Climate, Melting Ice and Rising Seas

Observing and Understanding to Reduce Risks

Richard B. Alley

May 23, 2017

45th annual NOAA Global Monitoring Annual Conference, Boulder, CO

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

NSF CRESIS PENNSTATE NASA earth THE OPERATORS' MANUAL


Thanks to Diane Stanitski,
Jim Butler, and to you

Fires have always occurred in some places…

The Big Meadows Fire,
Rocky Mountain National Park,
June, 2013,
was triggered by lightning

Fires have never occurred on the snow here…

Ski tracks, middle of the Greenland ice sheet

Suppose you're planning a campfire to cook s'mores. Where should you be more worried—where fires have always occurred, or never?

https://inciweb.nwcg.gov/photos/CAANF/2014-01-16-1131-COLBY/picts/2014_01_18-20.07.15.072-CST.jpeg

Fires have always occurred
Humans cause them, too

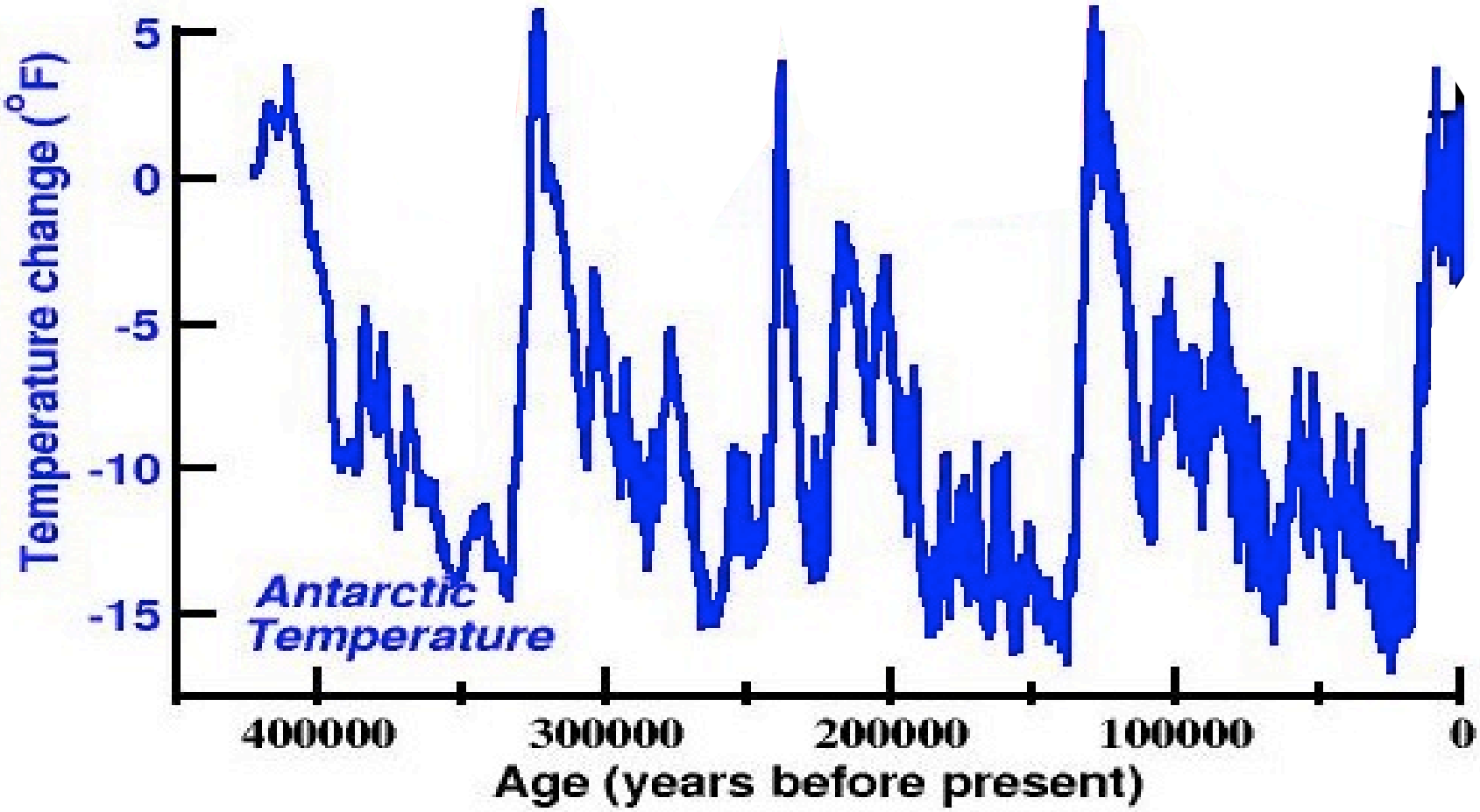
Human-caused fires are common where and when nature could cause one

This is the destructive 2014 Colby fire near LA, from an illegal campfire

https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=82878

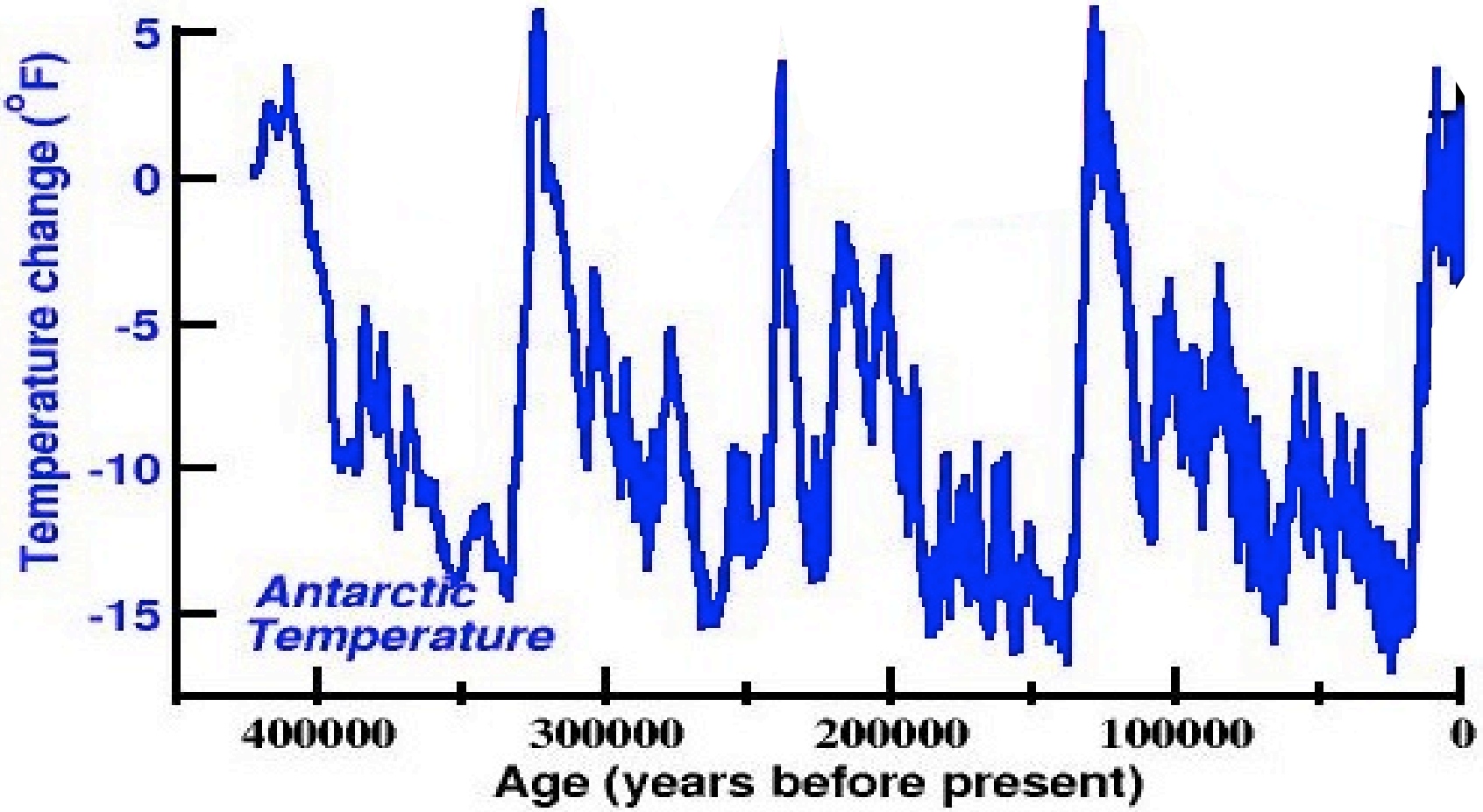
Climate has always changed

National Centers for Environmental Information



Climate has always changed

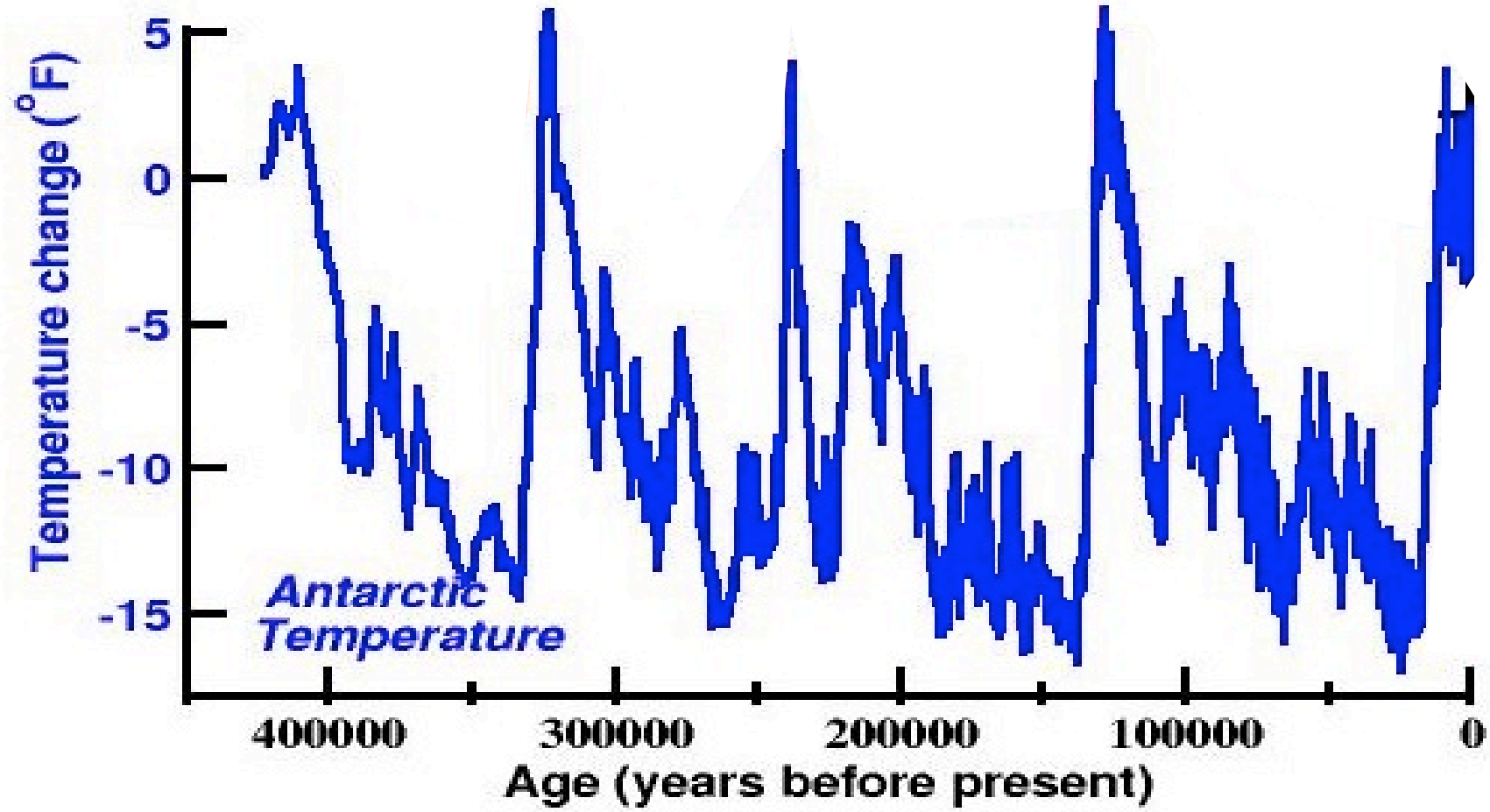
Senators and neighbors have used that to argue humans can't be changing the climate



Climate has always changed

Senators and neighbors have used that to argue humans can't be changing the climate

Would anyone make that argument for arson?

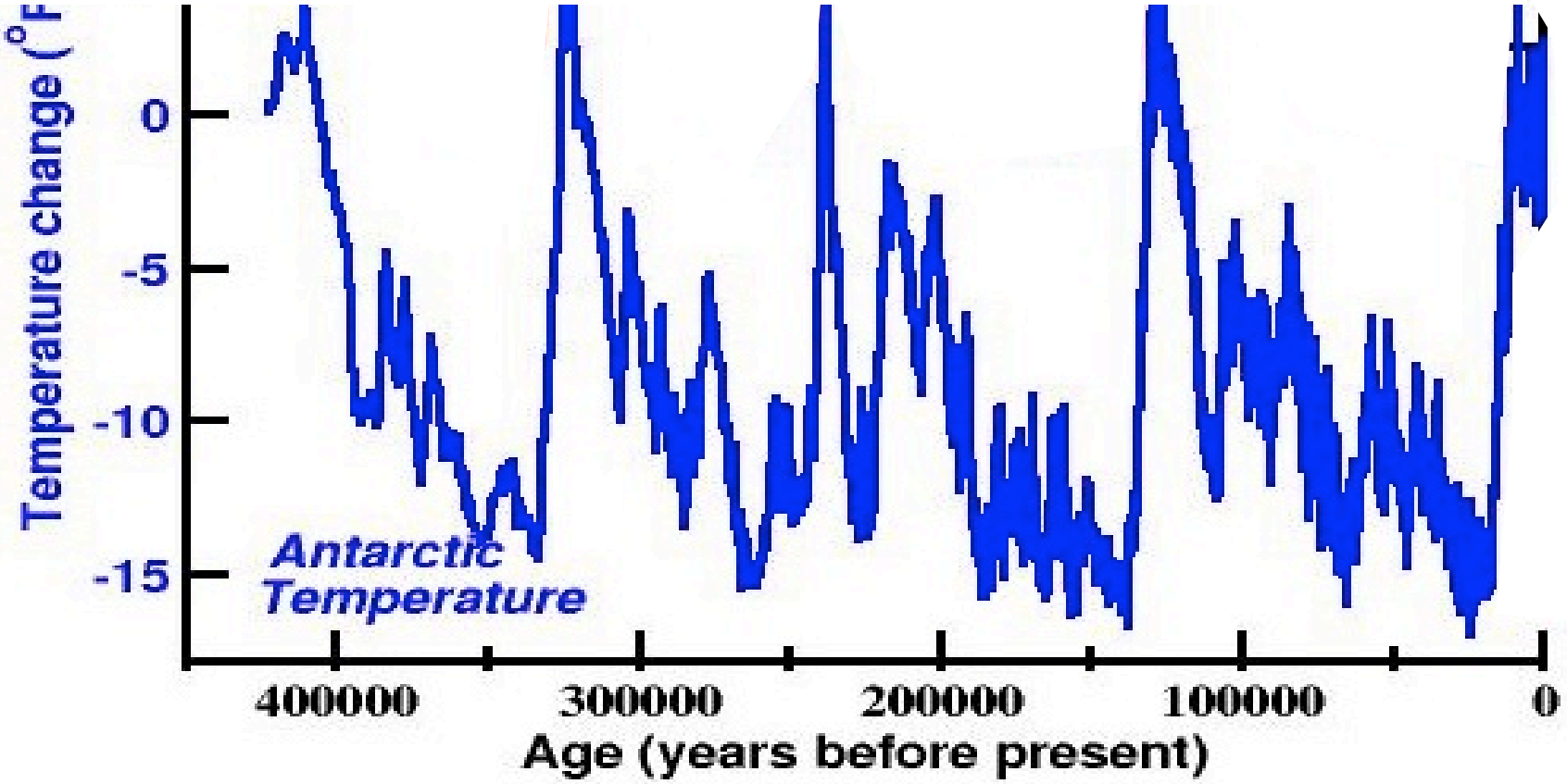


Climate has always changed

Senators and neighbors have used that to argue humans can't be changing the climate

We can easily burn a burnable place,

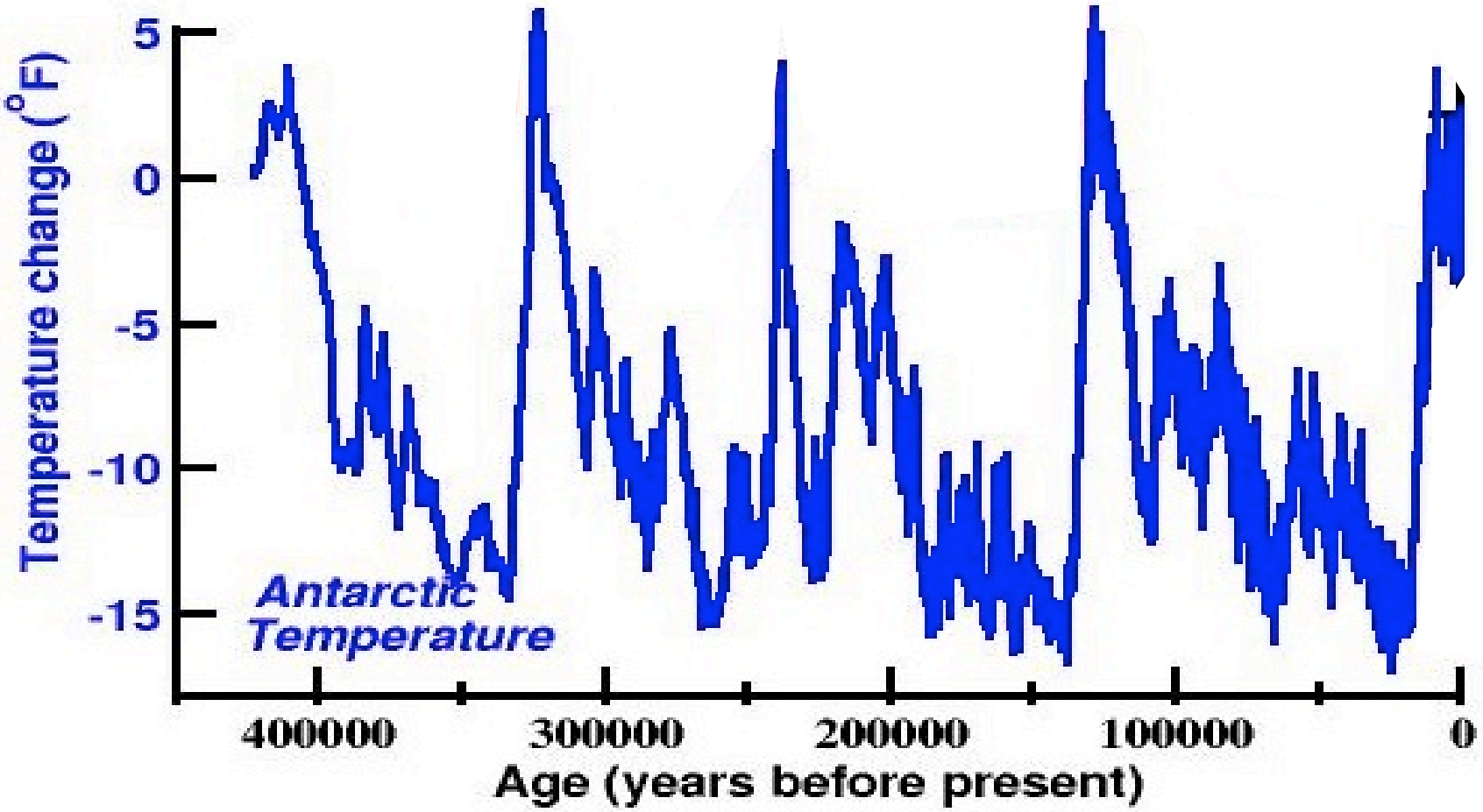
and change a changeable climate



It's a different talk, but natural changes in CO_2 have been most important in controlling climate.

We could rival biggest natural changes, but faster.

One example of natural CO_2 influence (of many!):



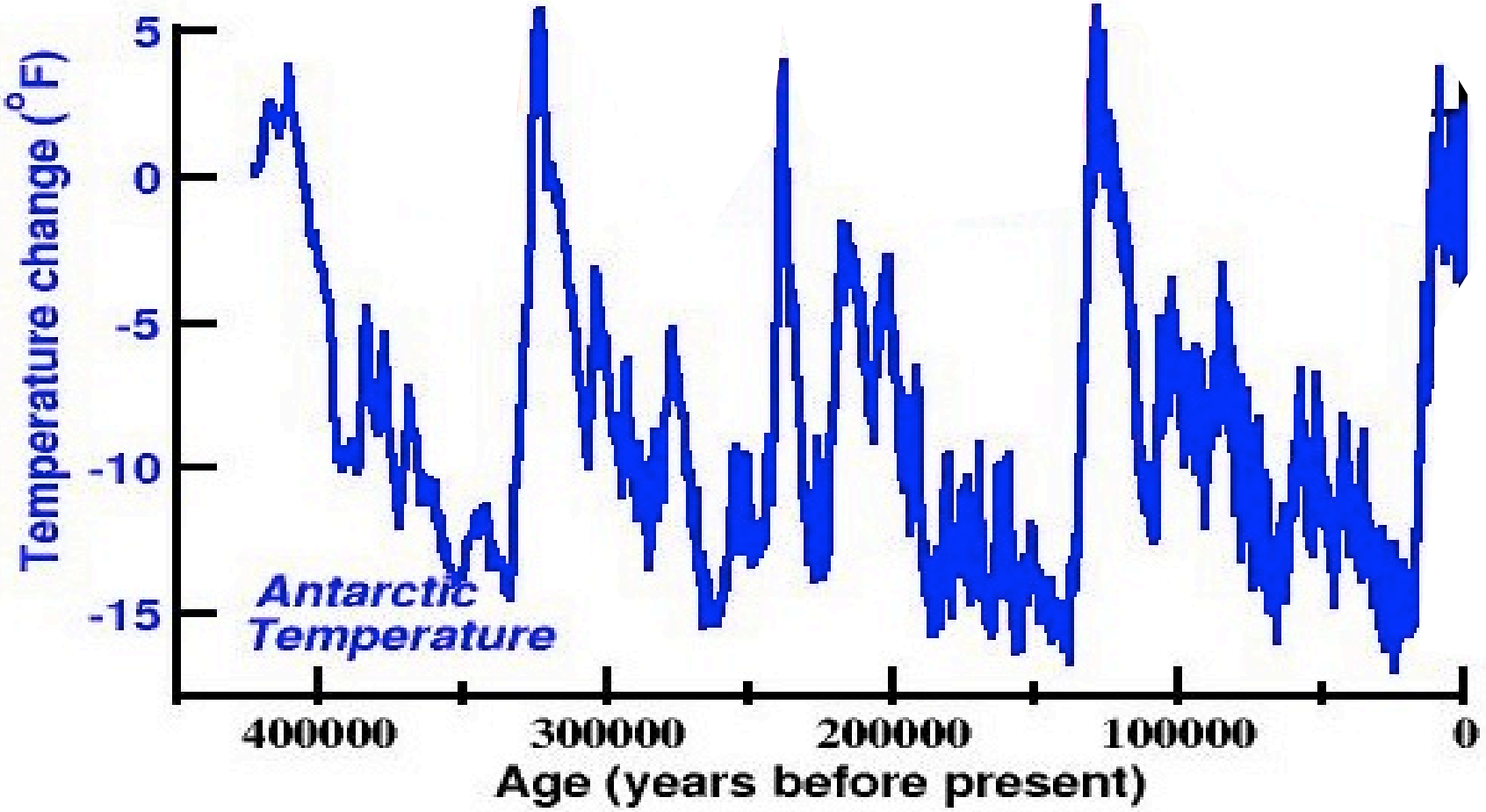
When orbits raised summer+yearly sun in north:

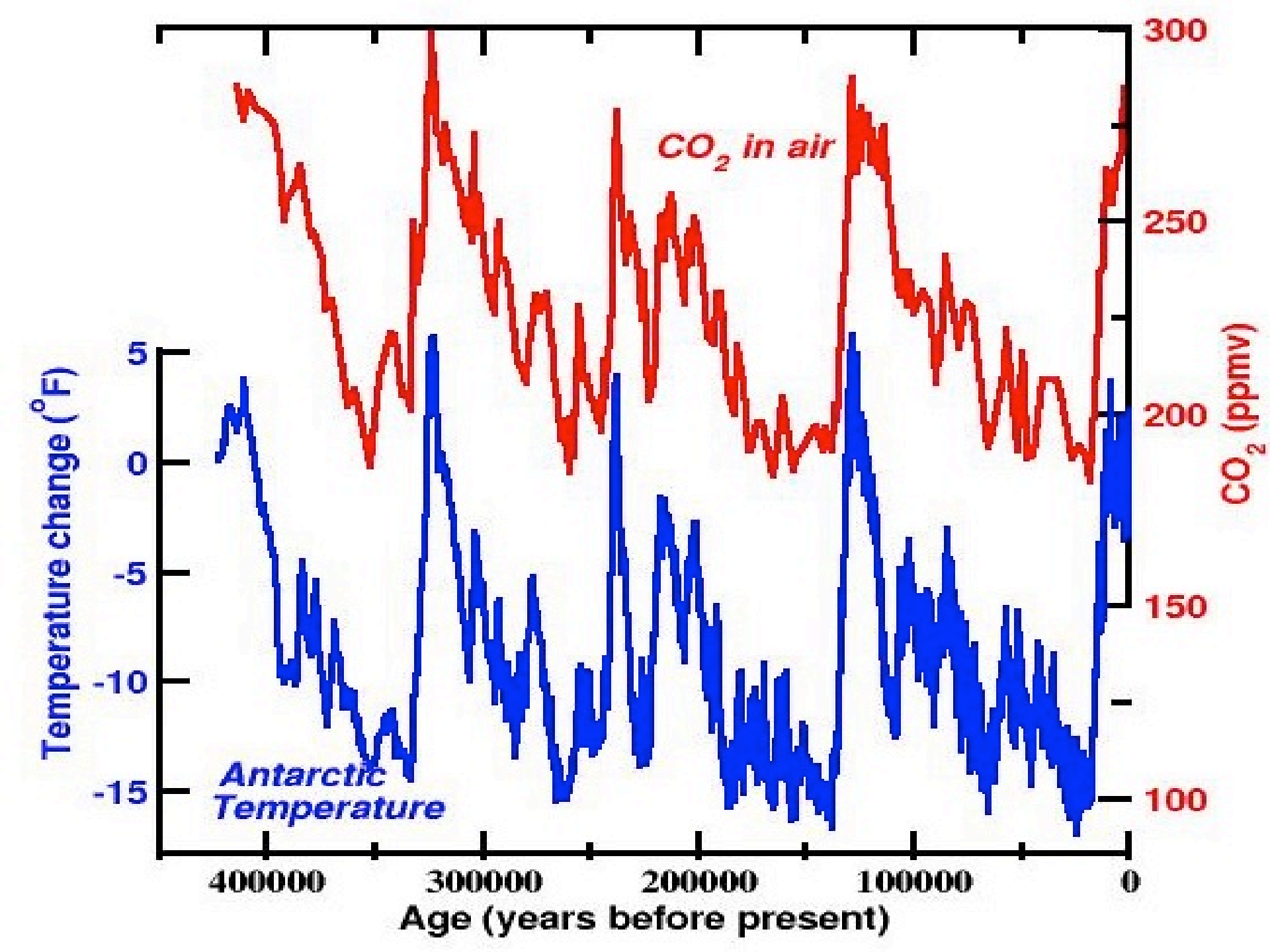
→Ice melted

→But the whole world warmed

→Including the half of the world getting less sun

→And that is really weird—why would less sun warm?

