State of Antarctic and Greenland Ice Sheet Mass Balance and Ice-Sheet Modeling

Richard B. Alley, Penn State

Please note: I work for
Penn State University,
And help UN IPCC, NRC, etc.,
But I am not representing them,
Just me.

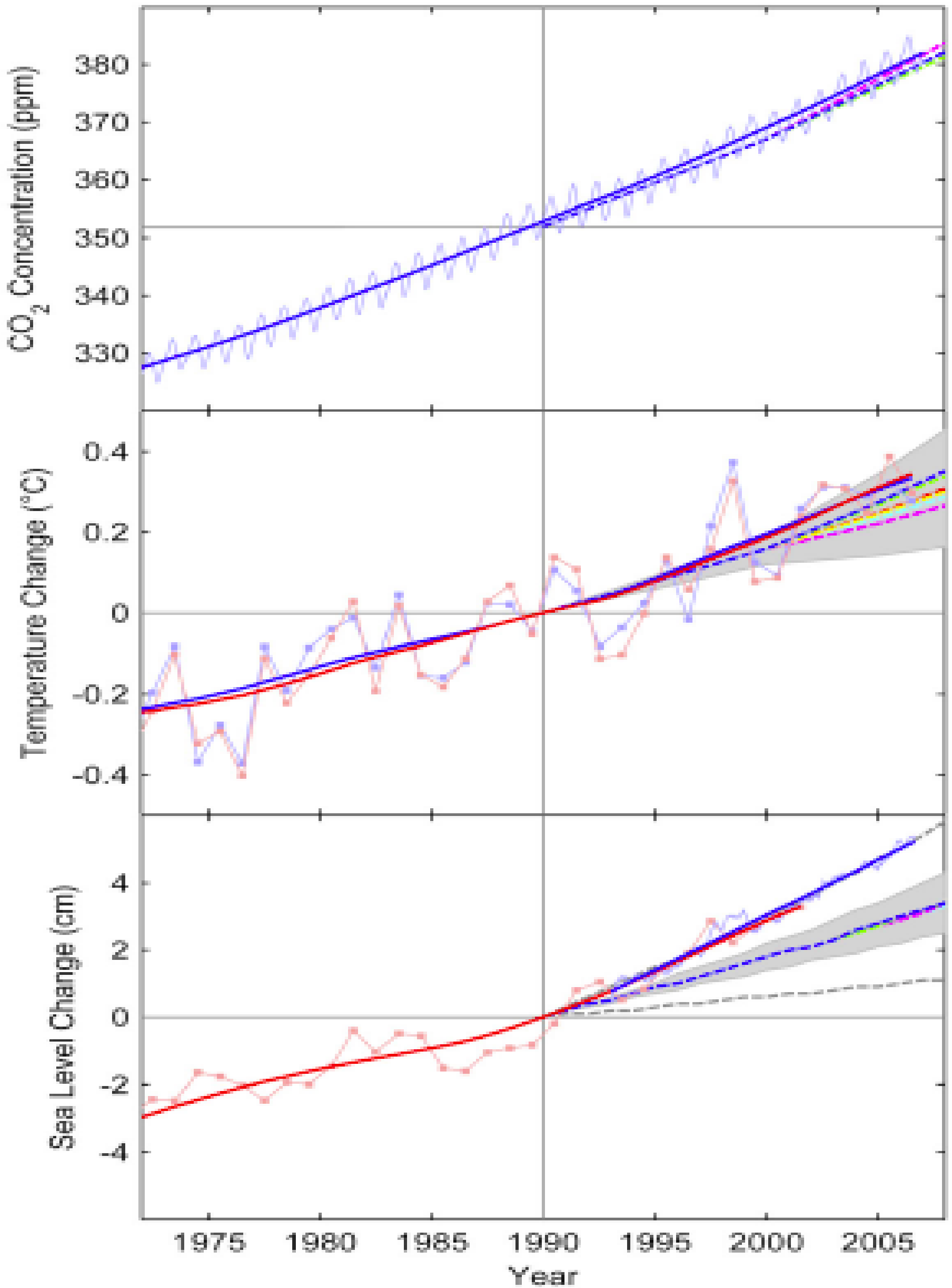
****AAAS, Chicago, 2009****

G. Comer Foundation

Photo by R.B. Alley, Scoresby Sund

No agreed-upon worst case; maybe 3-4x this rise?

Don't believe this could happen faster than centuries, but we might in decades reach the level that would commit us to this over centuries. Generally NOT in cost/benefit projections.



CO2 in atmosphere has followed IPCC-linked projections closely.

Temperature rise has been a bit larger than central projections, but well within error bars.

Sea-level rise has been well above central projections, and barely within error bars.

Rahmstorf et al., Science, 2007

IPCC on Ice Sheets

- 2001: Noted large uncertainties, but suggested central estimate of slight net growth over next century, with snowfall increase in cold parts exceeding melting increase in warmer parts, and with little ice-flow change
- 2007: Ice sheets now shrinking, in part because of ice-flow change in response to warming
- "Models used to date do not include…the full effects of changes in ice sheet flow, because a basis in published literature is lacking… understanding of these effects is too limited to… provide a best estimate or an upper bound for sea level rise." (IPCC WG1 AR4 SPM 2007)

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] Best estimate	Temperature Change *Likely* range	Sea Level Rise (m at 2090-2099 relative to 1980-1999) 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

Table notes:

[a] These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth Models of Intermediate Complexity (EMICs), and a large number of Atmosphere-Ocean Global Circulaion Models (AOGCMs).

[b] Year 2000 constant composition is derived from AOGCMs only.

Model-based projections of global average sea level rise at the end of the 21st century (2090-2099) are shown in Table SPM-3. For each scenario, the midpoint of the range in Table SPM-3 is within 10% of the TAR model average for 2090-2099. The ranges are narrower than in the TAR mainly because of improved information about some uncertainties in the projected contributions[15]. {10.6}

[15] TAR projections were made for 2100, whereas projections in this Report are for 2090-2099. The TAR would have had similar ranges to those in Table SPM-2 if it had treated the uncertainties in the same way. [p. 15]

