Ice sheets and sea-level rise
Constraining the unknown unknowns

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Symposium on Advanced Assimilation

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

G. Comer Foundation


Thanks to Fuqing Zhang for his leadership, and to you for coming to this fascinating meeting
earth
THE OPERATORS' MANUAL
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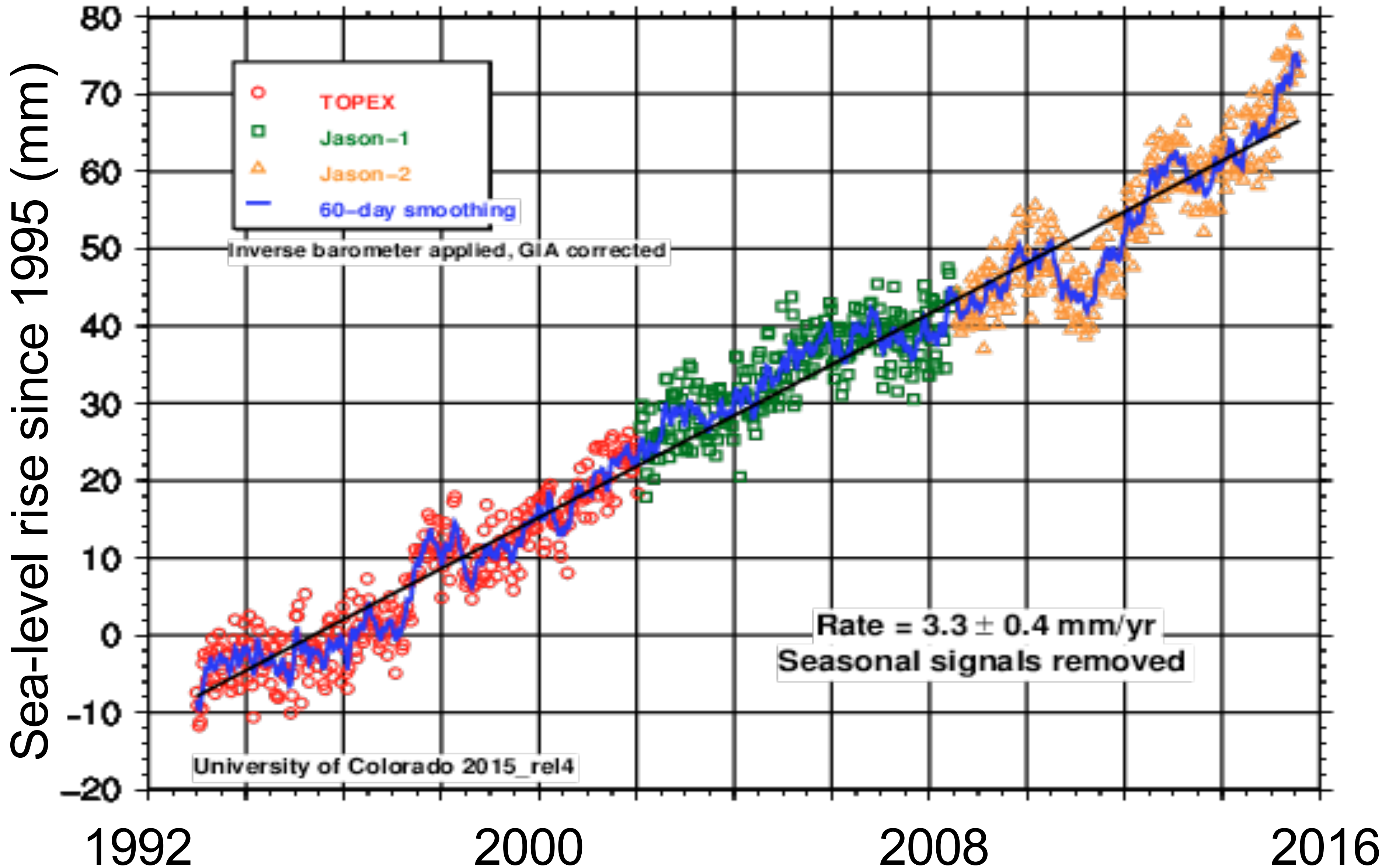
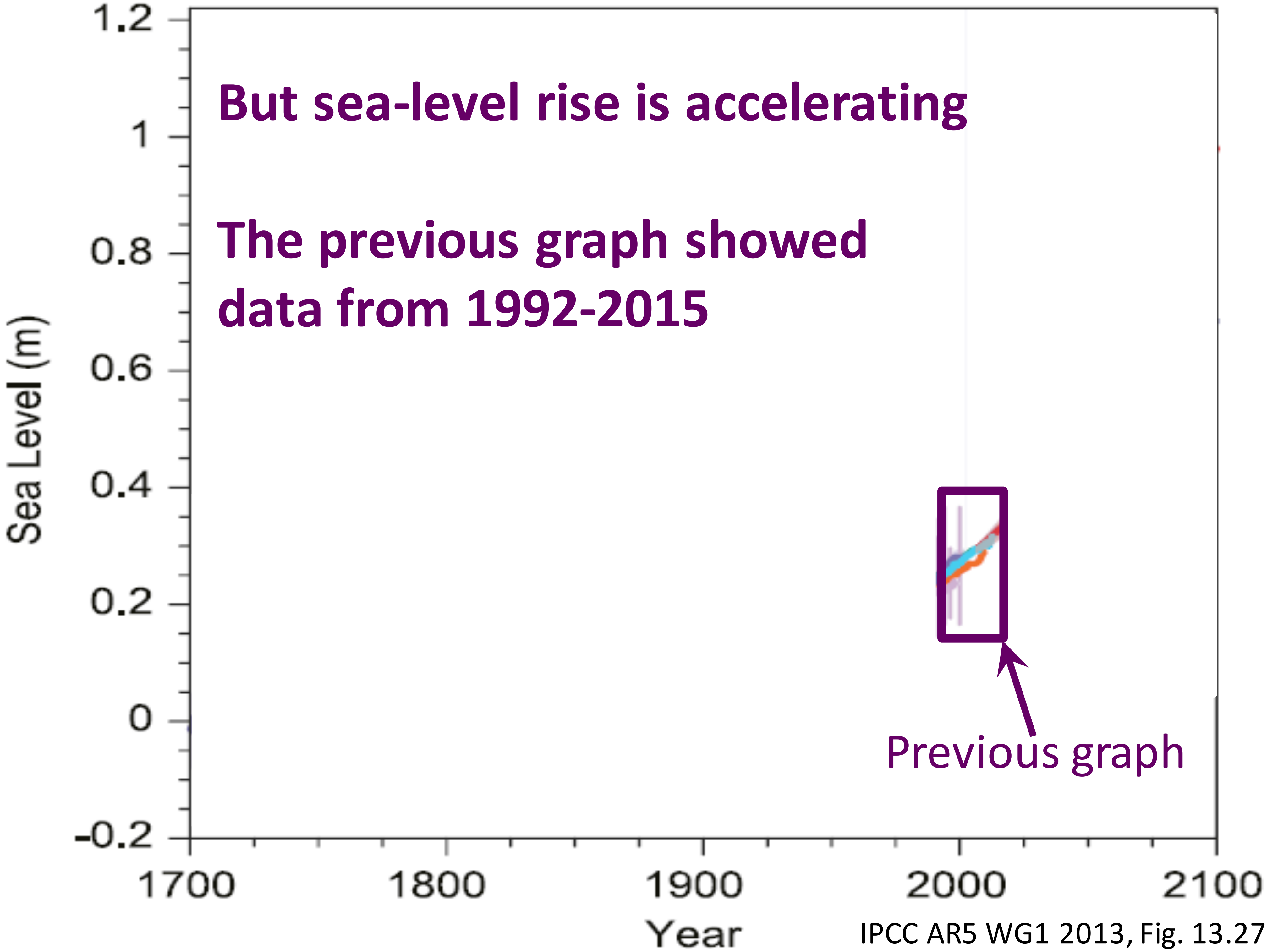
CRESIS
PENNSTATE
1855

Data show sea level is rising. At this rate, 1 foot of rise would take almost a century.

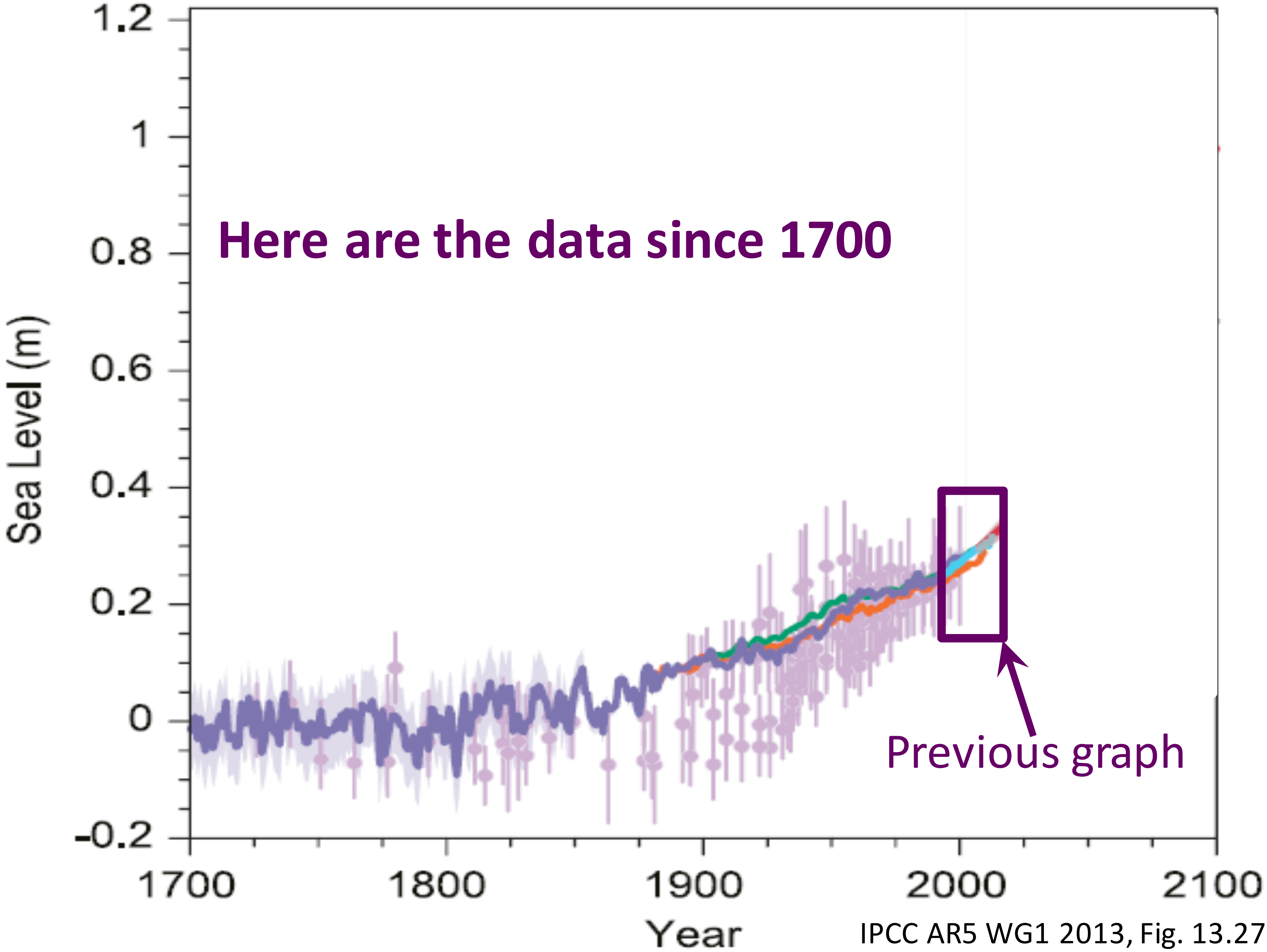
http://sealevel.colorado.edu/



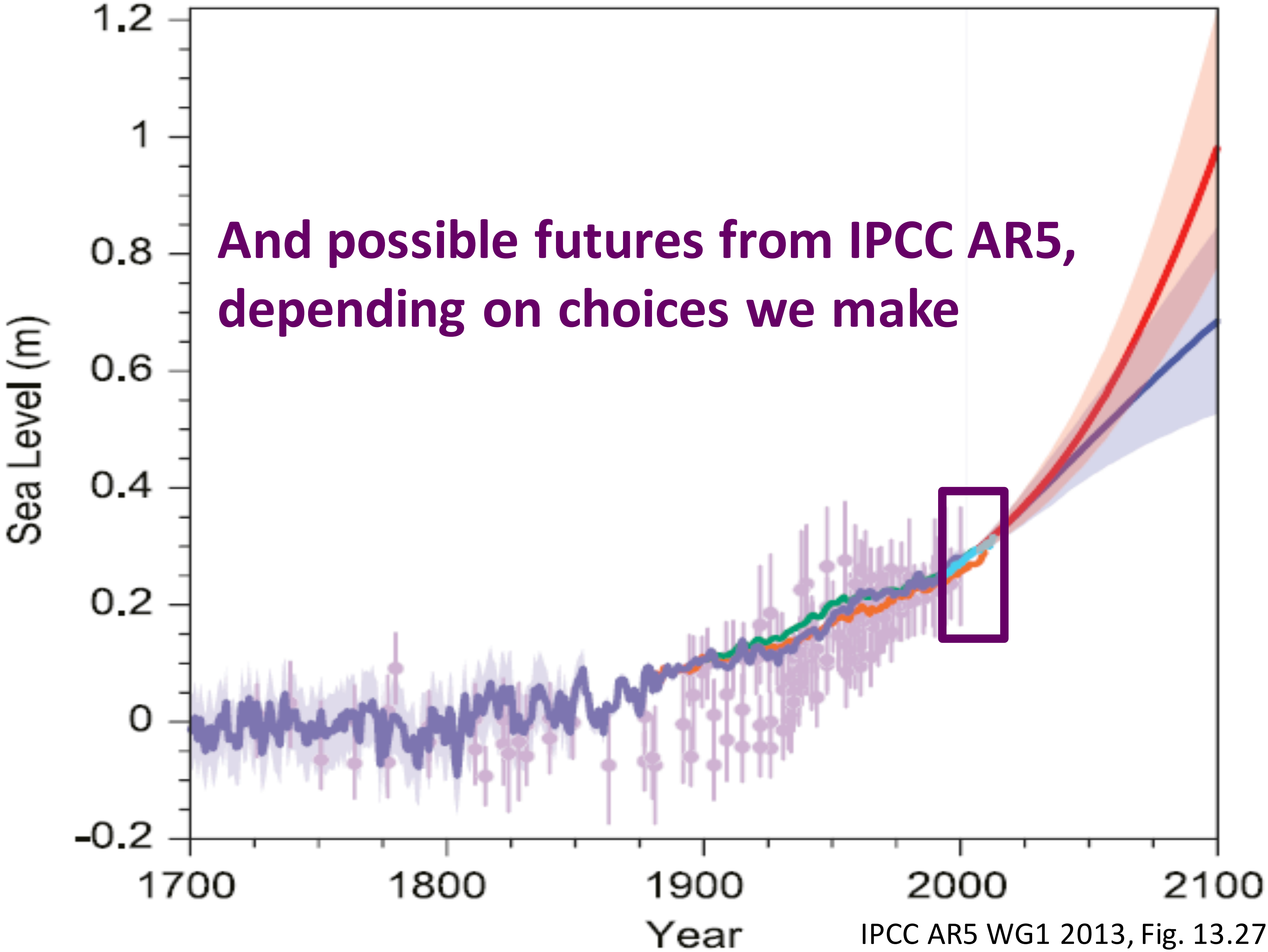

Even a little sea-level
rise can matter a lot
Hurricane Gustav, 2008, FEMA photo library