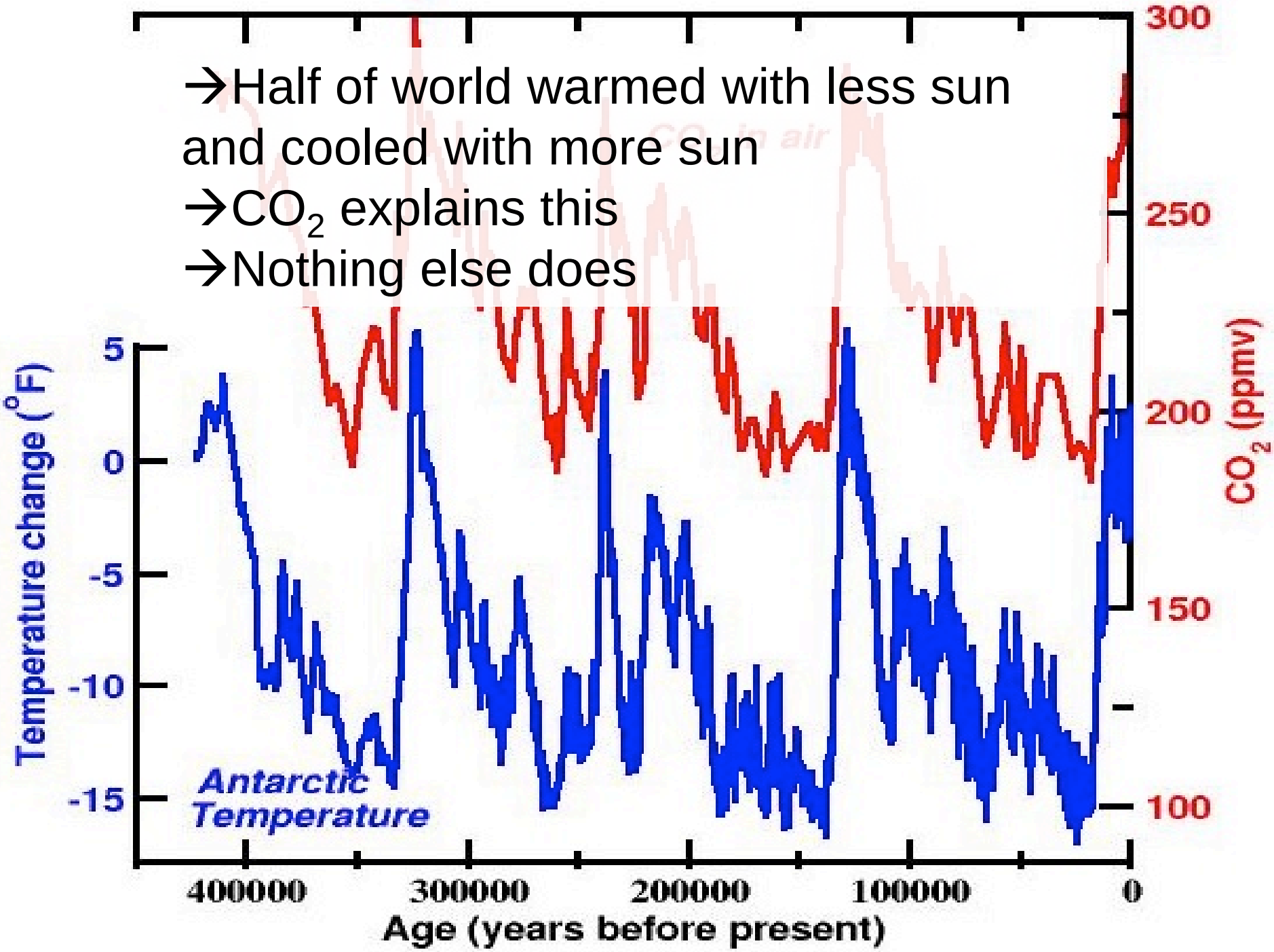


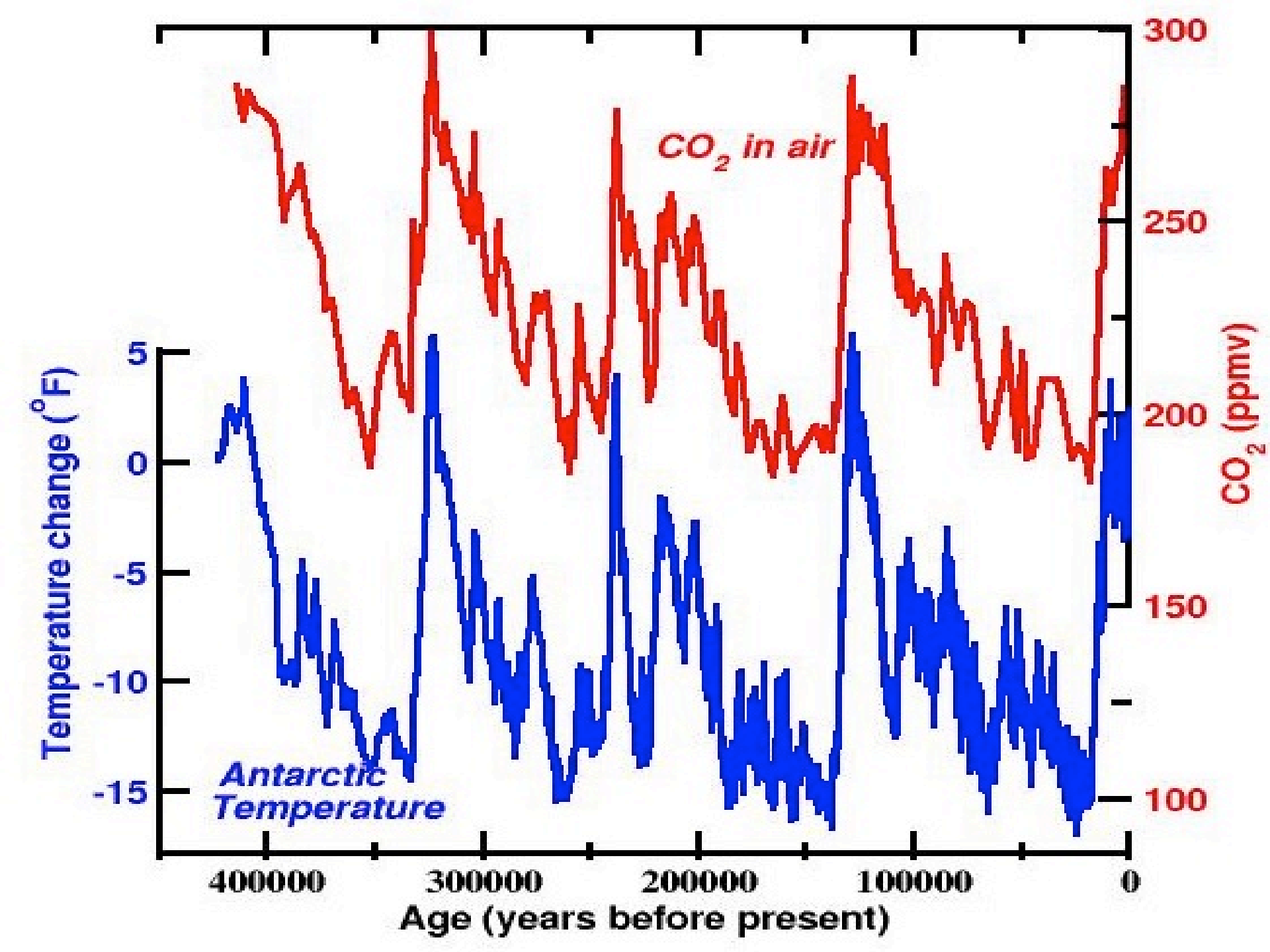

CO_2 in air
Antarctic Temperature
Temperature change (°F)
CO_2 (ppmv)
5
0
-5
-10
-15
300
250
200
150
100
400000
300000
200000
100000
0
Age (years before present)

→Half of world warmed with less sun and cooled with more sun

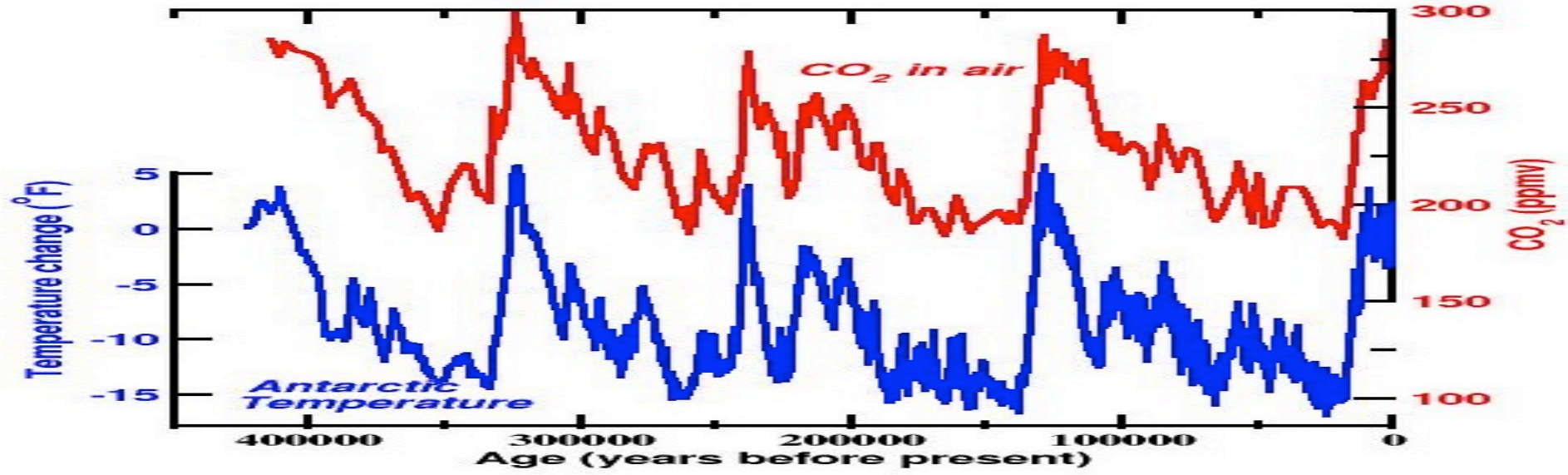
→CO_2 explains this

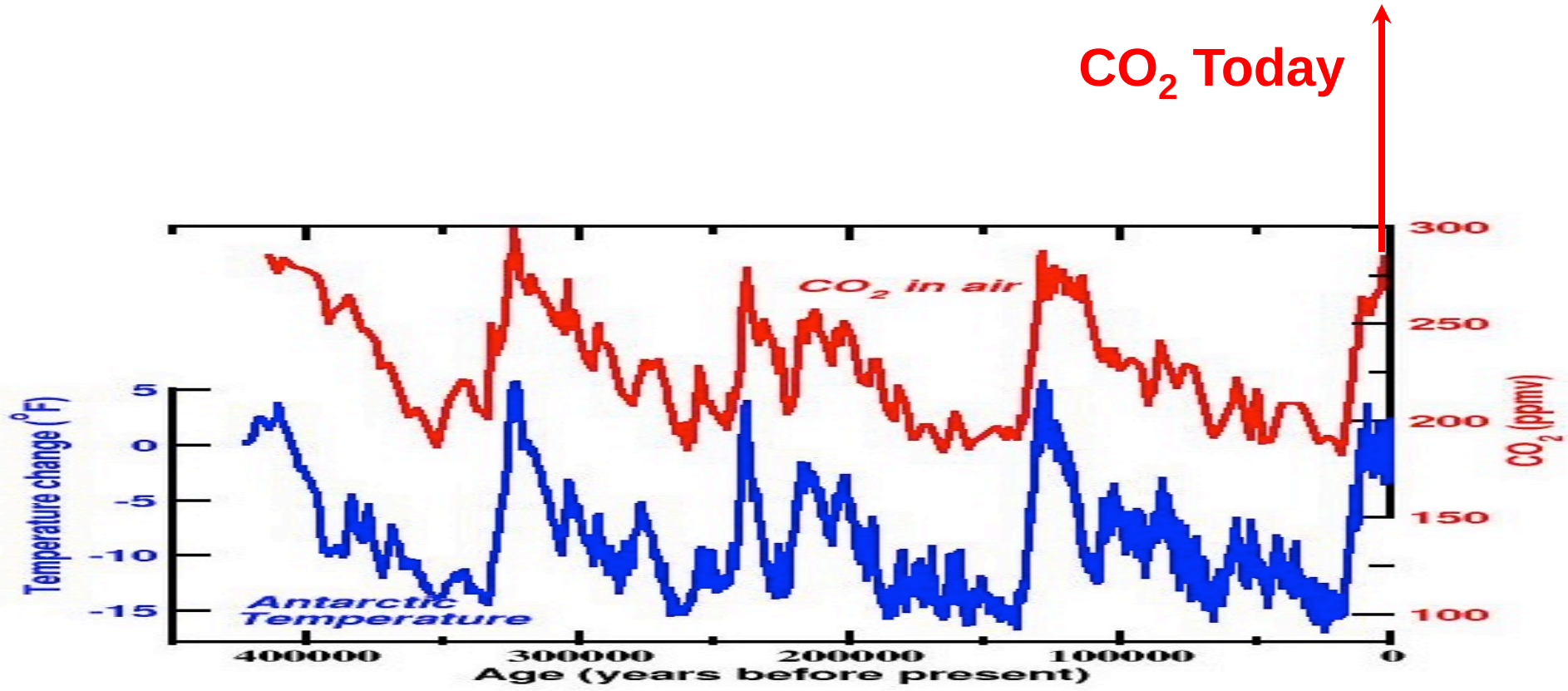
→Nothing else does




CO_2 in air
Antarctic Temperature
Temperature change (°F)
CO_2 (ppmv)
5
0
-5
-10
-15
300
250
200
150
100
400000
300000
200000
100000
0
Age (years before present)

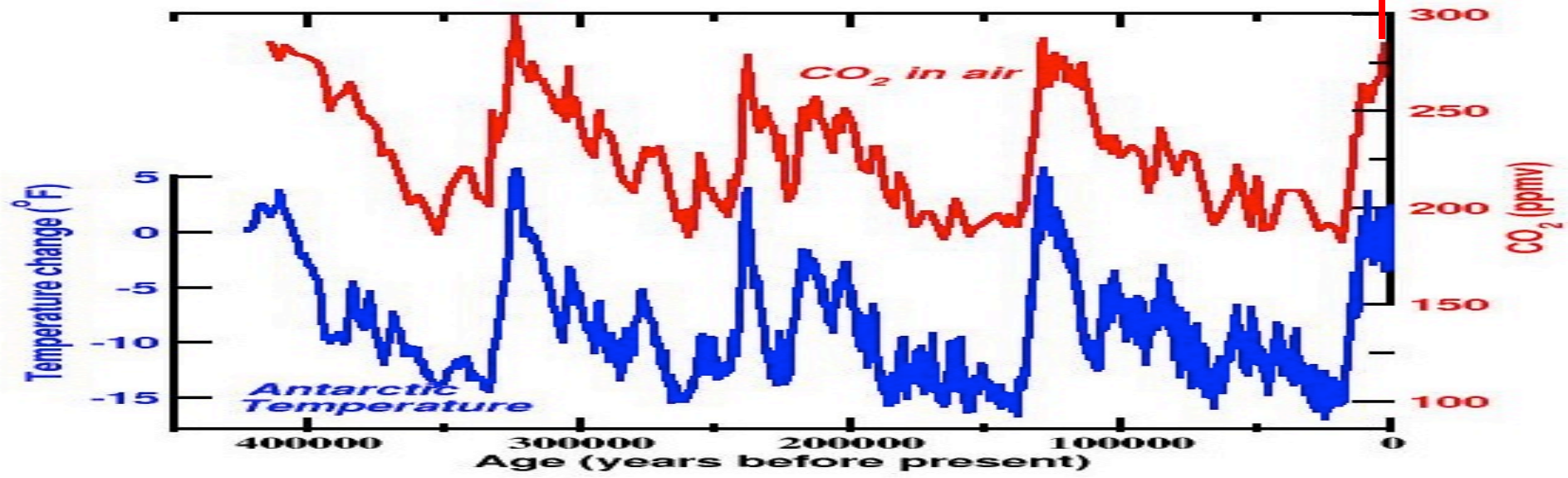
Warming effect of CO_2 raises real questions about future




CO_2 Today
CO_2 in air
Antarctic Temperature
Temperature change (°F)
CO_2 (ppmv)
5
0
-5
-10
-15
300
250
200
150
100
400000
300000
200000
100000
0
Age (years before present)

Business as usual

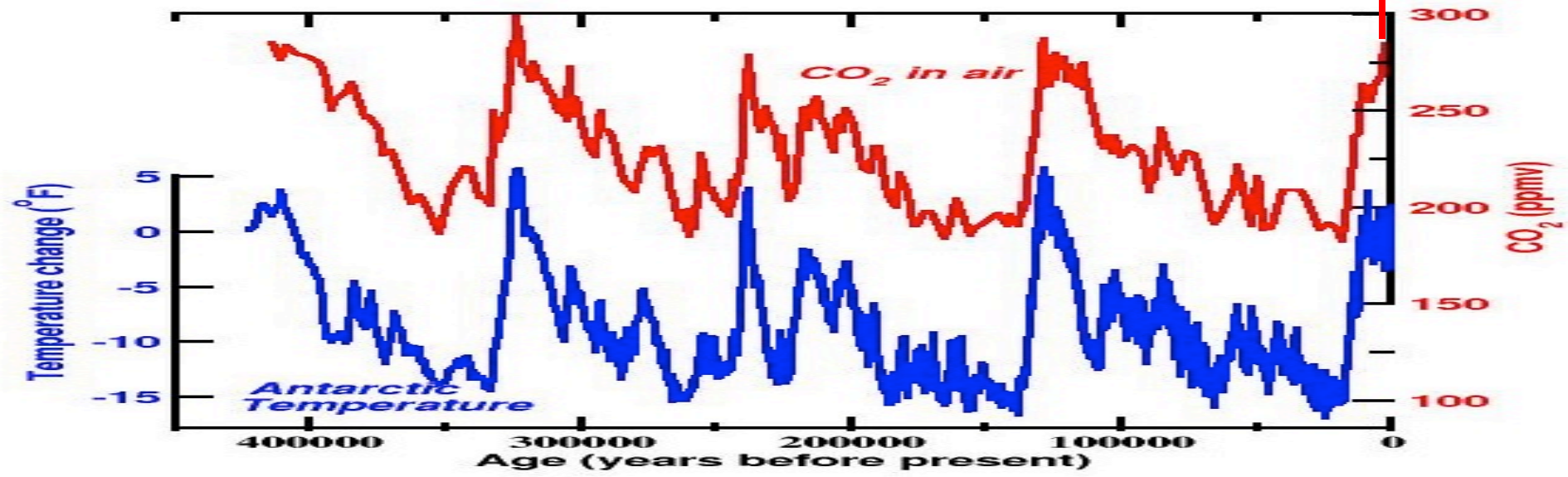
CO_2 Today



Business as usual

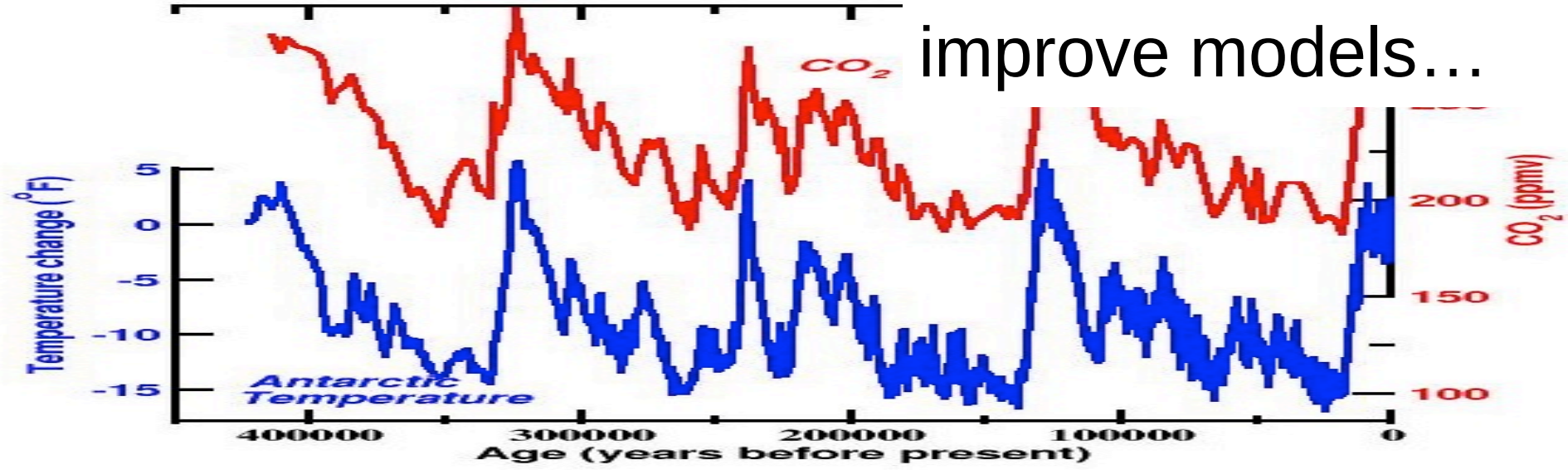
To handle wisely, we need you!

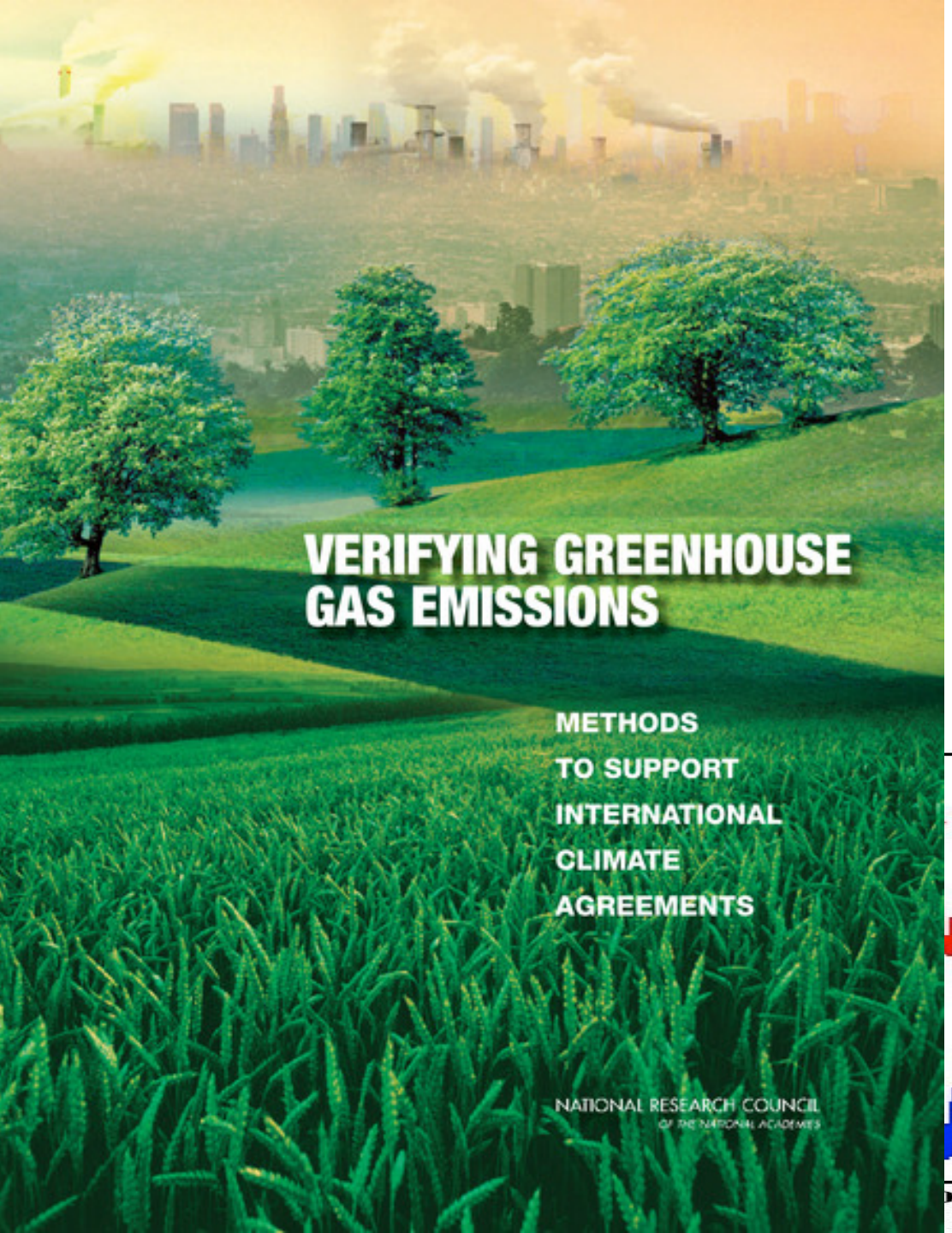
CO_2 Today



Business as usual

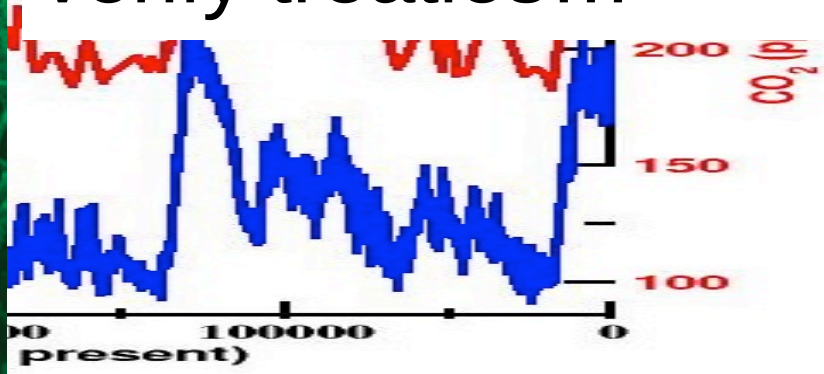
To handle wisely, we need you!
To document sources, sinks, feedbacks, allow assimilation to improve models…