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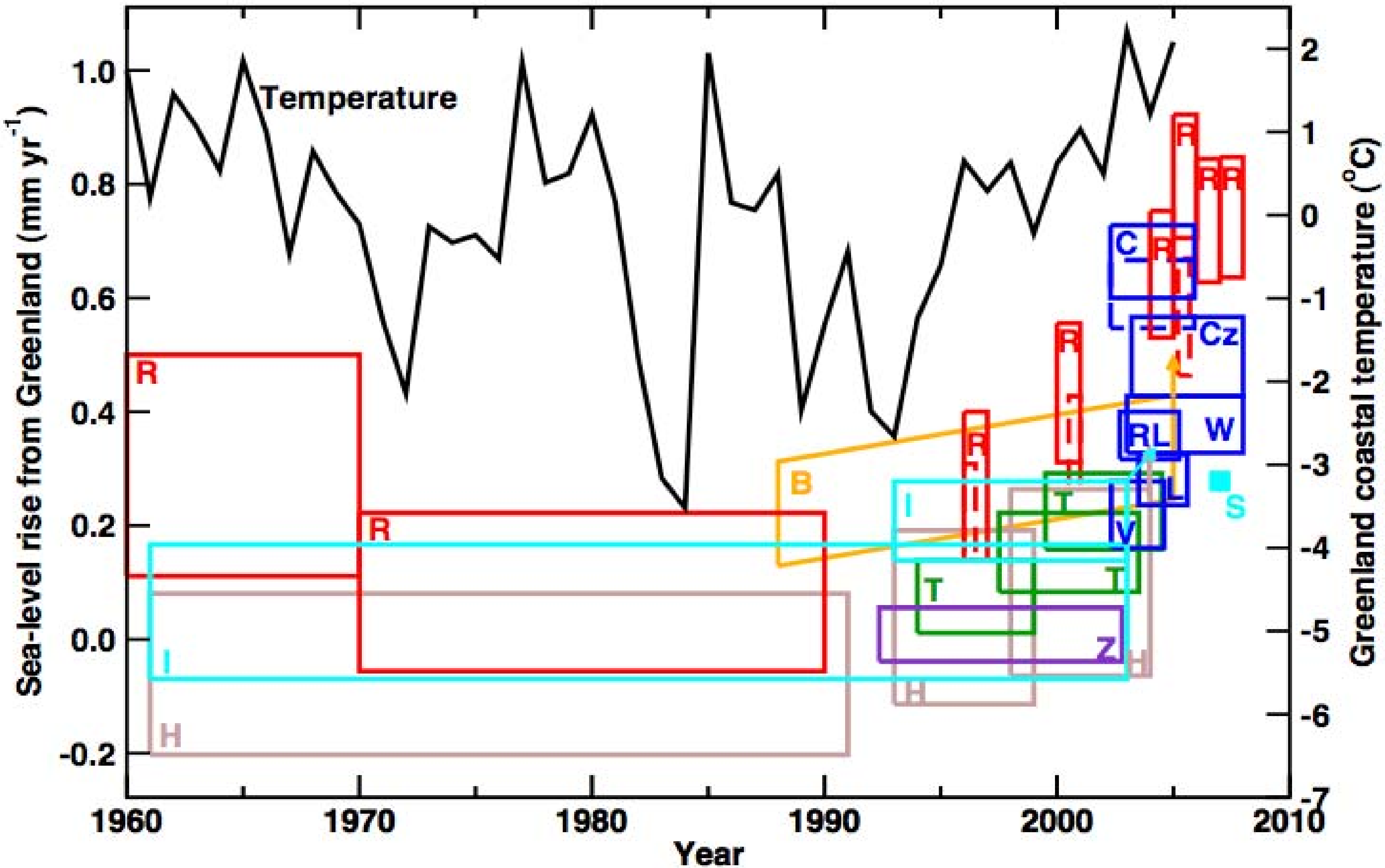
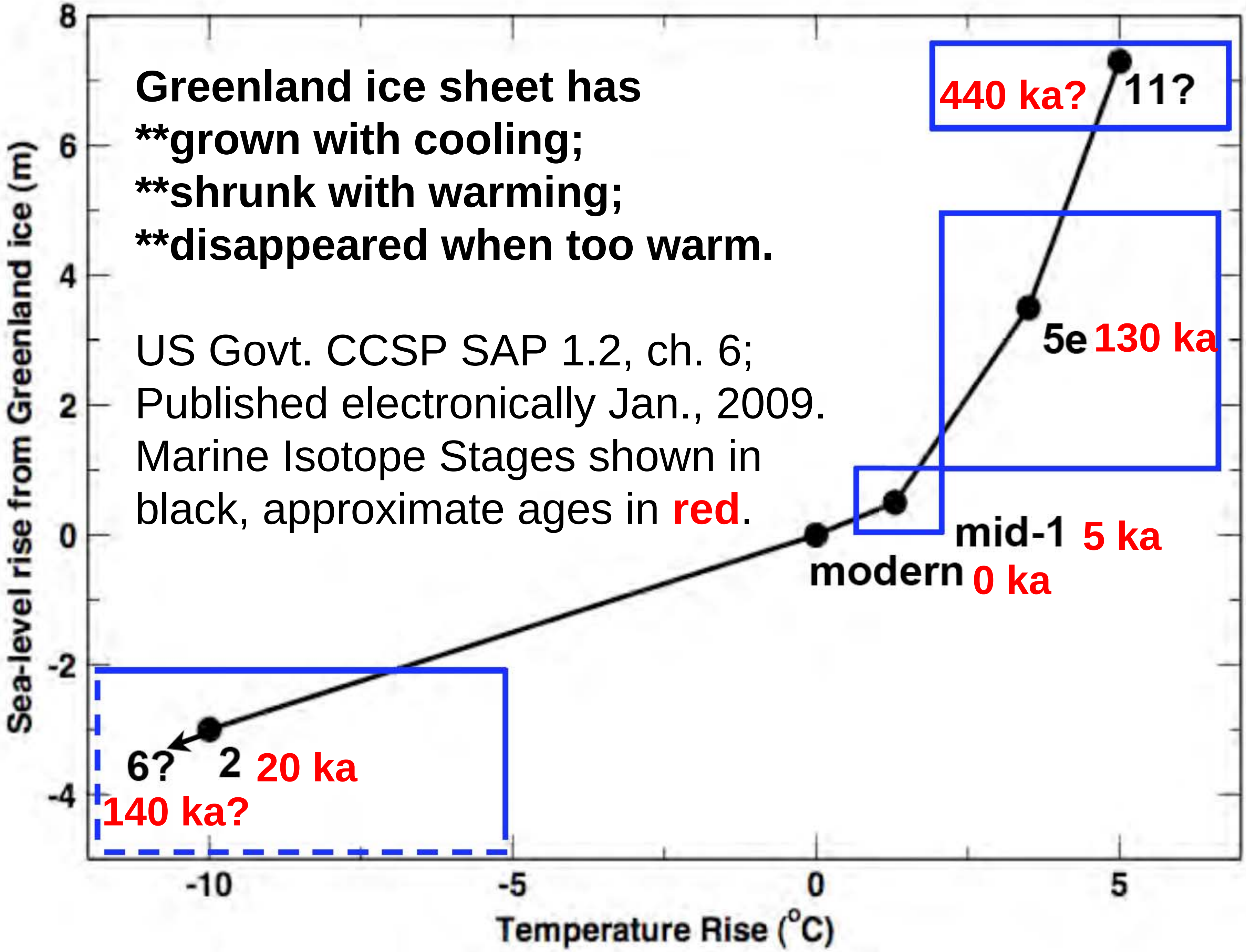
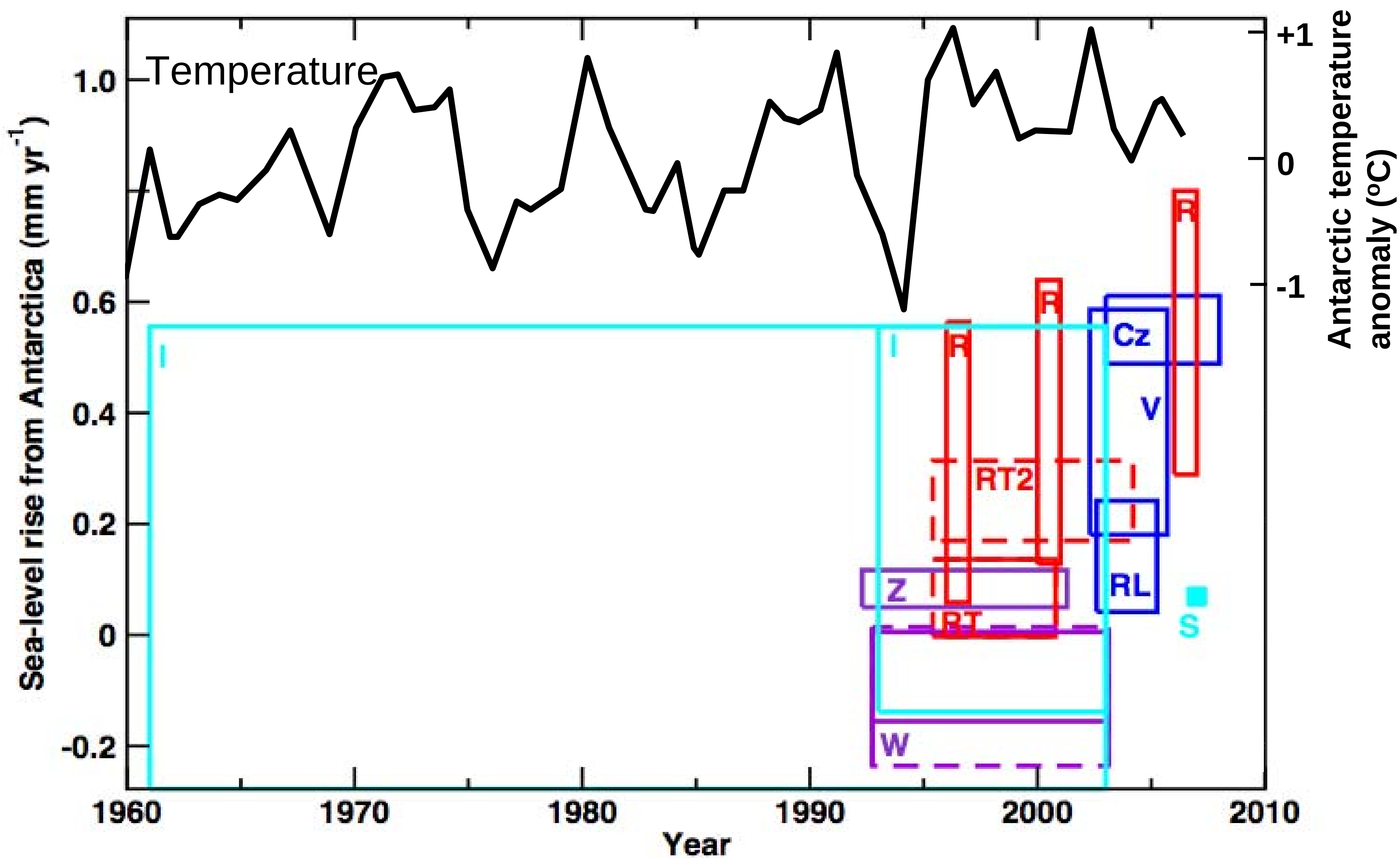
Merged S & W Greenland coastal temperatures infilled, Ilulissat, Nuuk and Qaqortoq. Vinther, B.M., K.K. Andersen, P.D. Jones, K.R. Briffa and J. Cappelen, Extending Greenland Temperature Records into the late 18th Century, JGR, 111, D11105. http://www.cru.uea.ac.uk/cru/data/greenland/swgreenlandave.dat) B=Box+ 2006; C=Chen+ 2006; Cz=Cazenave+ 2008; H=Hanna+ 2005; I=IPCC 2007L=Luthcke+ 2006; T=Thomas+ 2006; Z=Zwally+ 2006; R (dashed)=Rignot+Kanagaratnam 2006; R (solid)=Rignot+ 2008 S=Shepherd+ 2007; RL=Ramillien+ 2006; V=Velicogna+Wahr 2005; W=Wouters+ 2008



