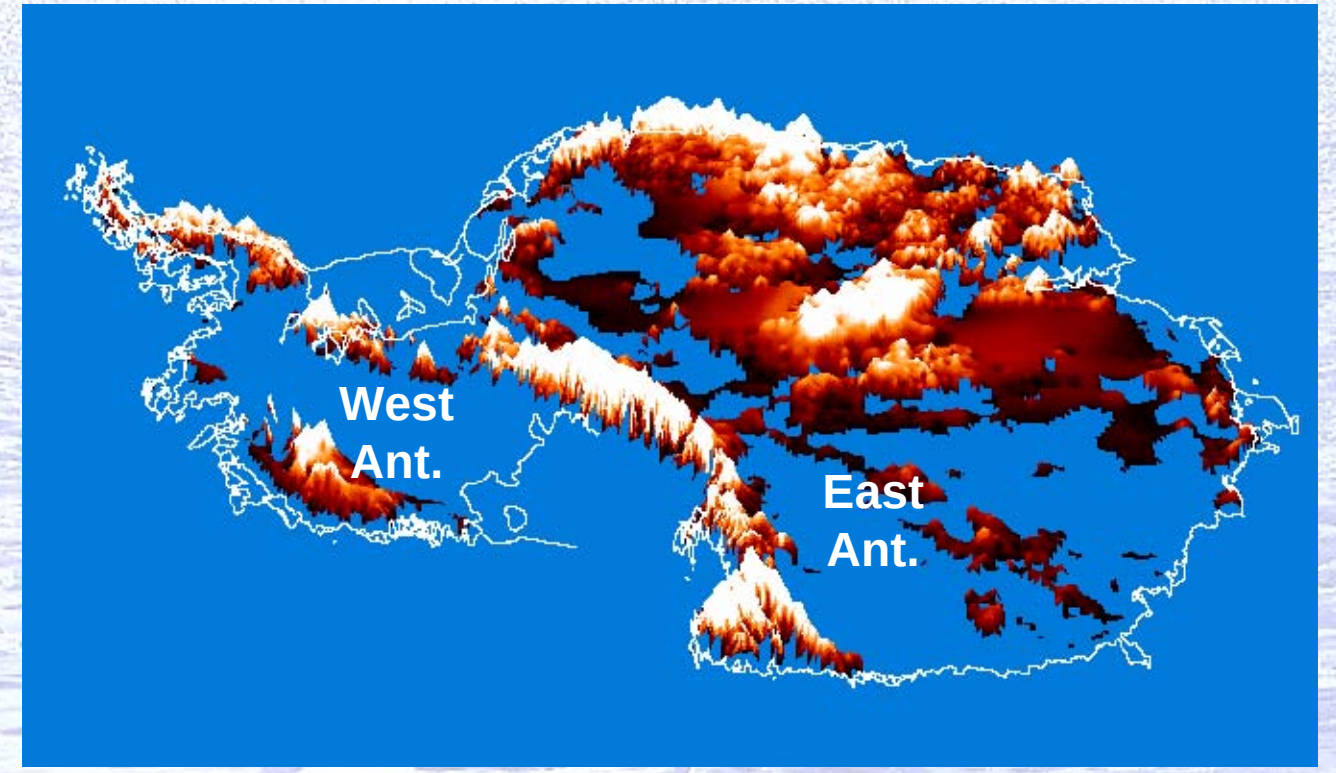
- Central region of Greenland is below sea level
- Jacobshavns Isbrae occupies subglacial channel connected to central depression