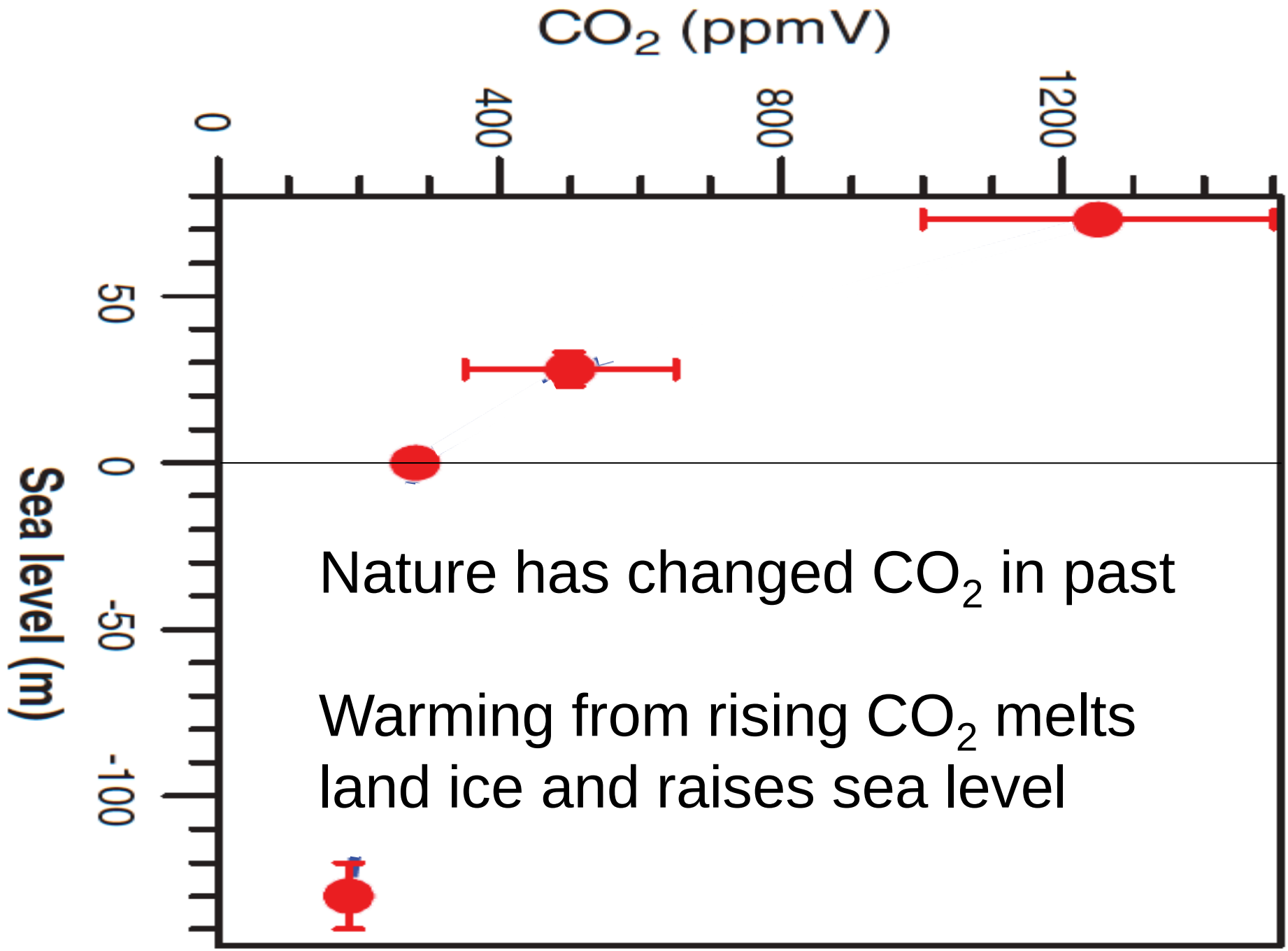
Business as usual

To handle wisely, we need you!
To document sources, sinks, feedbacks, allow assimilation to improve models, verify treaties…

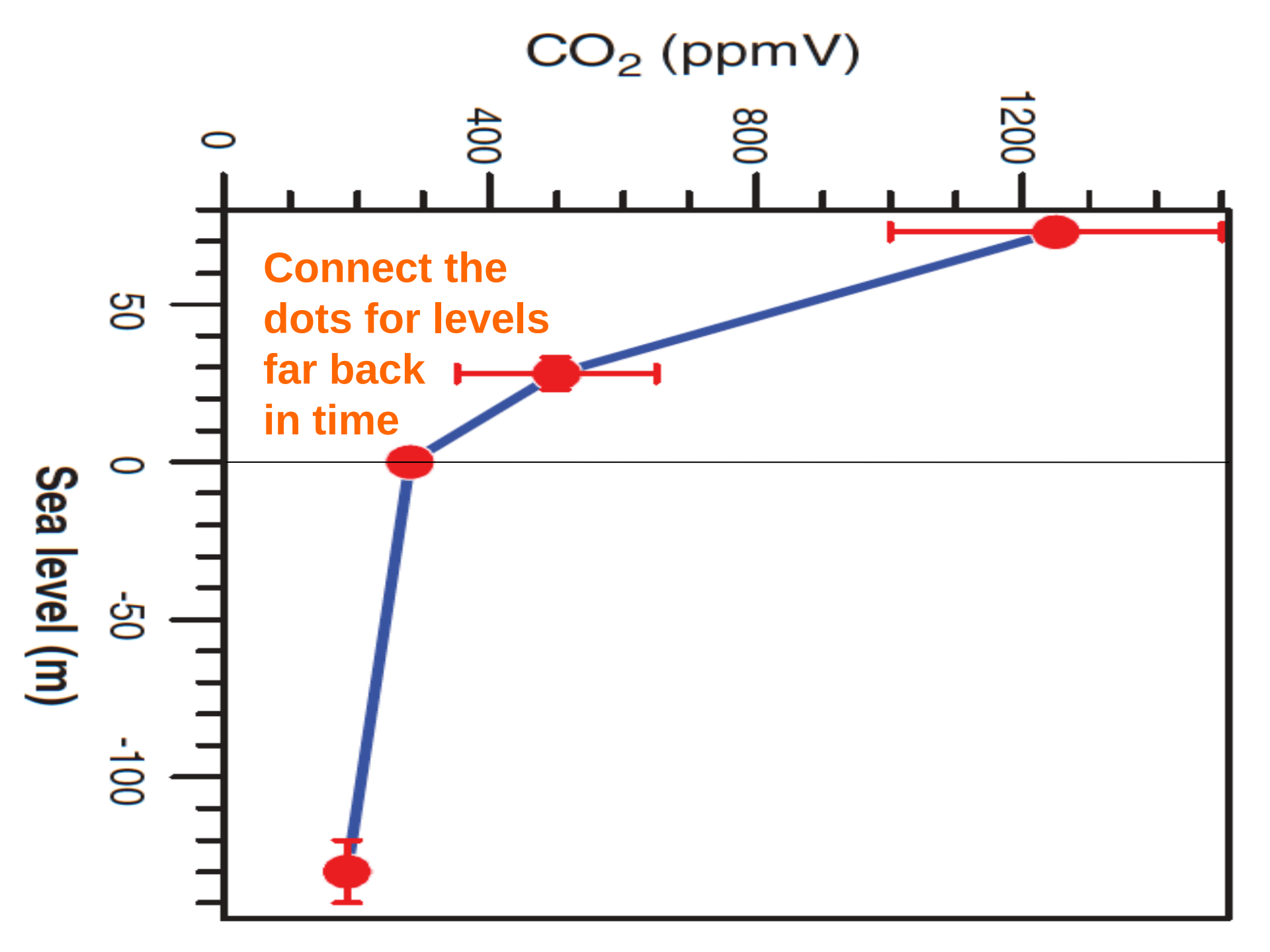


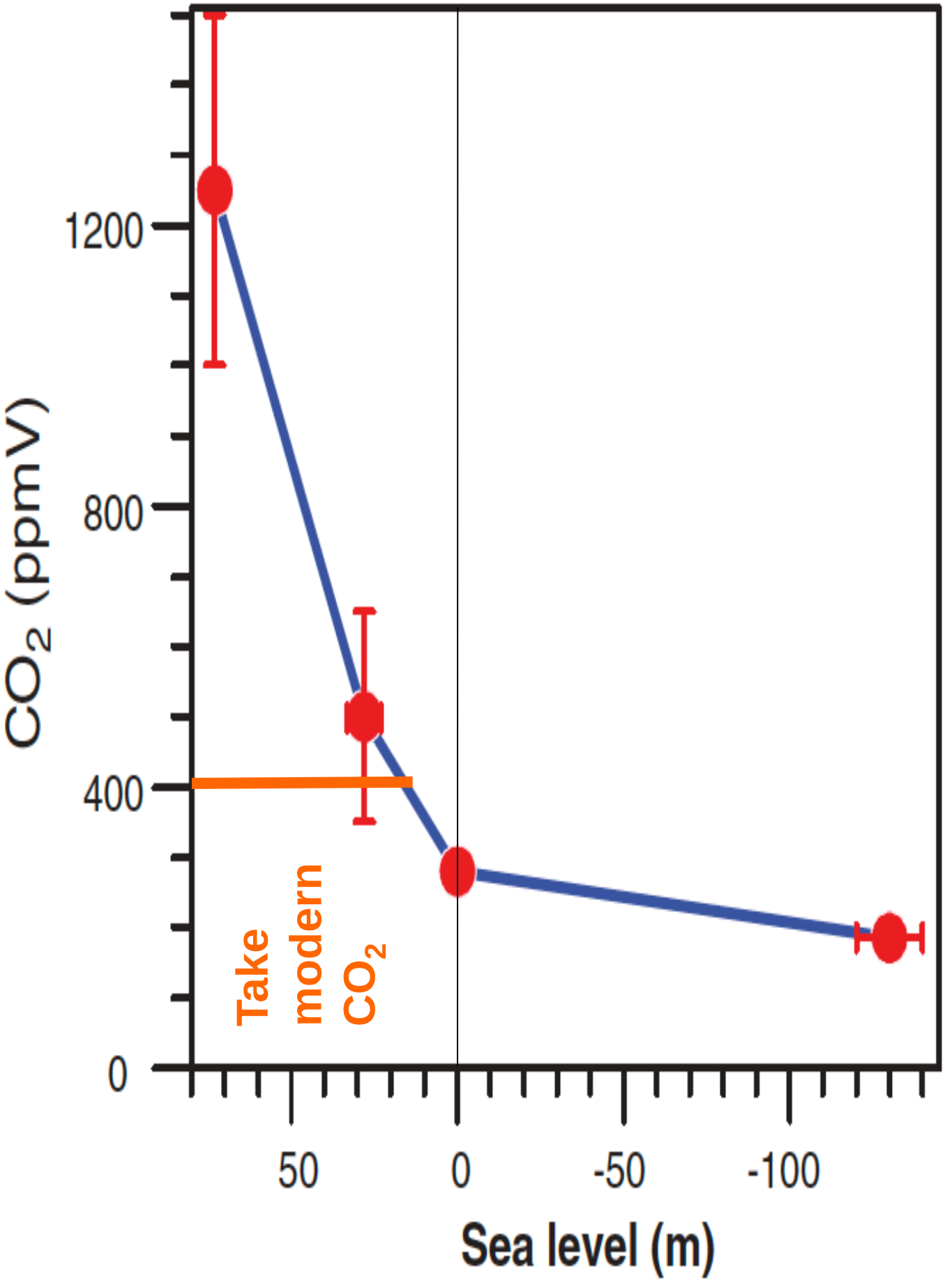

Originally, I thought I'd talk about CO_2
And how important you and your data are
But you know all that
So, something else
I've been working a lot on sea-level rise…

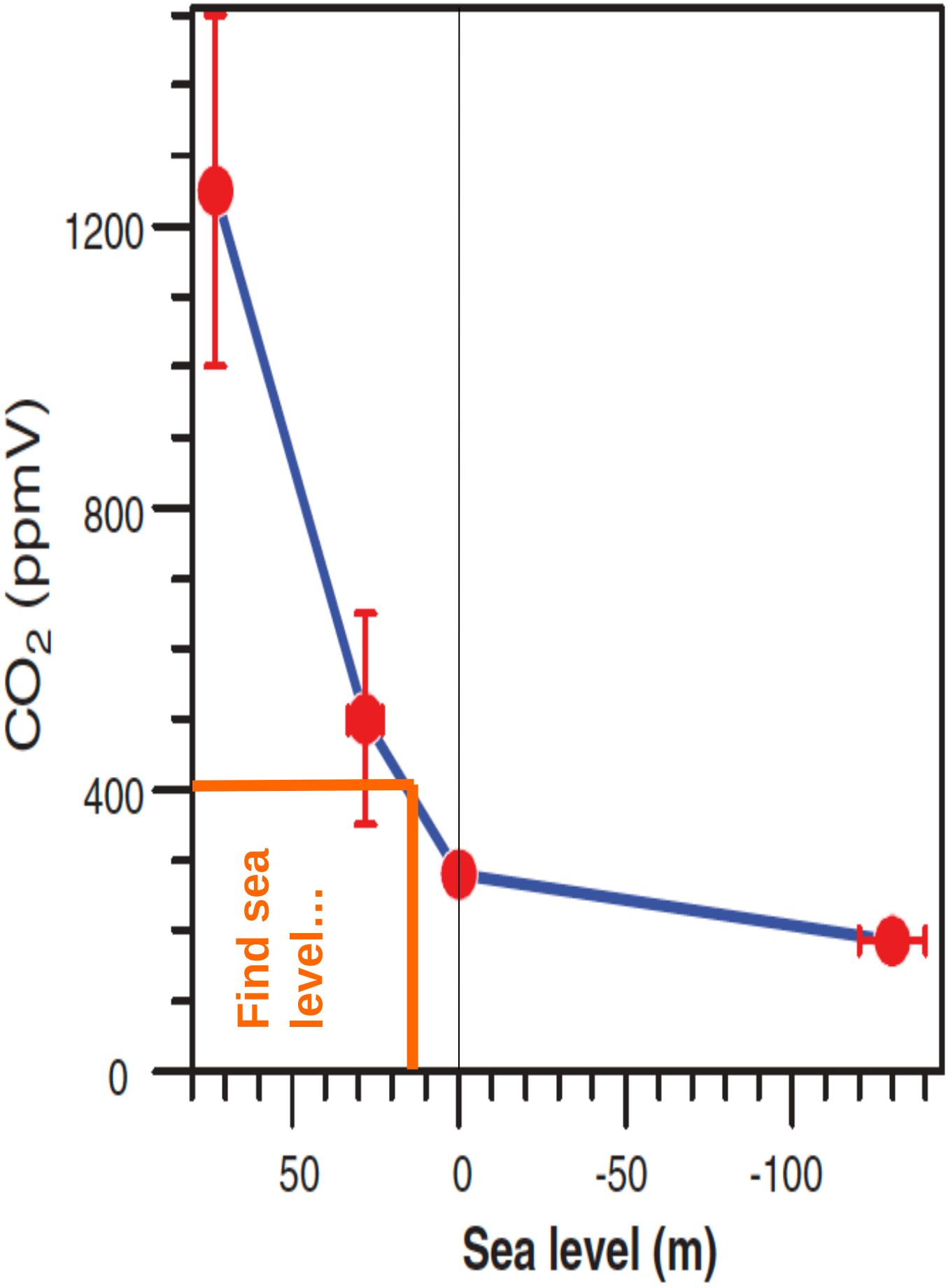

Let’s look a bit at
→ uncertainties,
→ the value of knowledge
→and making knowledge actionable…

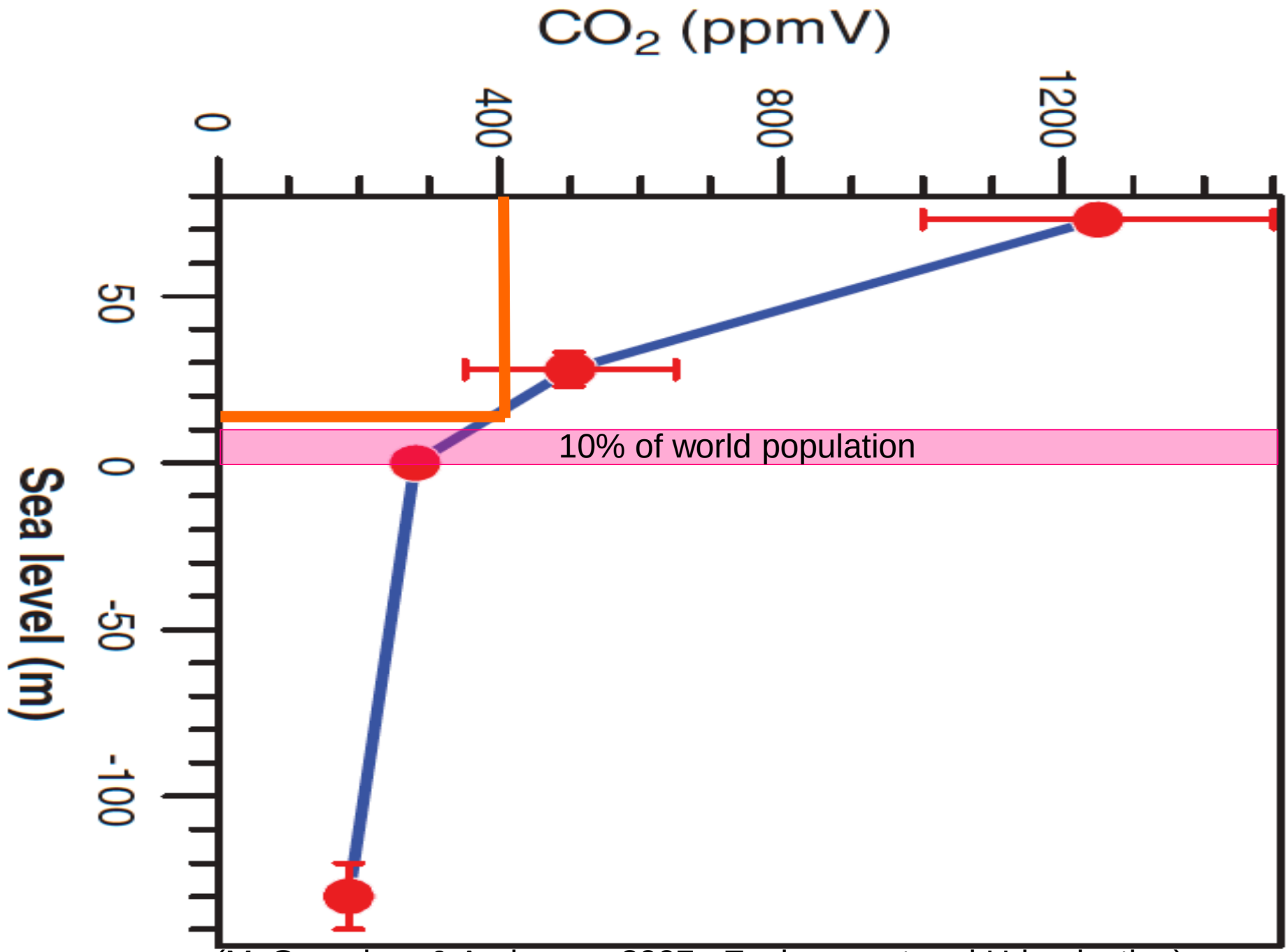


Alley et al., Science, 2005

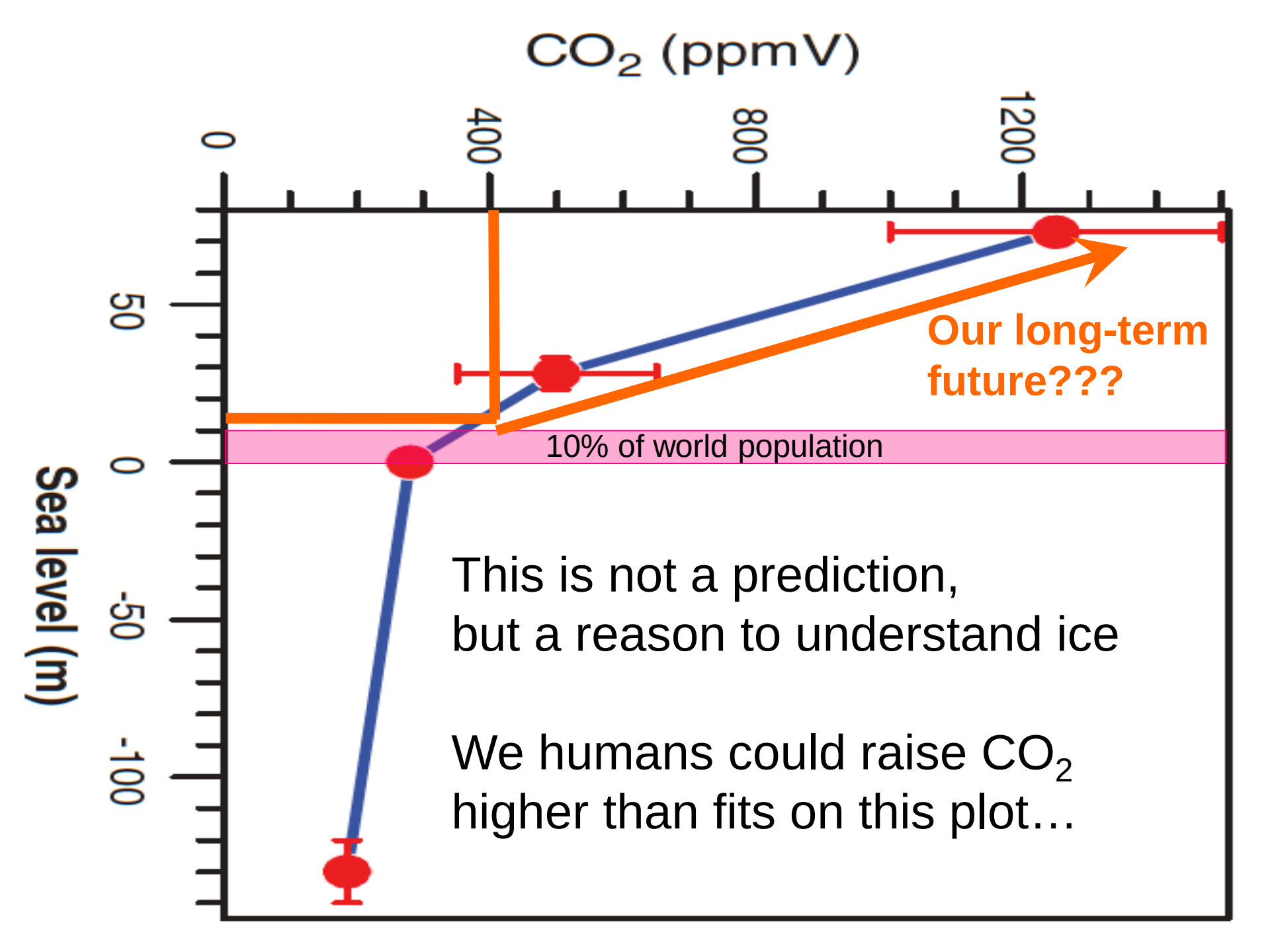

CO_2 (ppmV)
0
400
800
1200
Connect the dots for levels far back in time
50
0
-50
-100
Sea level (m)

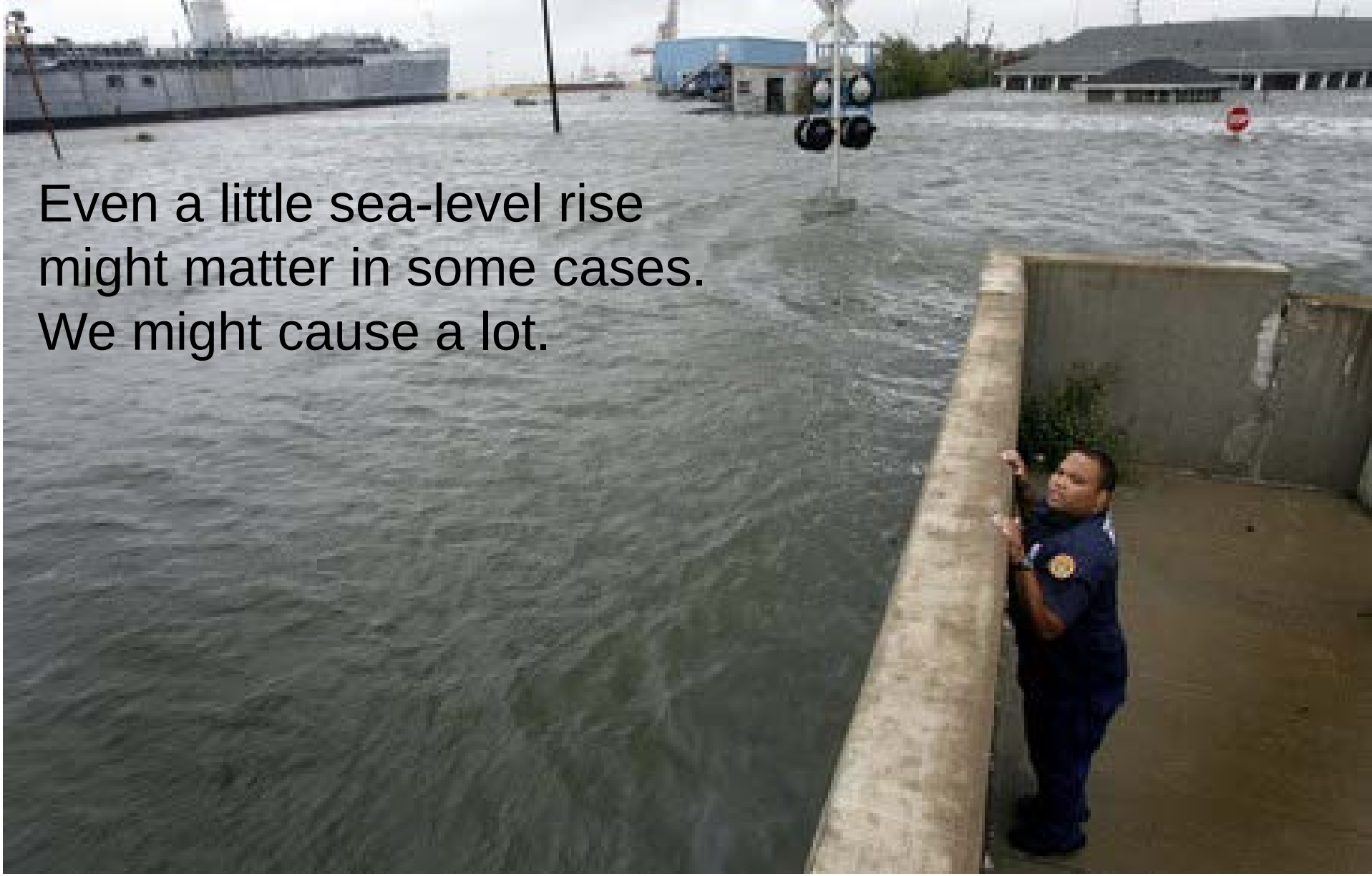

1200
800
400
0
CO_2 (ppmV)
Take modern CO_2
50
0
-50
-100
Sea level (m)


1200
800
400
0
CO_2 (ppmV)
Find sea level...
50
0
-50
-100
Sea level (m)



(McGranahan & Anderson, 2007, Environment and Urbanization).