tan+orange=snowfall-melt-assumed discharge; green+violet primarily altimetry; red=snowfall-melt-discharge; dark blue=GRACE; light blue=assessment; updated from Alley et al., 2007


Greenland ice sheet has
**grown with cooling;
**shrunk with warming;
**disappeared when too warm.
US Govt. CCSP SAP 1.2, ch. 6;
Published electronically Jan., 2009.
Marine Isotope Stages shown in
black, approximate ages in red.
440 ka?
11?
5e
130 ka
mid-1
5 ka
modern
0 ka
6?
2
20 ka
140 ka?
Sea-level rise from Greenland ice (m)
Temperature Rise (°C)
8
6
4
2
0
-2
-4
-10
-5
0
5

Cz=Cazenave+ 2008; I=IPCC 2007; R=Rignot+ 2008; RL=Ramillien+ 2006; RT=Rignot+Thomas 2002; RT2=update of RT including additional losses from Thomas+ 2004 + Rignot+ 2005; V=Velicogna+Wahr 2006; W=Wingham+ 2006; Z=Zwally+ 2005; Temperature=Steig+ 2009 hand-digitized average of E+W Antarctic.



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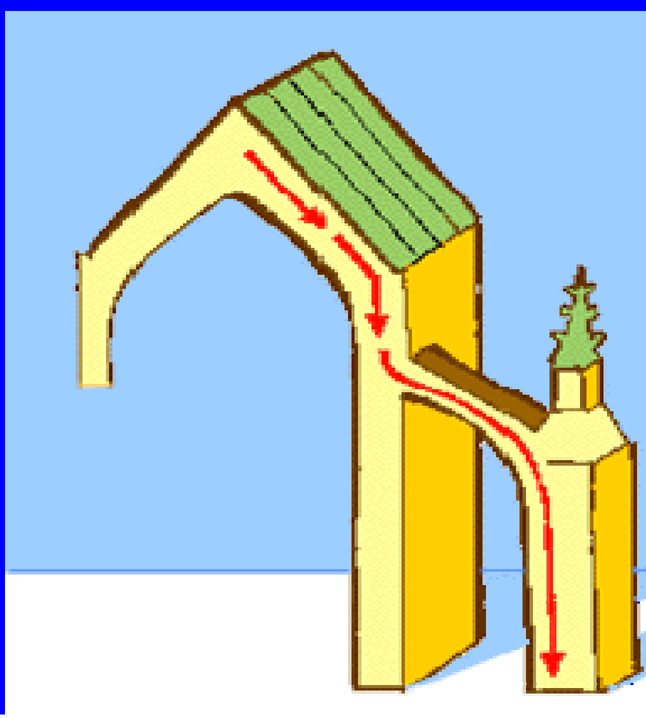
All piles tend to spread under own weight:

- Strong things resist spreading (a block of wood), but weak things spread easily (pancake batter);
- Lubrication speeds spreading (pancake batter spreads faster on a greased griddle than on a waffle iron);
- Supports oppose spreading (a flying buttress keeps a cathedral from spreading and falling apart).



www.designcommunity.com/scrapbook/images/1032.gif

www.pbs.org/wgbh/buildingbig/skyscaper/gothic.html

An ice sheet is a two-mile-thick, continent-wide pile

- Spreads under its own weight;
- Snowfall on center adds to pile;
- Melting at edges, or break-off of icebergs, subtract from pile;
- Increase in snowfall grows pile; faster melting or faster flow shrink pile;
- Water in ice-sheet pile came from ocean, so sea level falls when ice sheet grows, and sea level rises when ice sheet shrinks.