Russel Huff, Univ. of Colorado

Antarctica

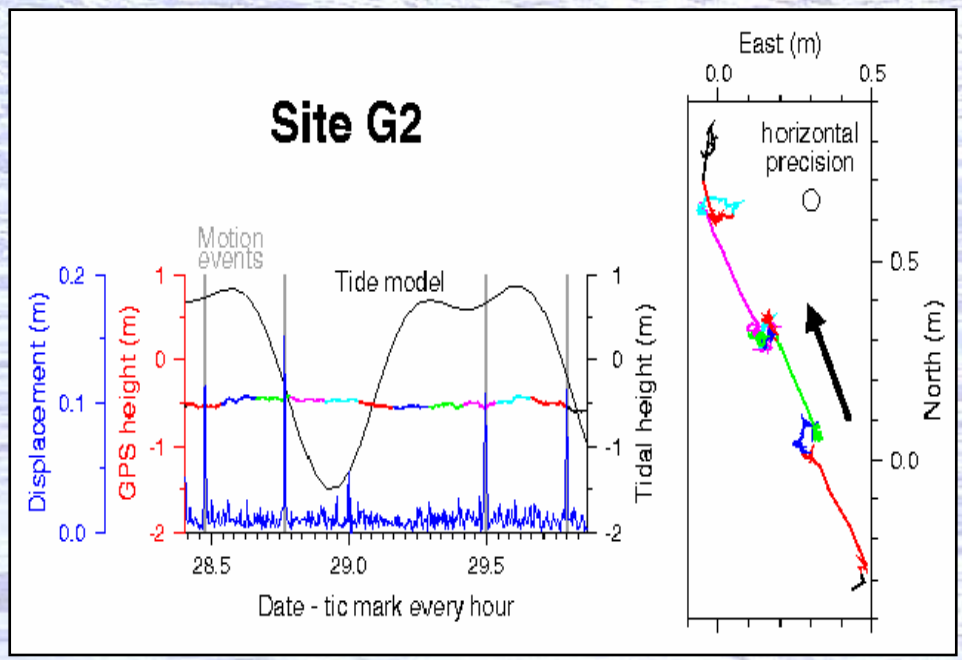


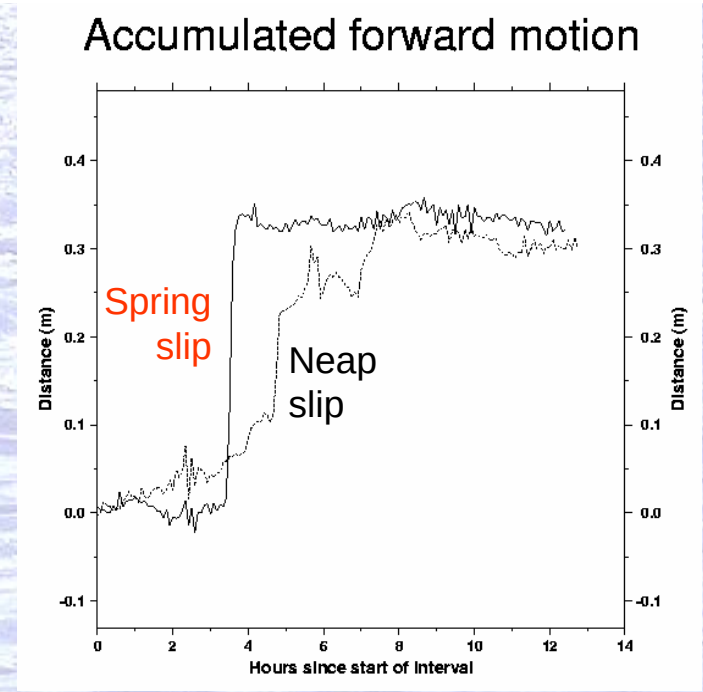
Nearly all of West Antarctica ice sheet and much of East Antarctica ice sheet rests on bed below sea level

Just one more water-driven effect to leave you with…

Ice Stream Sensitivity

- Tidal modulation
  - ±50% speed modulation is typical
  - Stick-slip is extreme case