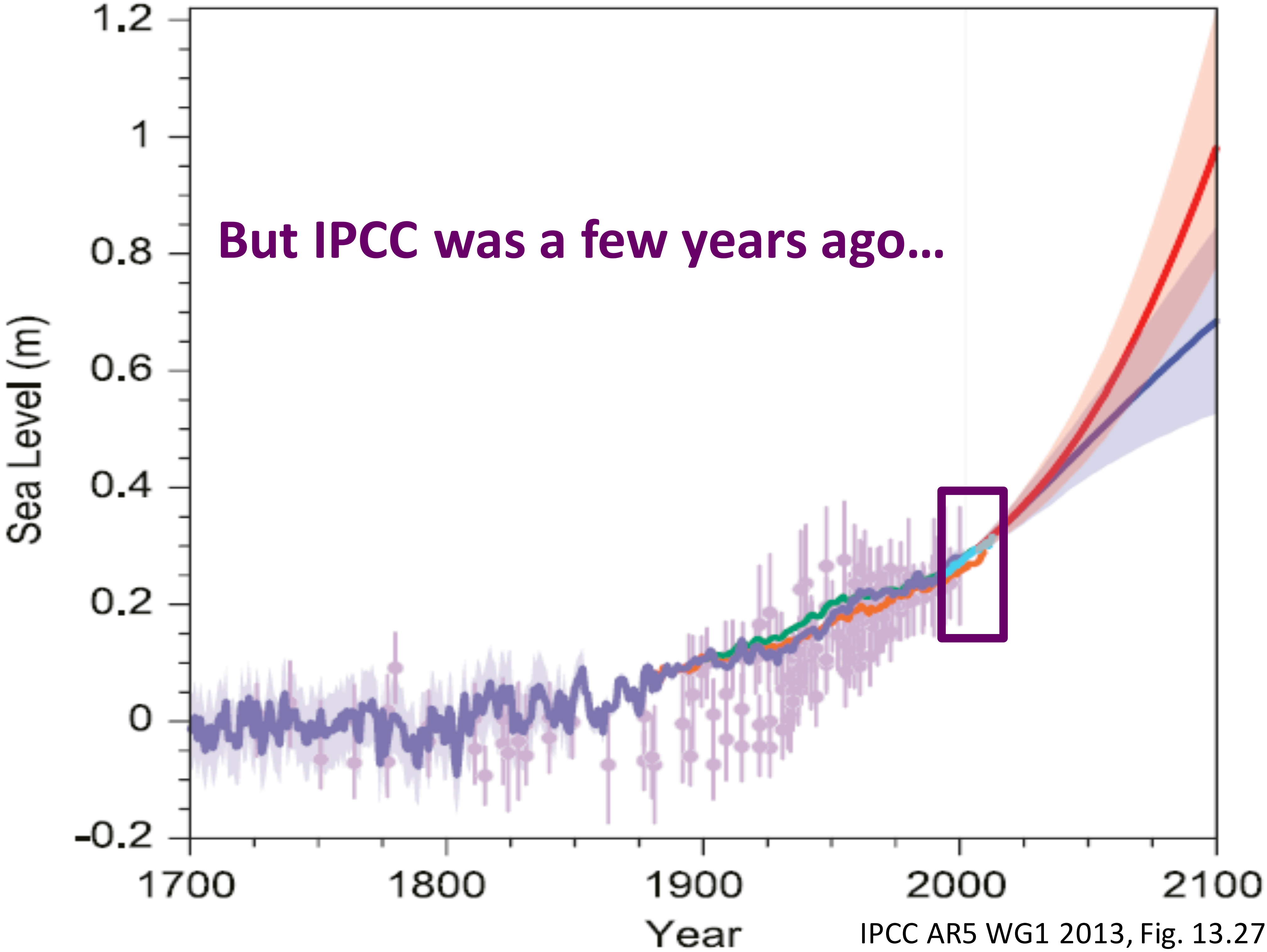
IPCC AR5 WG1 2013, Fig. 13.27



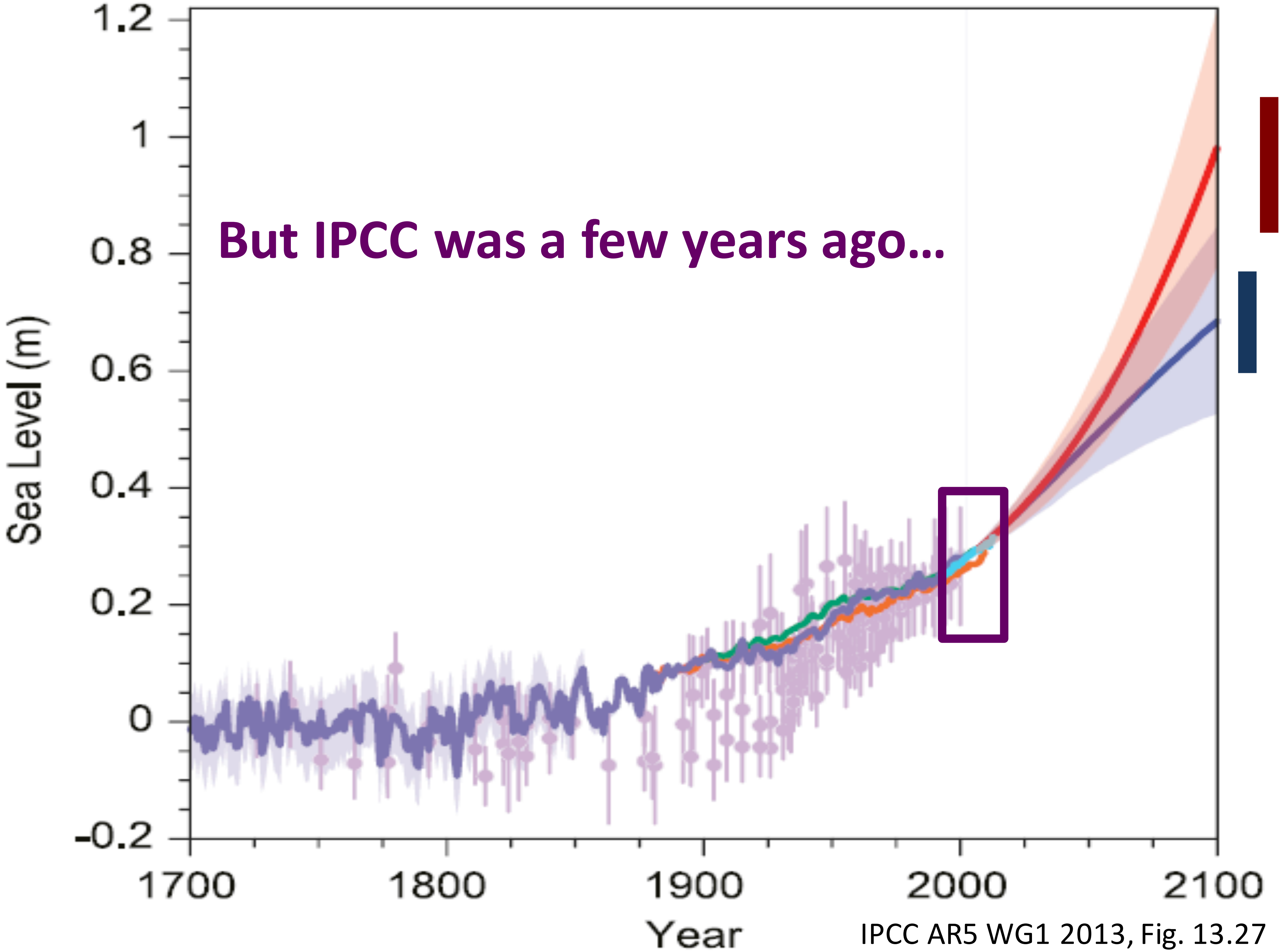
IPCC AR5 WG1 2013, Fig. 13.27



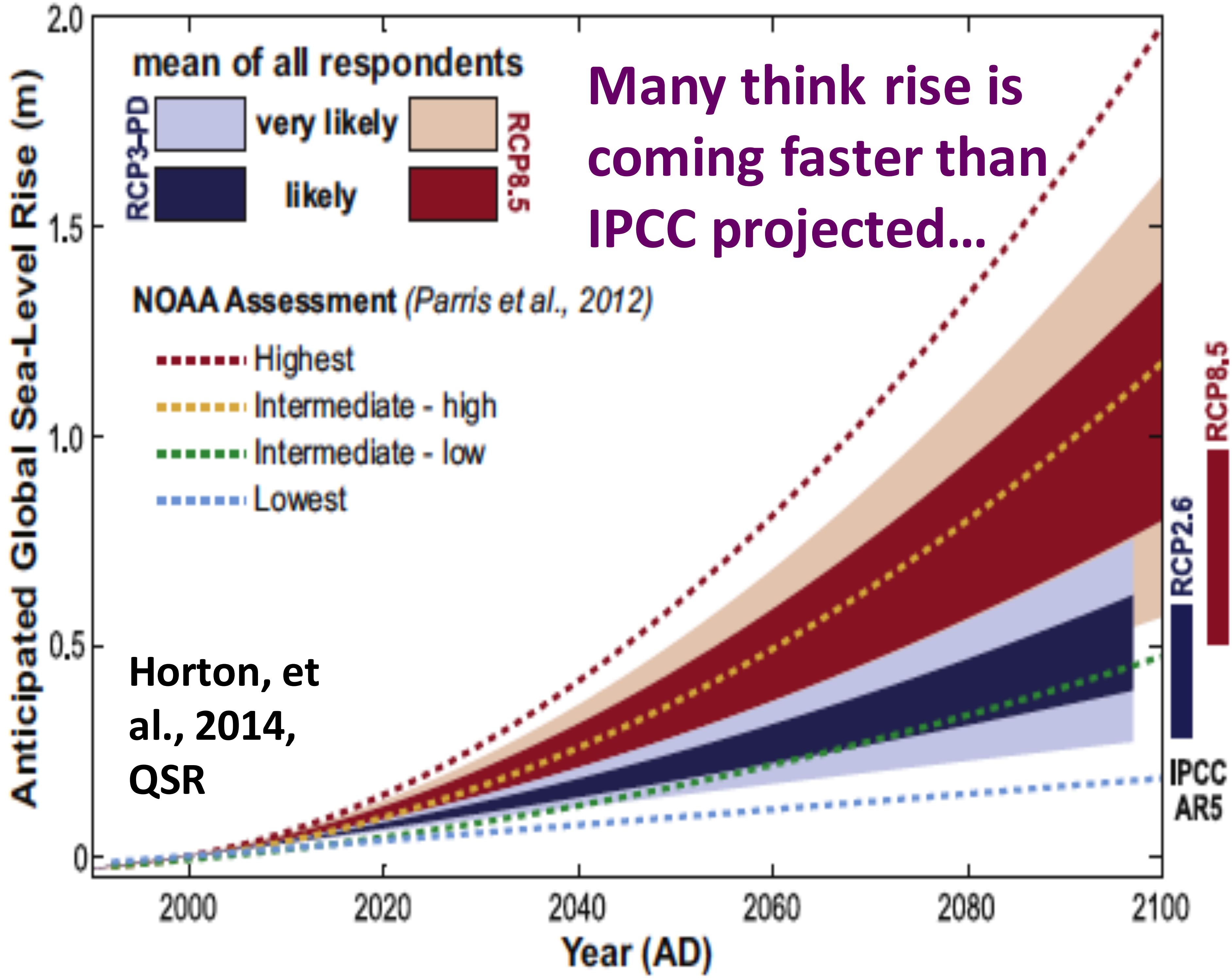
IPCC AR5 WG1 2013, Fig. 13.27



IPCC AR5 WG1 2013, Fig. 13.27

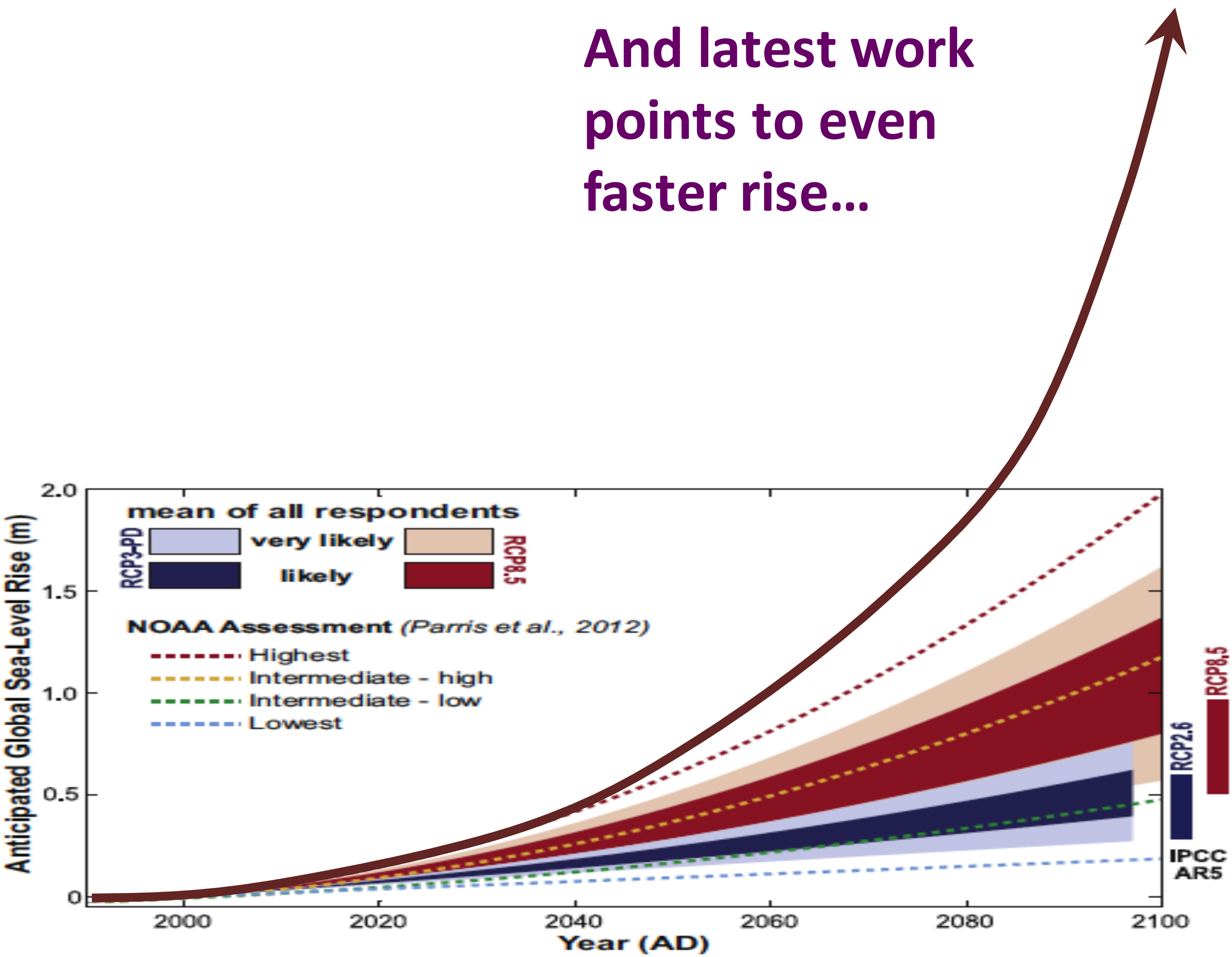


IPCC AR5 WG1 2013, Fig. 13.27

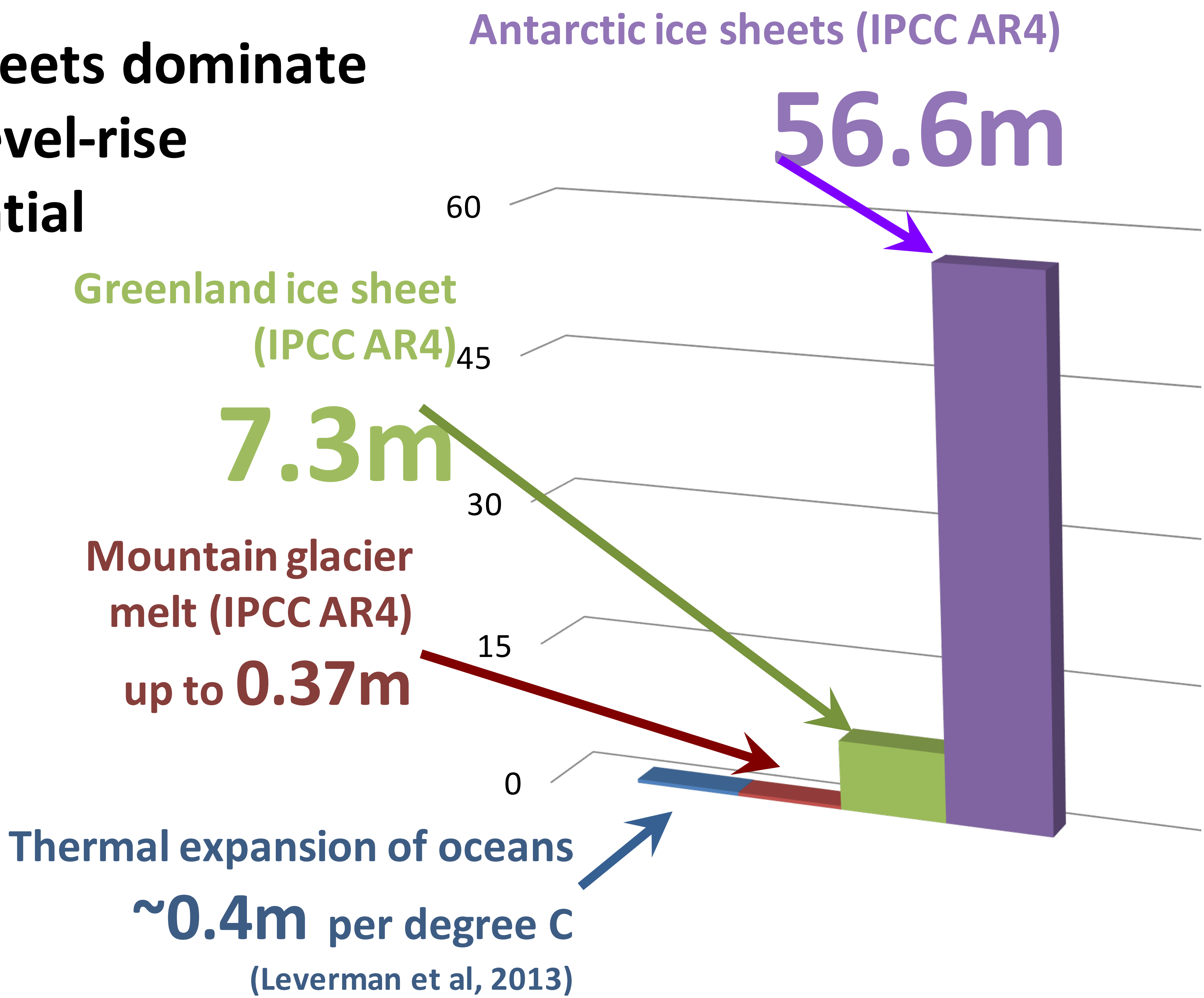


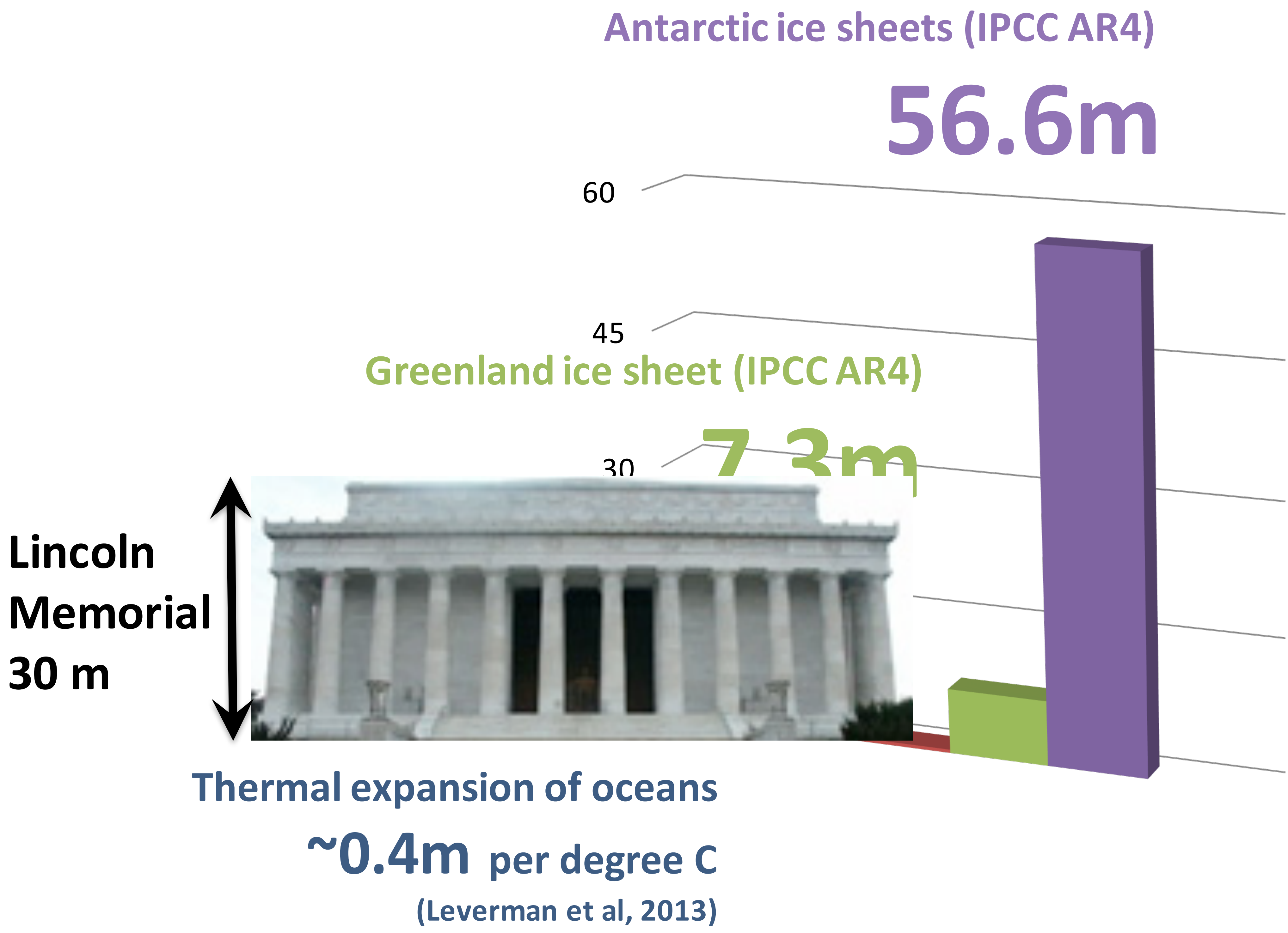
mean of all respondents
RCP3-PD
very likely
likely
RCP8.5
Many think rise is coming faster than IPCC projected...
NOAA Assessment (Parris et al., 2012)
Highest
Intermediate - high
Intermediate - low
Lowest
Horton, et al., 2014, QSR
Anticipated Global Sea-Level Rise (m)
2.0
1.5
1.0
0.5
0
2000
2020
2040
2060
2080
2100
Year (AD)
RCP8.5
RCP2.6
IPCC AR5