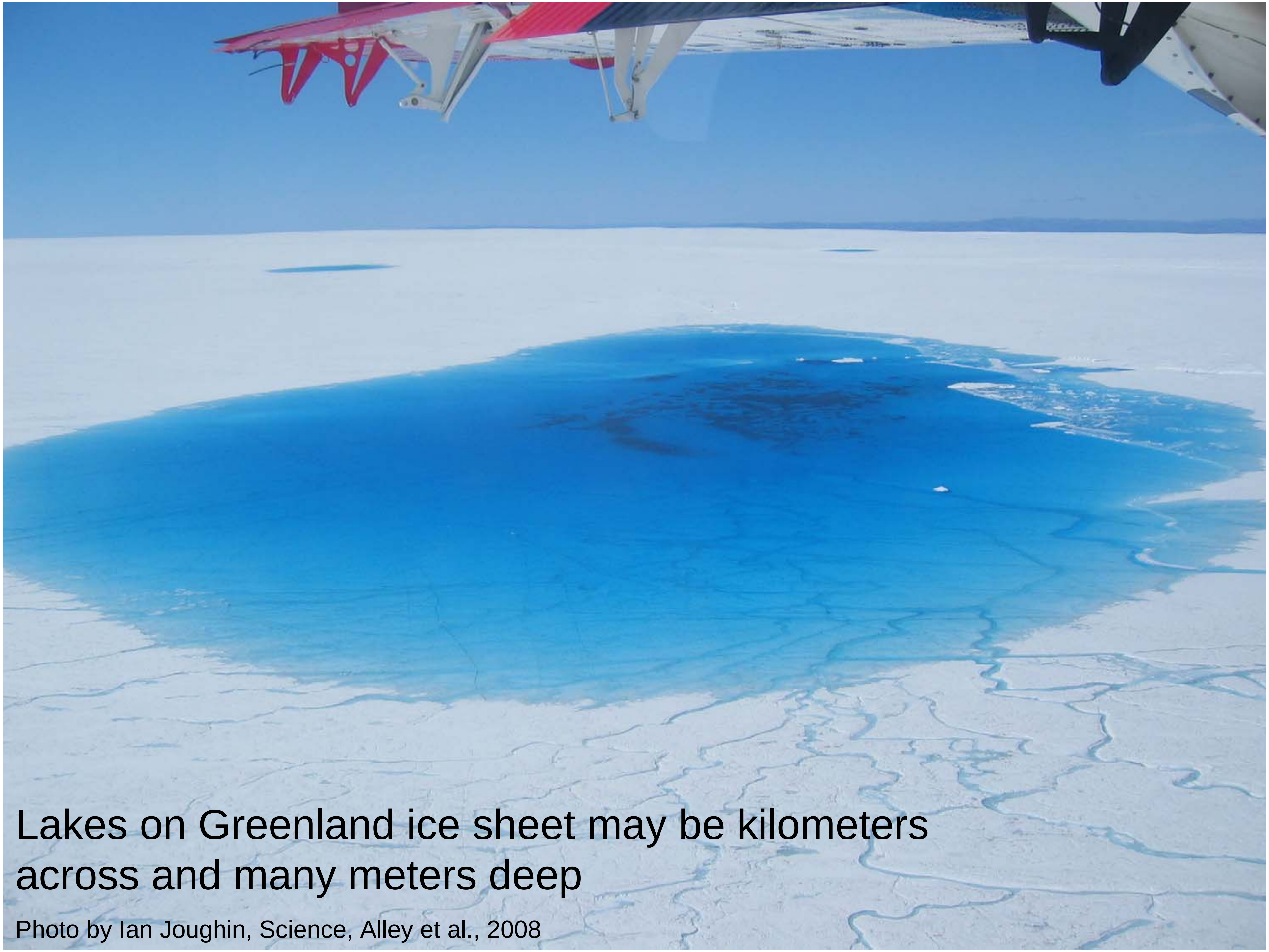
Meltwater drains through Greenland

- Accelerates flow somewhat by lubricating the bed (averaged over a year, effect of surface meltwater on basal velocity probably order of 10%, so while additional melt in future may speed mass loss, but probably not huge);
- Thermal effects of surface meltwater may be more important…

Zwally et al., 2002, Science

Bigger issue with meltwater:

- Central Greenland frozen to bed, with almost no basal motion;
- Thawing a frozen bed speeds motion, a little to a lot--2x useful first guess?
- Time for surface warming to penetrate to bed through ice is ~10,000 yr;
- Time for surface meltwater reaching bed to have similar effect ~10 minutes or less…



Lakes on Greenland ice sheet may be kilometers across and many meters deep

Photo by Ian Joughin, Science, Alley et al., 2008

Air-filled crevasses can penetrate only a small fraction of the ice-sheet thickness, but water-filled crevasses can break through to and along the bed.

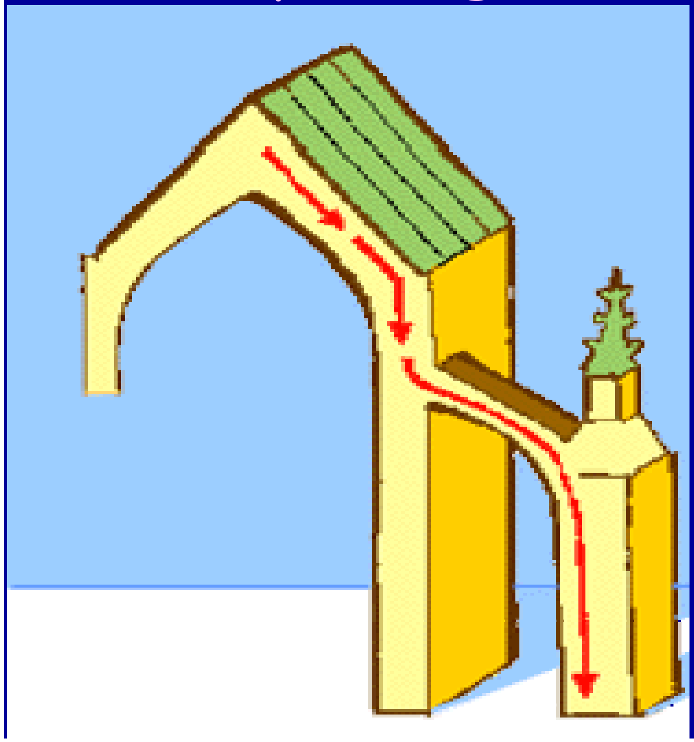
Photo from Sarah Das, Science, Das et al., 2008

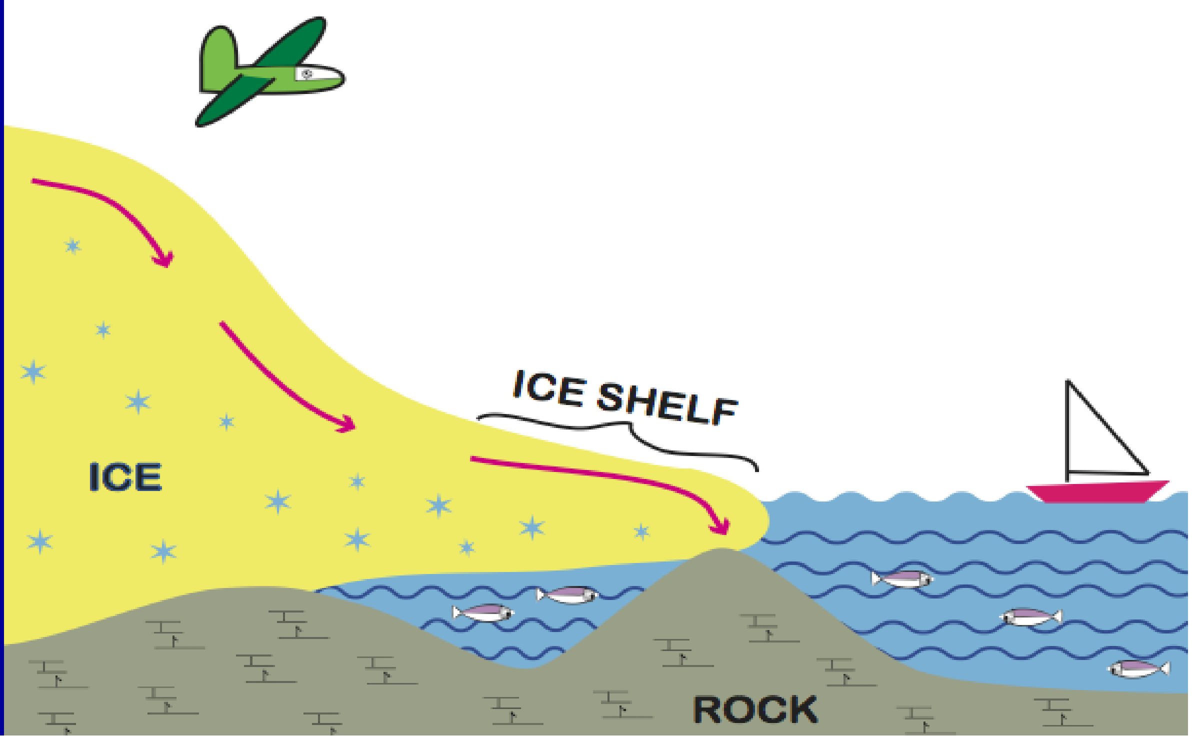
Meltwater-penetration:

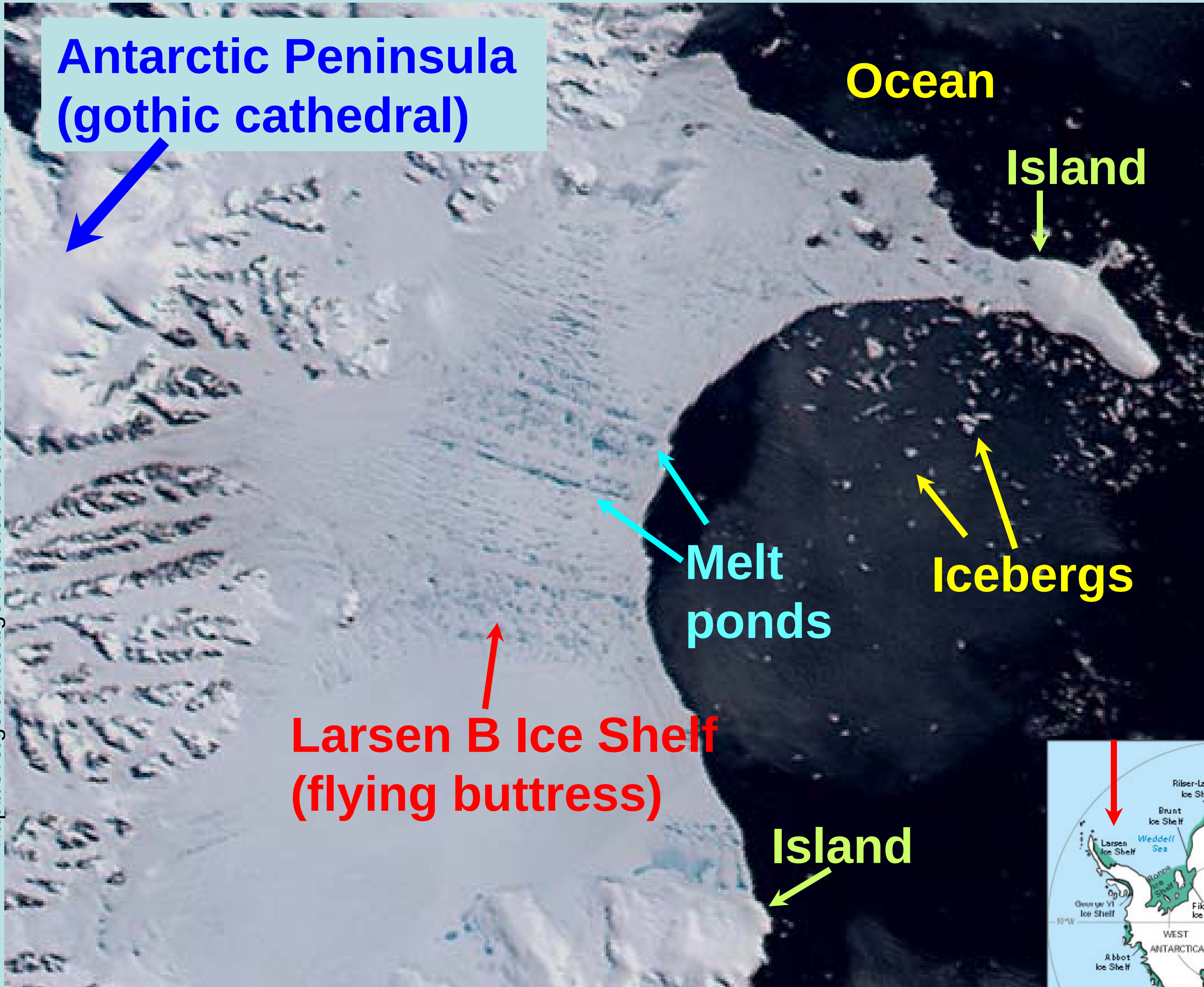
- Meltwater is getting through ice near edges of Greenland (Zwally et al., 2002)
- Mass loss will increase (up to 2x?) if meltwater access to bed migrates inland with warming (Parizek & Alley, 2004)
- Model: Meltwater accesses bed through lake-driven crevasses (Alley et al., 2005)
- Observed: Crevasse lake-drainage exceeding Niagara Falls (Das et al., 2008)
- Future: Work to do, but expect somewhat accelerated mass loss

Ice sheets have "flying buttresses", too

- Floating extensions called "ice shelves"--ice flows over water for a while before breaking off to make bergs;
- Ice shelves may run aground on islands or scrape past rocky sides of bays;
- Friction from this slows ice-sheet spreading;
- Warming air or water can attack ice shelves quickly, speeding ice-sheet spreading and sea-level rise.







12 mi
20 km

http://svs.gsfc.nasa.gov/vis/a000000/a002400/a002421/index.html

January 31, 2002

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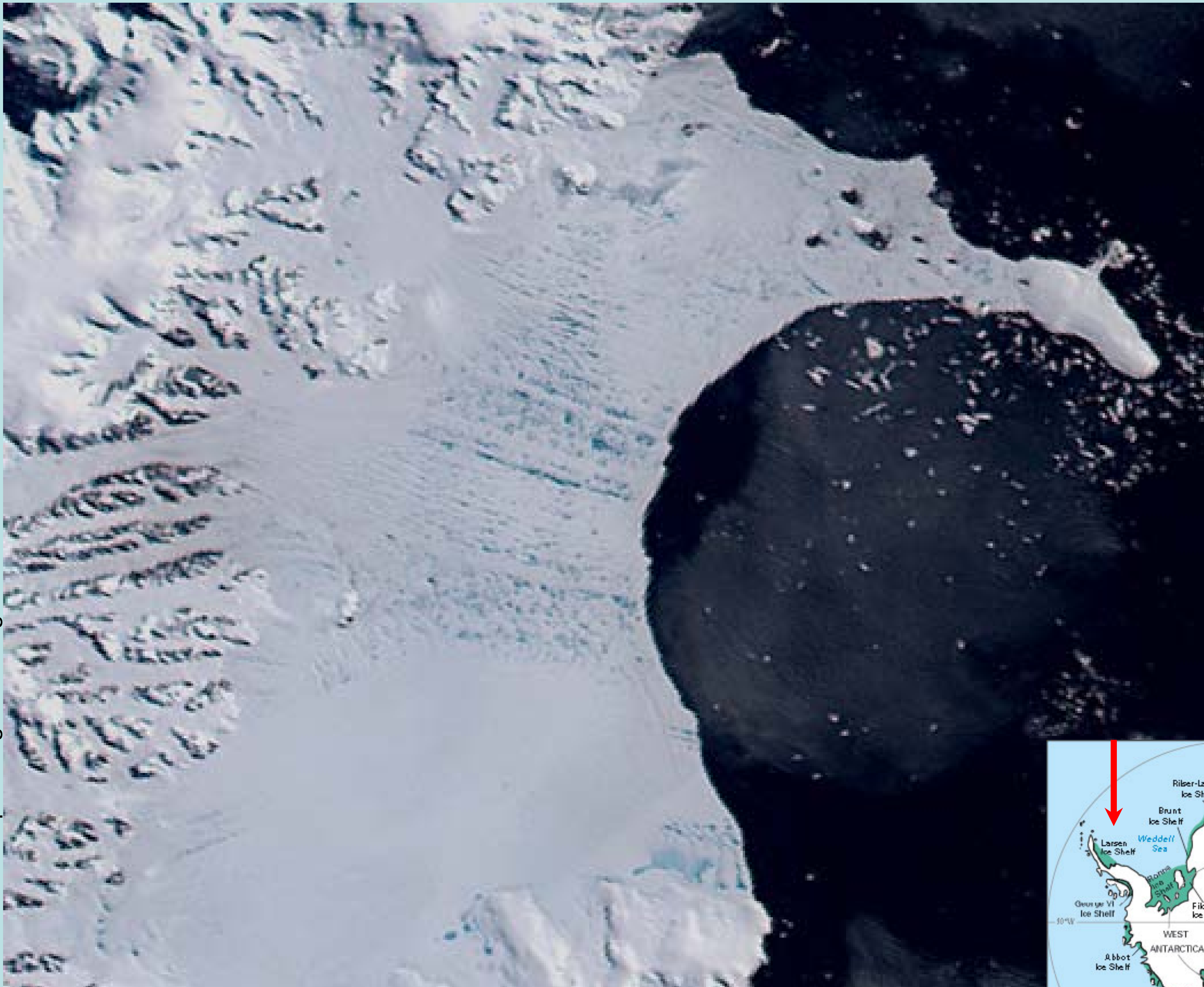