CO_2 (ppmV)
0
400
800
1200
50
0
-50
-100
Sea level (m)
Our long-term future???
10% of world population
This is not a prediction,
but a reason to understand ice
We humans could raise CO_2
higher than fits on this plot…

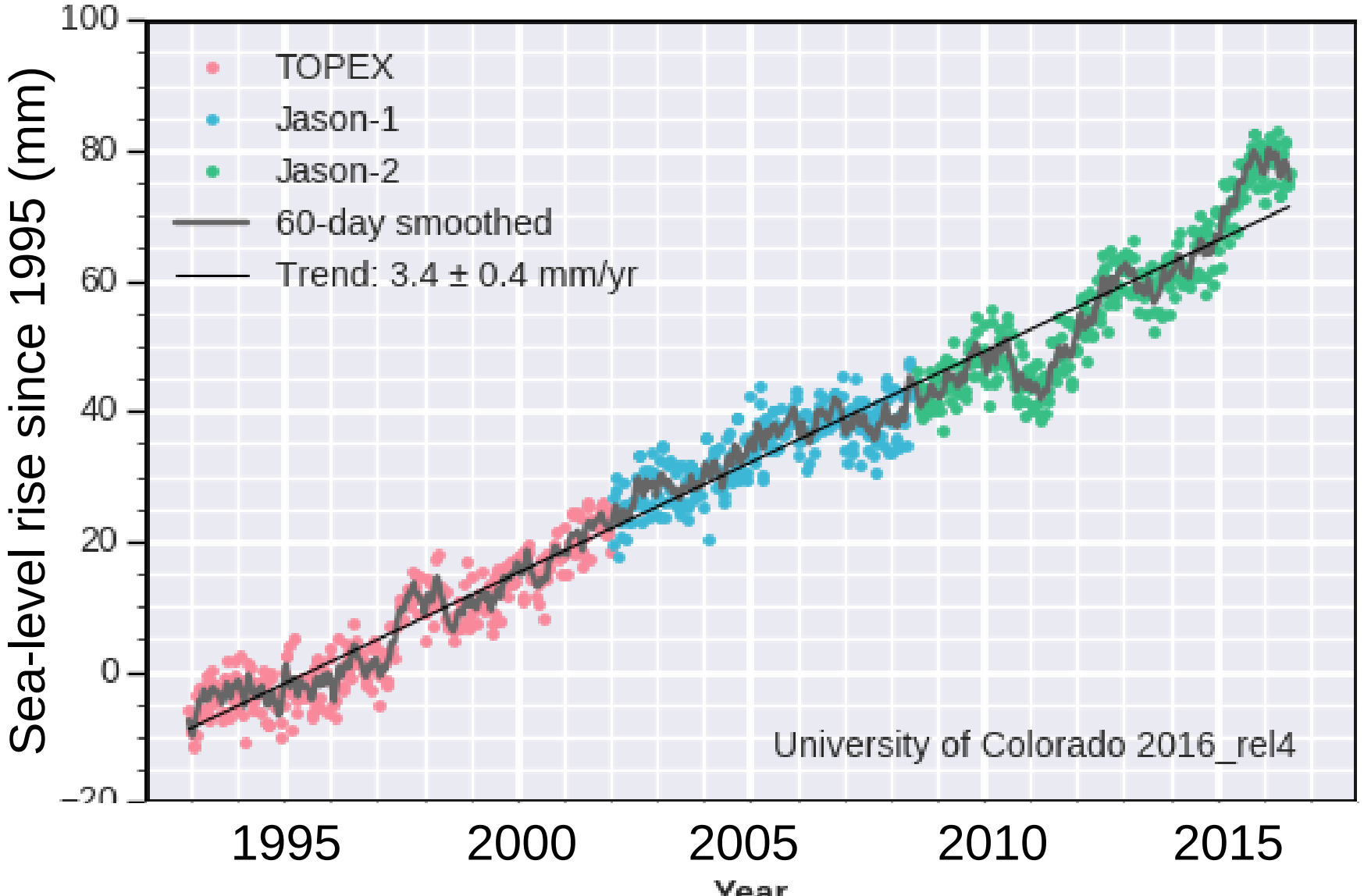


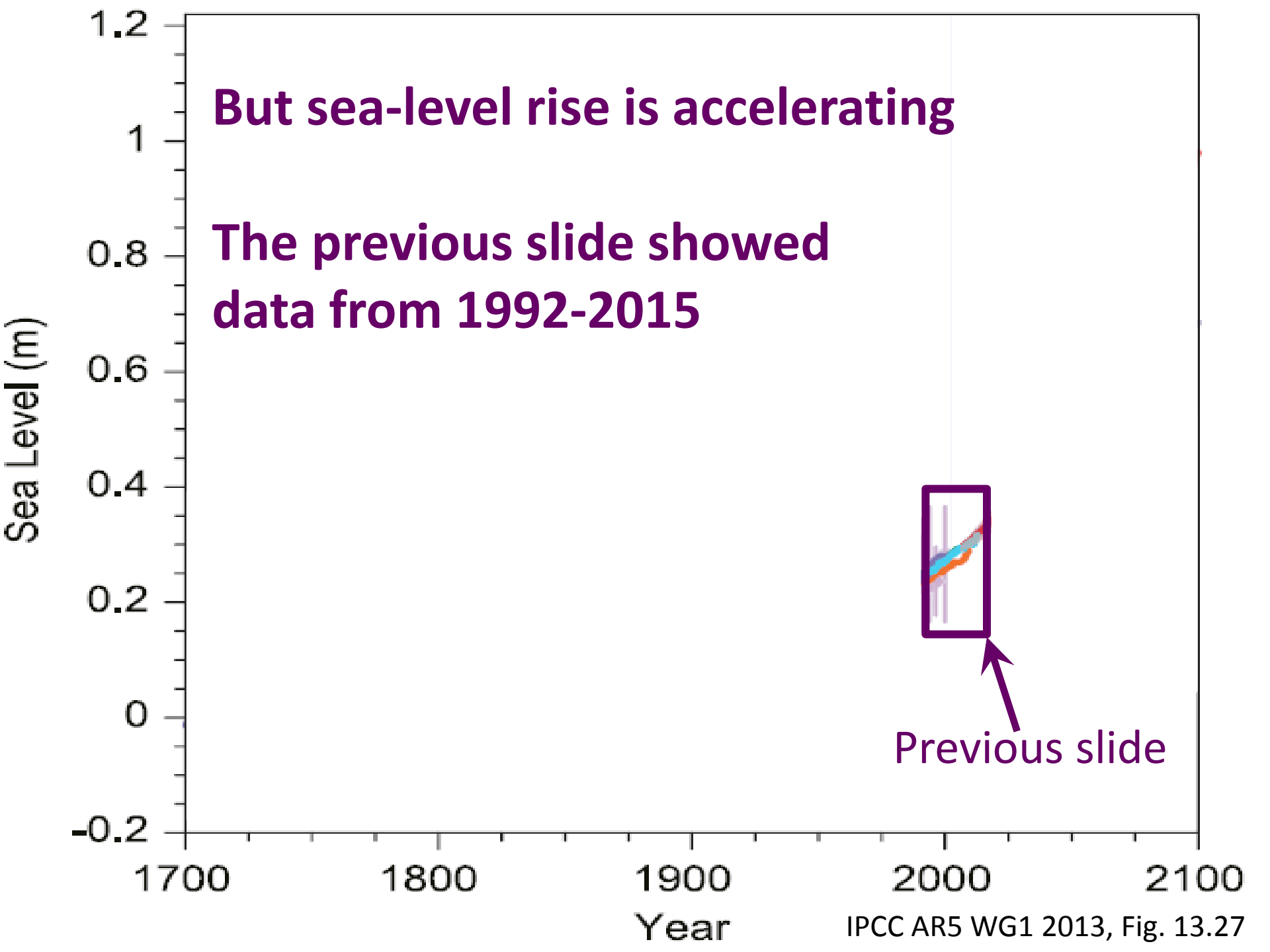
http://www.democraticunderground.com/discuss/duboard.php?az=view_all&address=389x3899732

A New Orleans Police Department officer peers over the Industrial Canal levee wall from the lower 9th Ward at the high water driven in by Hurricane Gustav. In the background, upper right is the flooded offices of Southern Scrap.

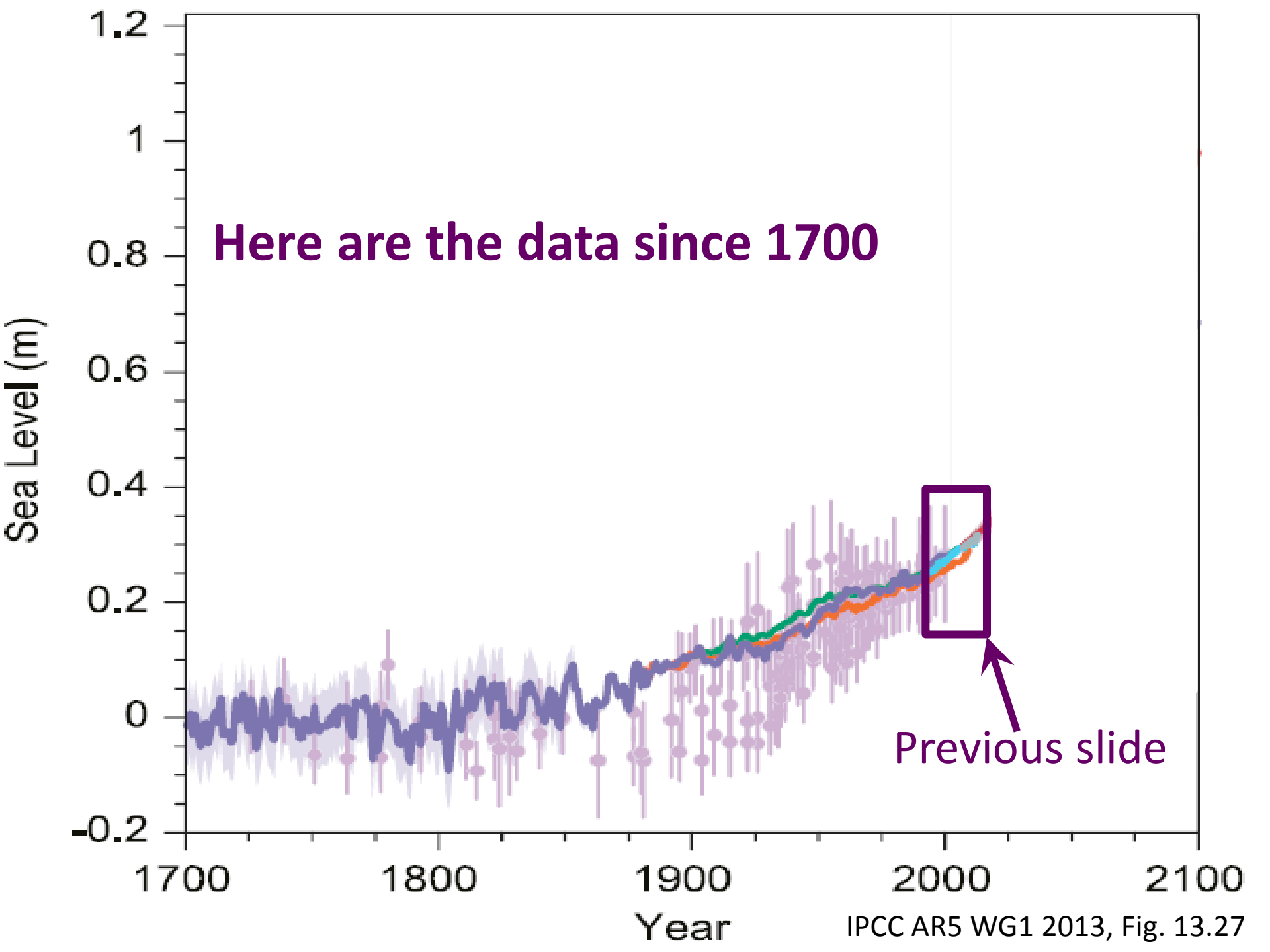
Data show sea level is rising. At this rate, 1 foot of rise would take almost a century.

http://sealevel.colorado.edu/

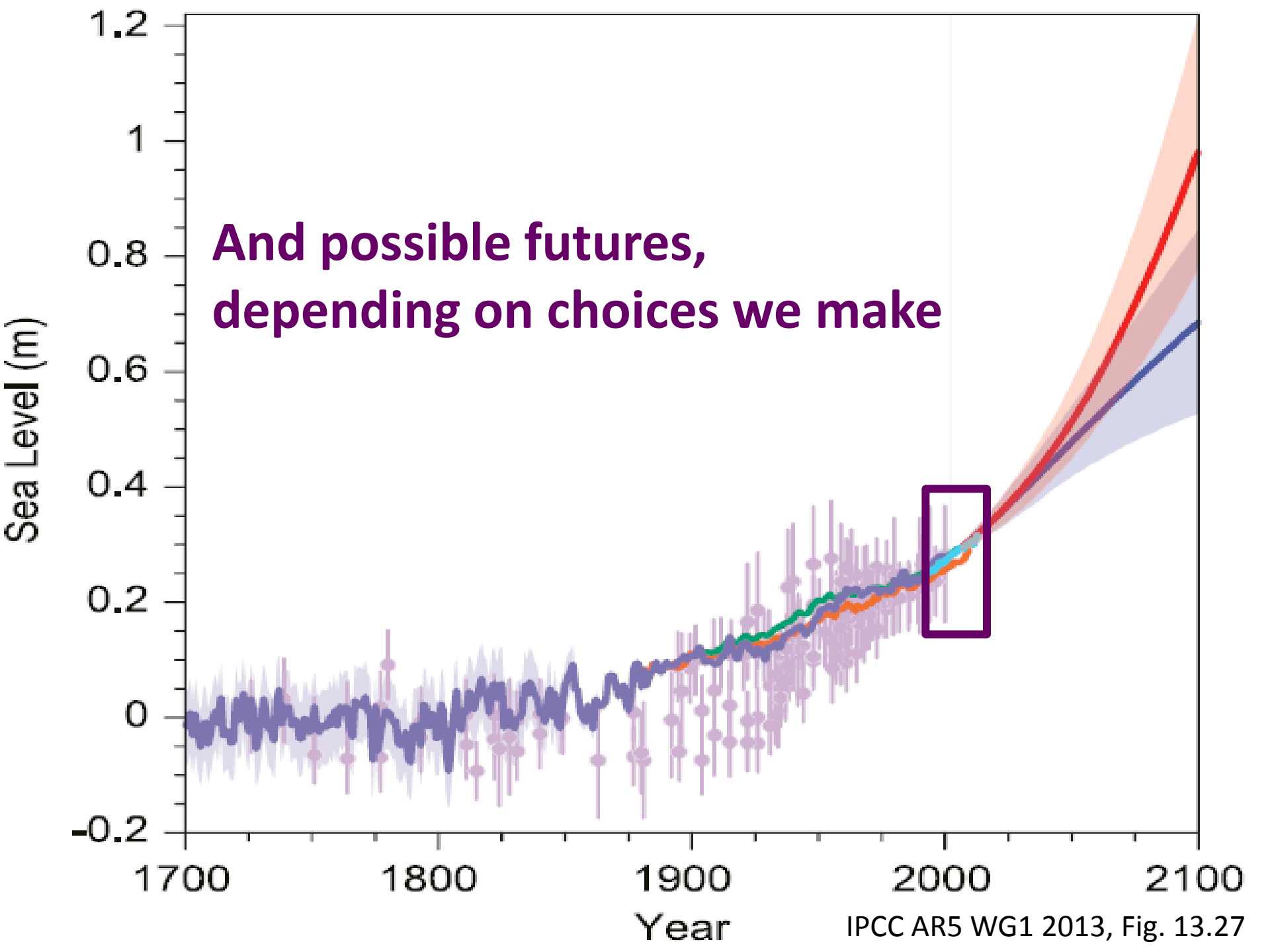




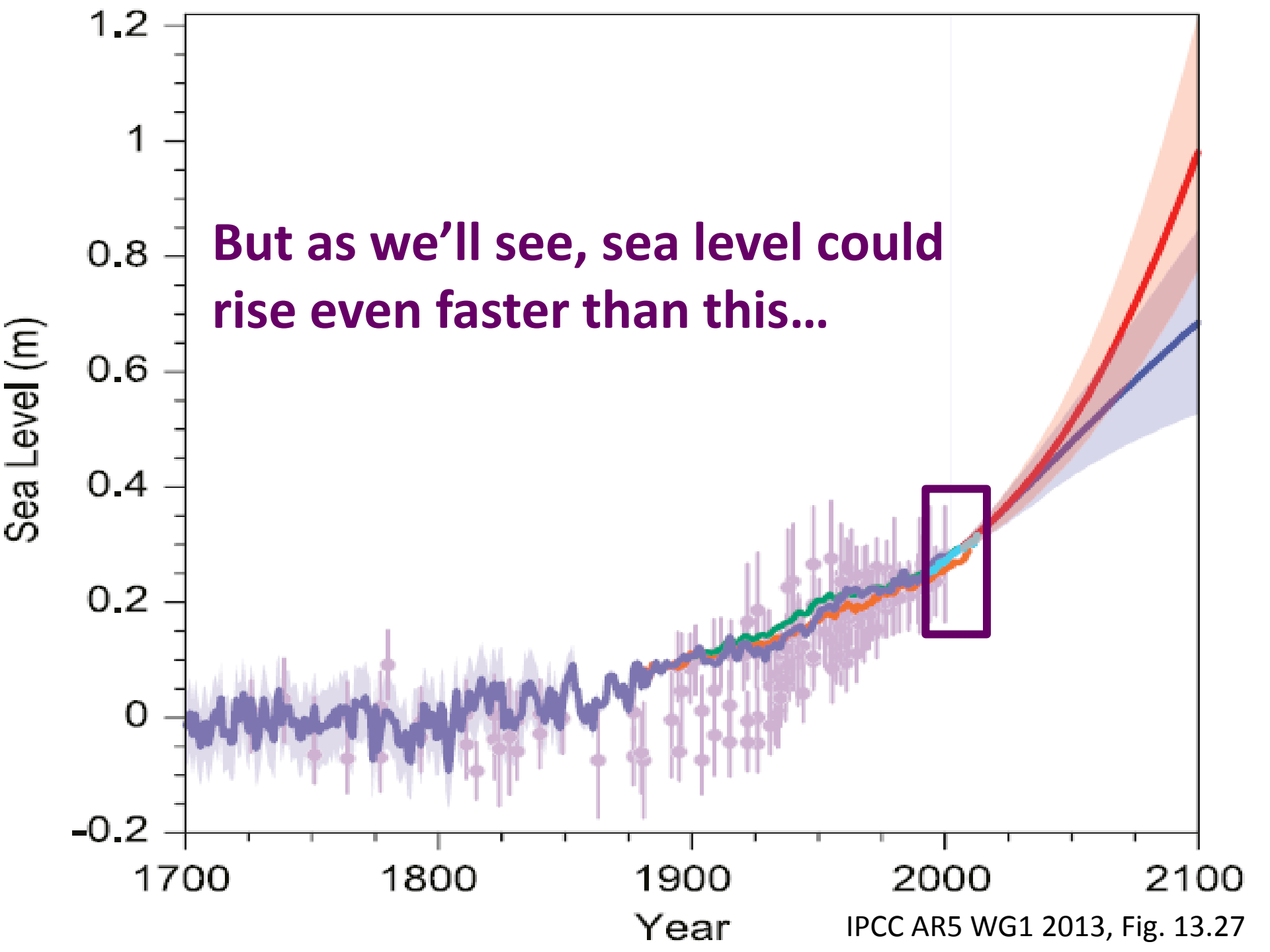
IPCC AR5 WG1 2013, Fig. 13.27



IPCC AR5 WG1 2013, Fig. 13.27



IPCC AR5 WG1 2013, Fig. 13.27



IPCC AR5 WG1 2013, Fig. 13.27

Economists often don't worry much

- They expect rise to be slow, small, well-known
- And response to be efficient

→If you see the sea nearing your beach house

→Then you quit maintaining your house so it isn't worth much when it goes under

→My house behind yours gets the valuable view

→So no worry, right?

- US 100-year loss projection can be less than New Orleans 2005 Hurricane Katrina losses
- Still invest a little in avoiding climate change, mostly in economy, and let your incredibly wealthy grandchildren deal with sea-level rise

Will response be efficient?

- Without blaming Katrina on sea-level rise…
- Before Katrina, I was among the Geo profs who taught, using publicly available, often government documents, that:

→Sea-level is rising

→New Orleans is sinking

→Protective delta is eroding

→Maximum storm strength may be rising

→This influences optimal levee engineering

- So, our economically efficient society surely appropriated the funds to improve the levees that protected New Orleans…

Special Report: Hurricane Katrina 10 Year An aerial view shows flooded roadways as the Coast Guard flies over New Orleans, Aug. 29, 2005, to assess initial Hurricane Katrina damage. *U.S. Coast Guard photograph by Petty Officer 2nd Class Kyle Niemi*

Why wasn’t the good information used?

Many possible reasons, but a true tension:

→ Hard for policymakers to act with large uncertainties

→ But may not have realized how bad it could get

U.S. Coast Guard photograph by Petty Officer 2nd Class Kyle Niemi

Worst-case scenarios?

You may see cost estimates of this type:
→Likely: we're economically efficient
→Worst-case: we lose all valuable things in zone flooded by rising sea

That isn't worst-case. Instead:
→Pay to build levees or other defenses
→Assume we are now safe, so
→Build more valuable things behind levees
→Lose levees, original and new valuable things

AROUND THE NATION

New Maps Label Much Of New Orleans Out Of Flood Hazard Area

Listen · 3:51 Queue Download Transcript

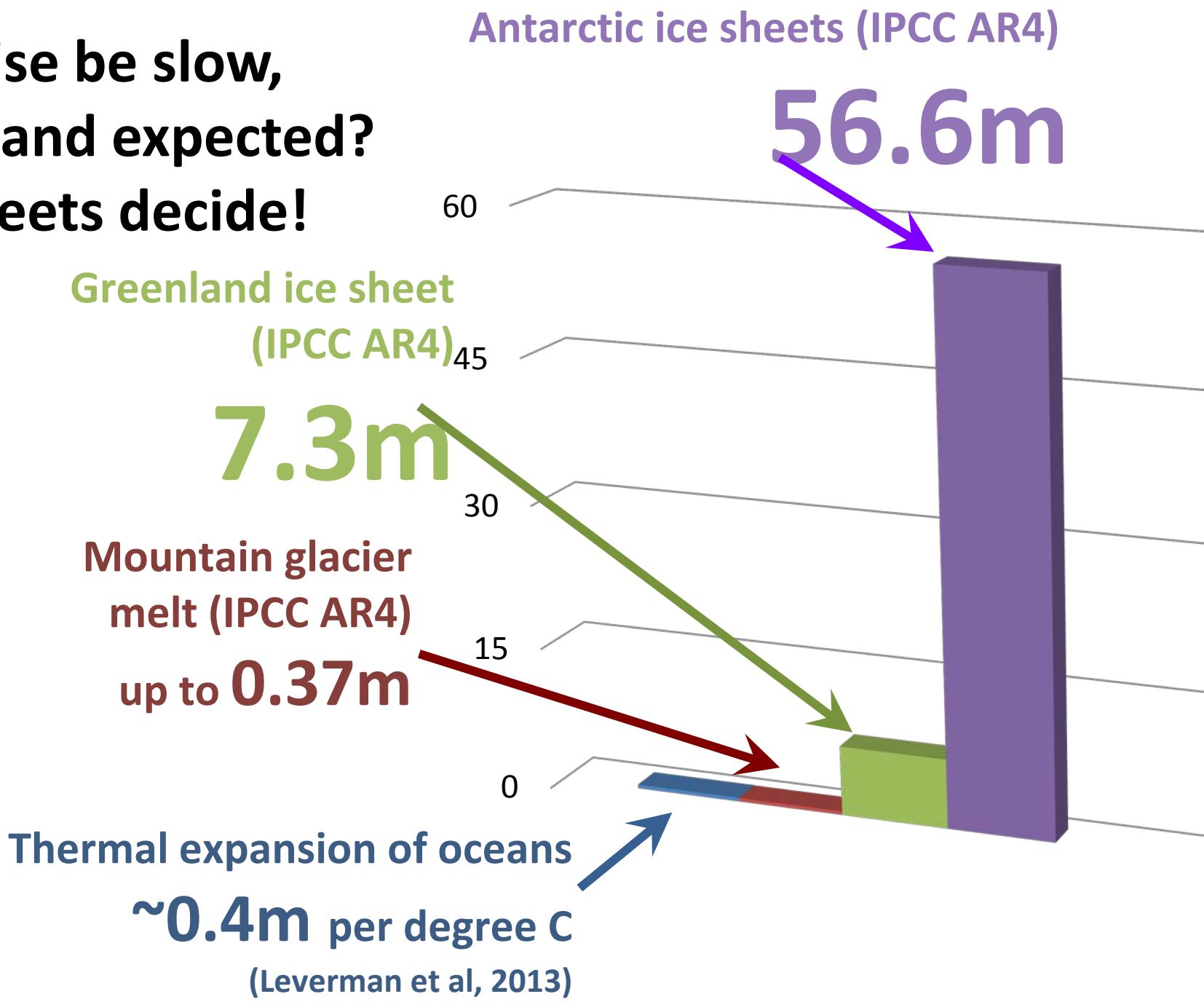
September 30, 2016 · 4:43 PM ET
Heard on All Things Considered

"The new maps are like a bureaucratic magic trick. At the stroke of midnight, the federal government waved its wand, and Friday morning more than half of New Orleans woke up in a land safe from storms and flooding.

"Statistically. For insurance purposes.

"After Hurricane Katrina, the federal government built the city a $14.5 billion flood protection system…"

Will rise be slow, small and expected? Ice sheets decide!