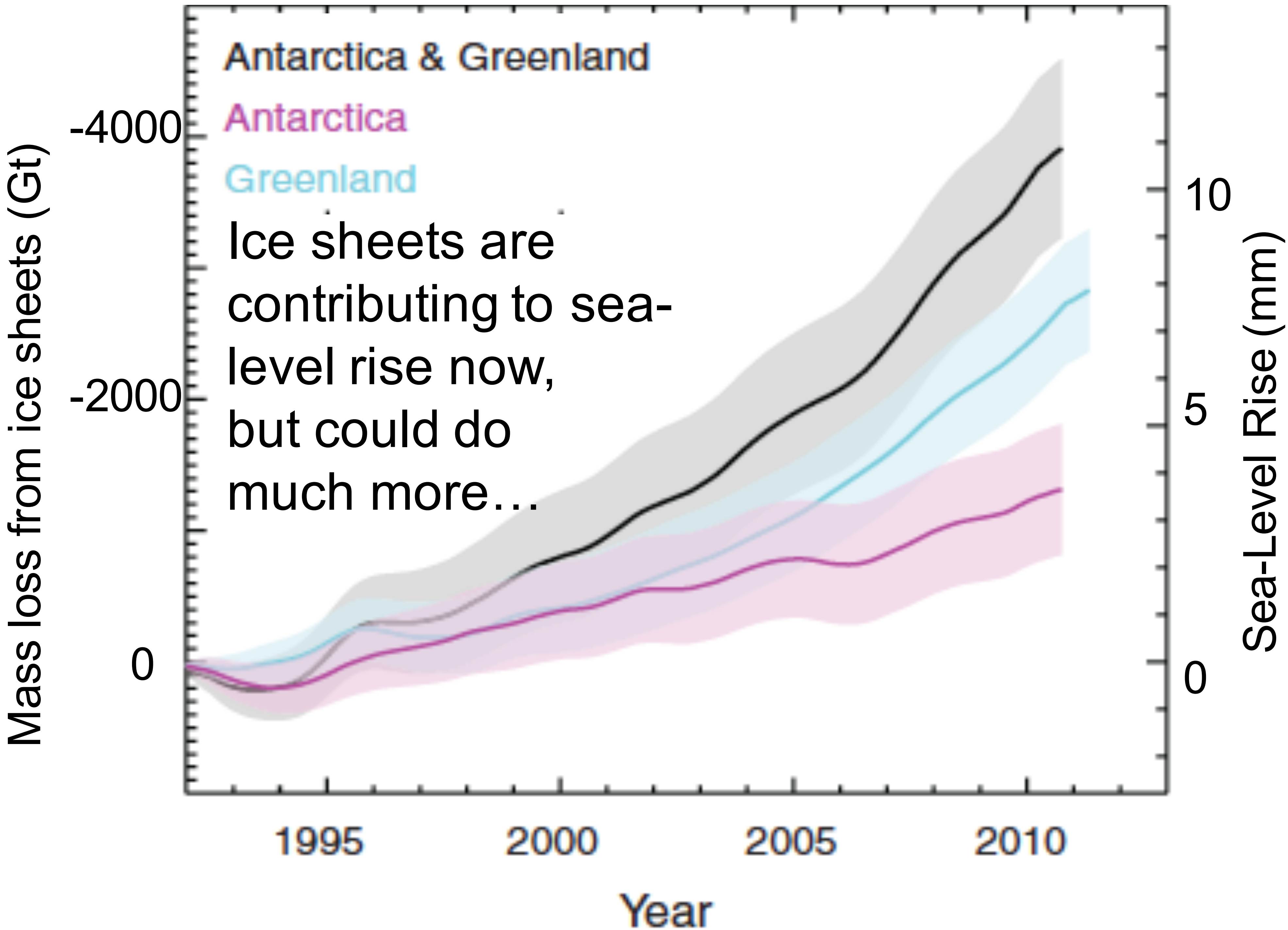
And latest work points to even faster rise…



Ice sheets dominate sea-level-rise potential




Antarctic ice sheets (IPCC AR4)
56.6m
60
45
Greenland ice sheet (IPCC AR4)
7.3m
30
Lincoln Memorial 30 m
Thermal expansion of oceans
~0.4m per degree C
(Leverman et al, 2013)



Shepherd et al., Science, 2012

Ice sheets could do more…

- Since 1992 ~0.6 mm/yr to sea-level rise
- That is over 200 billion tons of water per year, or about 50 cubic miles
- But, at that rate, more than 100,000 years for the ice sheets to disappear completely
- Nature has done much faster things before
- Is equivalent to me dieting for a year and losing weight equal to one-third of a single potato chip
- What happens if the ice sheets get too serious about dieting (Antarctic anorexia)?
- Let's do the physics and find out…

Carbon choices determine US cities committed to futures below sea level

www.pnas.org/cgi/doi/10.1073/pnas.1511186112

Benjamin H. Strauss[a,1], Scott Kulp[a], and Anders Levermann[b,c]

Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet

Ricarda Winkelmann,[1,2,3]* Anders Levermann,[1,2] Andy Ridgwell,[4,5] Ken Caldeira[3]

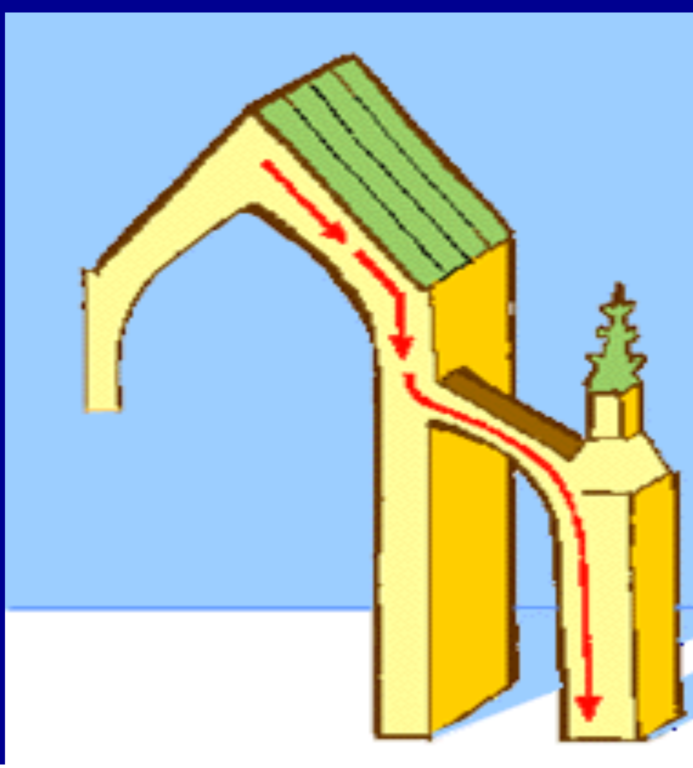
Winkelmann *et al.* Sci. Adv. 2015;1:e1500589 11 September 2015

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

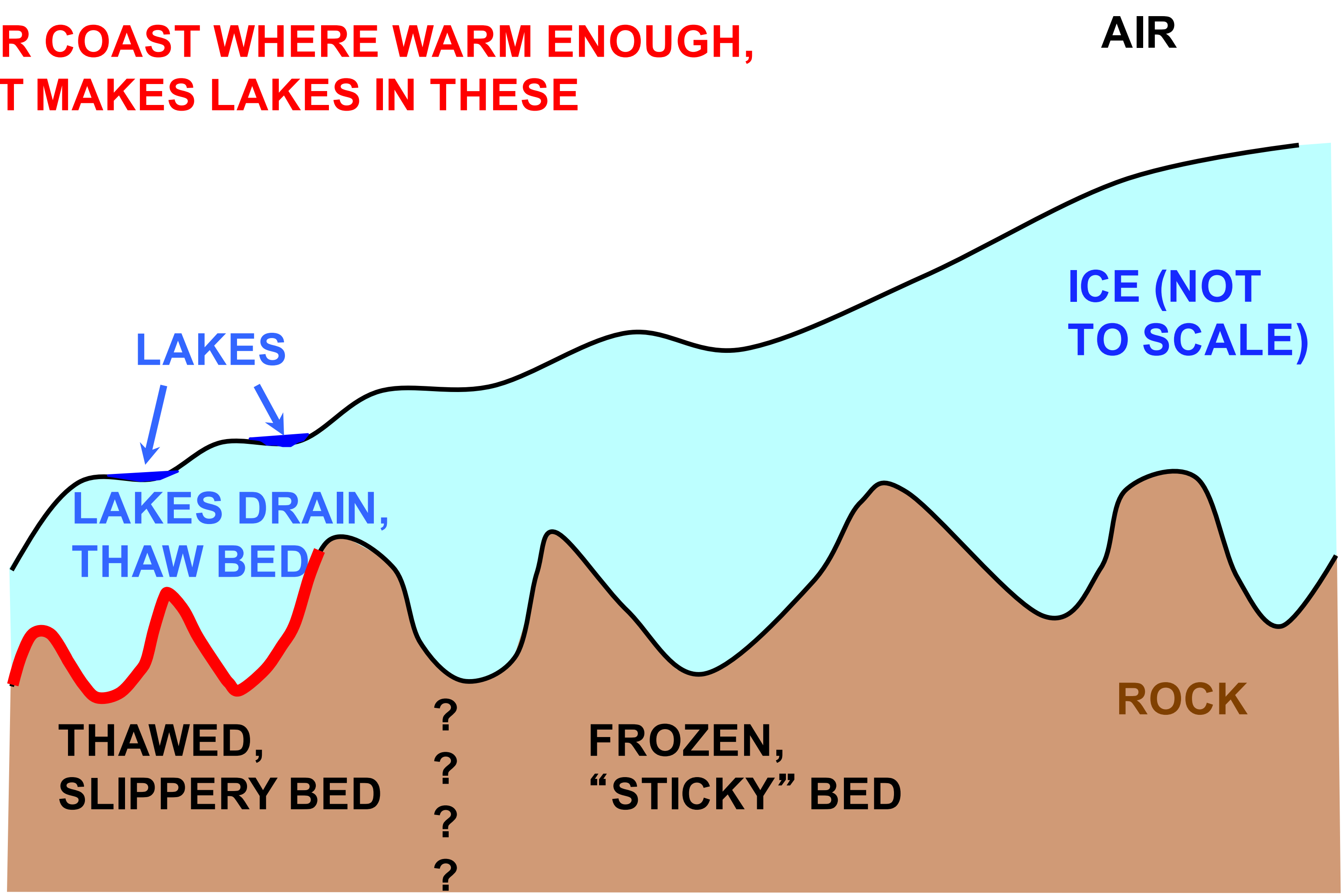
An ice sheet is a two-mile-thick, continent-wide pile

- 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 is from ocean, so sea level falls when ice sheet grows, and sea level rises when ice sheet shrinks;
- We'll look at changing lubrication of ice-sheet bed, and flying-buttress loss

Lakes breaking through Greenland affect lubrication a little, but not a lot

ICE FLOWING OVER BUMPY BED
MAKES LOCAL LOWS IN SURFACE

NEAR COAST WHERE WARM ENOUGH,
MELT MAKES LAKES IN THESE

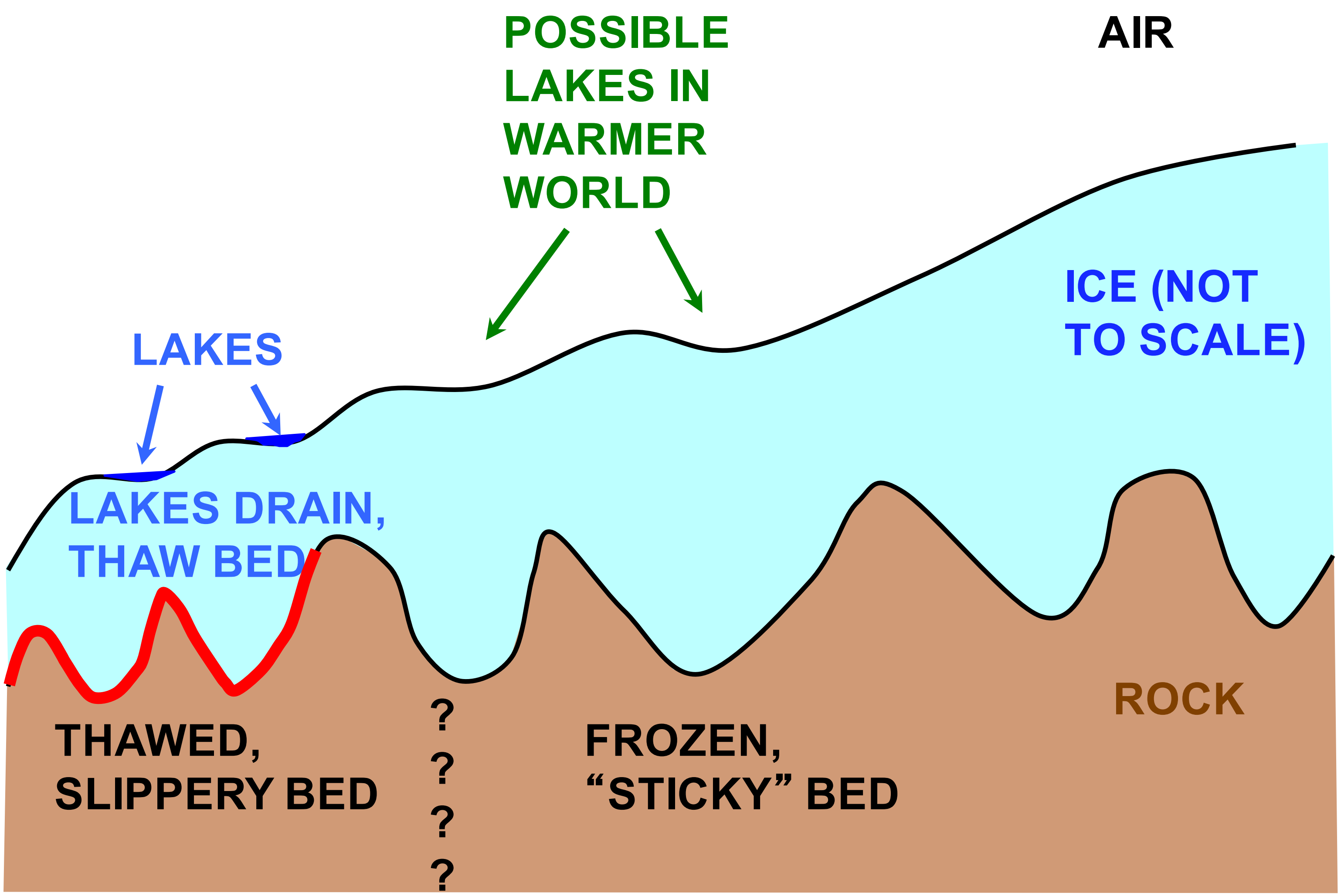


Large lakes form on top of Greenland’s ice in some places

Photo courtesy Ian Joughin (all rights reserved by Ian, 2008)

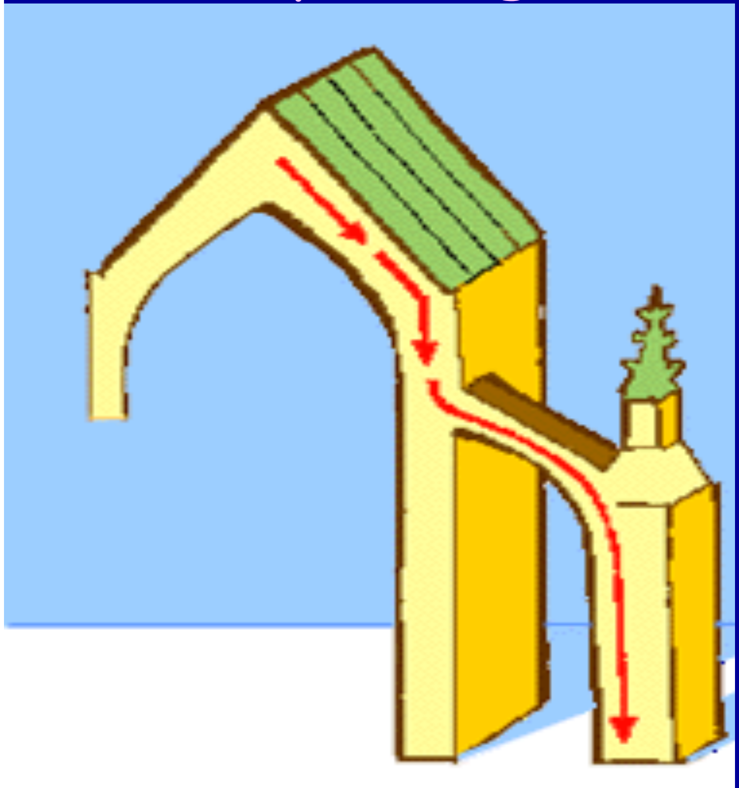
Then break through, draining faster than Niagara

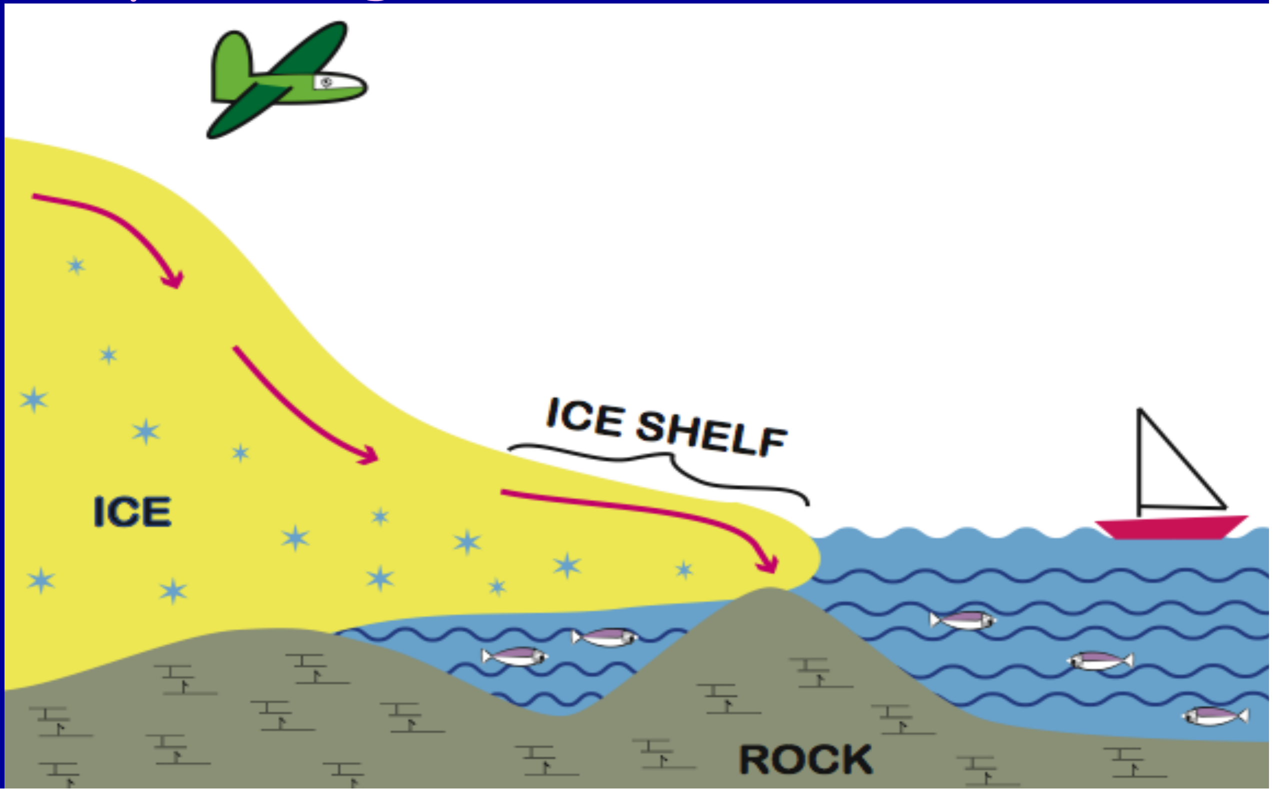
This may speed ice loss by melting a frozen bed or lubricating a bumpy bed