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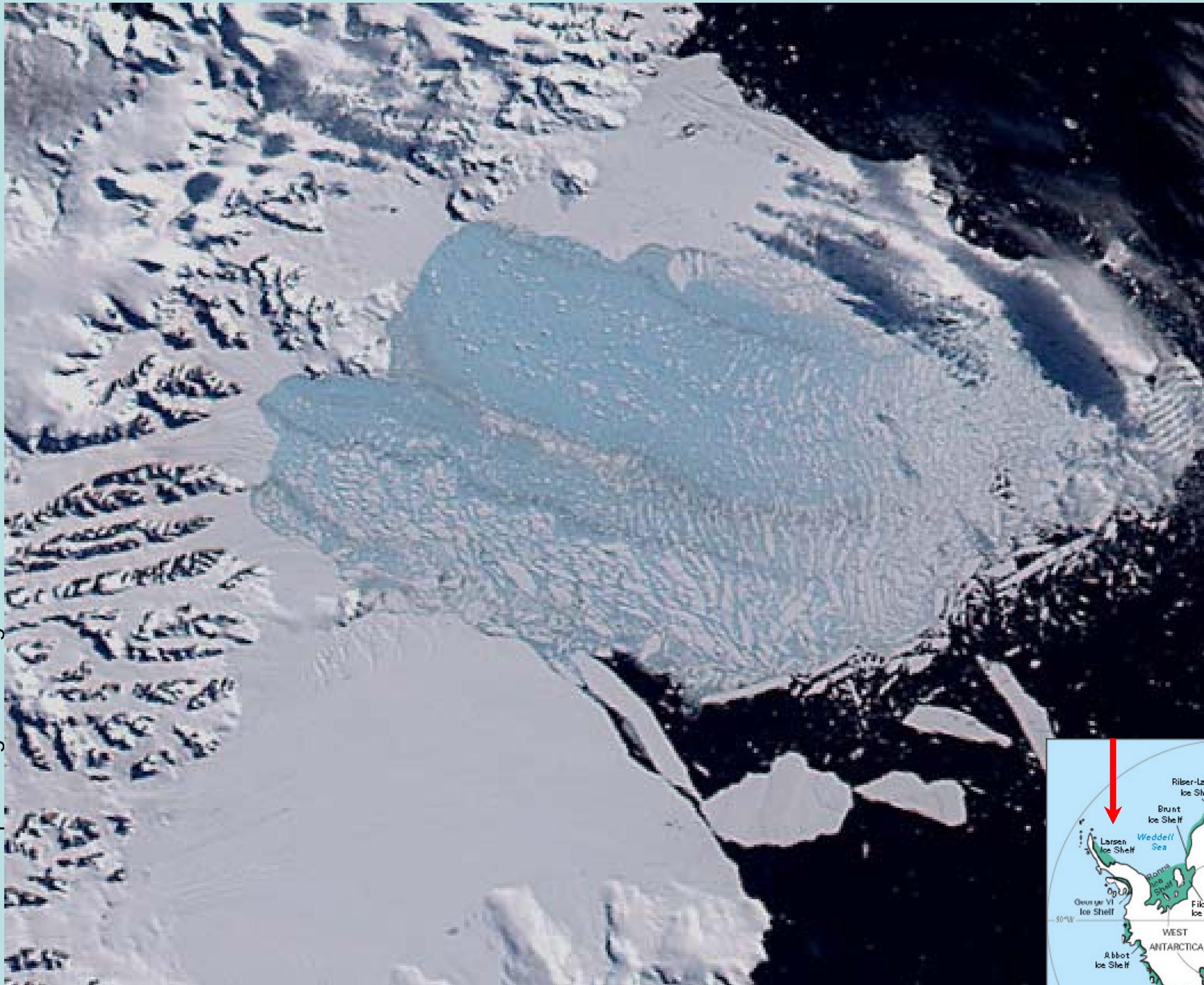


12 mi
20 km

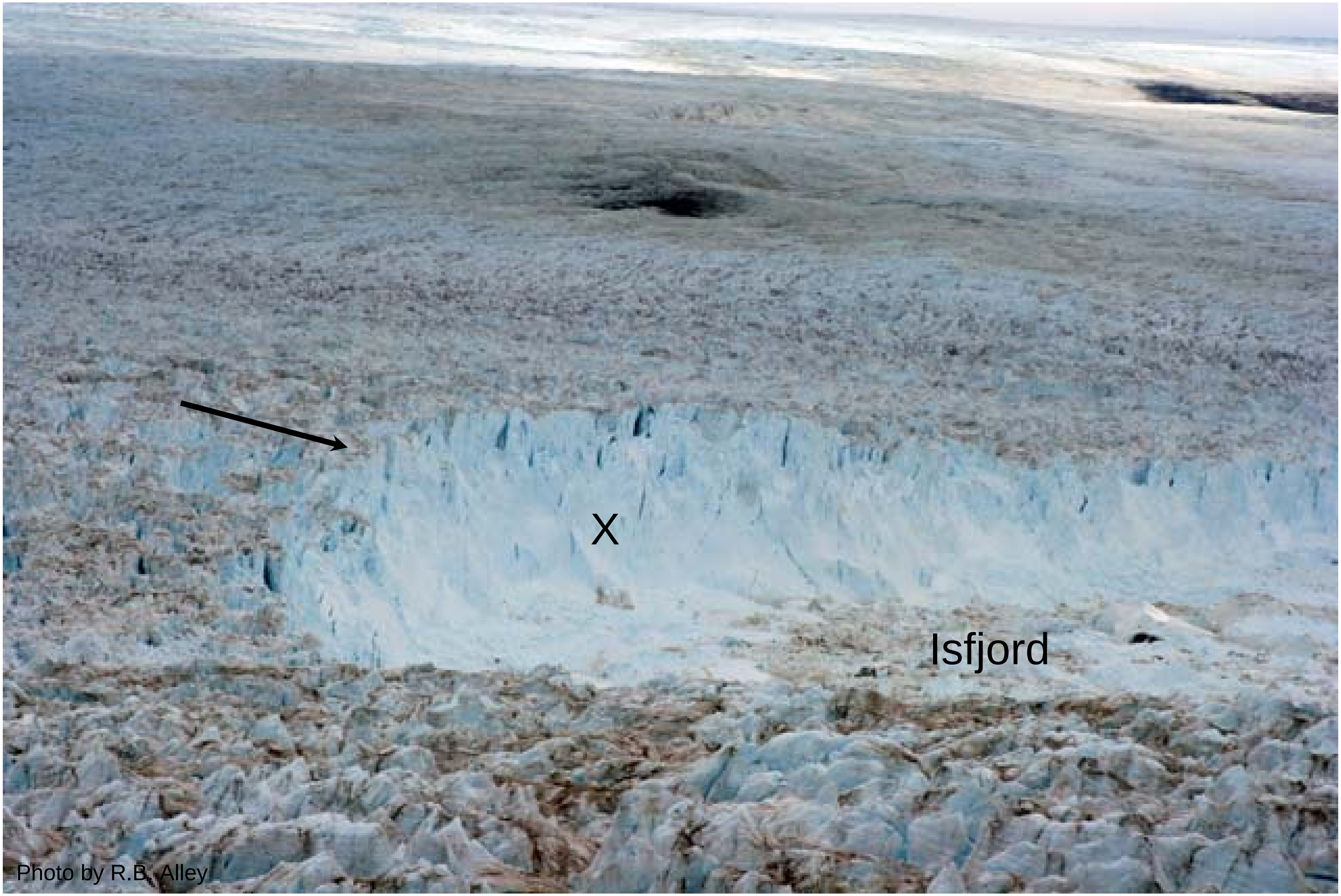
March 7, 2002. **8x tributary flow-speed increase followed**