Antarctic ice sheets (IPCC AR4)

56.6m

60

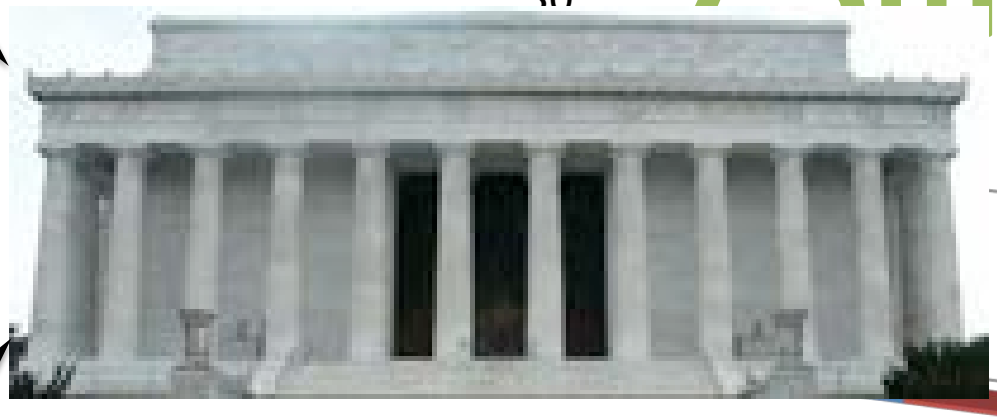
45

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)

Carbon choices determine US cities committed to futures below sea level

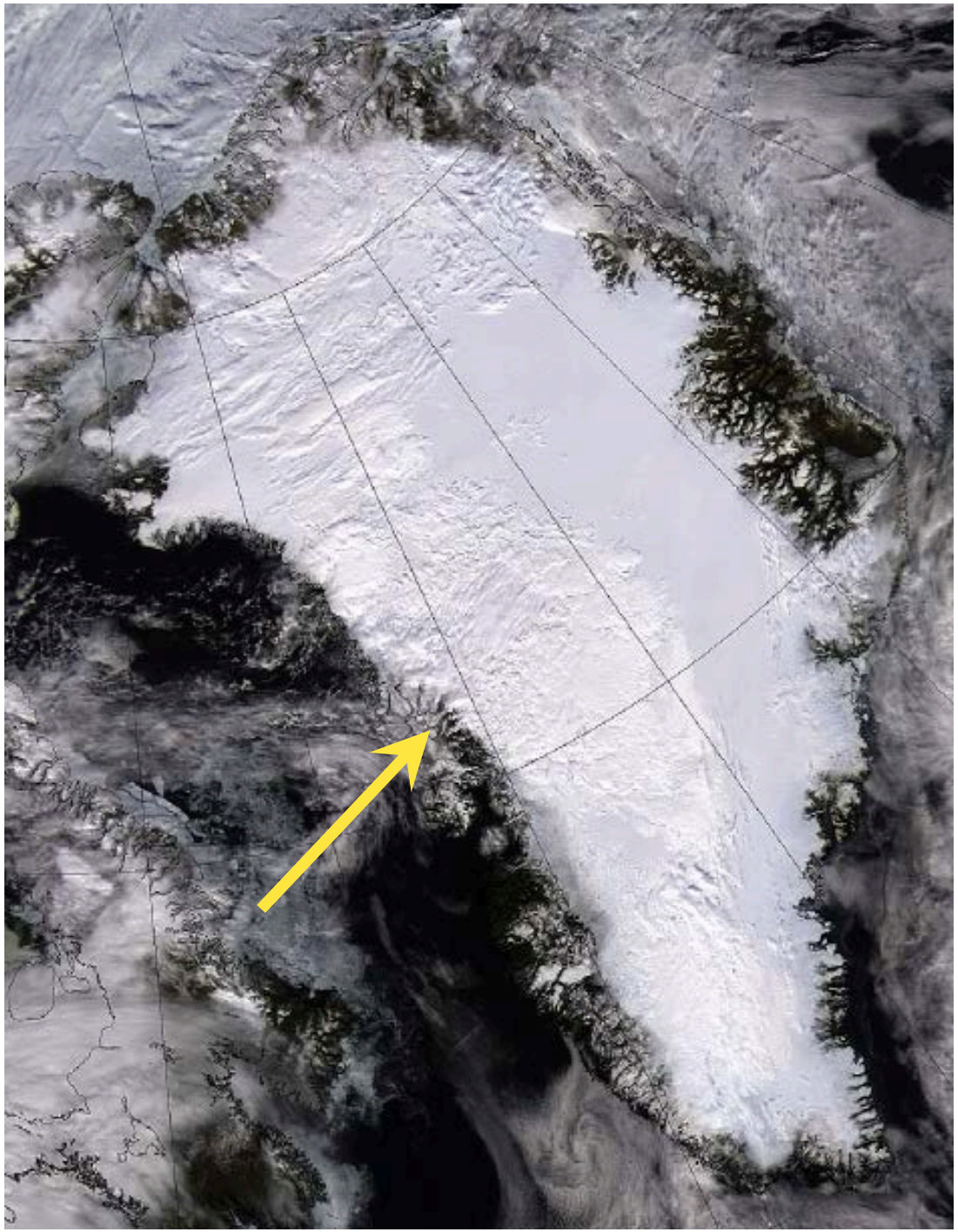
www.pnas.org/cgi/doi/10.1073/pnas.1511186112

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]

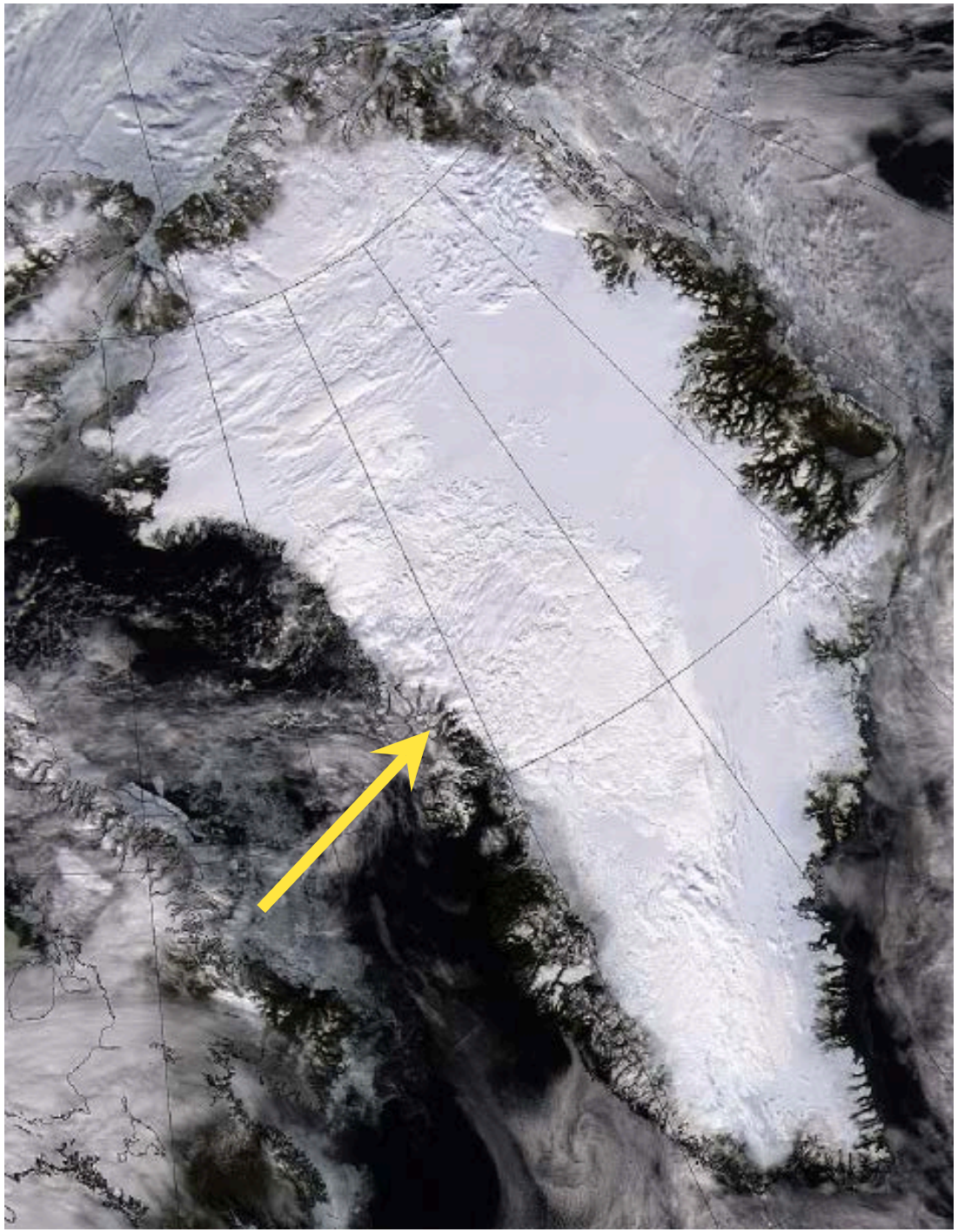
Winkelmann *et al*. Sci. Adv. 2015;1:e1500589 11 September 2015



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



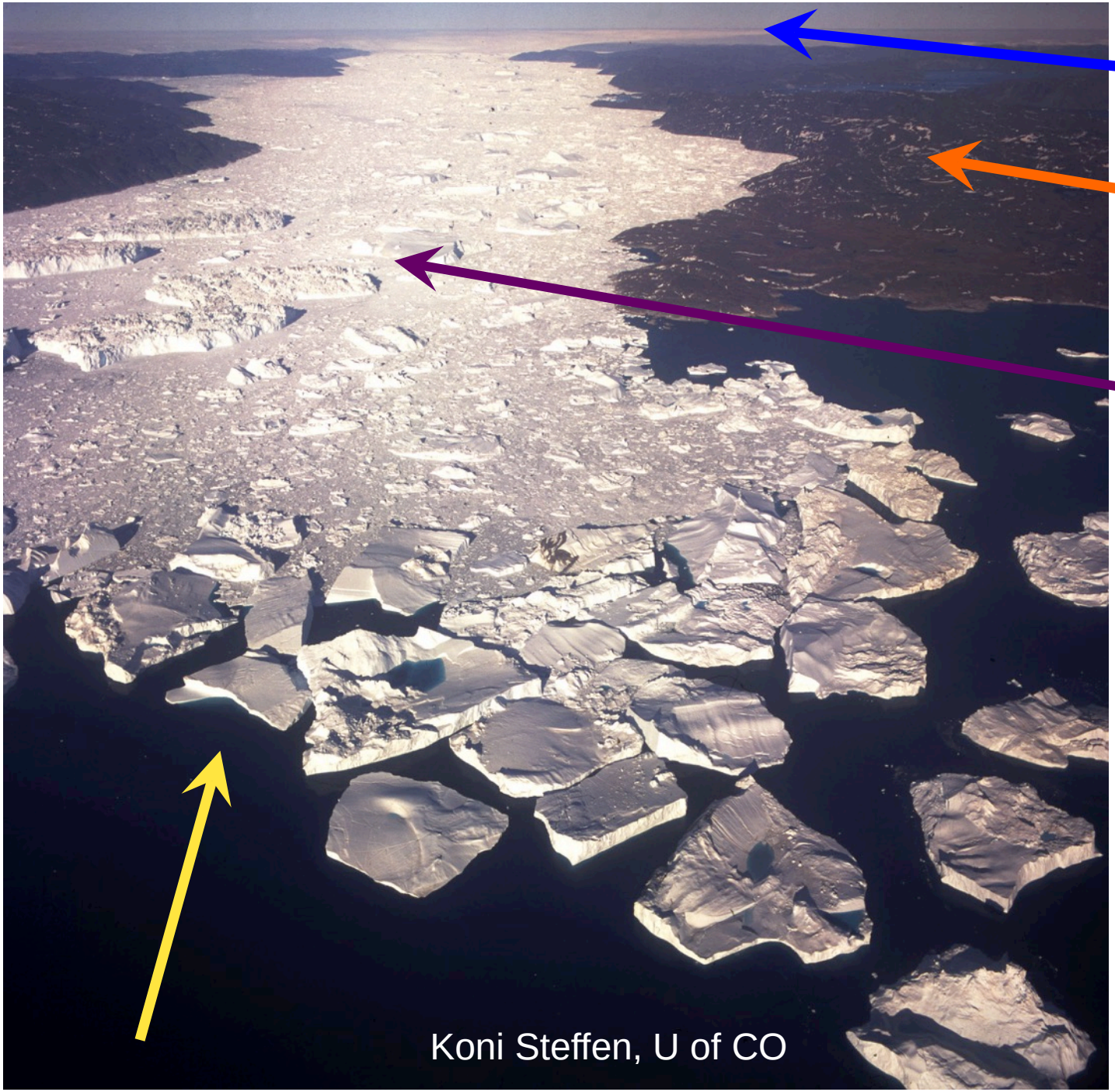
Jakobshavn had an ice shelf

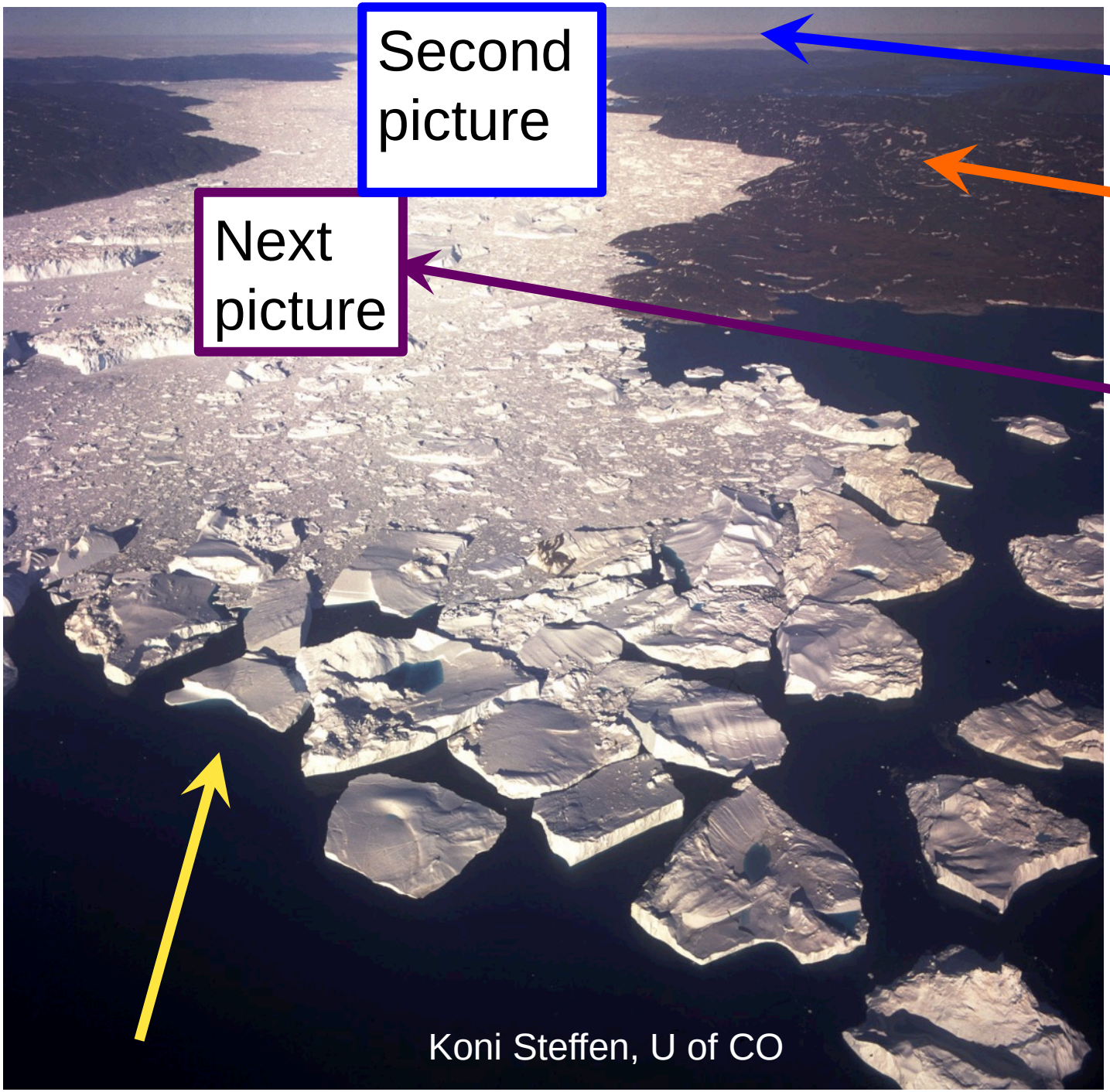
Then the ocean water warmed by 1ºC

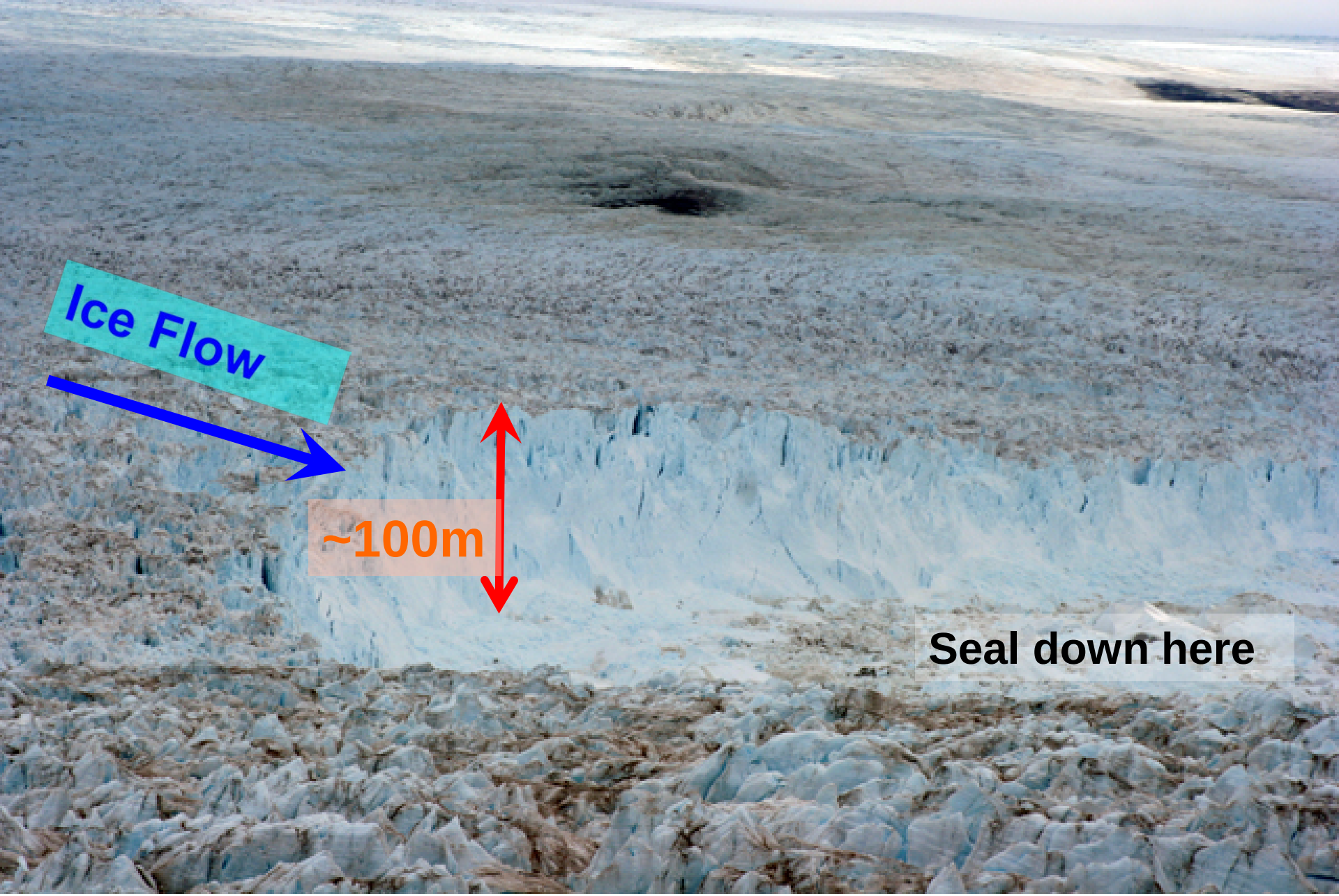
And the ice shelf broke off to leave a cliff

And the ice tripled its speed

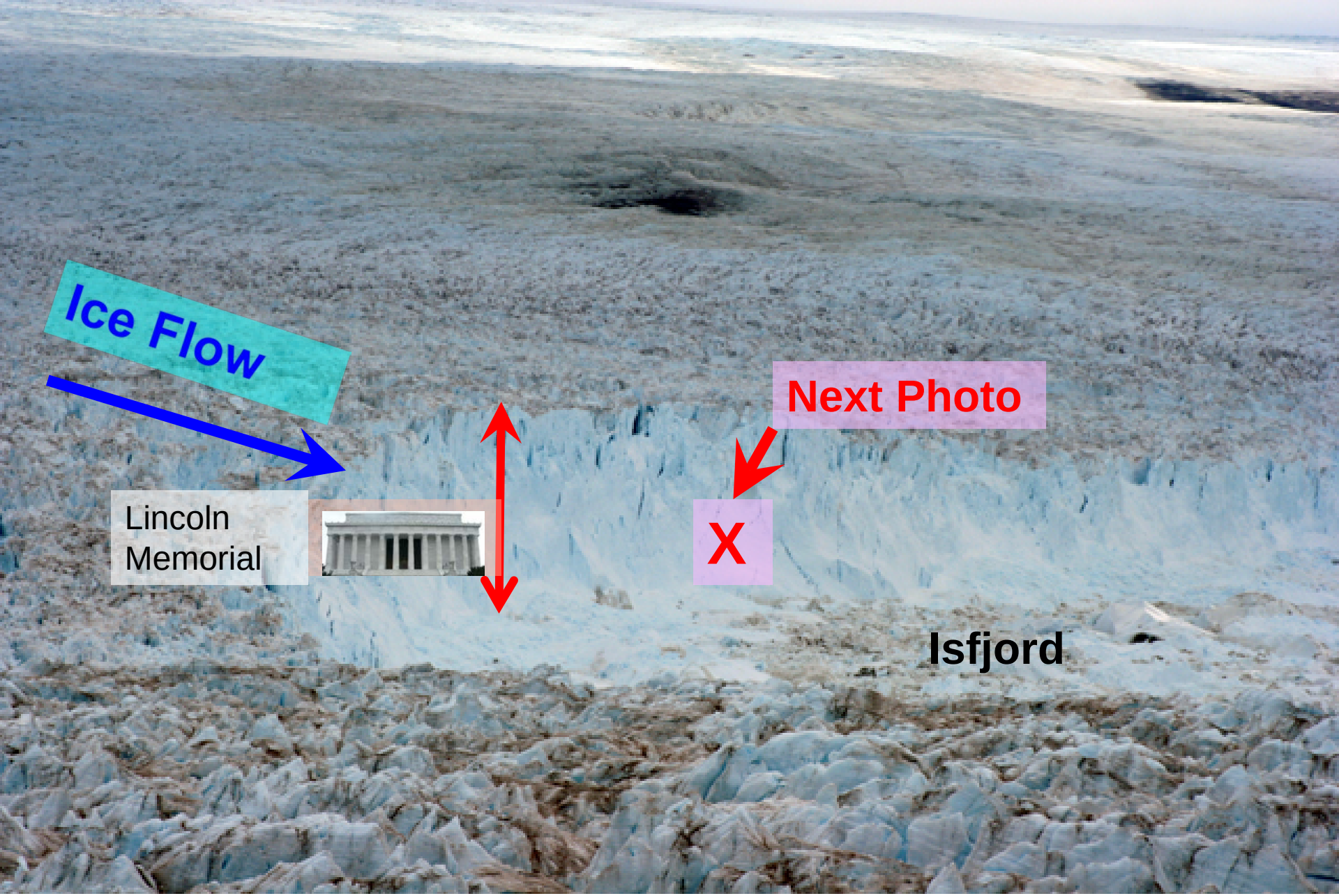
http://www.gsfc.nasa.gov/gsfc/earth/pictures/earthpic.htm