Ice sheets have "flying buttresses", too

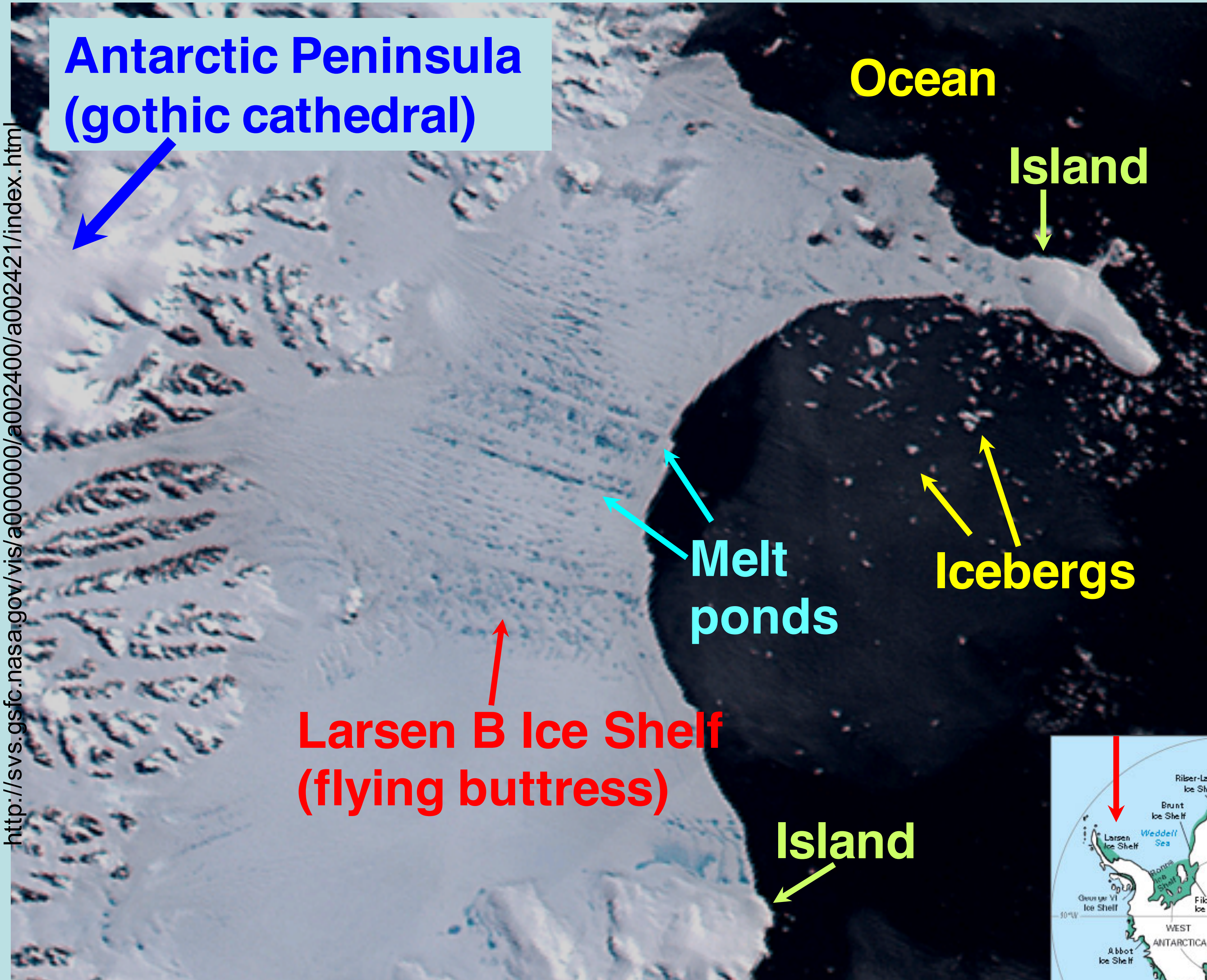
- Floating extensions called "ice shelves"--ice flows over water for a while before breaking off to make bergs;
- Ice shelves may run aground on islands or scrape past rocky sides of bays;
- Friction from this slows ice-sheet spreading;
- Warming air or water can attack ice shelves quickly, speeding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





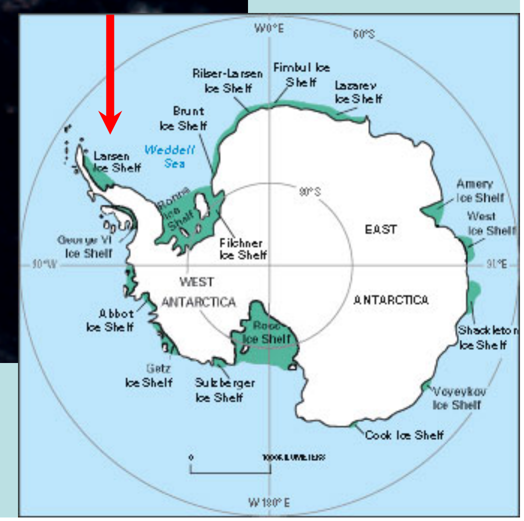
Gratuitous penguin picture (*Aptenodytes patagonicus*). St. Andrews Bay, South Georgia


Picture from on Heaney Glacier, which has retreated from down near tip of yellow arrow since ~1920, most since 1980.