Jakobshavn Ice Stream in Greenland

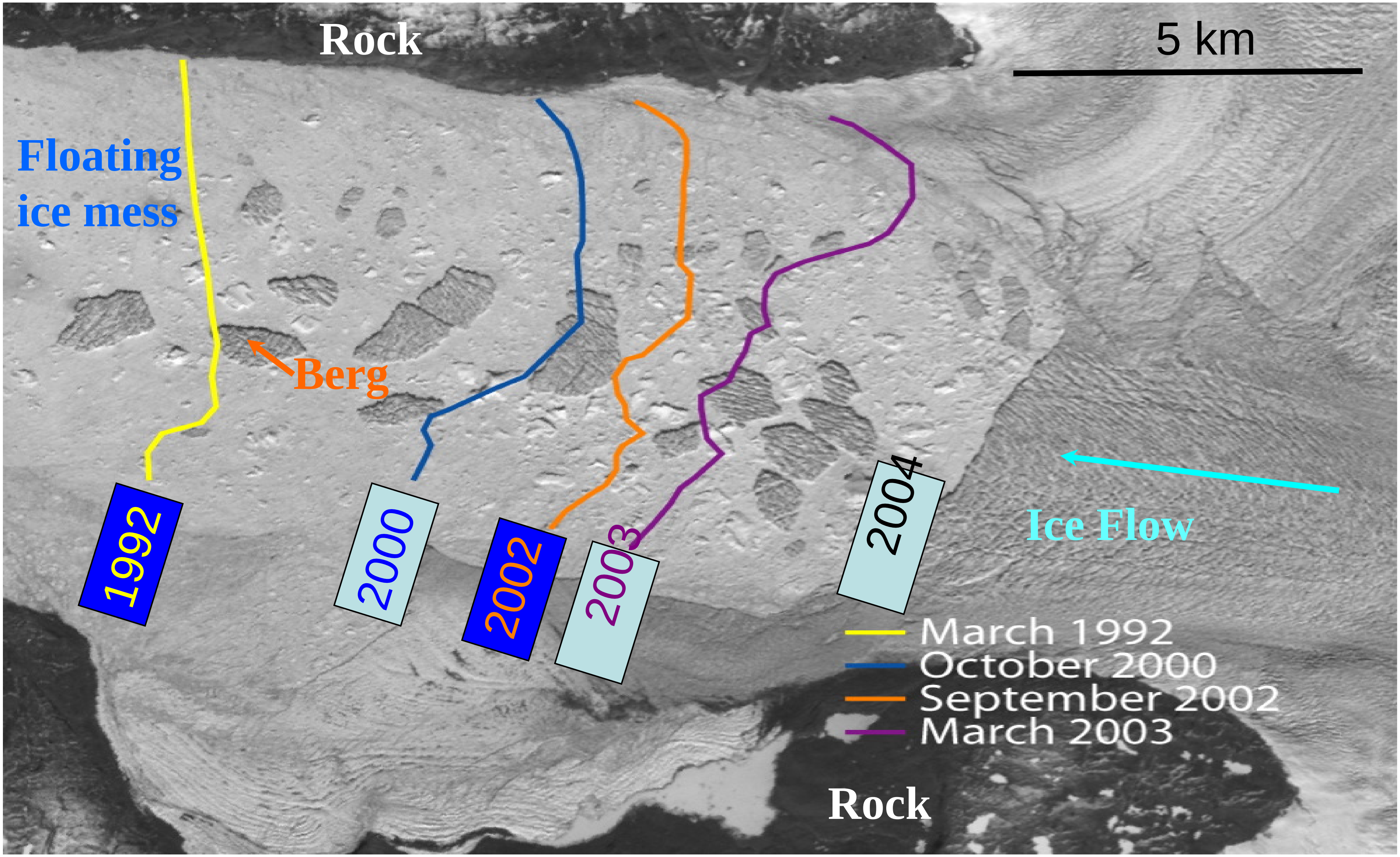
Discharge from many major Greenland ice streams has accelerated markedly.

Source: Prof. Konrad Steffen, Univ. of Colorado

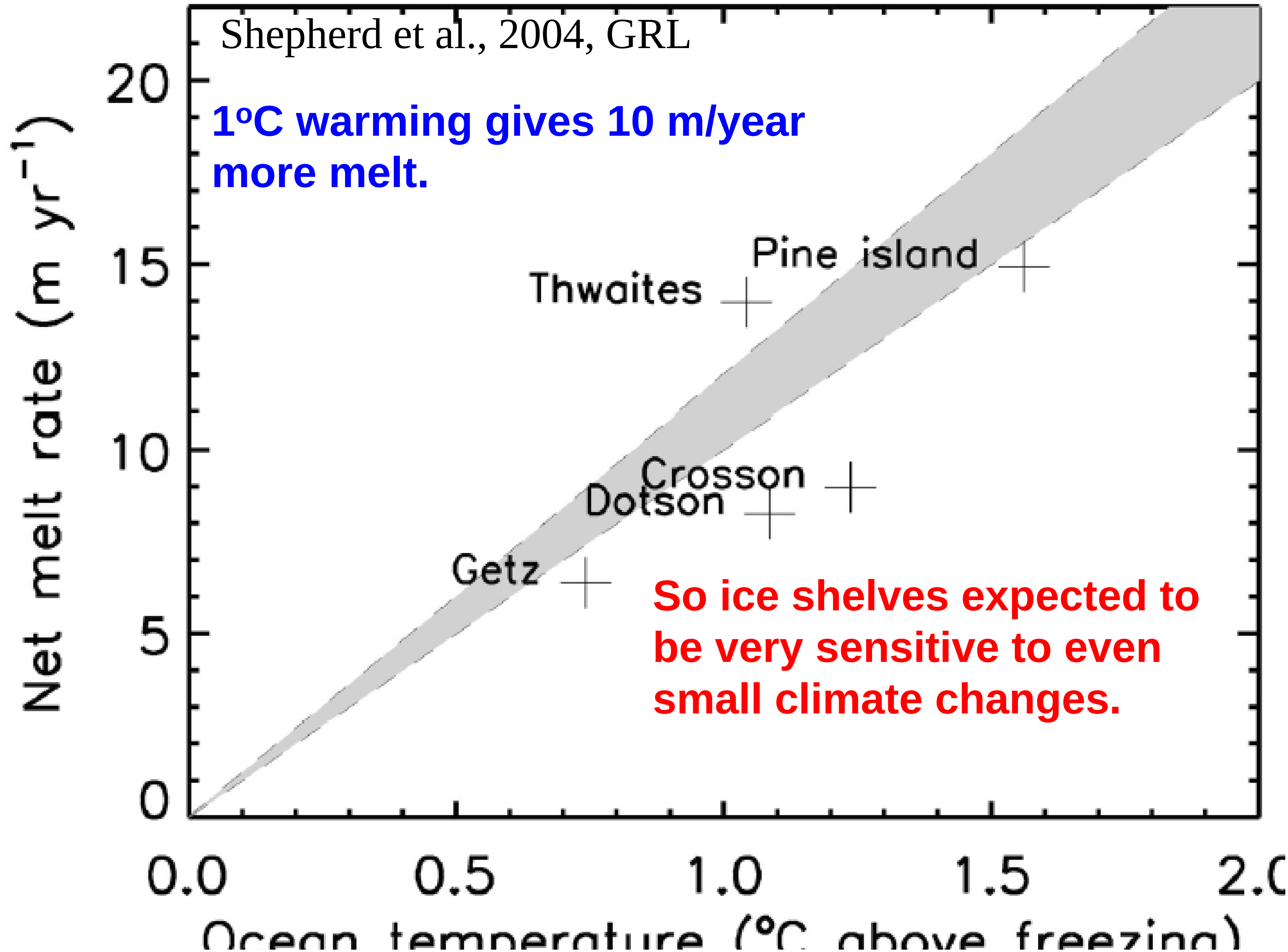
Seal, in Jakobshavn Isfjord. The fjord is so clogged with ice calved from the glacier that it is sometimes hard to realize that deep seawater lies beneath. This seal, far up the fjord, is good evidence that indeed an appropriately equipped swimmer can get here. Photo by R.B. Alley