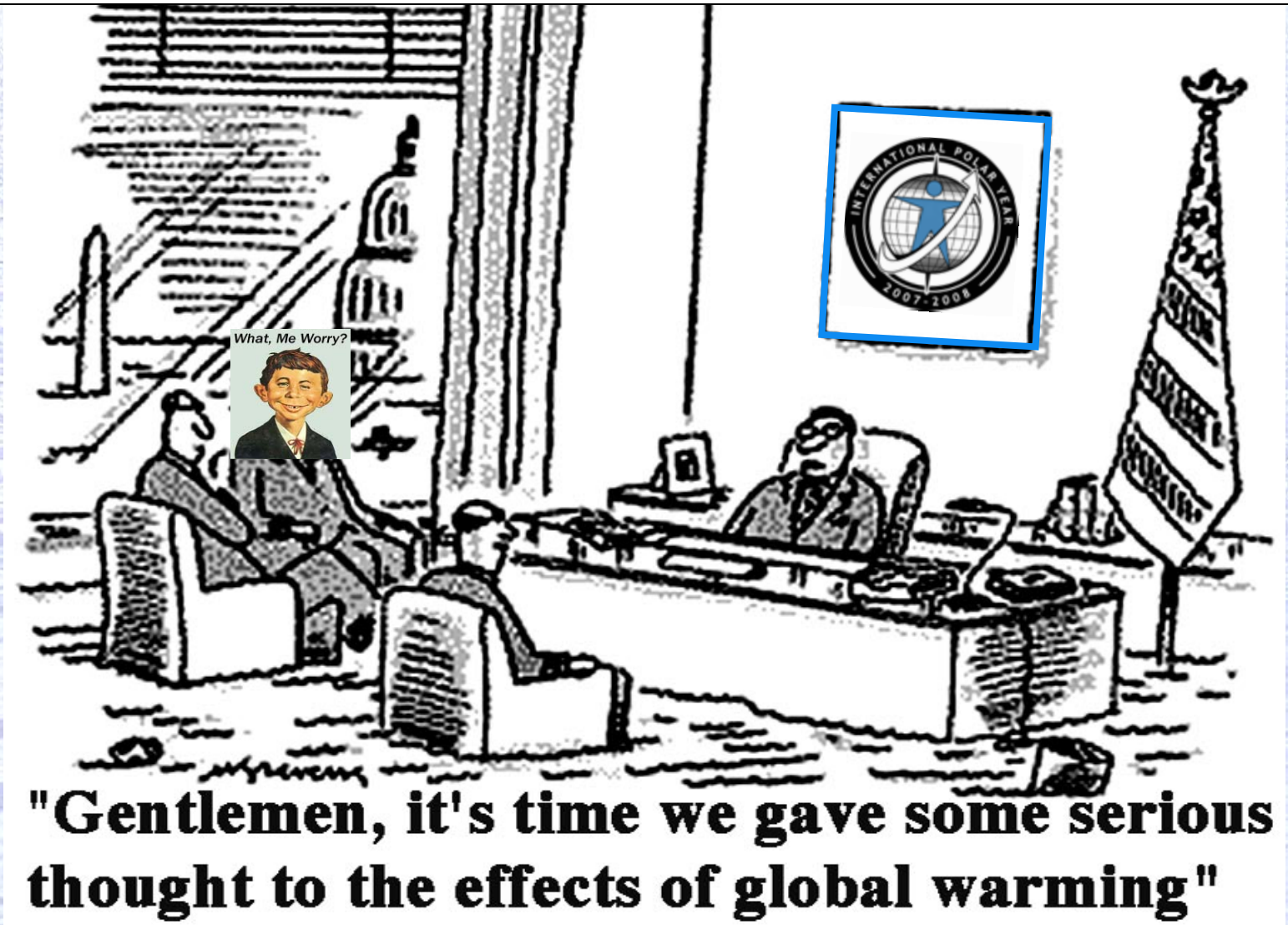


(Source: Bindschadler et al., 2003)

Summary

- Ice sheets HATE water
- Ice sheet loss (and rising sea level) will accelerate
  - Need to include rapid response characteristics in global climate models
- New modeling activities can lead, guide and leverage off of current and ongoing field studies
  - Must connect deep oceans to ice sheets
  - Tidewater glacier retreat an excellent analogue, but also unsolved
  - A 2-person effort is woefully inadequate

IPY is a Good Time to Learn about Ice Sheets



Thank you!

Photo: I. Joughin

Questions?