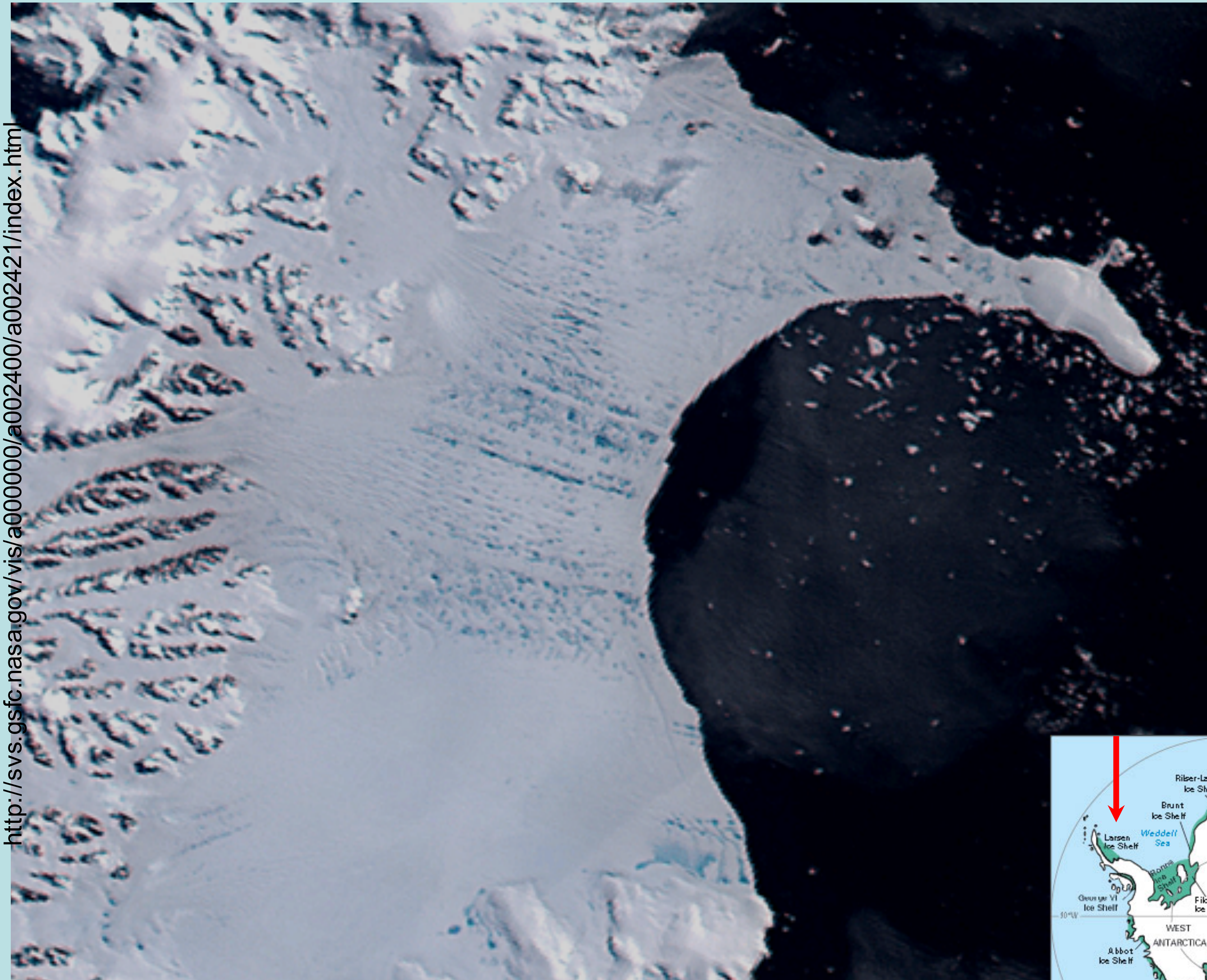


http://svs.gsfc.nasa.gov/vis/a000000/a002400/a002421/index.html

12 mi
20 km



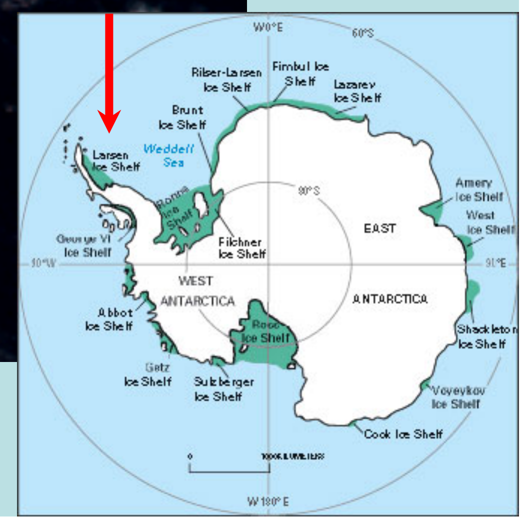
January 31, 2002



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

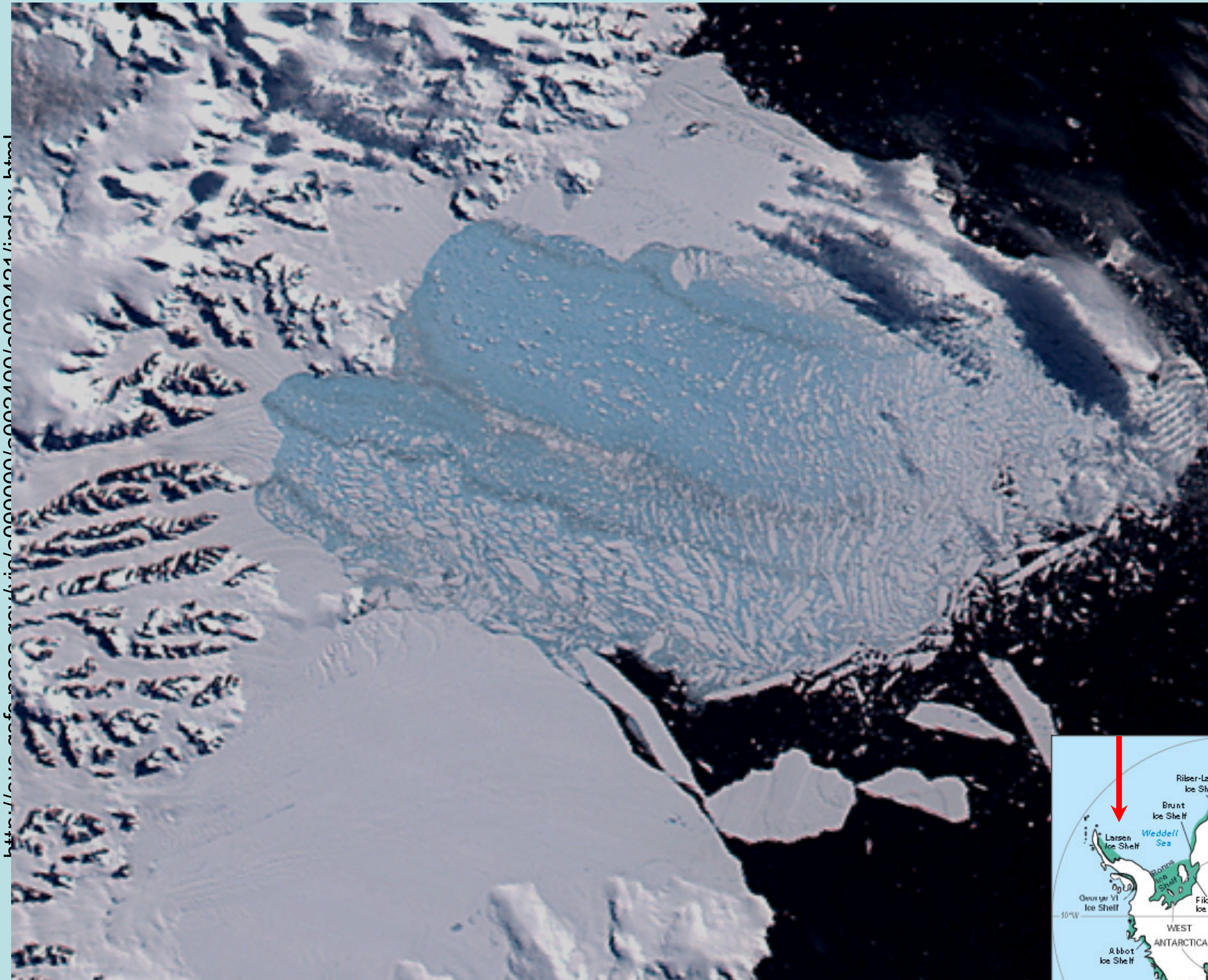
12 mi

20 km



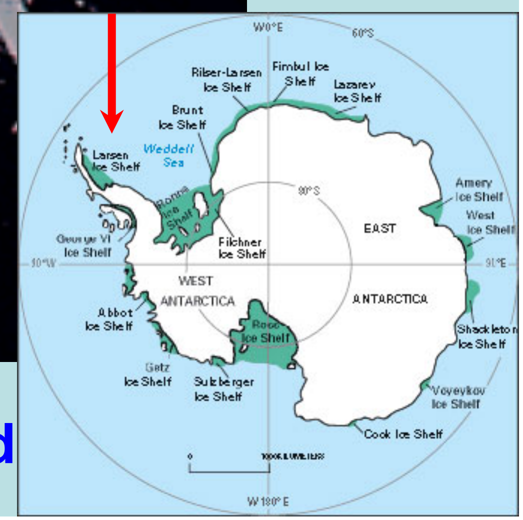
January 31, 2002

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

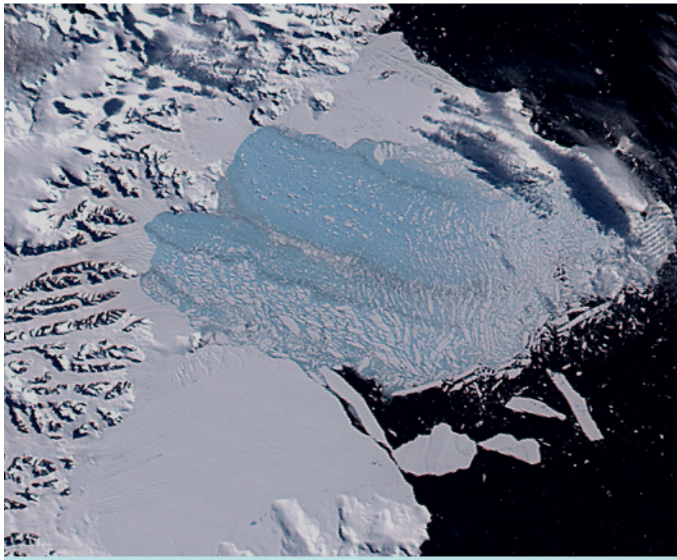


12 mi

20 km

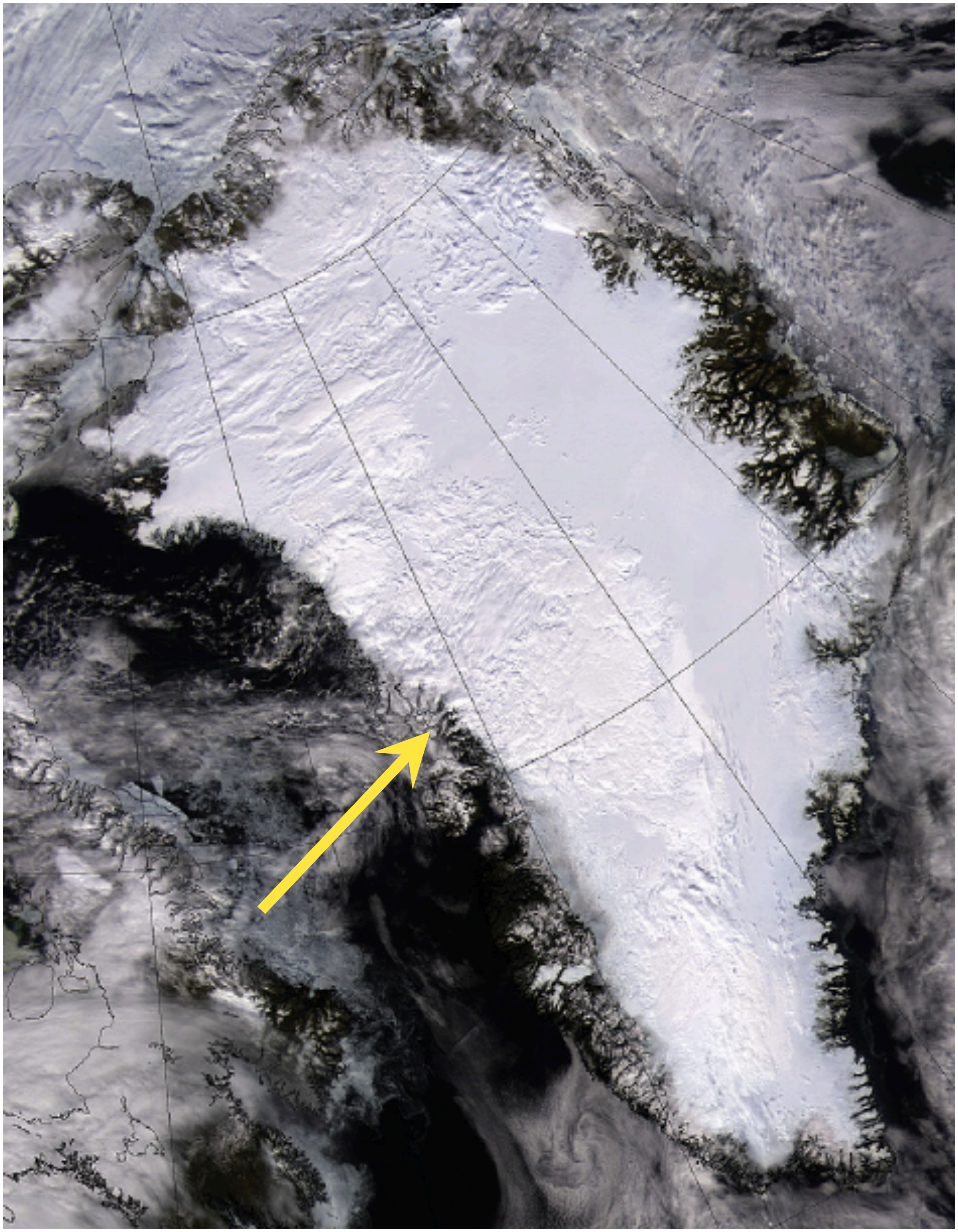


March 7, 2002. **8x tributary flow-speed increase followed**



Not much ice behind Larsen B; loss can't raise sea level much

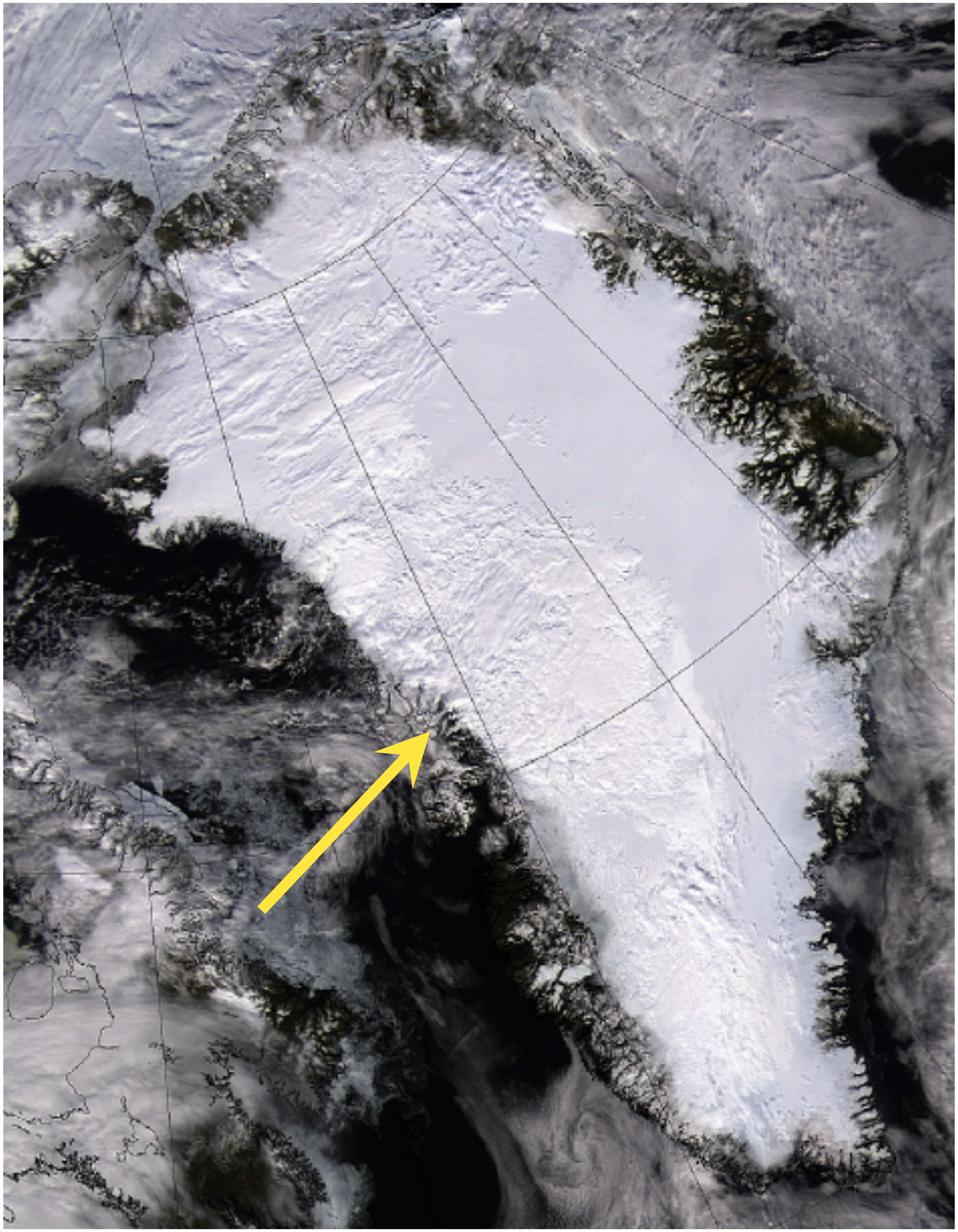
Many more ice shelves with lots of ice behind them that can raise sea level a lot.



To see how ice shelves matter even more, let's go to Greenland…

We'll fly in along the yellow arrow to Jakobshavn Glacier

http://www.gsfc.nasa.gov/gsfc/earth/pictures/earthpic.htm



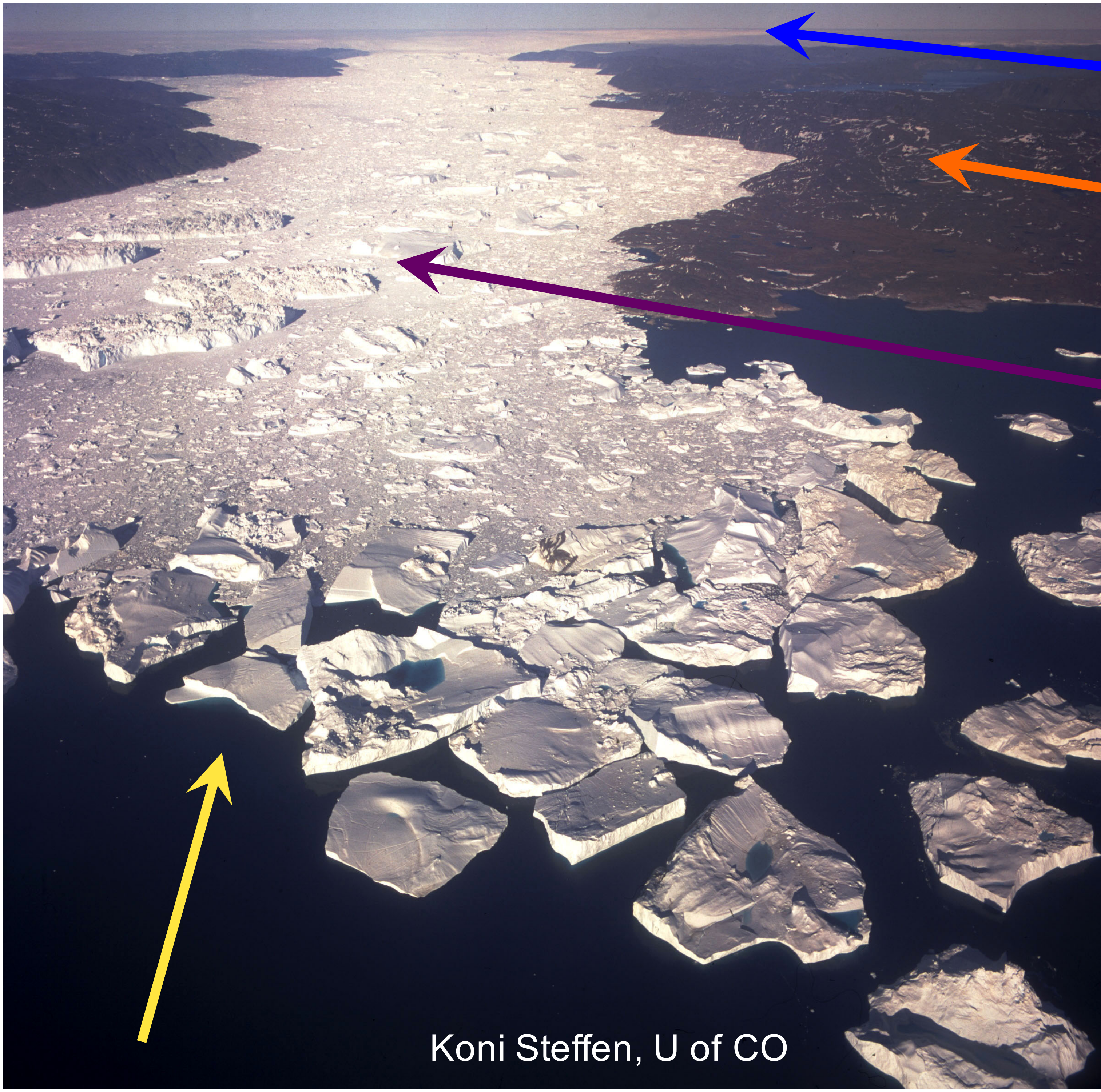
Jakobshavn had an ice shelf

Then the ocean water warmed by 1°C

And the ice shelf broke off to leave a cliff

And the ice tripled its speed

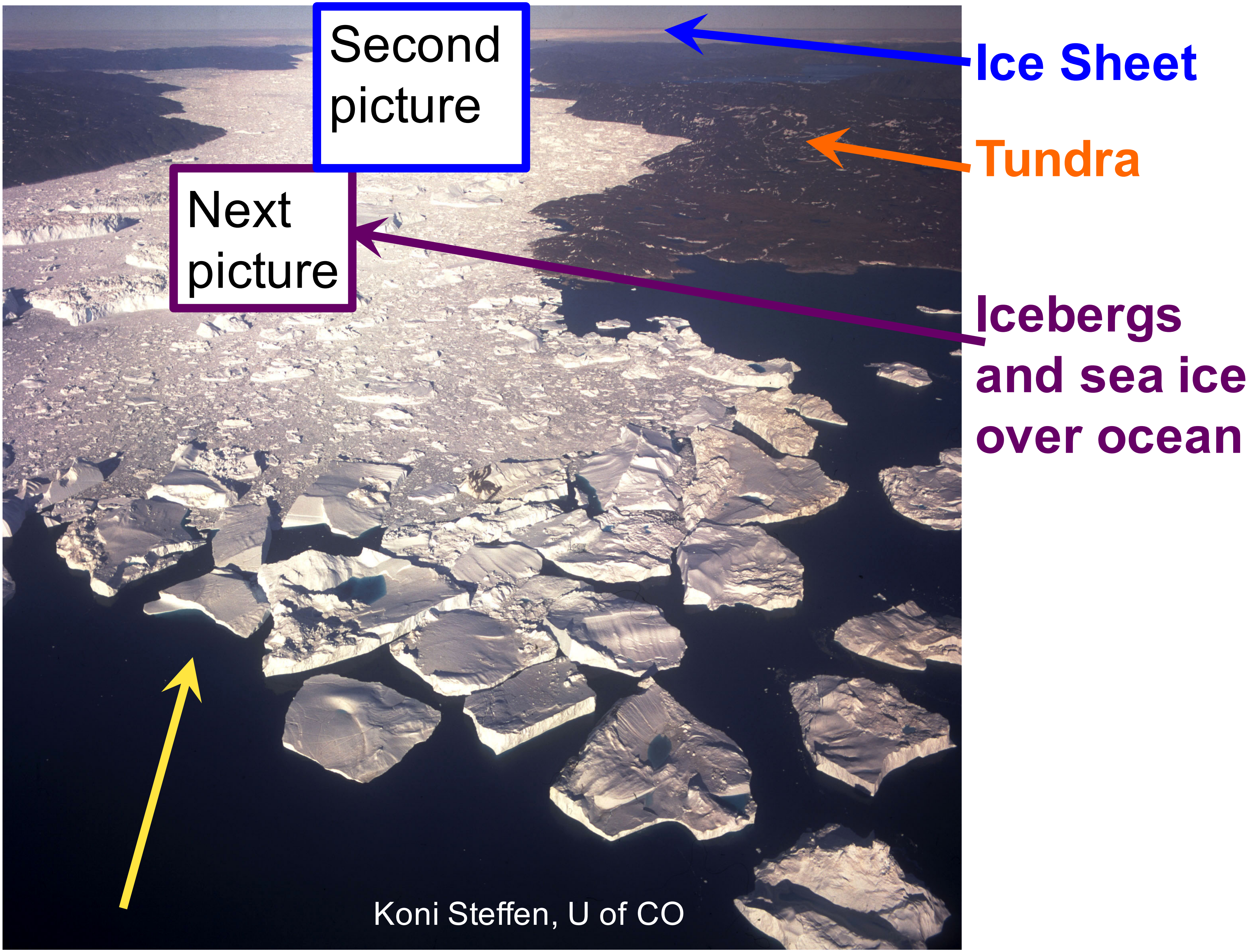
http://www.gsfc.nasa.gov/gsfc/earth/pictures/earthpic.htm

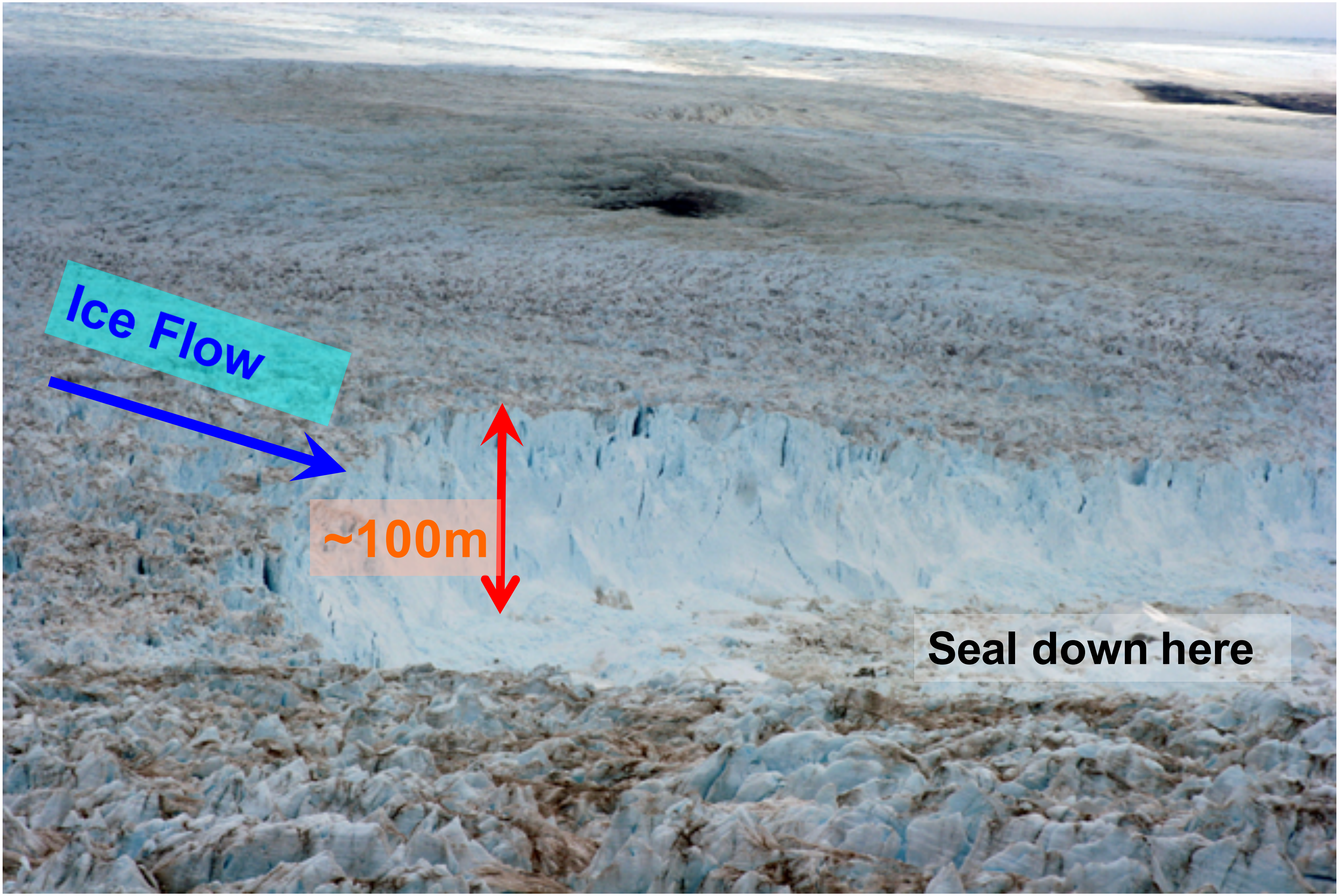


Ice Sheet

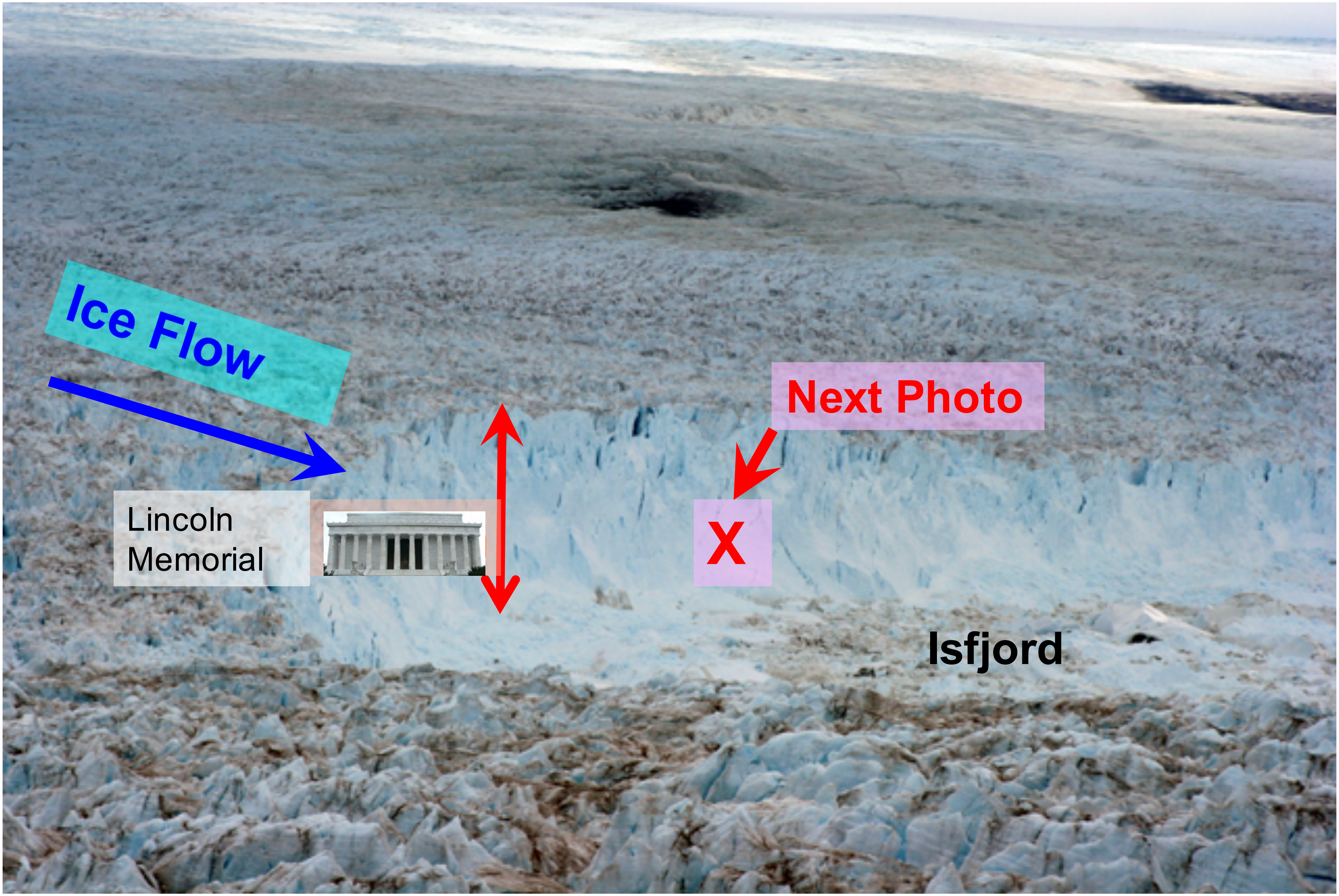
Tundra

Icebergs
and sea ice
over ocean


Second picture
Next picture
Ice Sheet
Tundra
Icebergs and sea ice over ocean
Koni Steffen, U of CO