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


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

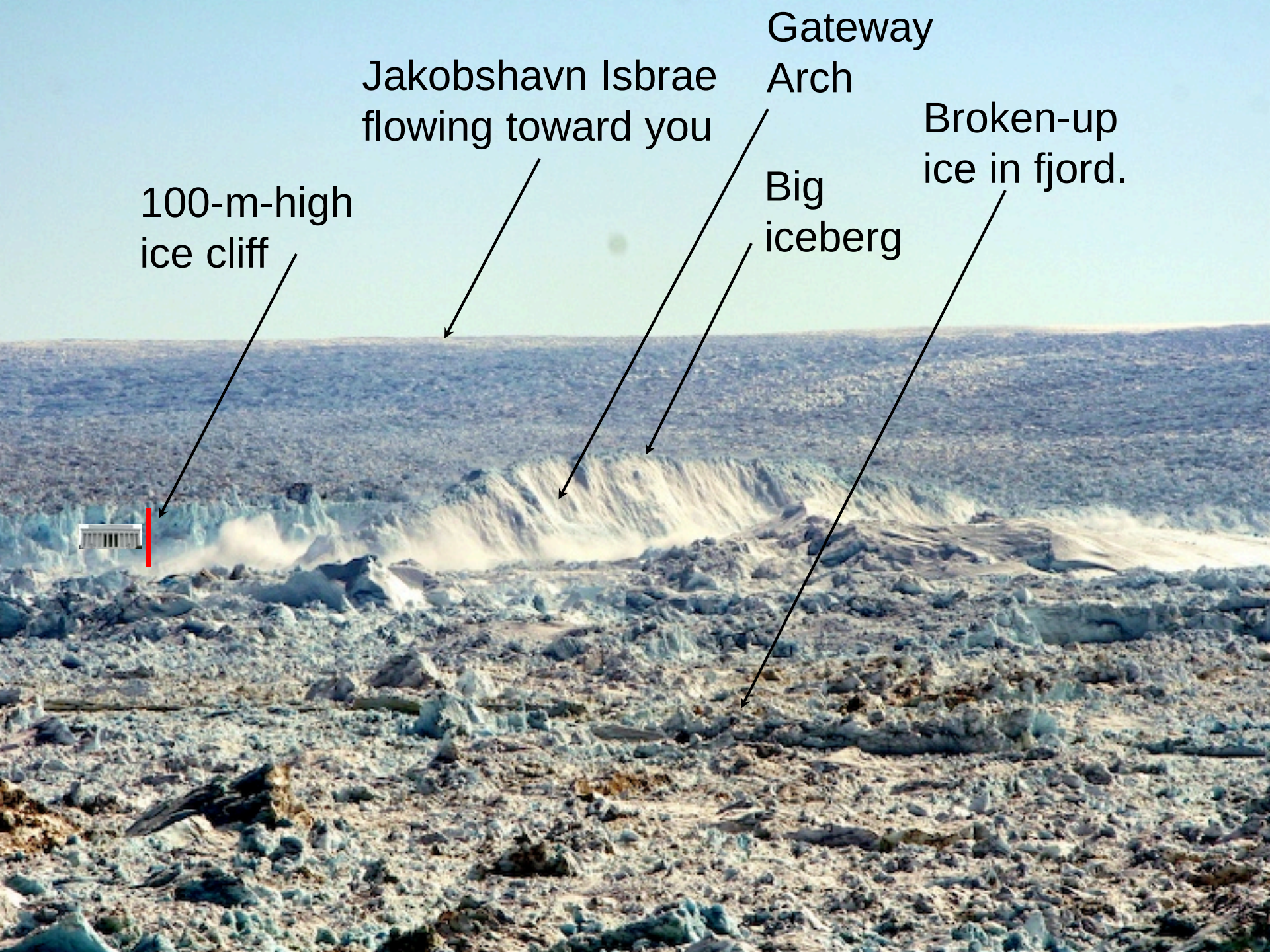

Close to breaking, so, about
as high as an ice cliff can be…

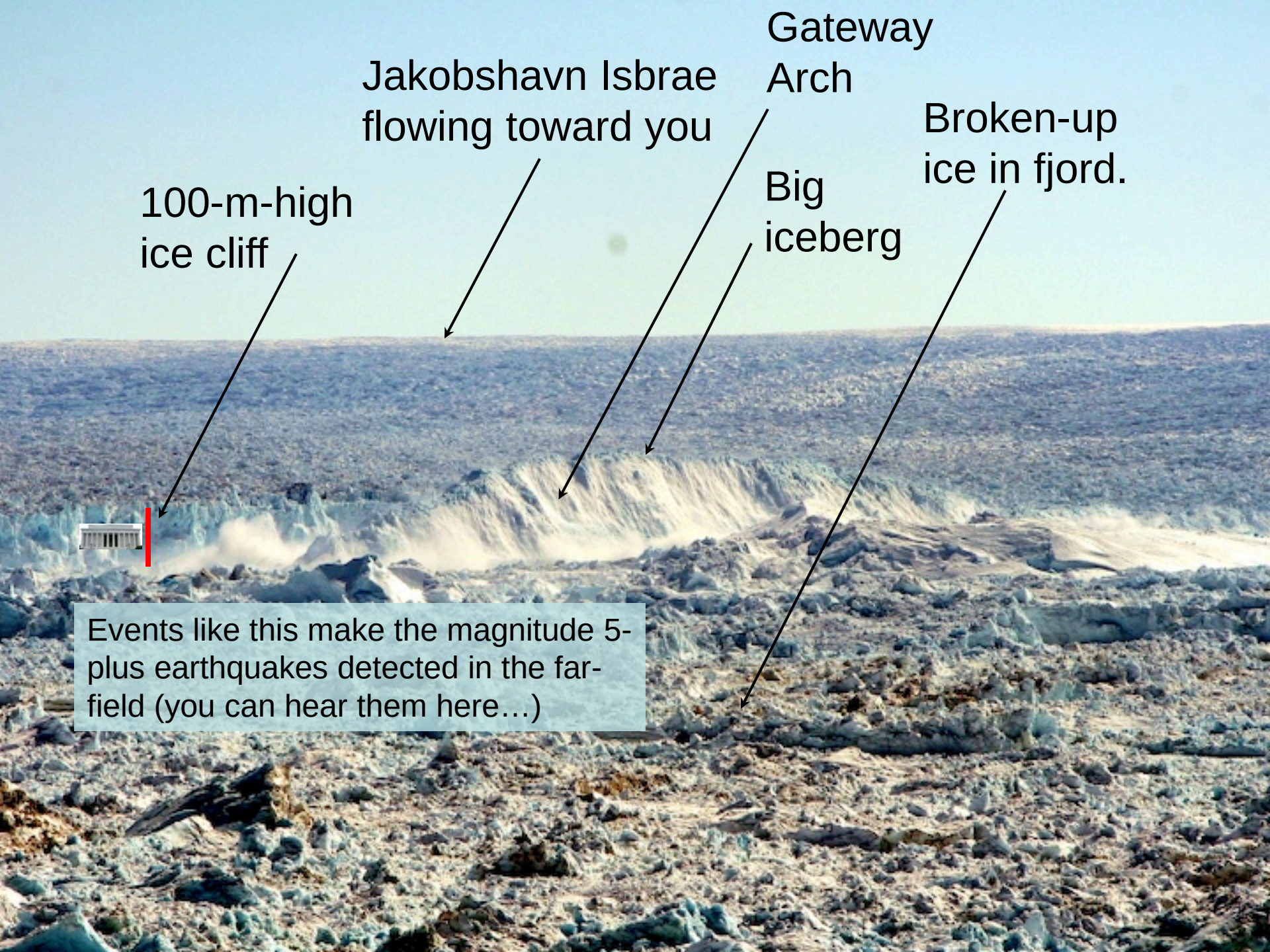
Calving Event, Jakobshavn Glacier

Martin Truffer photographer, working with Mark Fahnestock and Ian Joughin

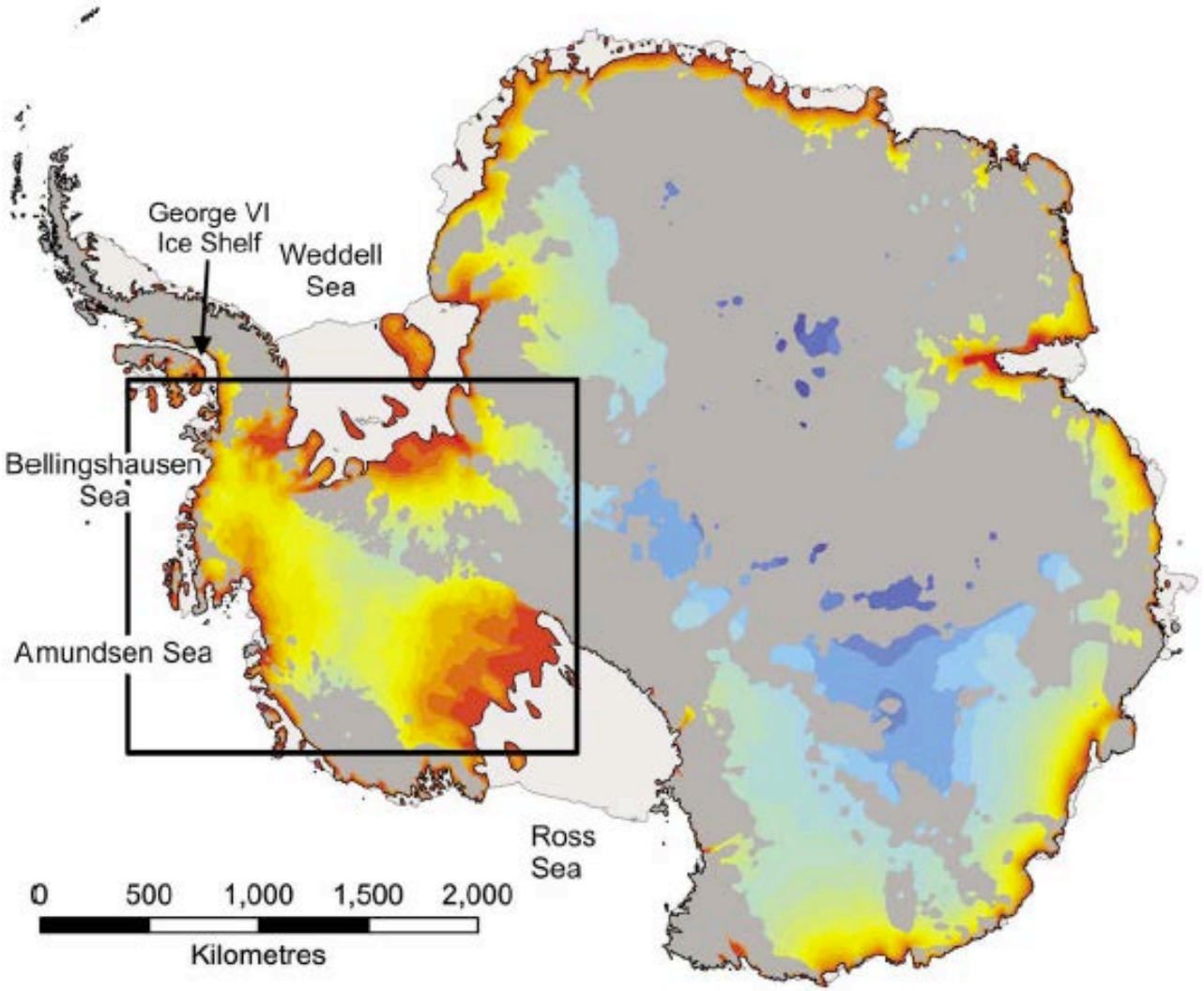
Field of view is about 2 km across at the 10 km distance of the calving face

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 (you can hear them here…)

Tied for highest ice cliff on Earth
Now, breaks, waits, breaks, waits
If higher, might break, break, break…



West Antarctica could make a cliff much higher that breaks faster, and failure there could raise sea level more than 3 m

Earth and Planetary Science Letters 412 (2015) 112–121

Contents lists available at ScienceDirect

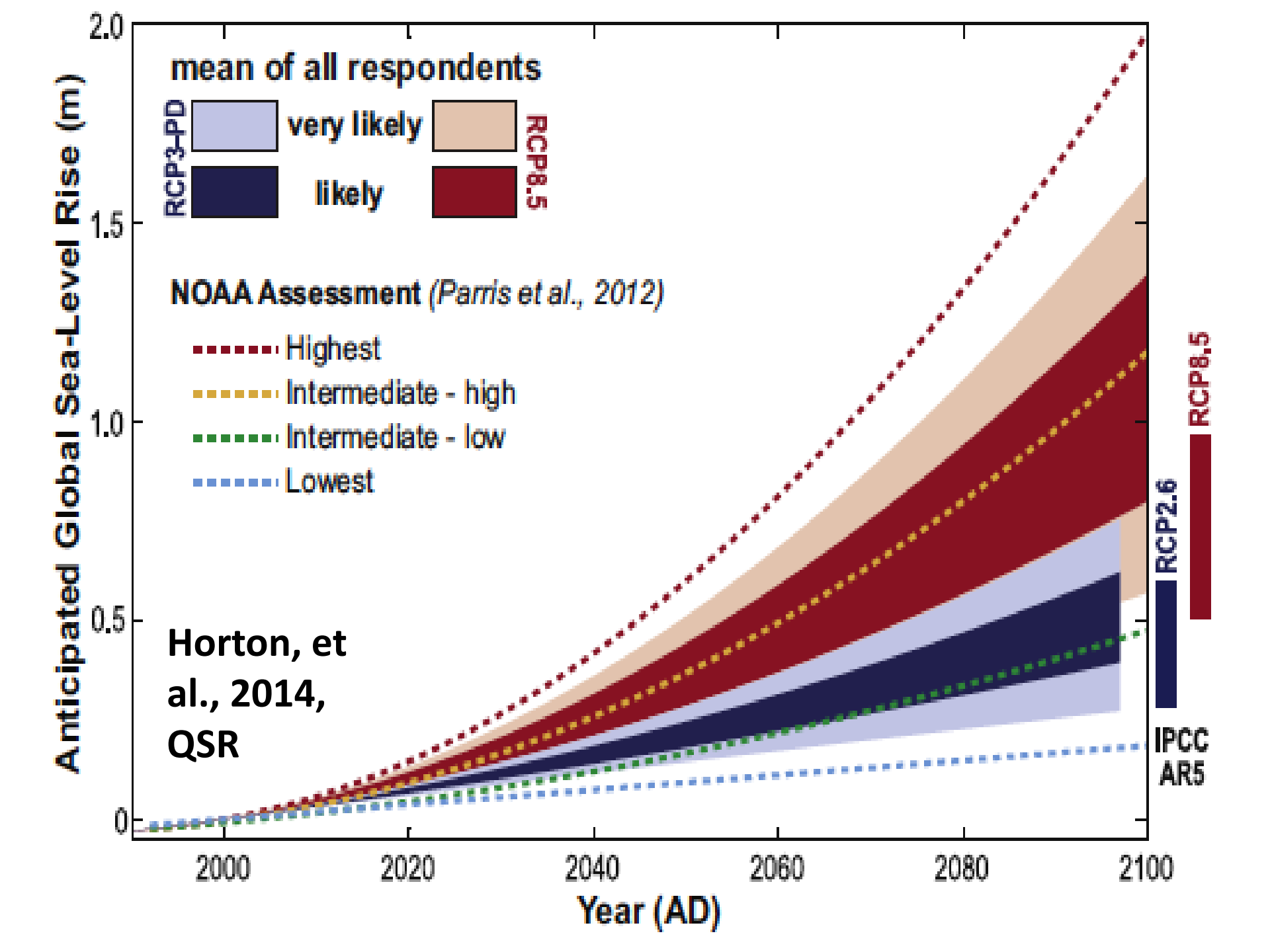
Earth and Planetary Science Letters

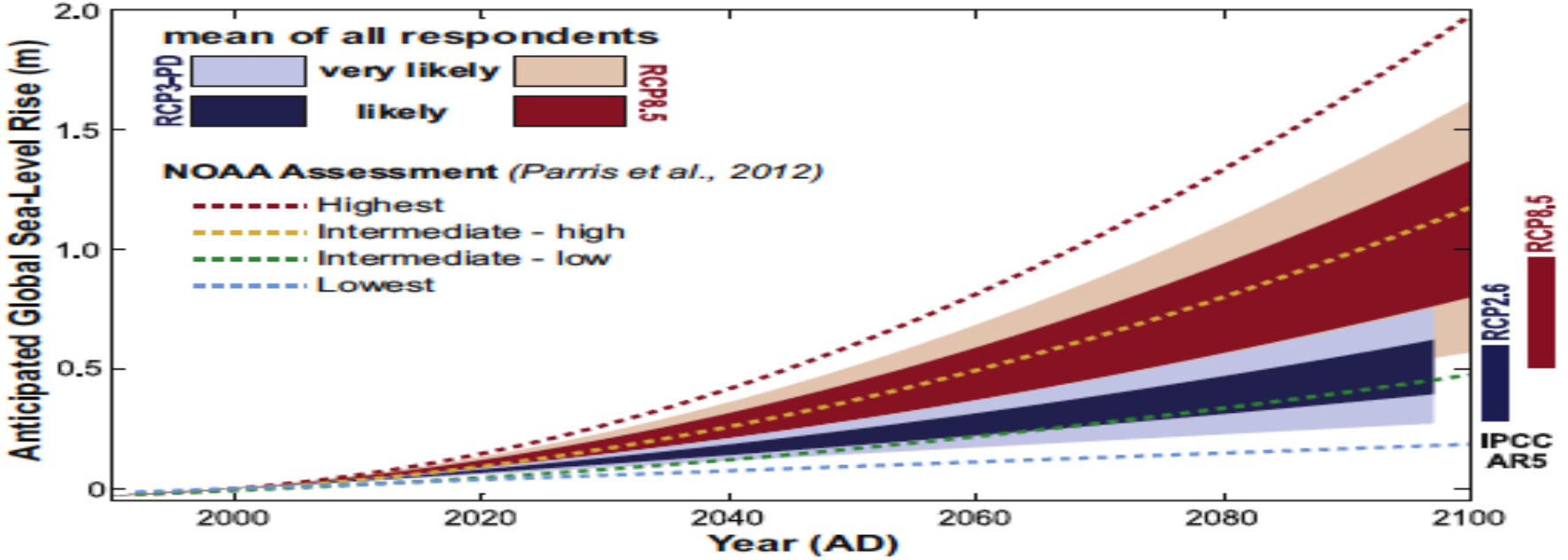
www.elsevier.com/locate/epsl

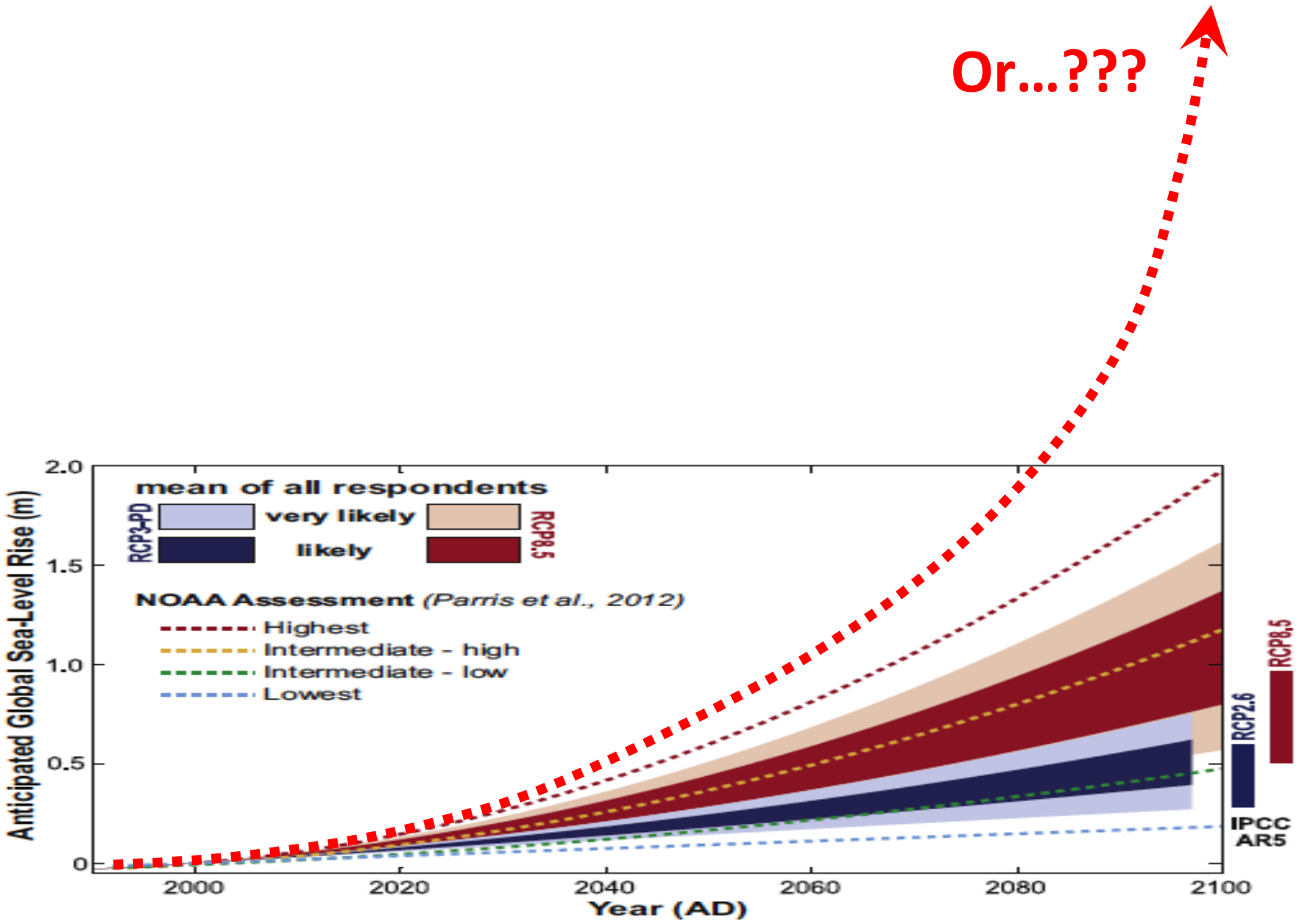
Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure

David Pollard [a,*], Robert M. DeConto [b], Richard B. Alley [a,c]

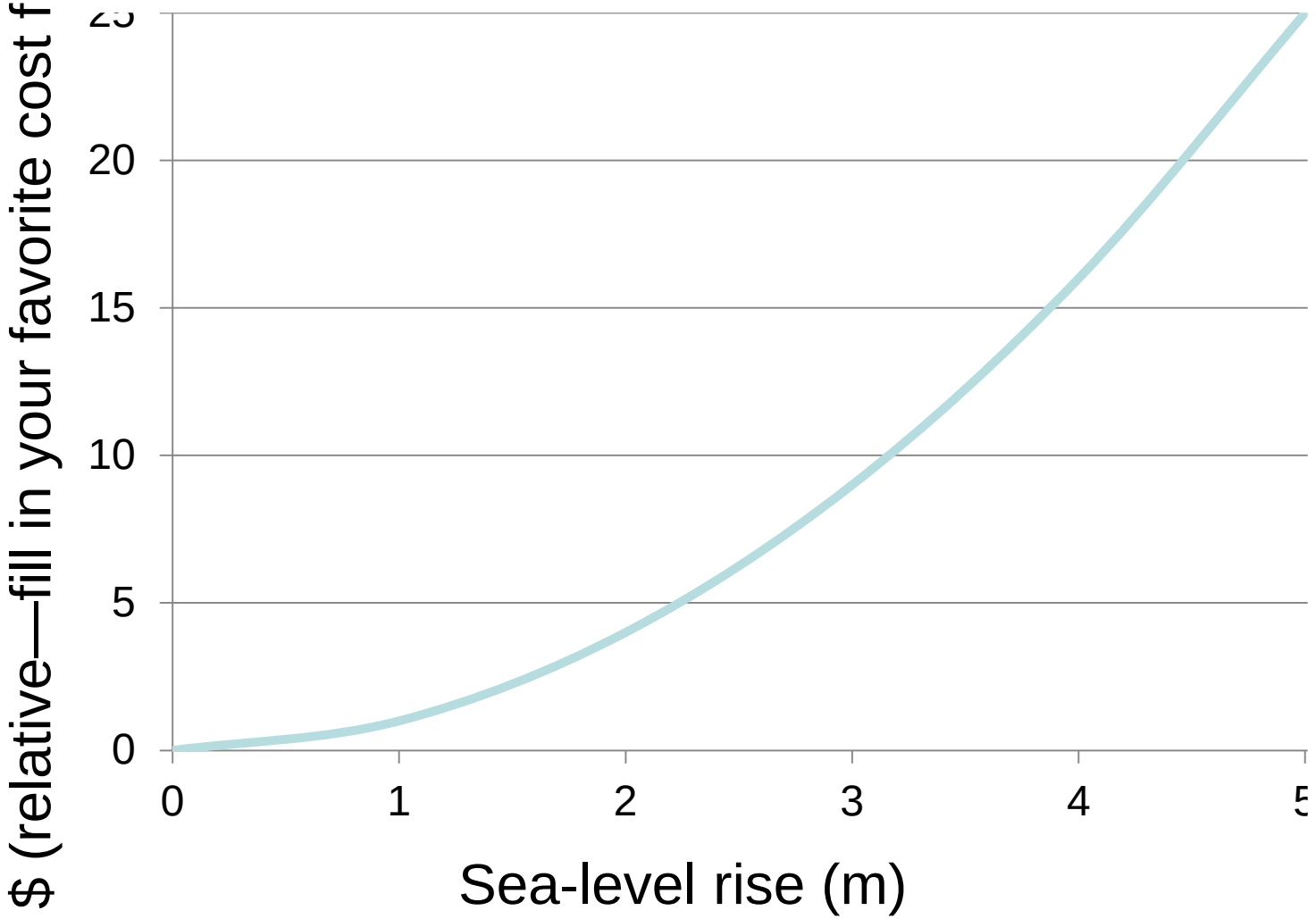
"Incorporating these mechanisms in our ice-sheet model accelerates the expected collapse of the West Antarctic Ice Sheet to decadal time scales…"


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

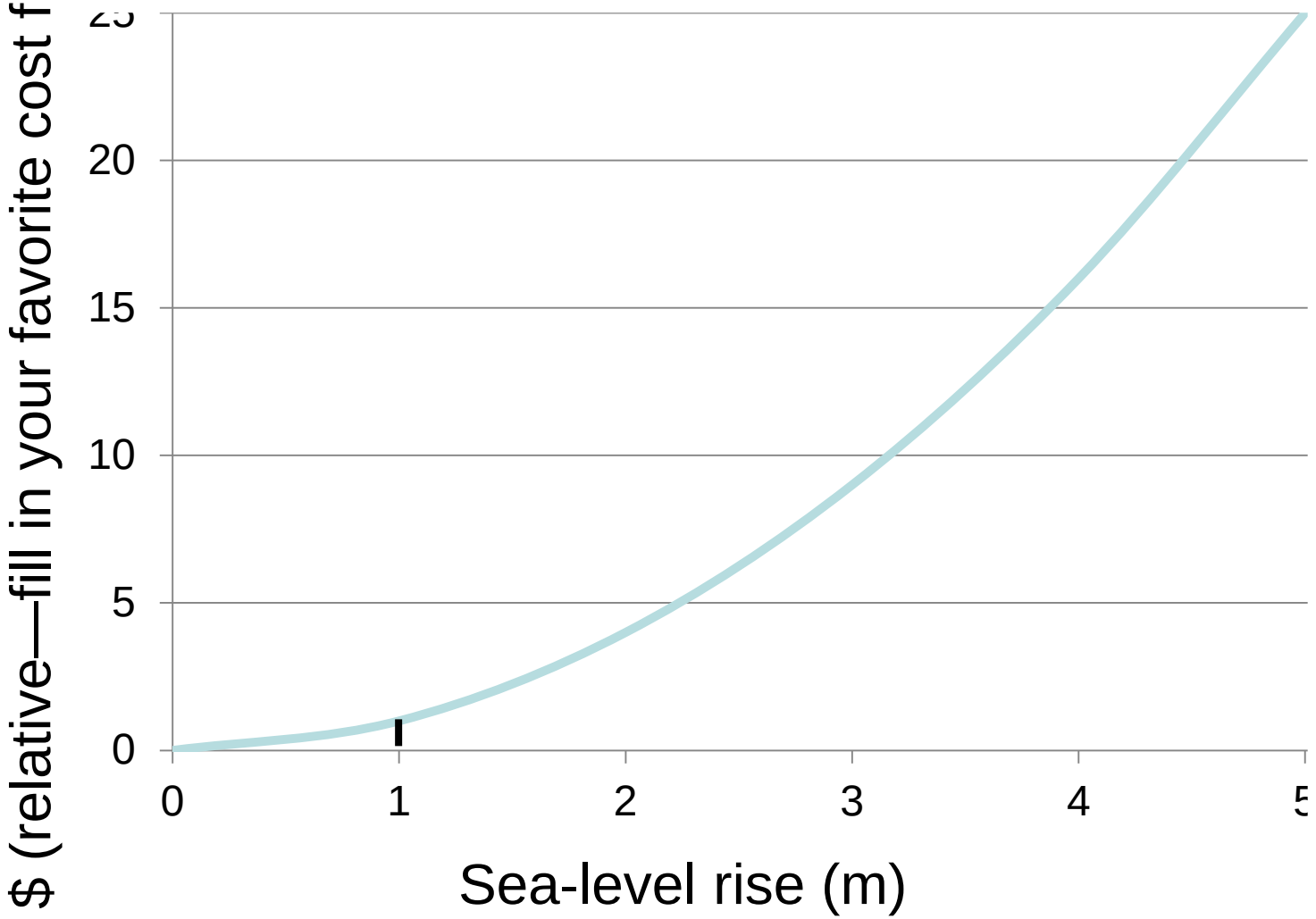

mean of all respondents
very likely
likely
RCP2.6
RCP8.5
NOAA Assessment (Parris et al., 2012)
Highest
Intermediate - high
Intermediate - low
Lowest
Anticipated Global Sea-Level Rise (m)
Year (AD)
2.0
1.5
1.0
0.5
0
2000
2020
2040
2060
2080
2100
RCP8.5
RCP2.6
IPCC AR5