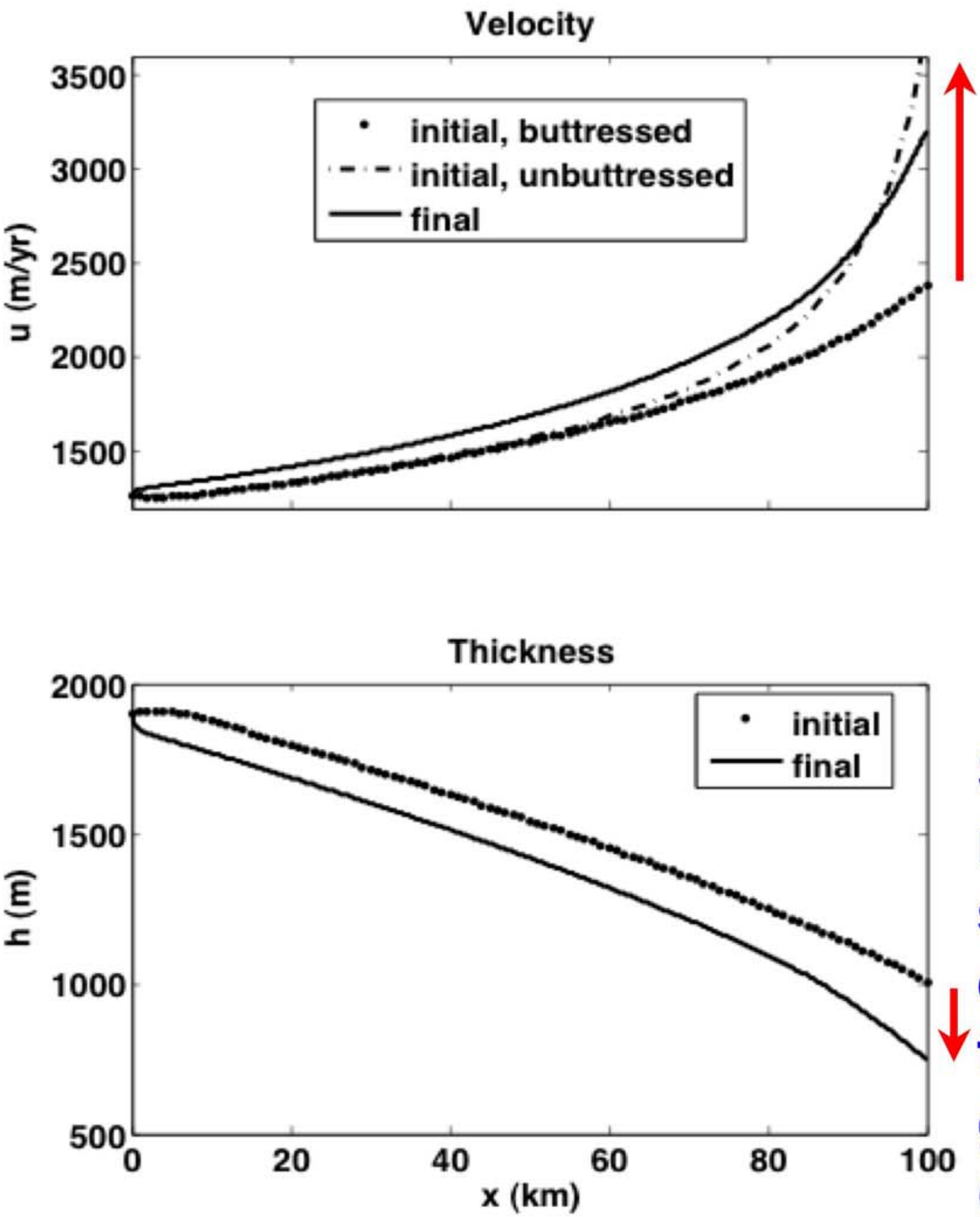


The calving front of Jakobshavn. Ice flows down from the Greenland ice sheet on the left, along the arrow. On the right is the Isfjord, ocean water clogged with loose icebergs that have calved off. “X” marks the couple-hundred-foot-high cliff where icebergs form, falling down into the Isfjord where broken ice covers sea water.



Jakobshavn Isbrae, W. Greenland. Retreat with speed doubling during ice-shelf loss, which likely was caused by warming. Image courtesy Ian Joughin (Alley et al., 2005).


Shepherd et al., 2004, GRL
1°C warming gives 10 m/year
more melt.
So ice shelves expected to
be very sensitive to even
small climate changes.
Pine island
Thwaites
Crosson
Dotson
Getz
Net melt rate (m yr⁻¹)
0
5
10
15
20
0.0
0.5
1.0
1.5
Ocean temperature (°C above freezing)



Instantaneous speed-up from loss of small ice shelf with side drag initially offsetting 50% of spreading tendency of freely floating ice. Dupont & Alley, 2005; Payne et al similar

"One-off" forcing (kick it once and not again), like Pine Island Glacier ice stream; response not allowed inland of ice stream.

e-folding time for thinning and other response ~20 years.

Simple models can match real events, and show strong ice sensitivity to edge changes. Integrated full-ice-sheet models generally lack this (improvements coming).

Modeling the real physics

- Simplified models exist that capture the key physics
- All require tuning of poorly known physical variables
- Comprehensive models with key physics being developed
- Likely to require data-assimilation for initialization
- Efforts underway at some large modeling centers to add ice sheets (e.g., Los Alamos for NCAR model, GFDL)
- I don't see resource commitment to ice sheets that is devoted to oceans and atmospheres
- I doubt problem soluble without such resources
- That's a personal opinion (but an informed one…)
- There will be need for a lot of field, laboratory and remote-sensing work to support the modeling effort

Synopsis

- Warming melts ice and raises sea level
- No reliable evidence that snowfall rises enough with warming to offset increasing melting and spreading, and much evidence that snowfall doesn't rise enough
- Probably centuries or more to lose an ice sheet
- Might commit to dumping one within decades
- No reliable projections or worst-case scenarios
- Good work ongoing, but commitment of large modeling centers looks small to me compared to effort on other key parts of climate system


Photo by R.B. Alley