Calving front of Jakobshavn



Calving front of Jakobshavn

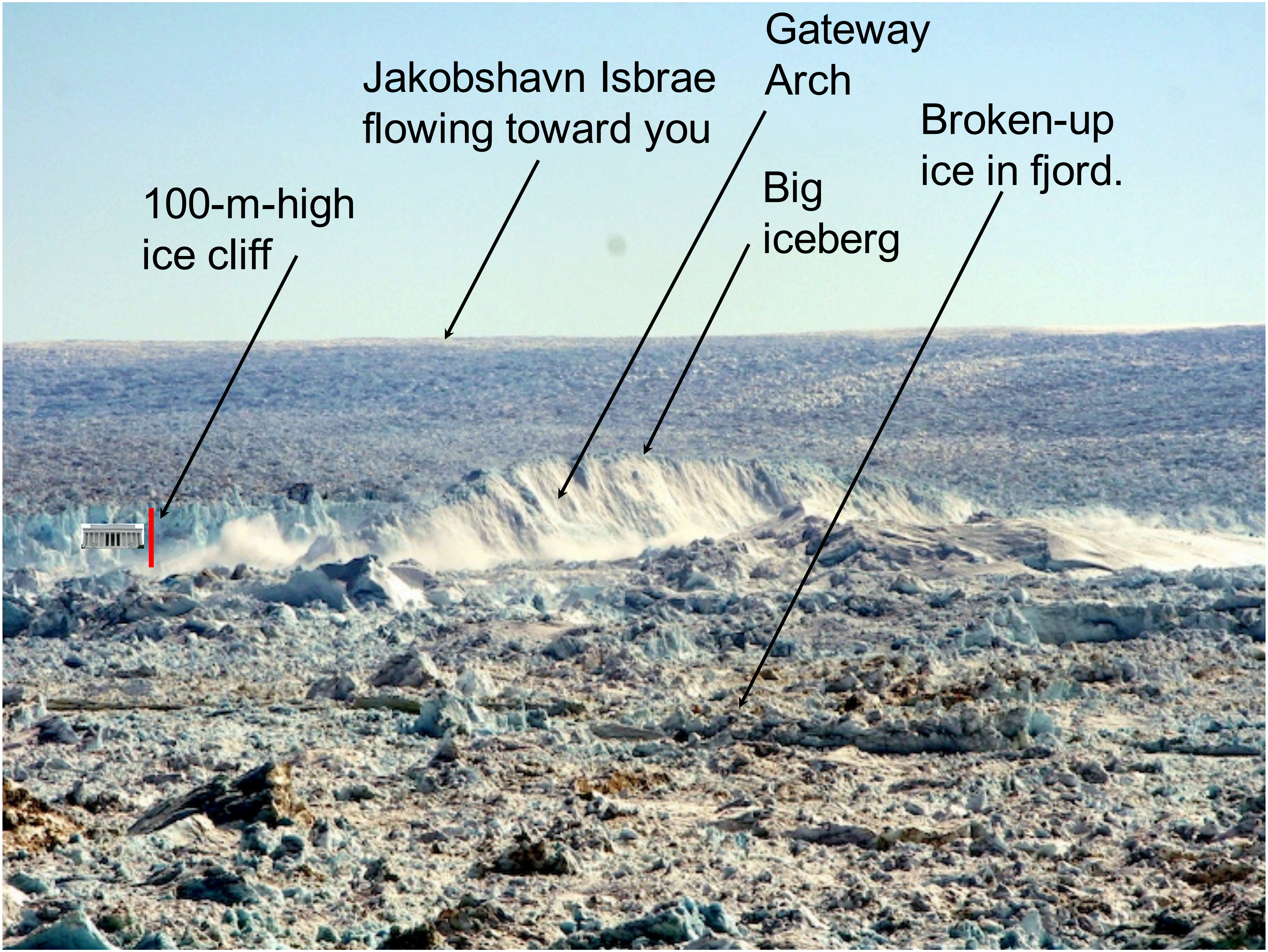

Close to breaking, so, about
as high as an ice cliff can be…

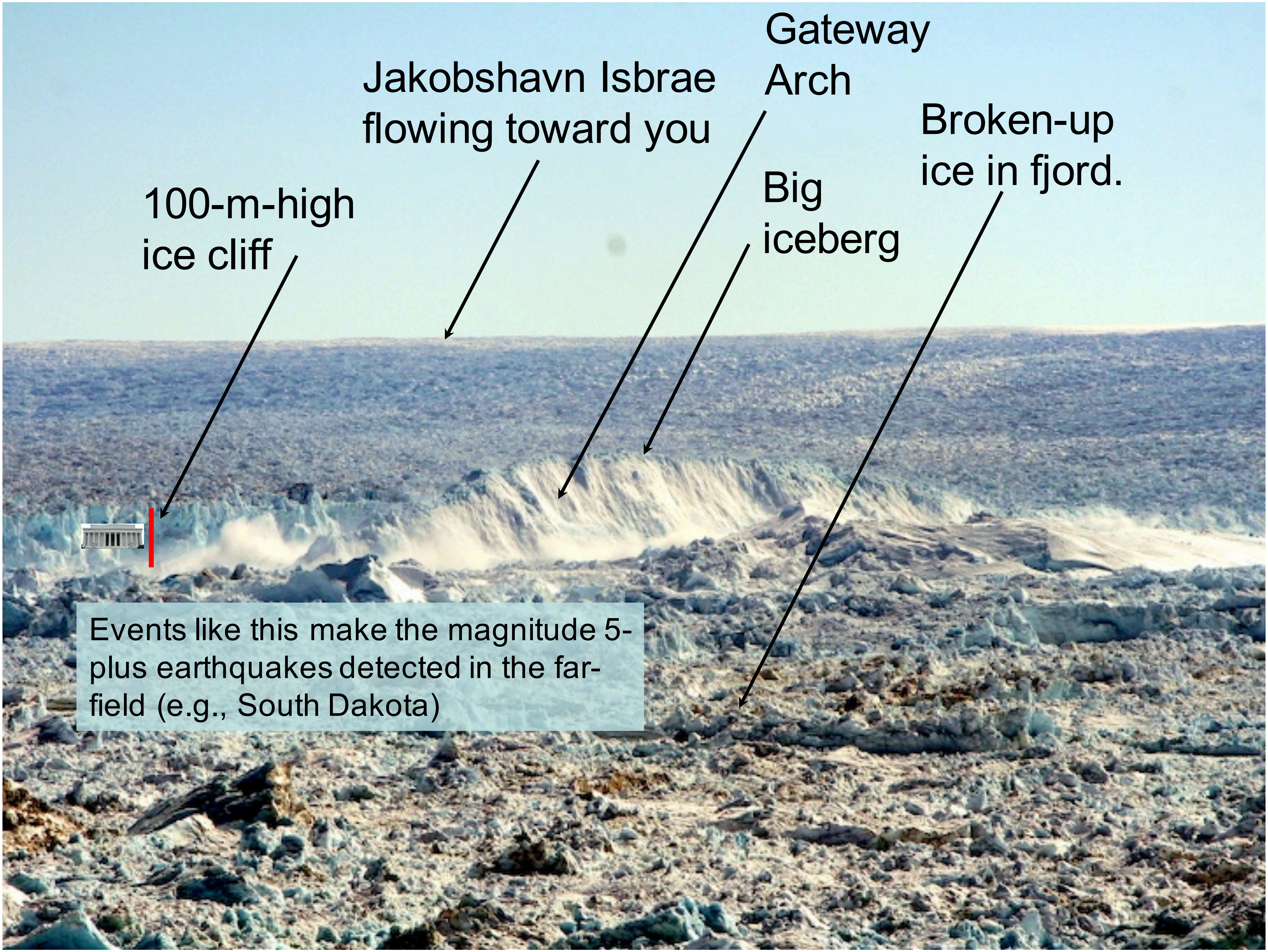
Calving Event, Jakobshavn Glacier

Martin Truffer photographer, working with Mark Fahnestock and Ian Joughin

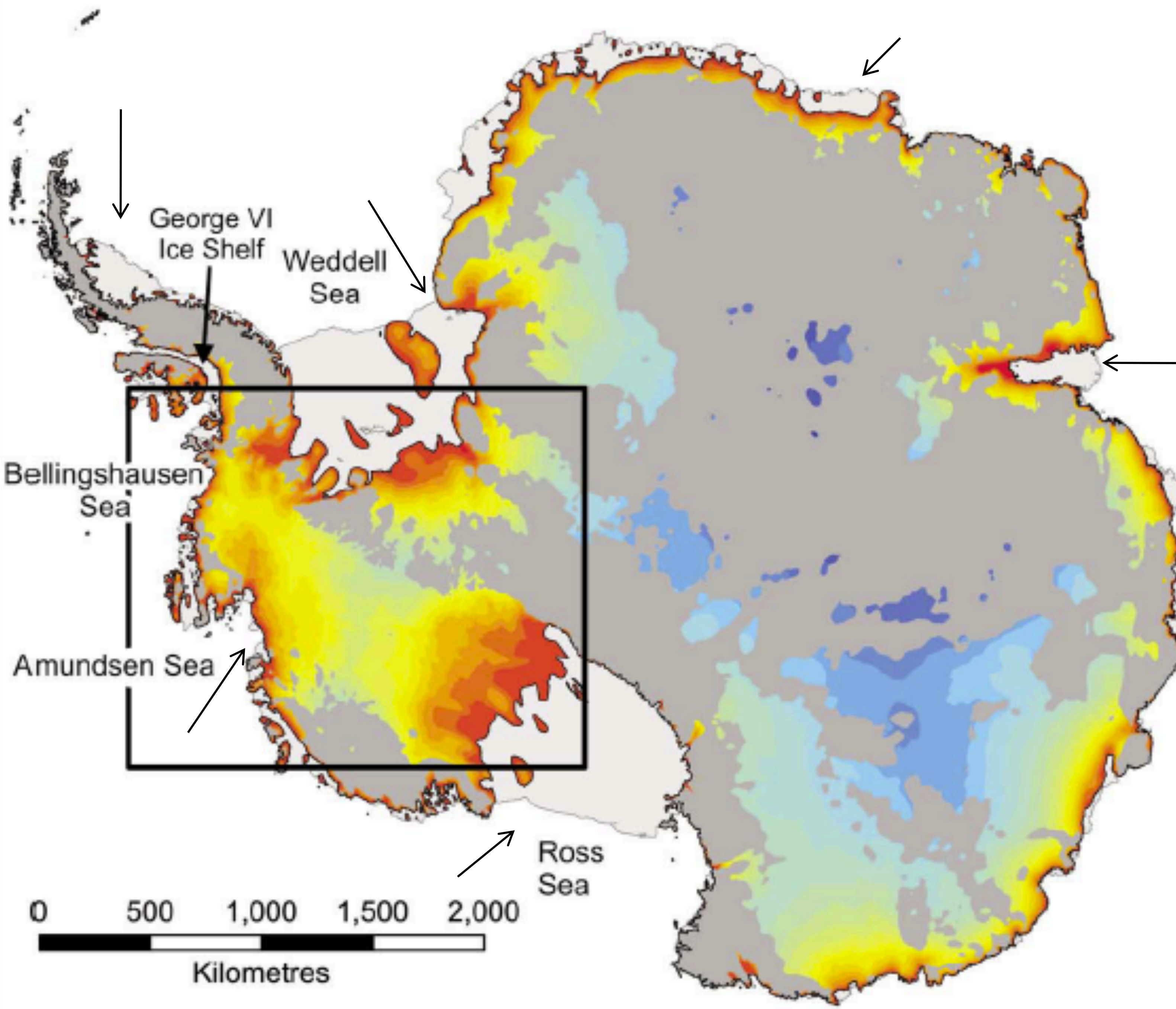
Field of view is about 2 km across at the 10 km distance of the calving face

Time series duration is ~90 seconds

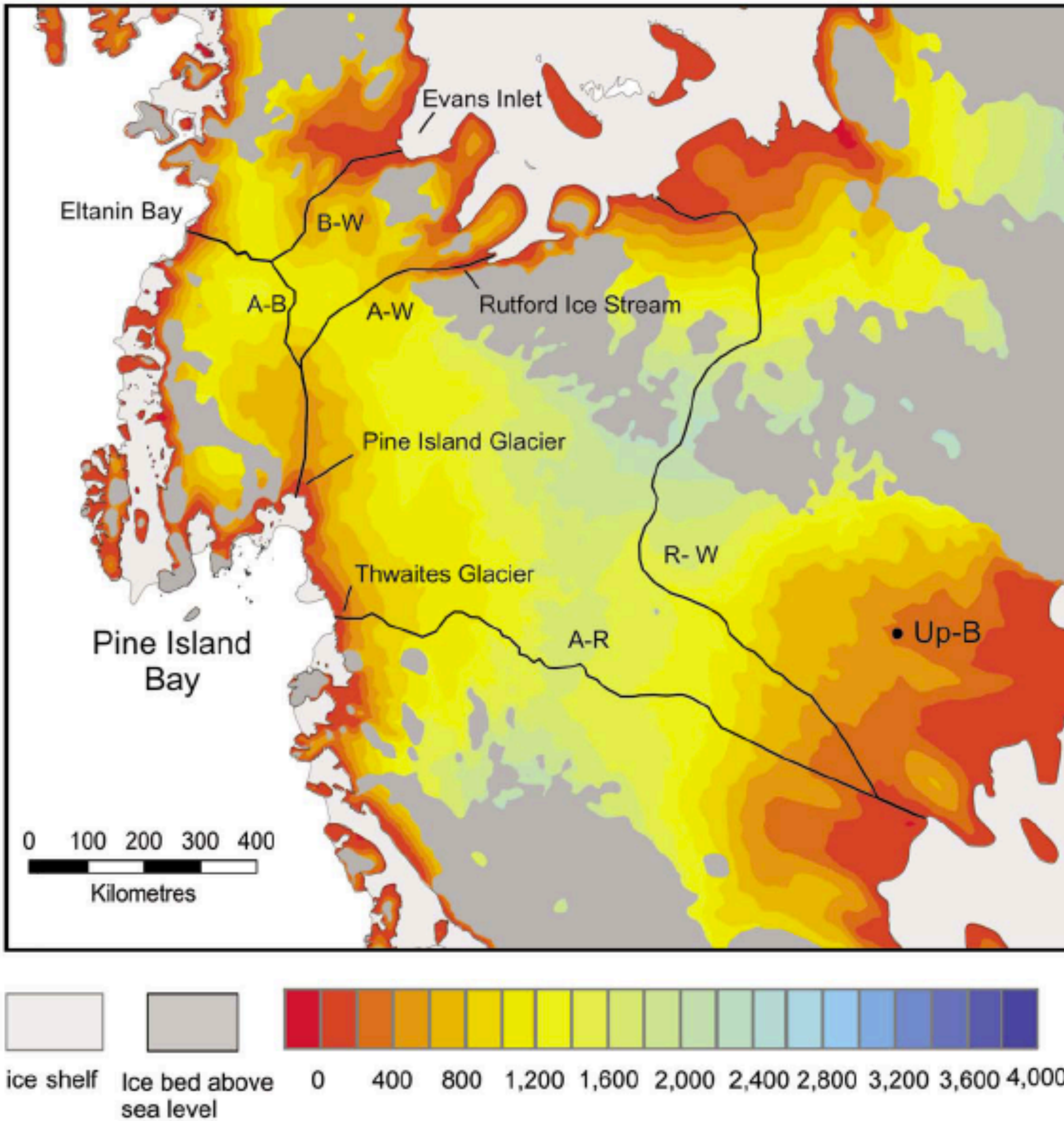

Gateway
Arch
Jakobshavn Isbrae
flowing toward you
Broken-up
ice in fjord.
Big
iceberg
100-m-high
ice cliff


Gateway
Arch
Jakobshavn Isbrae
flowing toward you
Broken-up
ice in fjord.
Big
iceberg
100-m-high
ice cliff
Events like this make the magnitude 5-
plus earthquakes detected in the far-
field (e.g., South Dakota)