Or…???
mean of all respondents
very likely
likely
RCP3-PD
RCP8.5
NOAA Assessment (Parris et al., 2012)
Highest
Intermediate - high
Intermediate - low
Lowest
Anticipated Global Sea-Level Rise (m)
2.0
1.5
1.0
0.5
0
2000
2020
2040
2060
2080
2100
Year (AD)
RCP2.6
RCP8.5
IPCC AR5

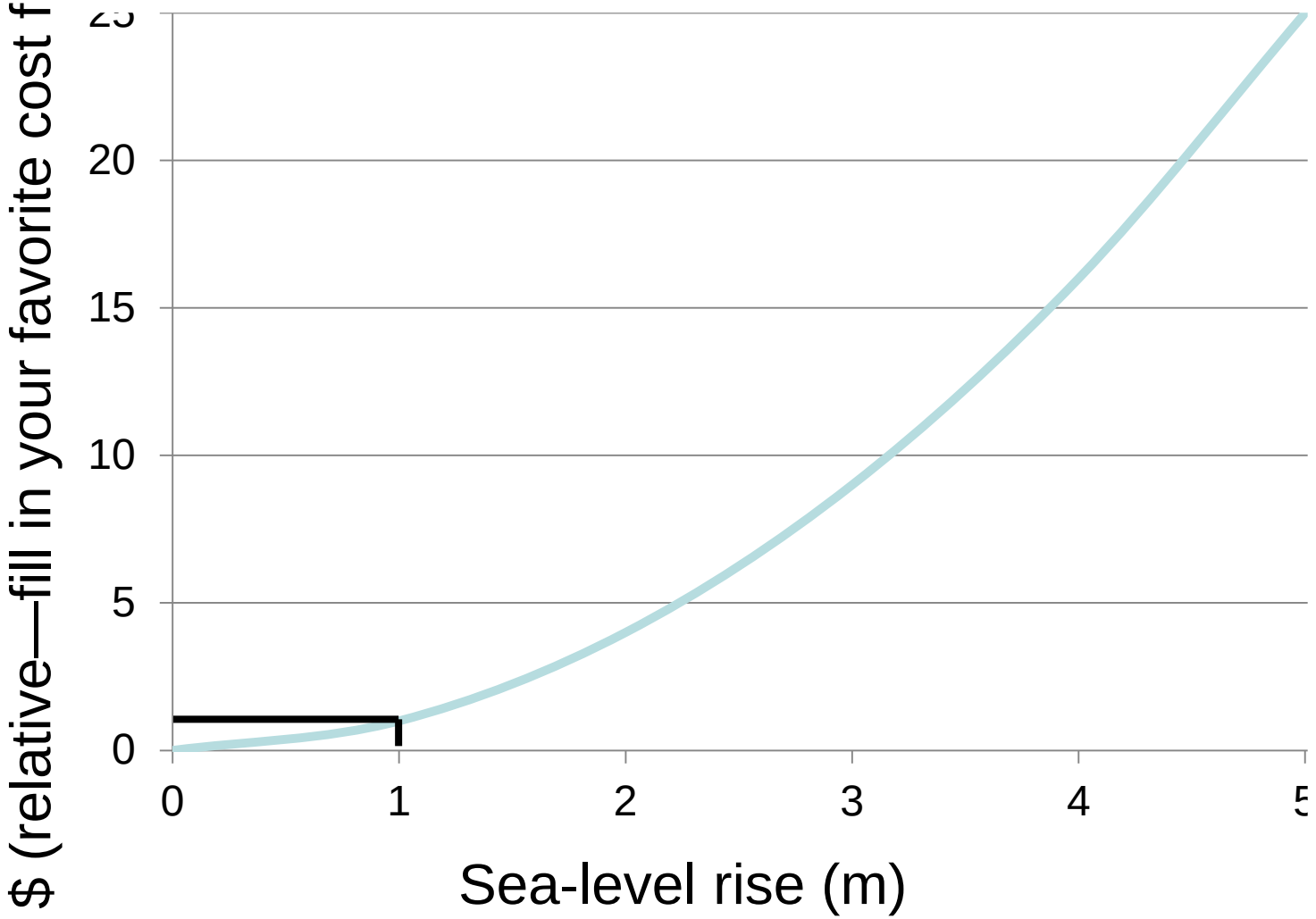
Costs rise faster than sea level (here $=k\Delta sea\_level^2$)



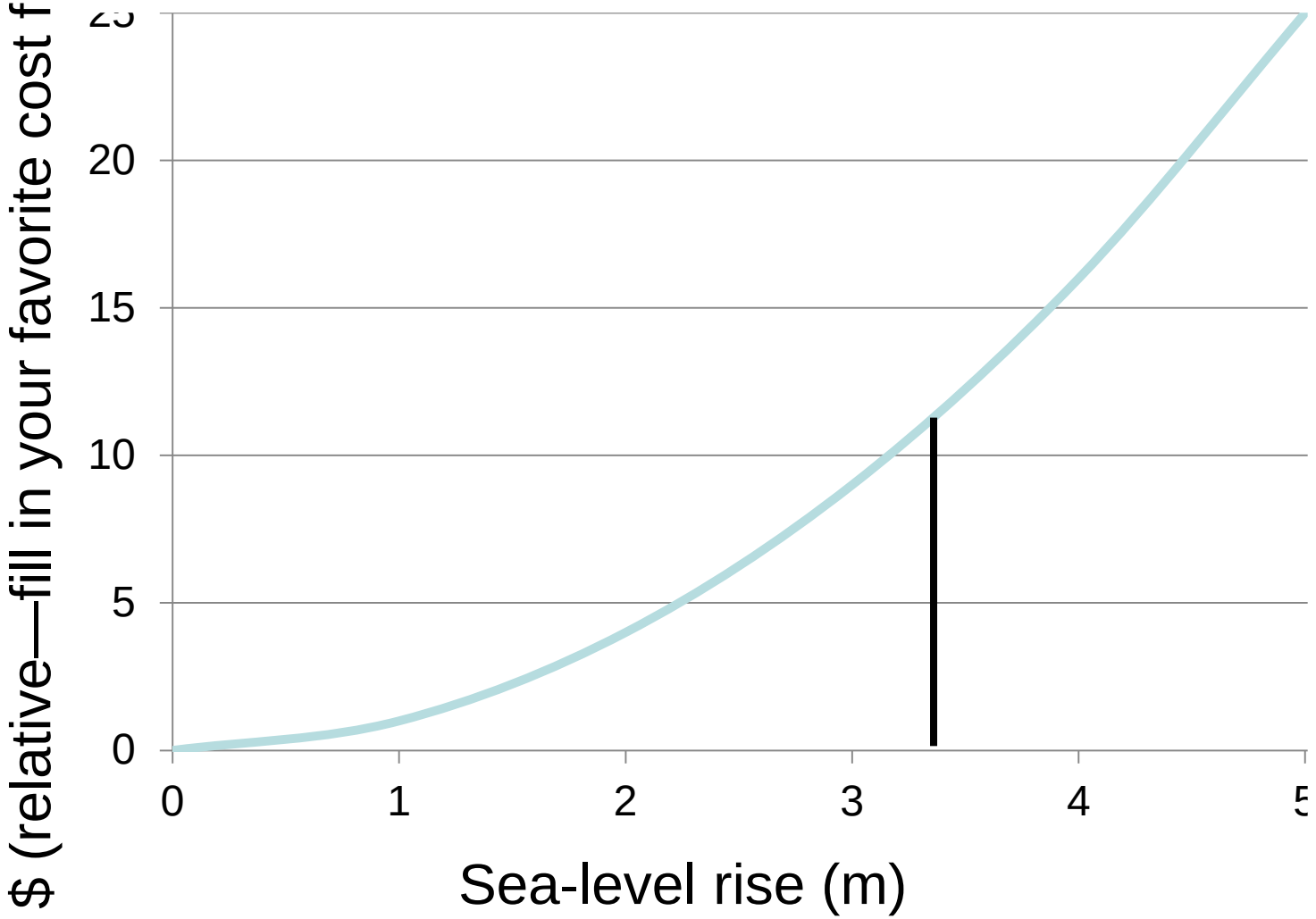
1 m of sea-level rise with stable WAIS (West Antarctic Ice Sheet)



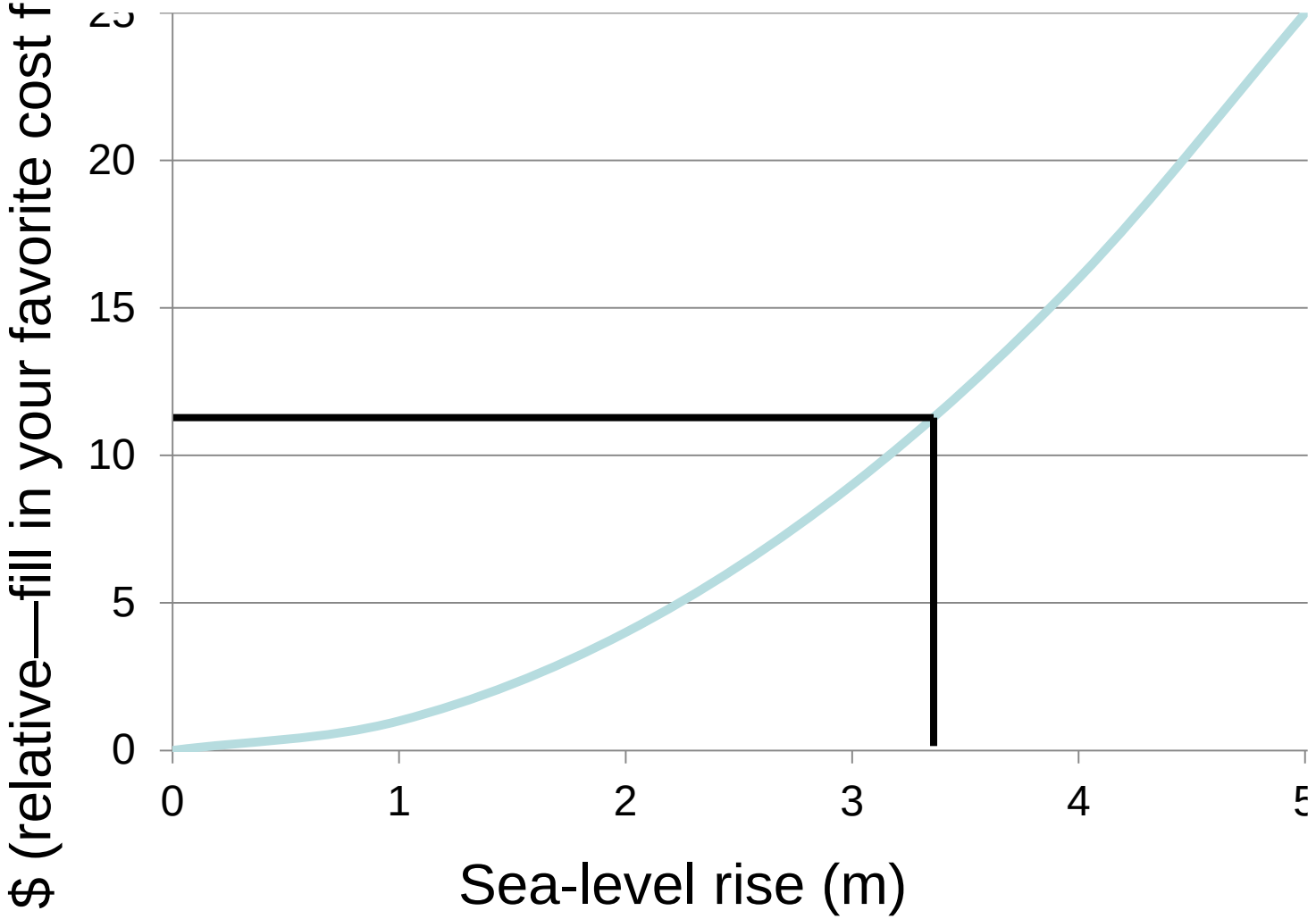
1 m of sea-level rise with stable WAIS has some cost (how much? Depends on how well we respond, etc.)



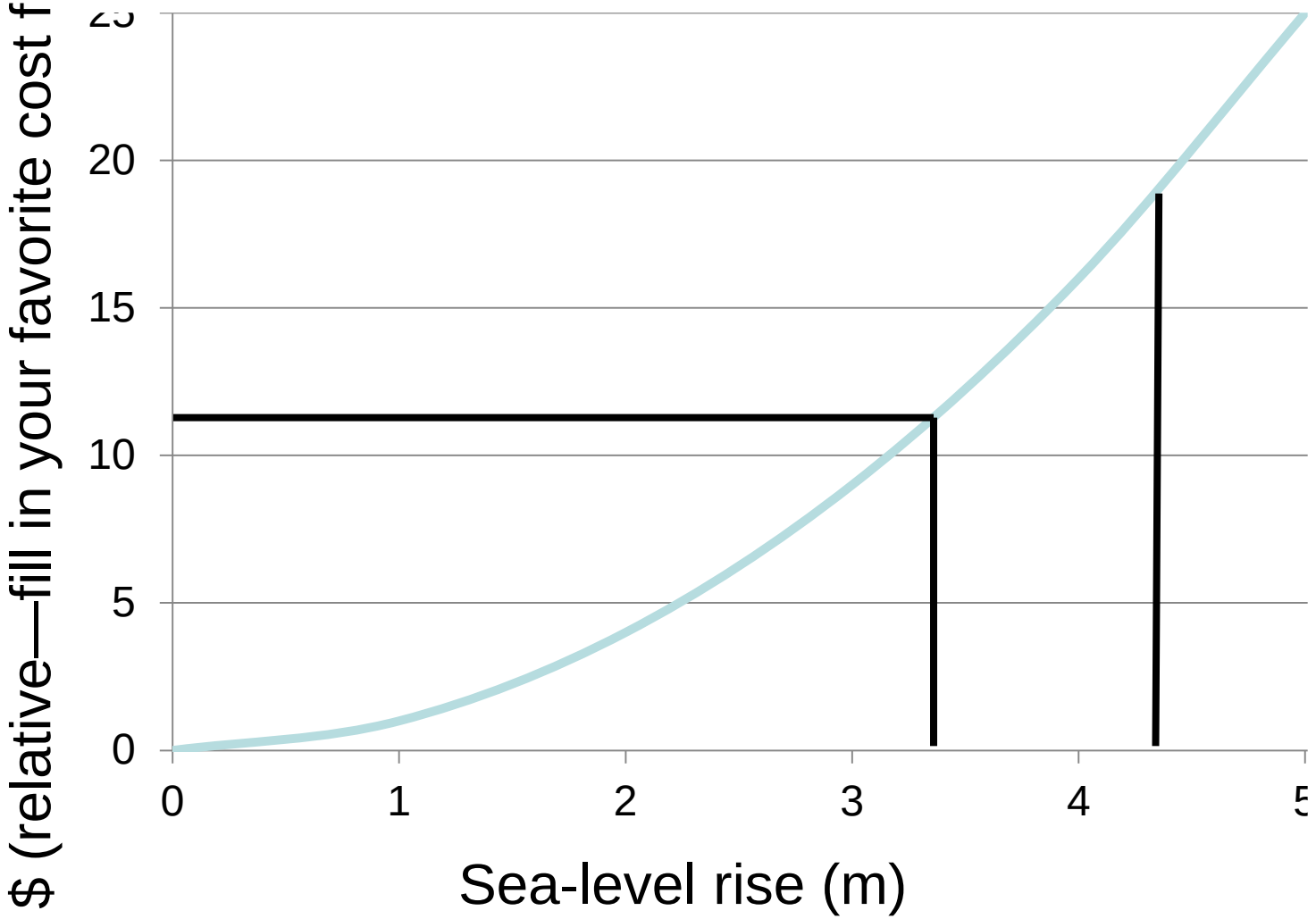
But suppose WAIS goes rapidly, with 3.3 m of sea-level rise



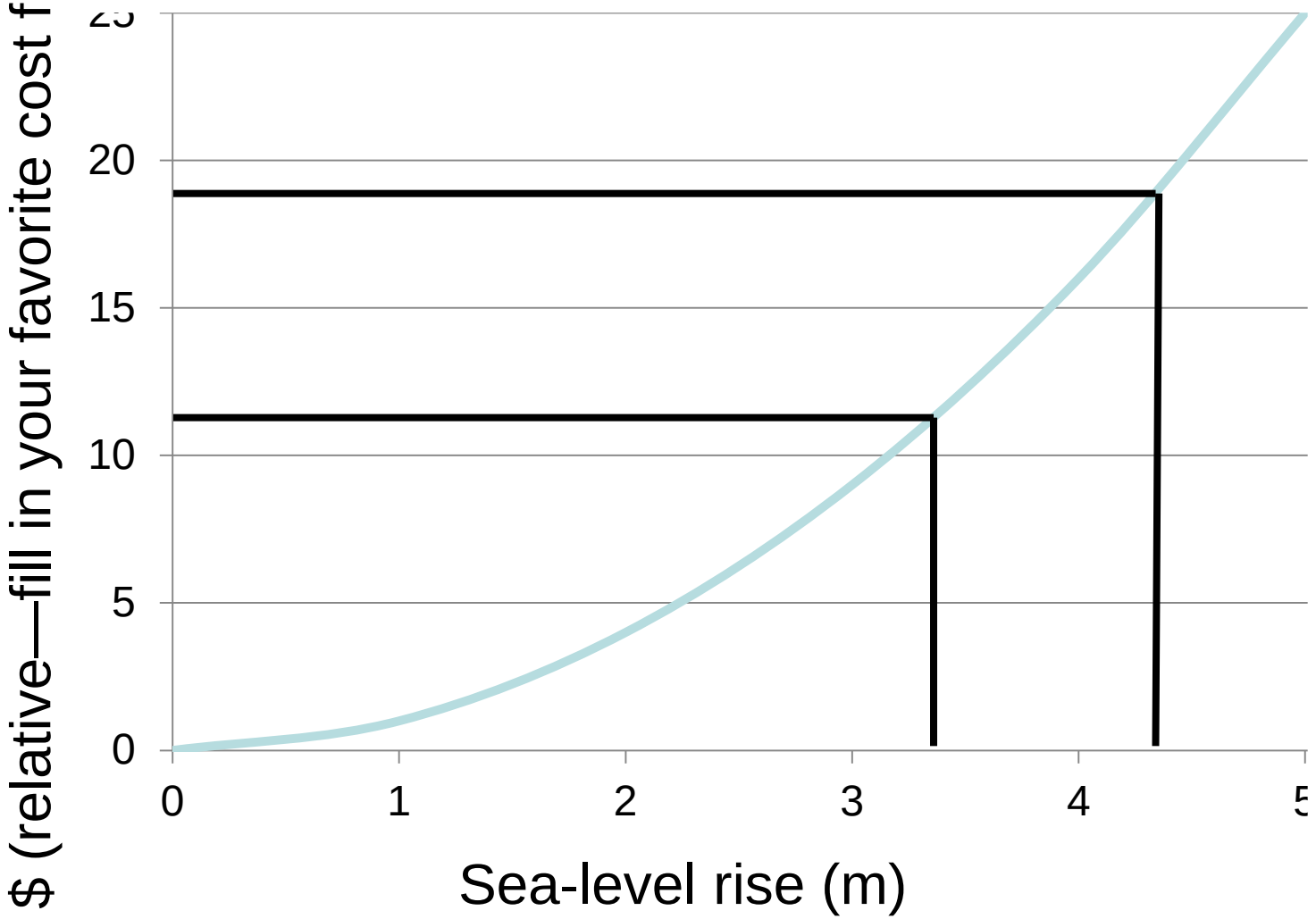
But suppose WAIS goes rapidly, with 3.3 m of sea-level rise, and a big cost



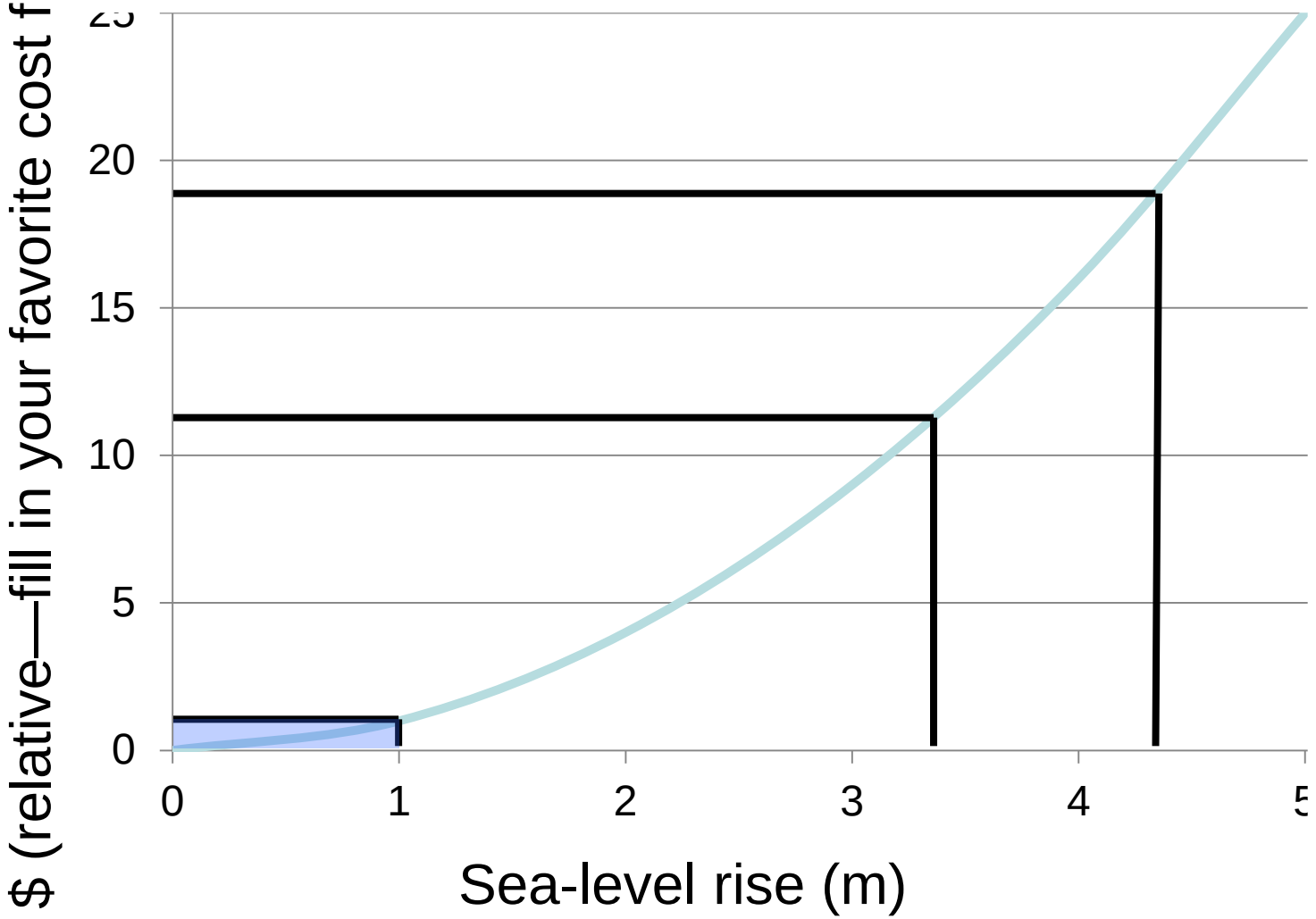
Now ask the cost of the next 1 m of sea-level rise from other sources



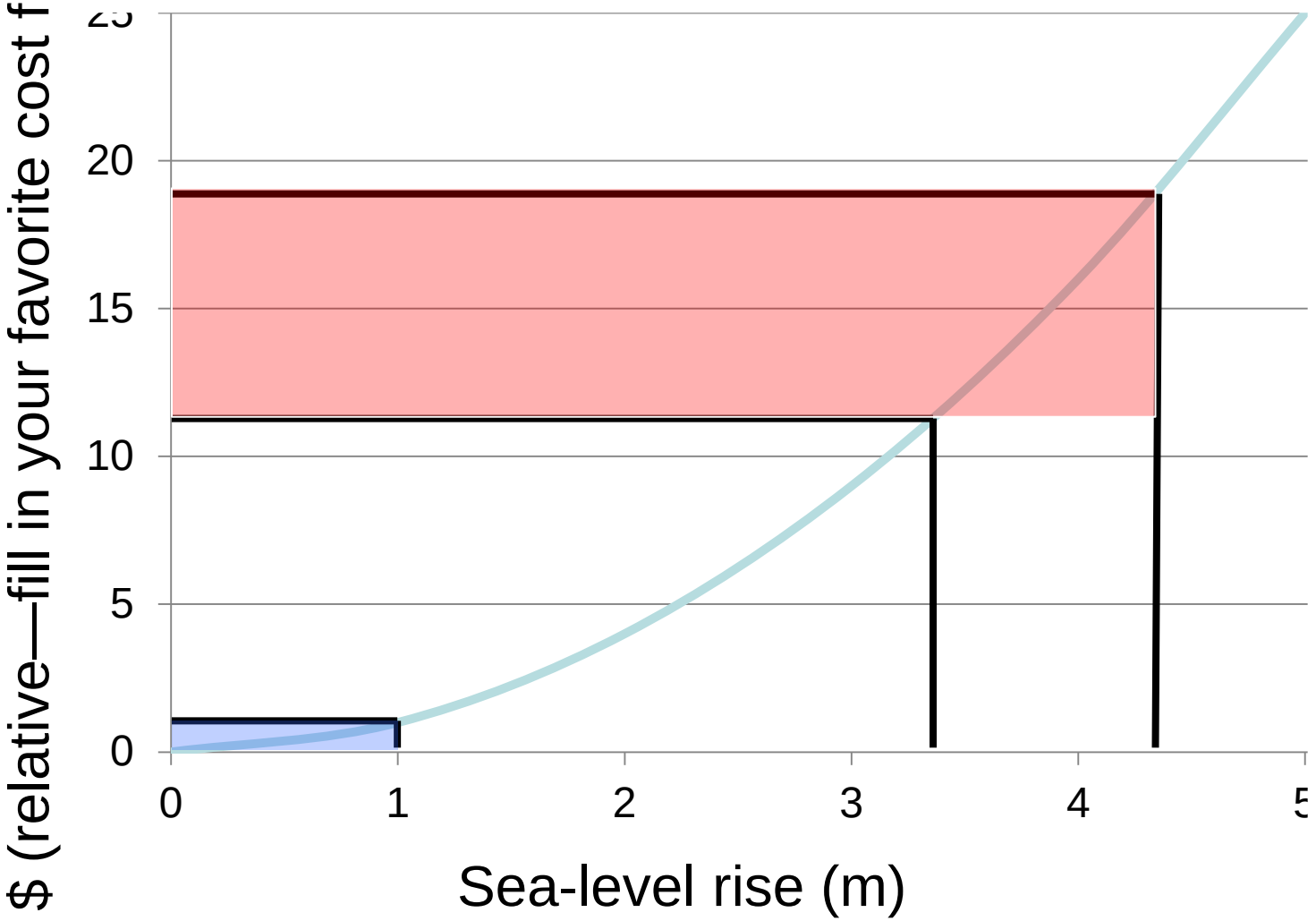
Now ask the cost of the next 1 m of sea-level rise from other sources—It's large