Now, breaks, waits, breaks, waits
If too high, breaks breaks breaks…

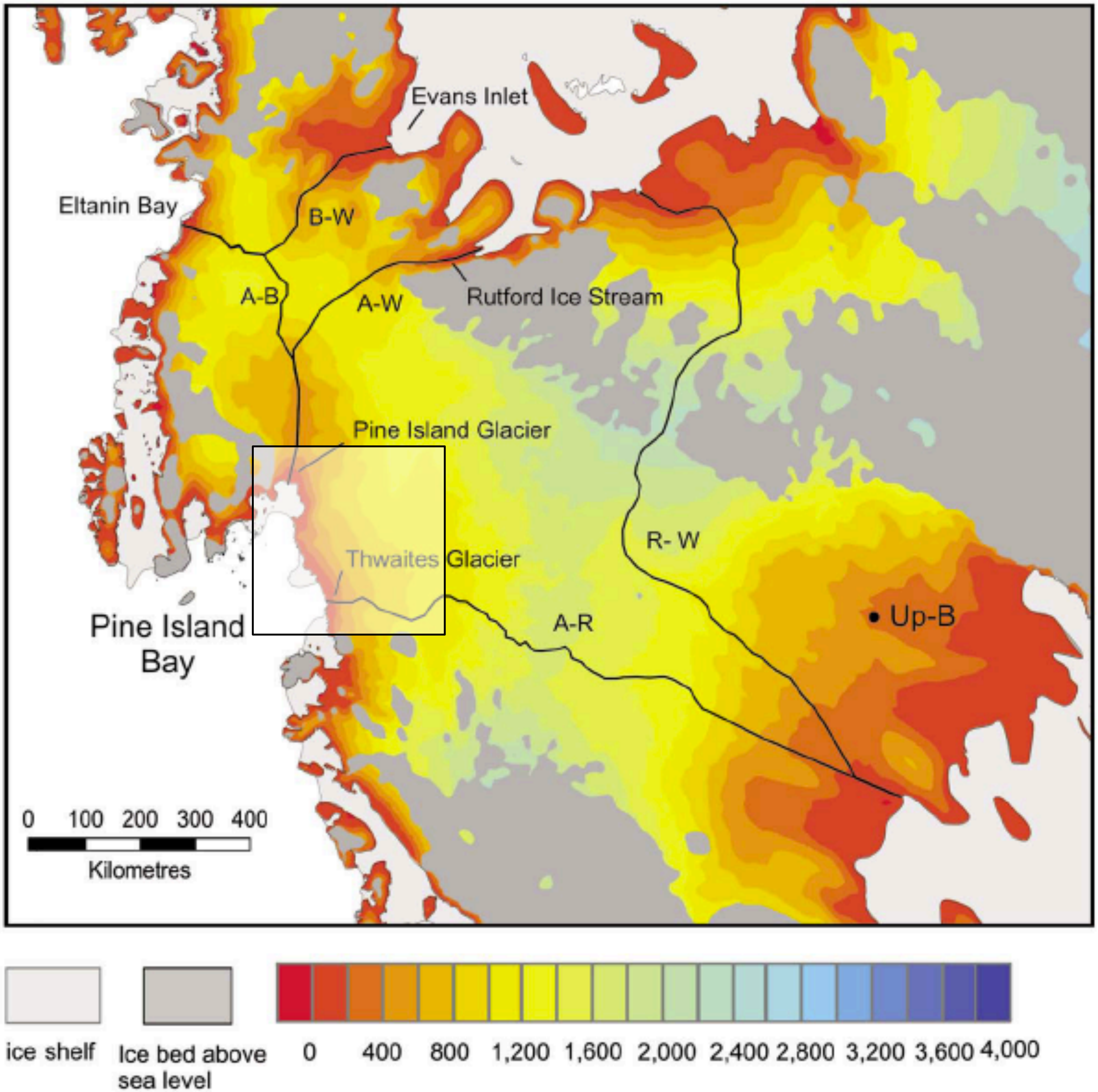


Lots of "flying buttress" ice shelves—arrows point to just a few. Colored regions—bed deep enough to dump icebergs

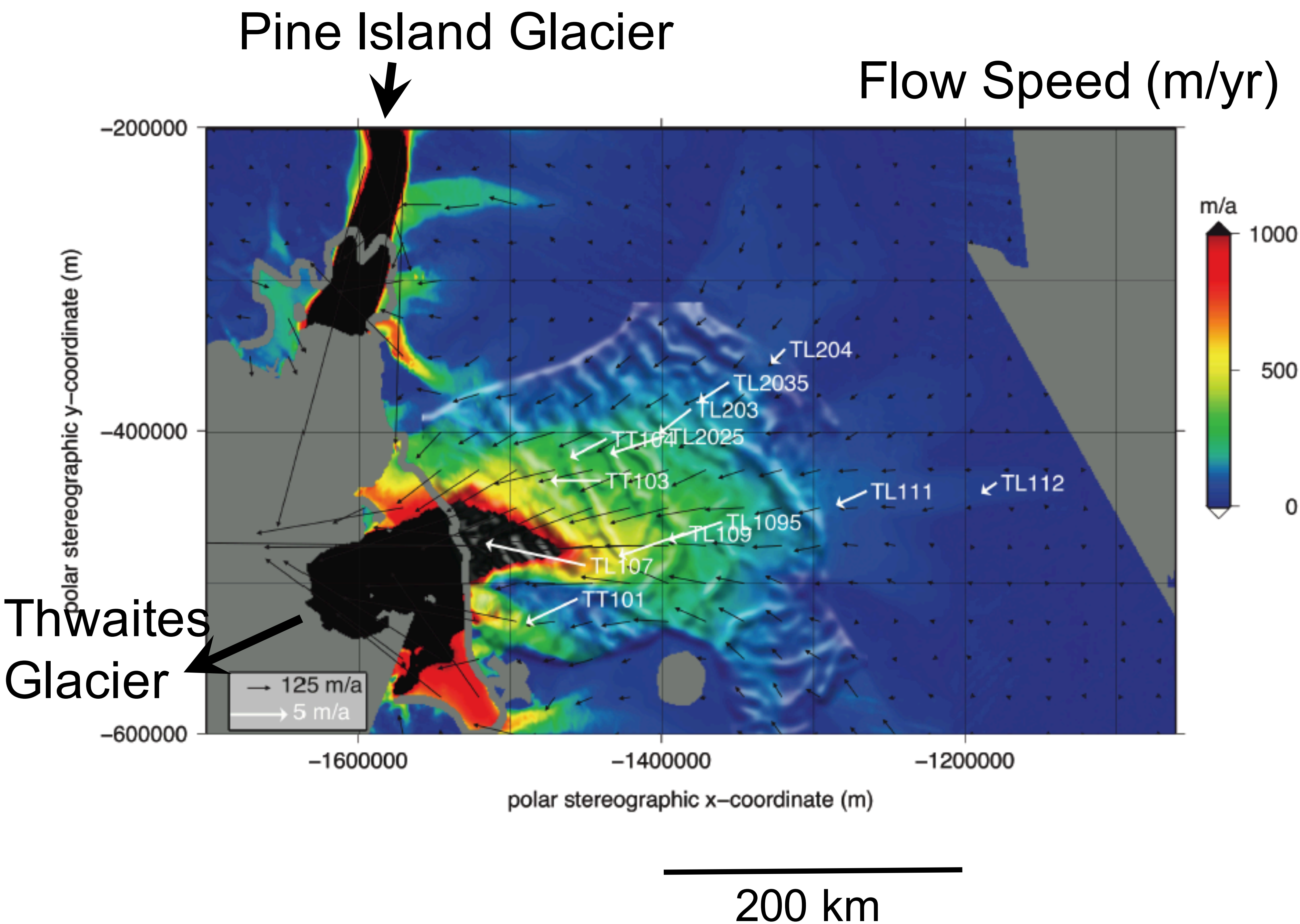


West Antarctica—the bigger worry.

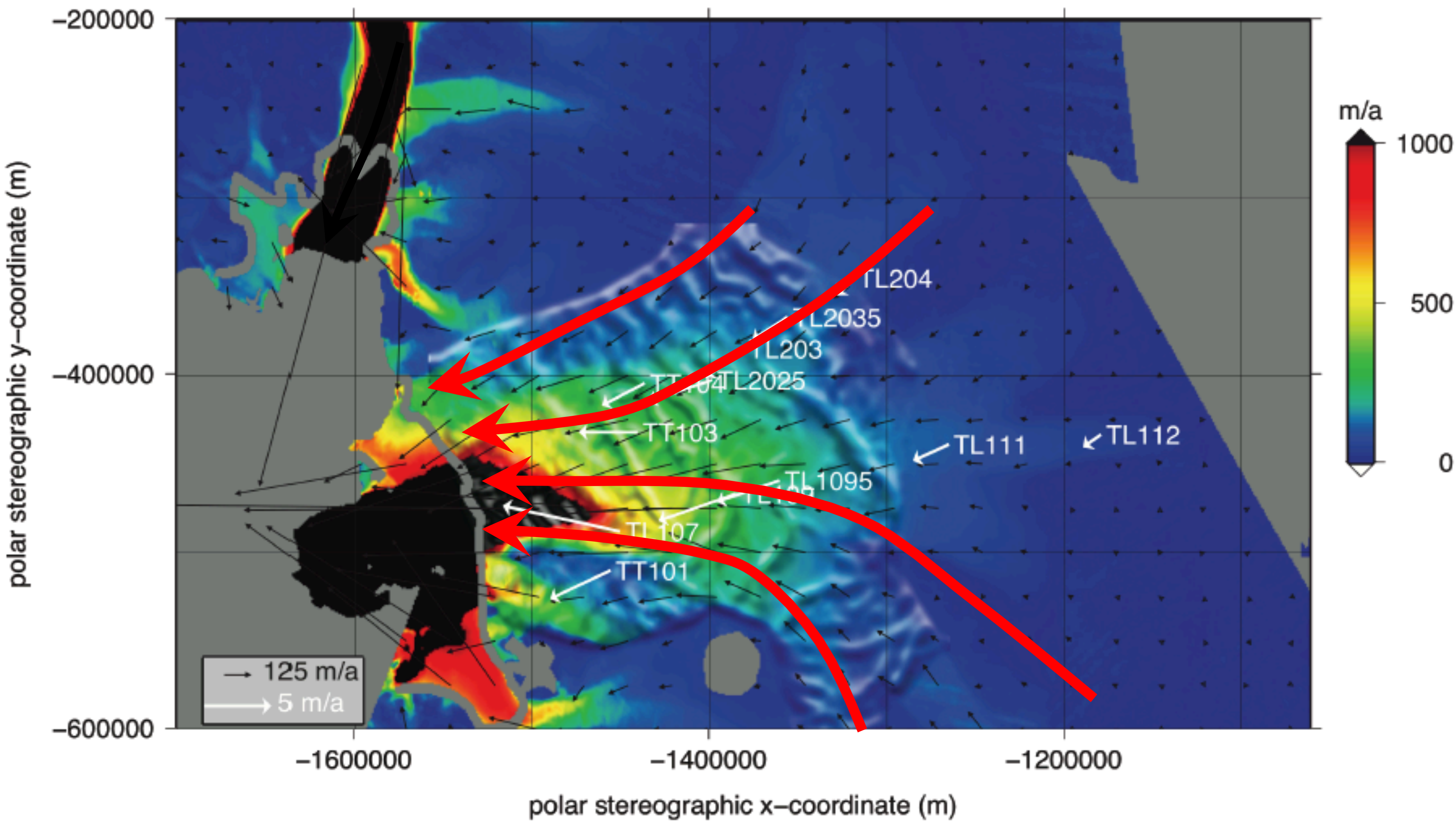
From Vaughan et al., 2011, Geochemistry Geophysics Geosystems.



The big issue is probably Thwaites Glacier in the "weak underbelly" of the West Antarctica ice sheet, where a wide ice stream leads into thick ice on a deep bed that could make icebergs FAST

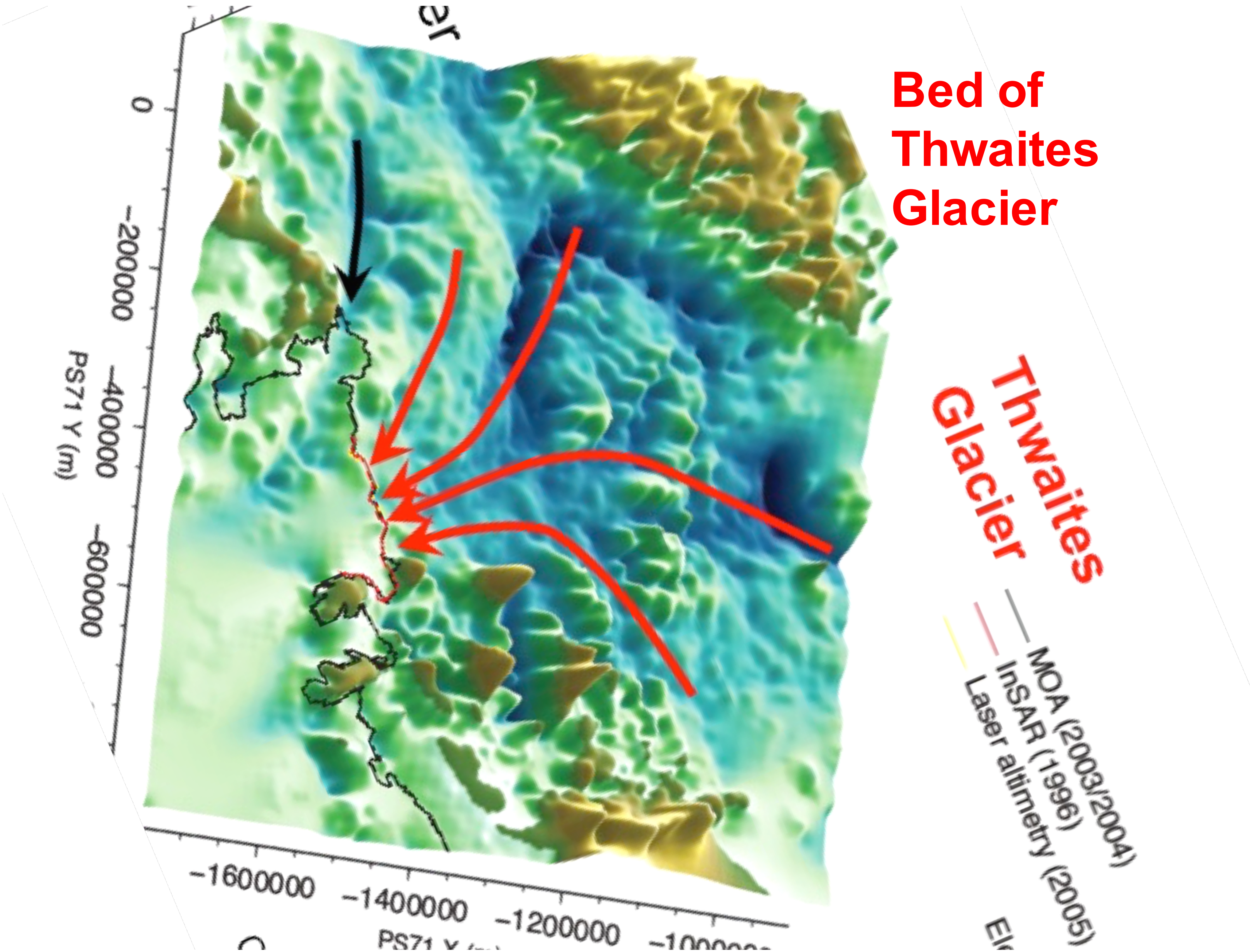


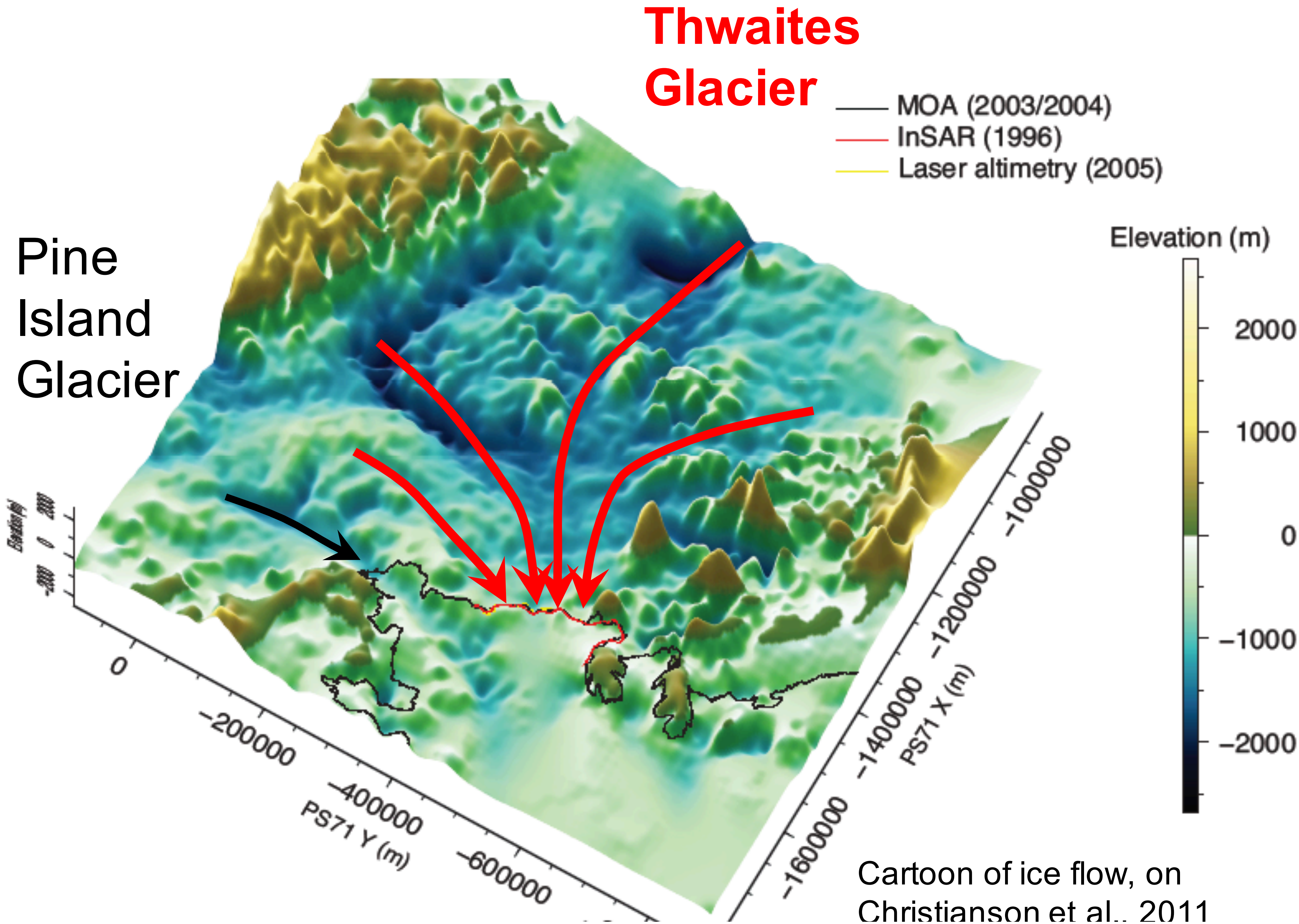
Christianson et al., 2011



m/a
1000
500
0
−200000
−400000
−600000
−1600000
−1400000
−1200000
polar stereographic x−coordinate (m)
polar stereographic y−coordinate (m)
TL204
TL2035
TL203
TL2025
TT103
TL111
TL112
TL1095
TT101
125 m/a
5 m/a

Bed of Thwaites Glacier

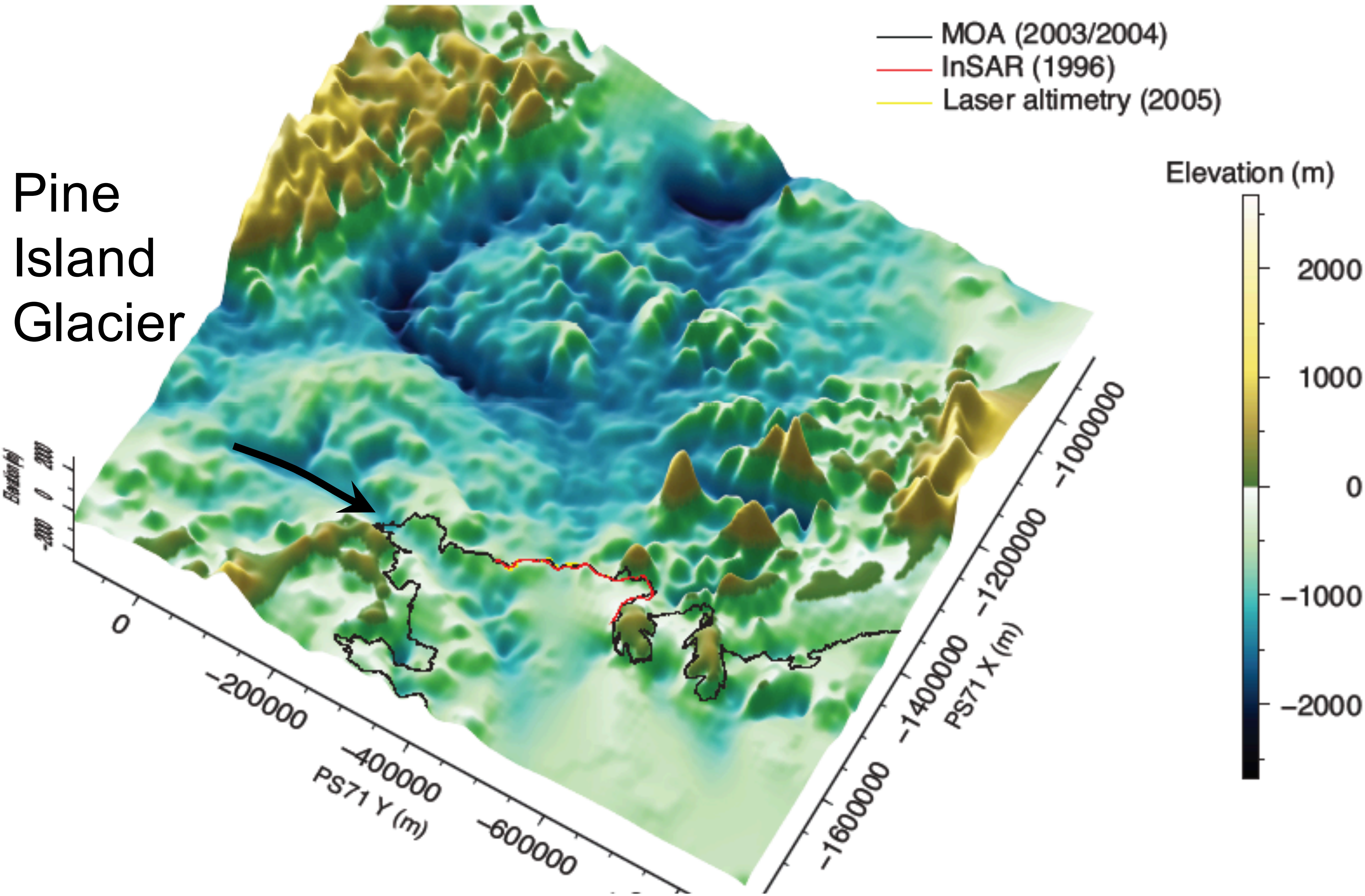


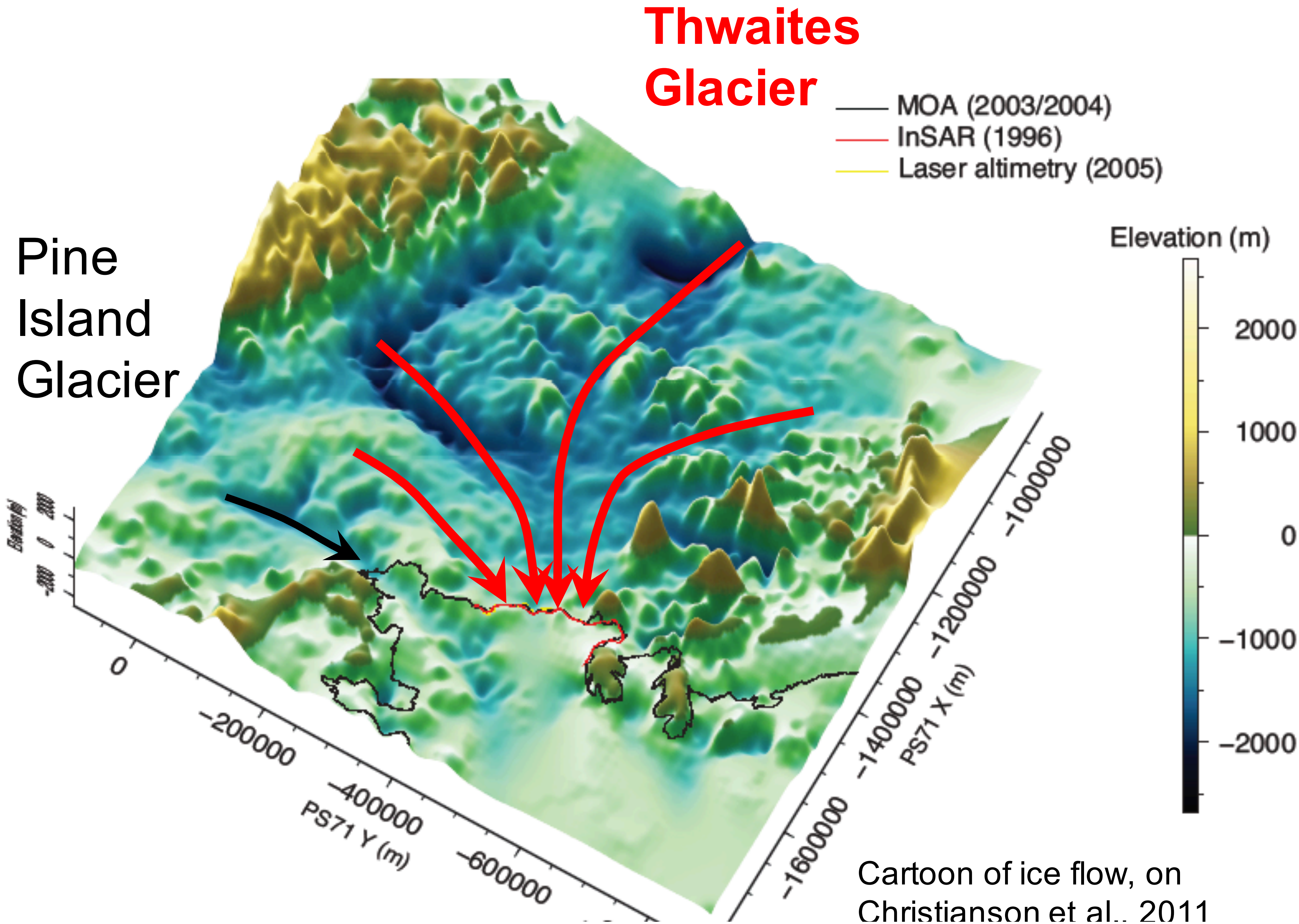


Cartoon of ice flow, on
Christianson et al., 2011

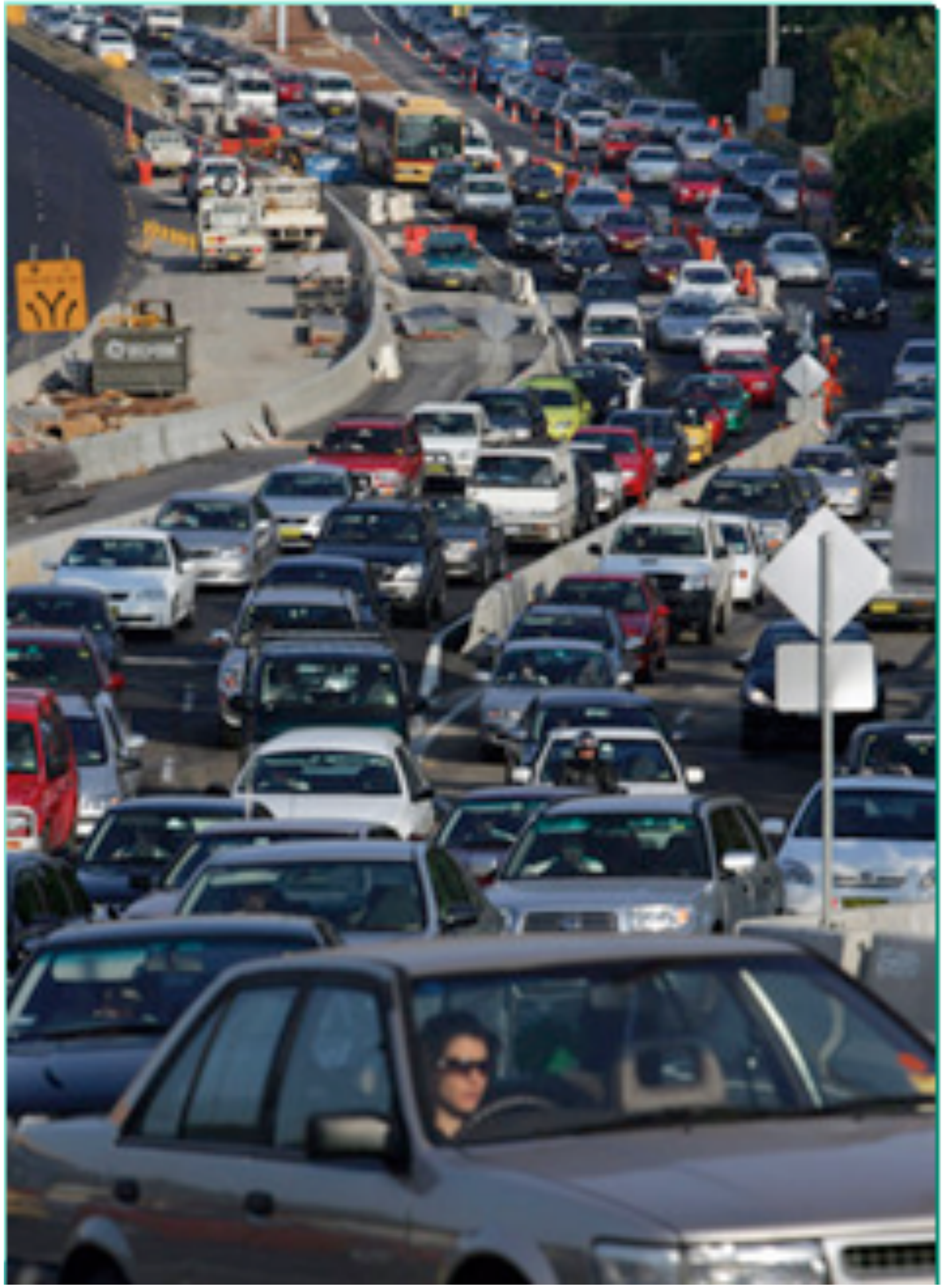
Christianson et al., 2011

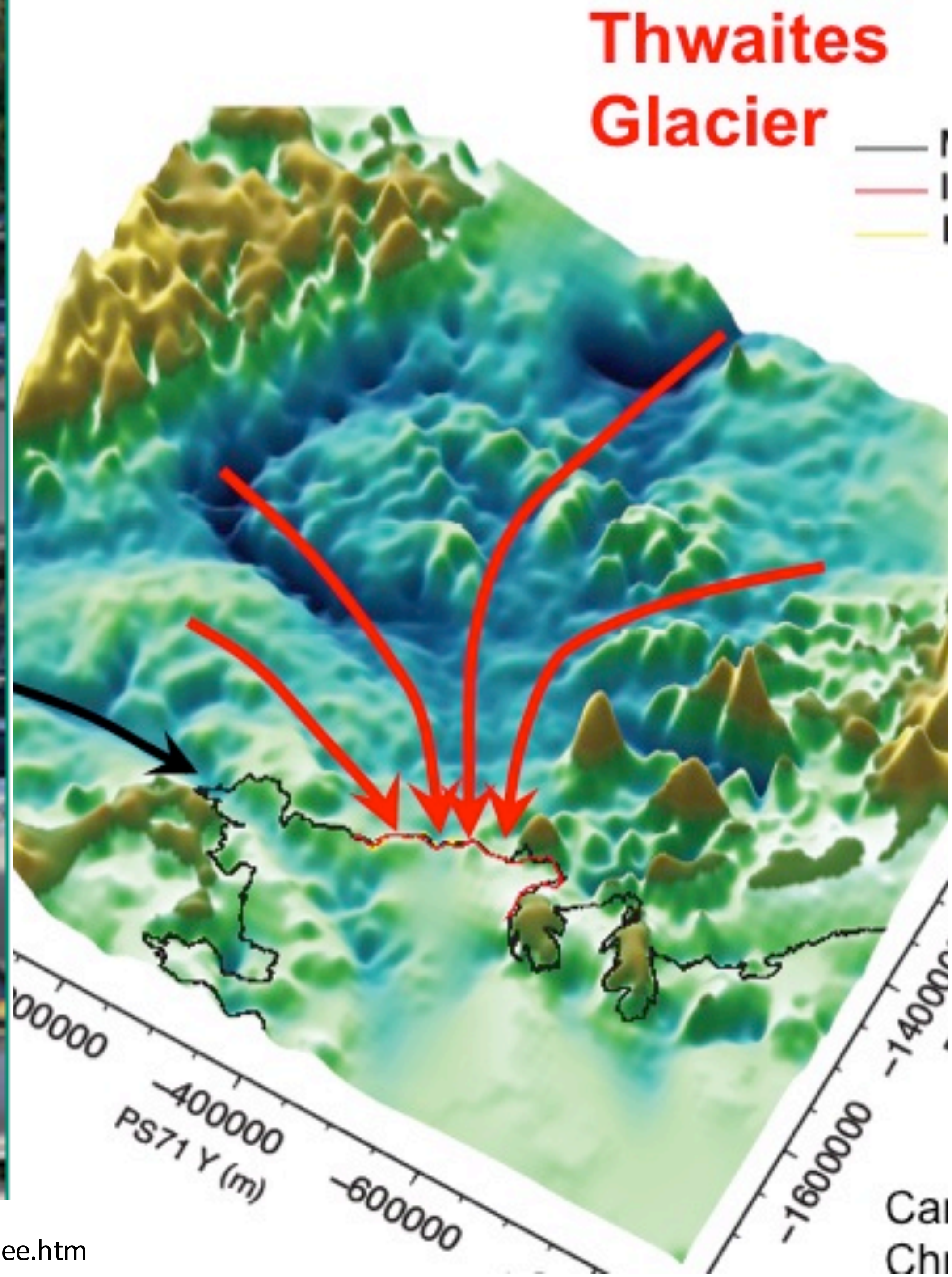
Pine Island Glacier





Cartoon of ice flow, on Christianson et al., 2011





http://www.ops.fhwa.dot.gov/wz/p2p/pmwkshop053013/hayee/hayee.htm


Thwaites retreat may give much higher cliff
that breaks, breaks, breaks…

Many poorly constrained parameters

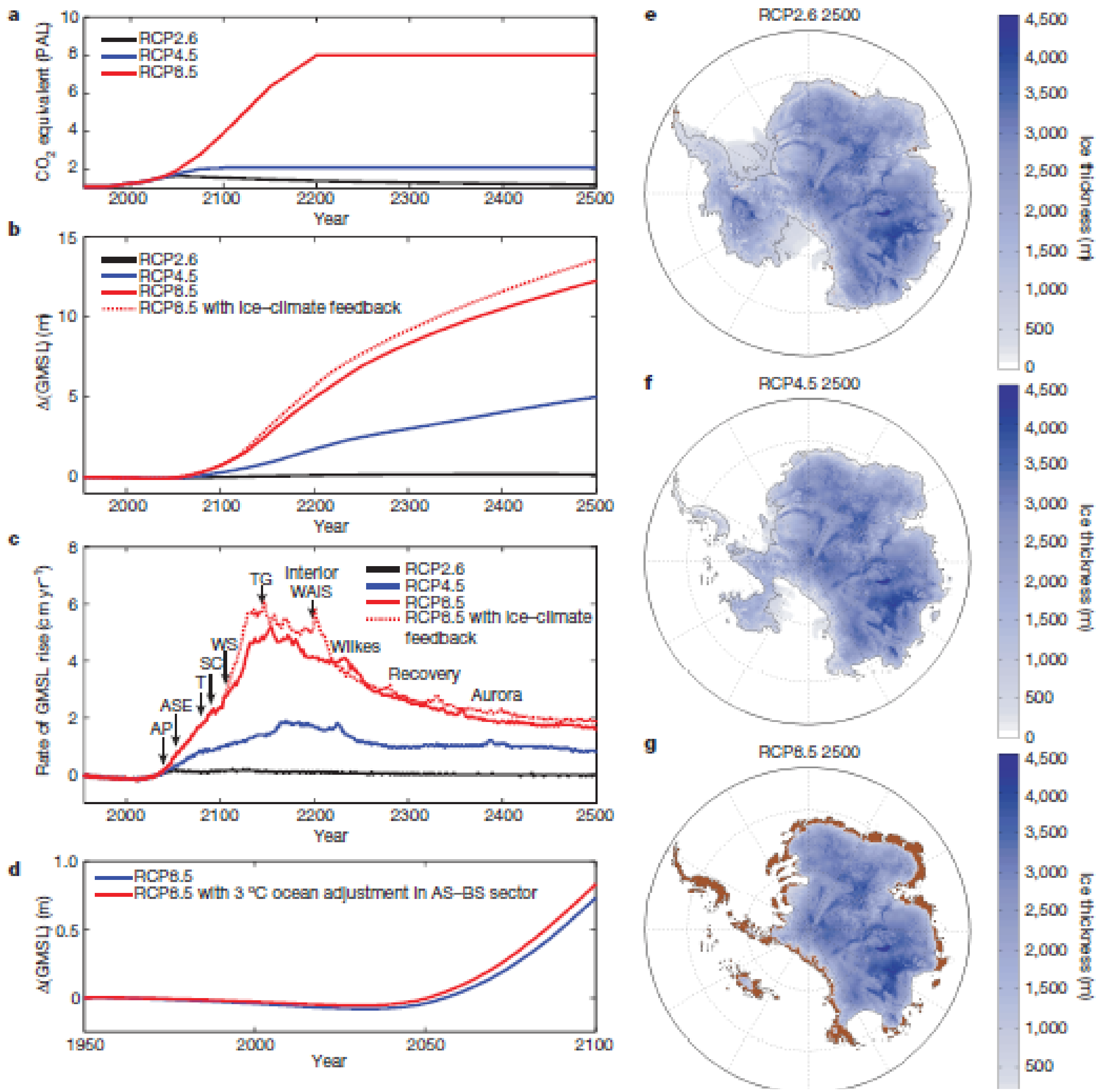
- With support, could measure some better
- Some fairly hard to do
- But, clearly highly important
- For example, Joughin et al. 2014 found West Amtarctic collapse already committed; we (Parizek et al., 2013) found maybe/maybe not in part based on exploring a wider range of bed flow laws (plastic as well as viscous)
- Usual approach now is some sort of data assimilation or large-ensemble simulations varying poorly known parameters to match "snapshots" of ice-sheet state, recent behavior or longer-term time-trends

Many poorly constrained parameters

- Edwards et al. (2015, *Nature*) used a model with enough physics to match recent behavior, matched it, and concluded large, rapid sea-level rise from West Antarctica "implausible"
- Pollard, DeConto & Alley (2015, *EPSL*) couldn't match constraints from further back in time without including physics you just saw
- Including those physics (DeConto & Pollard, 2016, *Nature*) successfully matched history as well as more-recent changes
- And, with those parameters, found that strong warming brings the large and rapid sea-level rise deemed "implausible" by the simpler model

Future 500 years (DeConto and Pollard, 2016)

In these runs:
→ Humans choose whether sea-level rise large
→ NOT worst case
→ Specified maximum retreat rate not strongly physical; could be faster, not sure how much
→ So far, paleo-data point to fast retreat, but don't constrain how fast




Our community:
→ Still data-poor
→ But improving
→ Big opportunities for big data, data assimilation, etc.

But, ice sheets:

→ Timescales range from very short to >10 thousand yr

→ Future forcing may go beyond any in >10 million yr

→ Great care needed in choosing model(s)

Based on new work:

→ Past assessments seem overly optimistic

→ Because of reliance on incomplete models

→ And failure to incorporate full range of data


In dealing with important questions and deep uncertainty, model choice especially critical for interpreting big data.