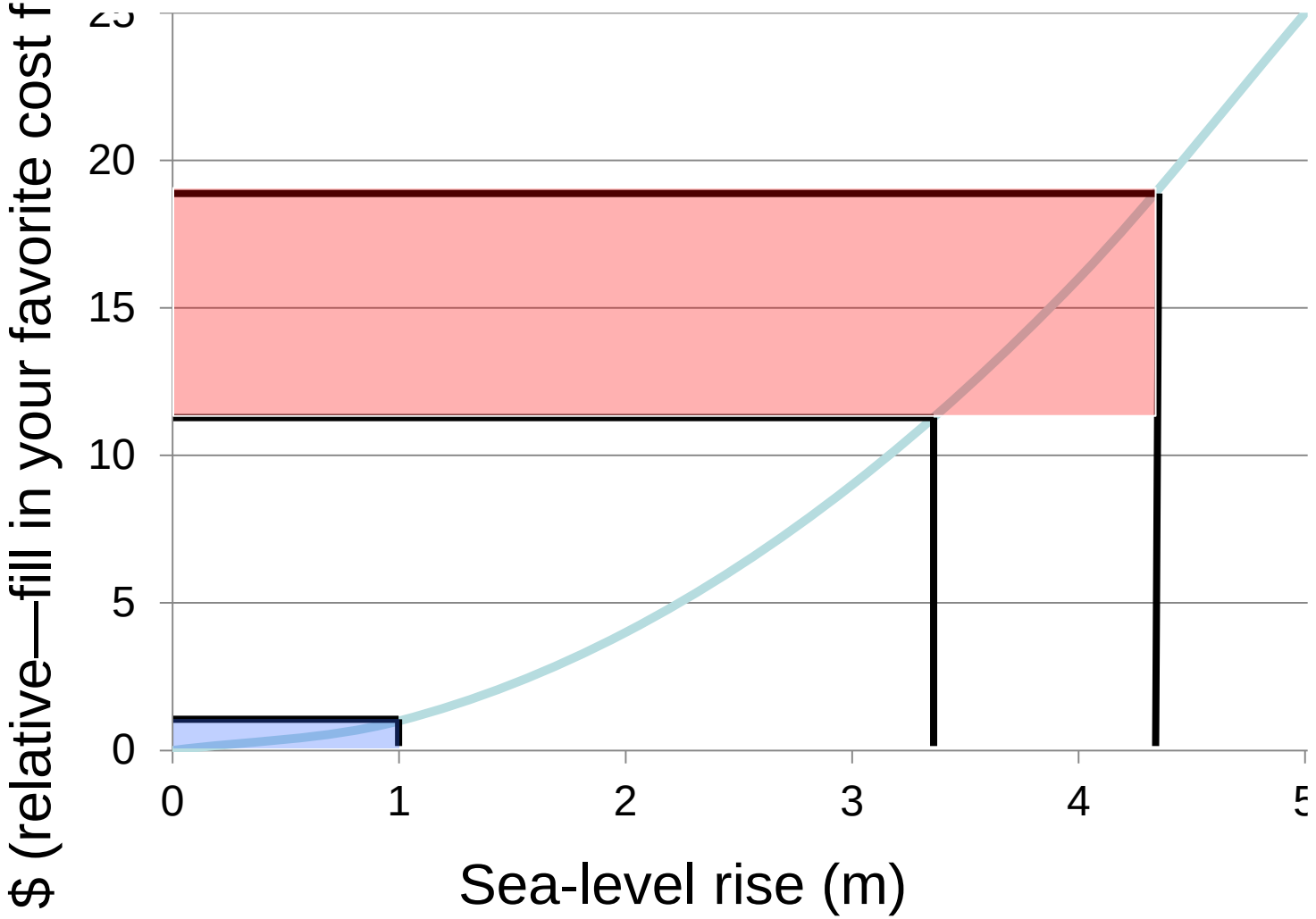
Cost of 1 m of sea-level rise with stable WAIS is small…

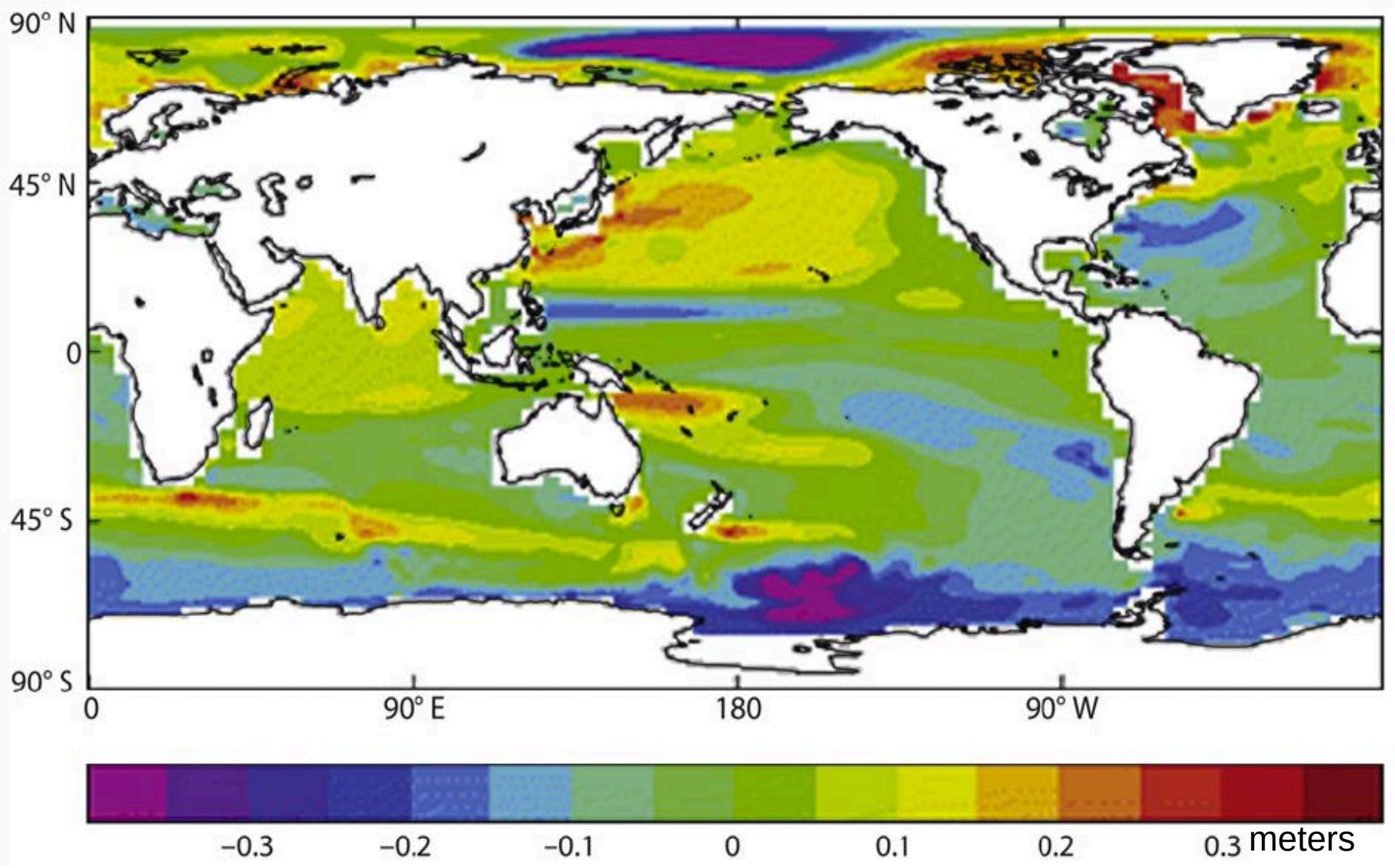


Cost of 1 m of sea-level rise with stable WAIS is small…and cost of same 1 m of sea-level rise with WAIS loss is large



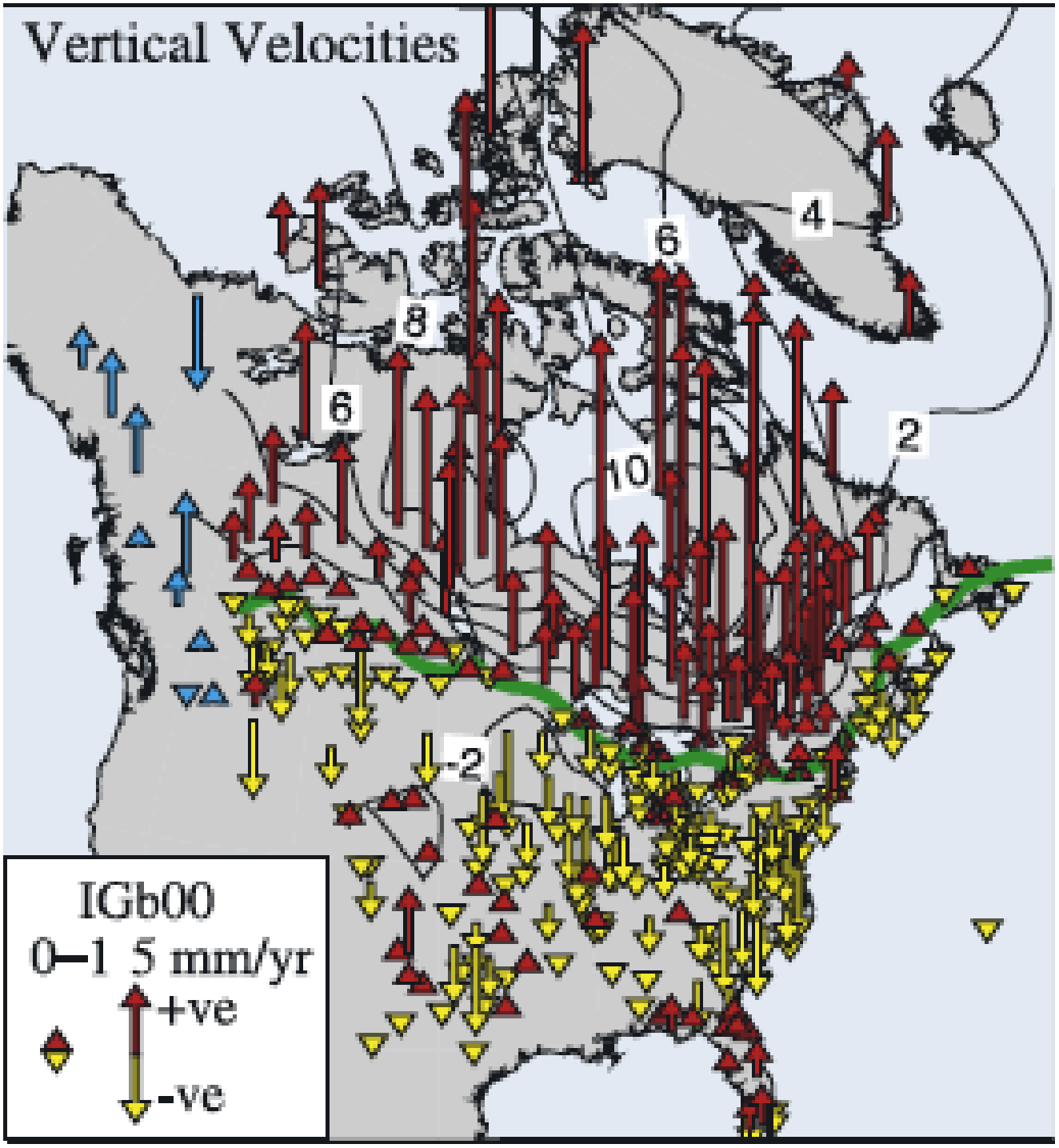
The worse it gets, the more valuable it is to mitigate or adapt, and the more valuable knowledge is!



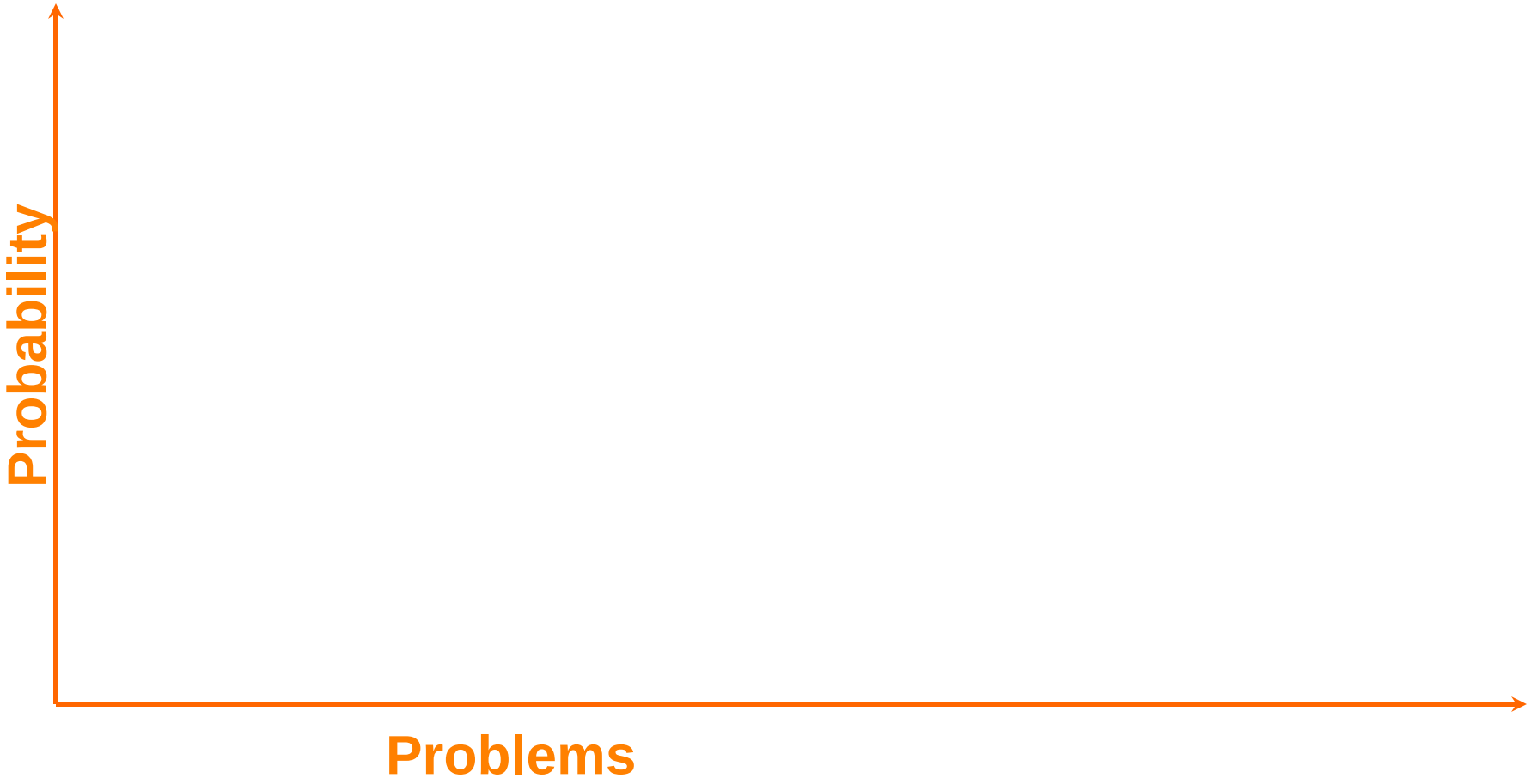


Lowe & Gregory 2006 JGR, 4x CO2, difference between local and global average sea-level rise (m), Hadley Centre model, from changing temperature, salinity, winds, and air pressure.

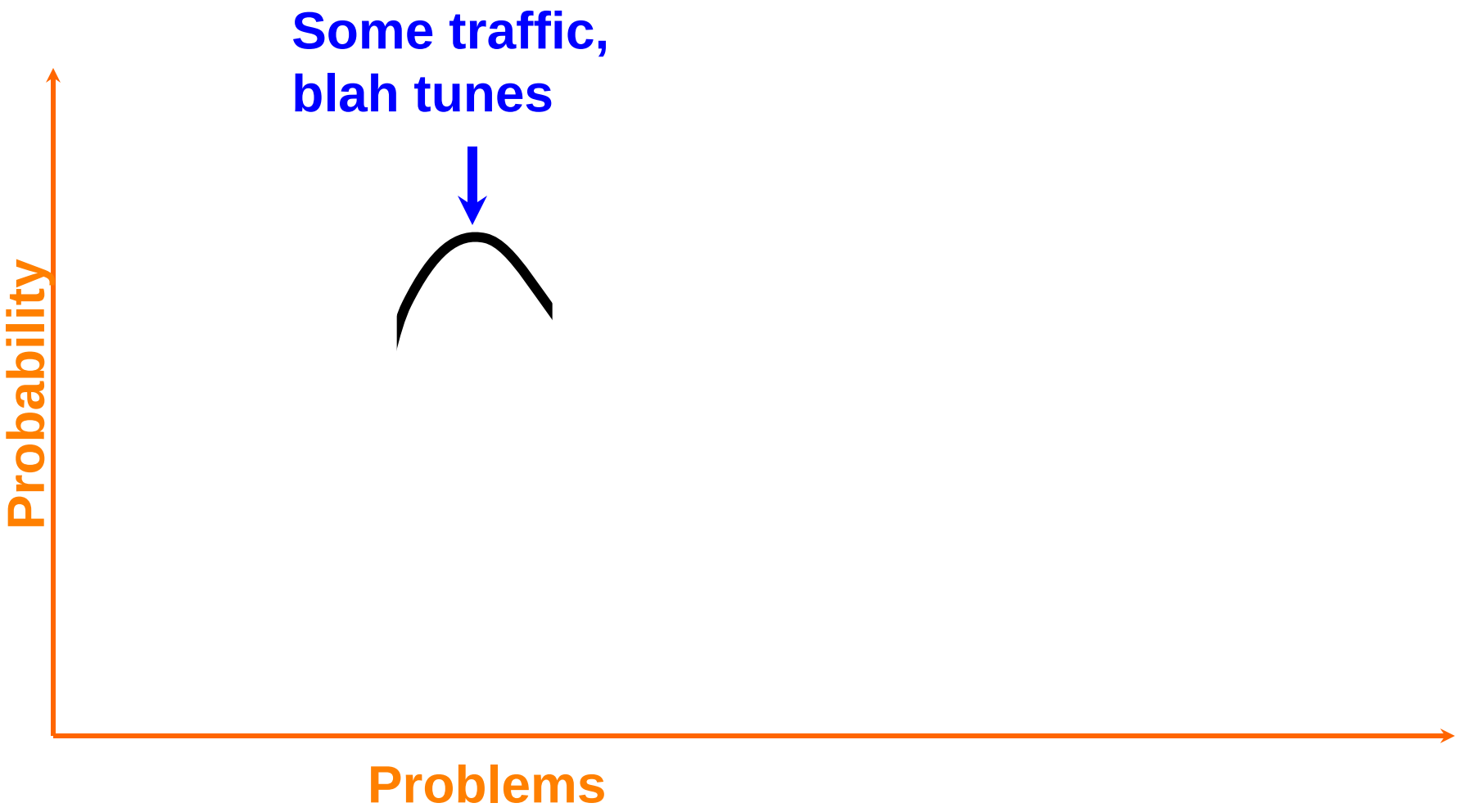
Local changes from isostasy (shown here; still responding to the end of the ice age), sediment compaction, or water or oil removal can be important.



Sella et al., 2007, GRL



Suppose you have to drive somewhere. What are you likely to encounter, and what do you plan for?



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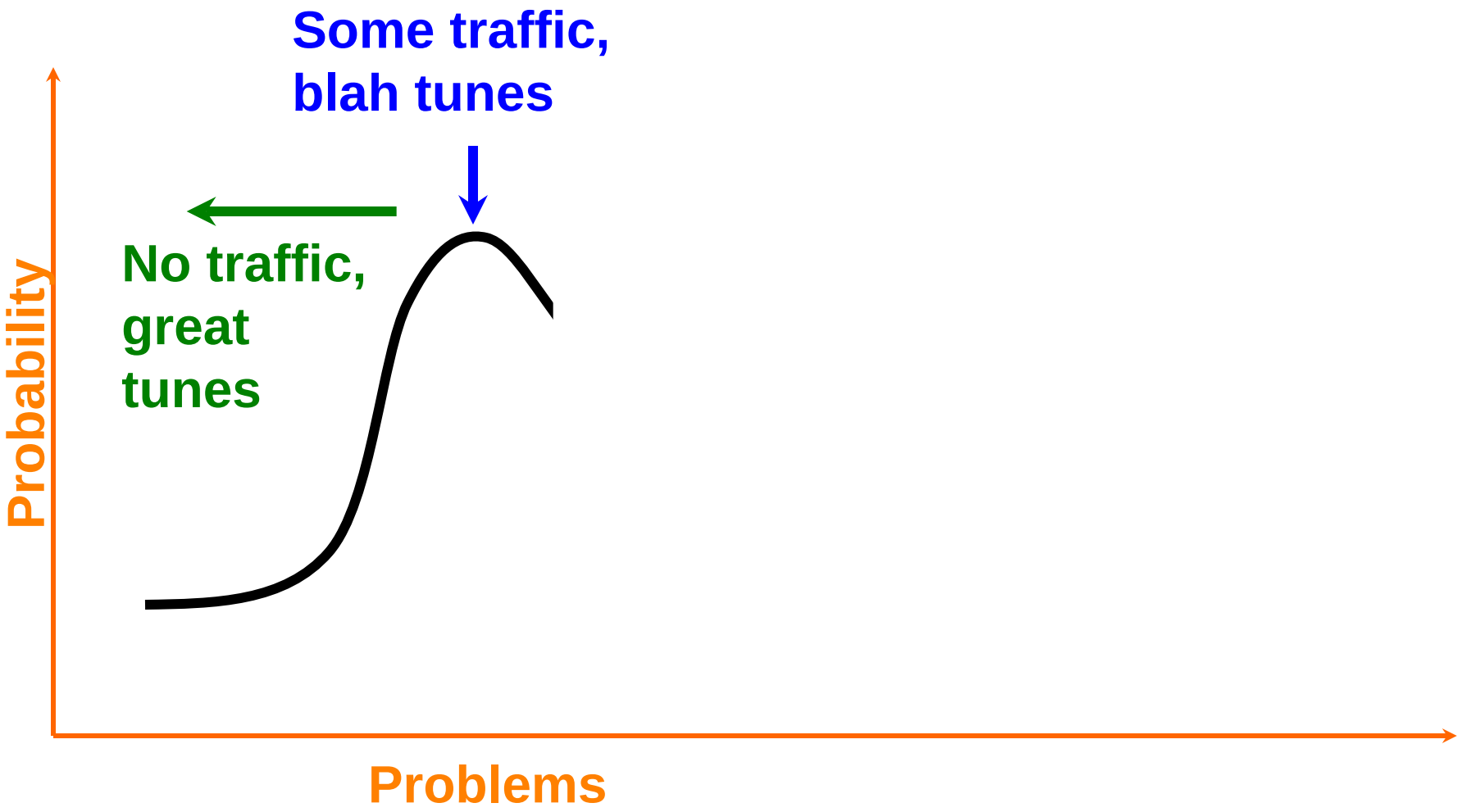
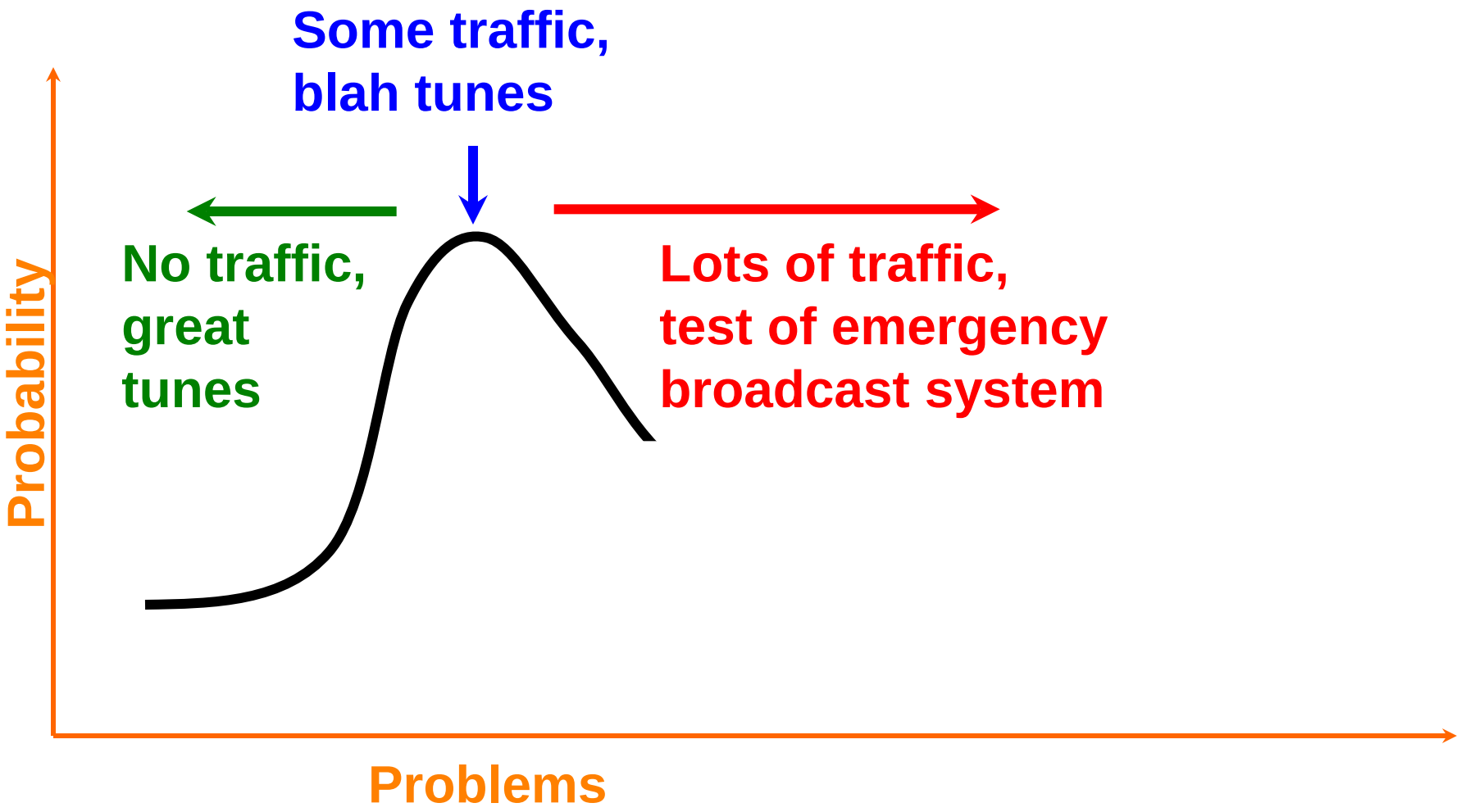
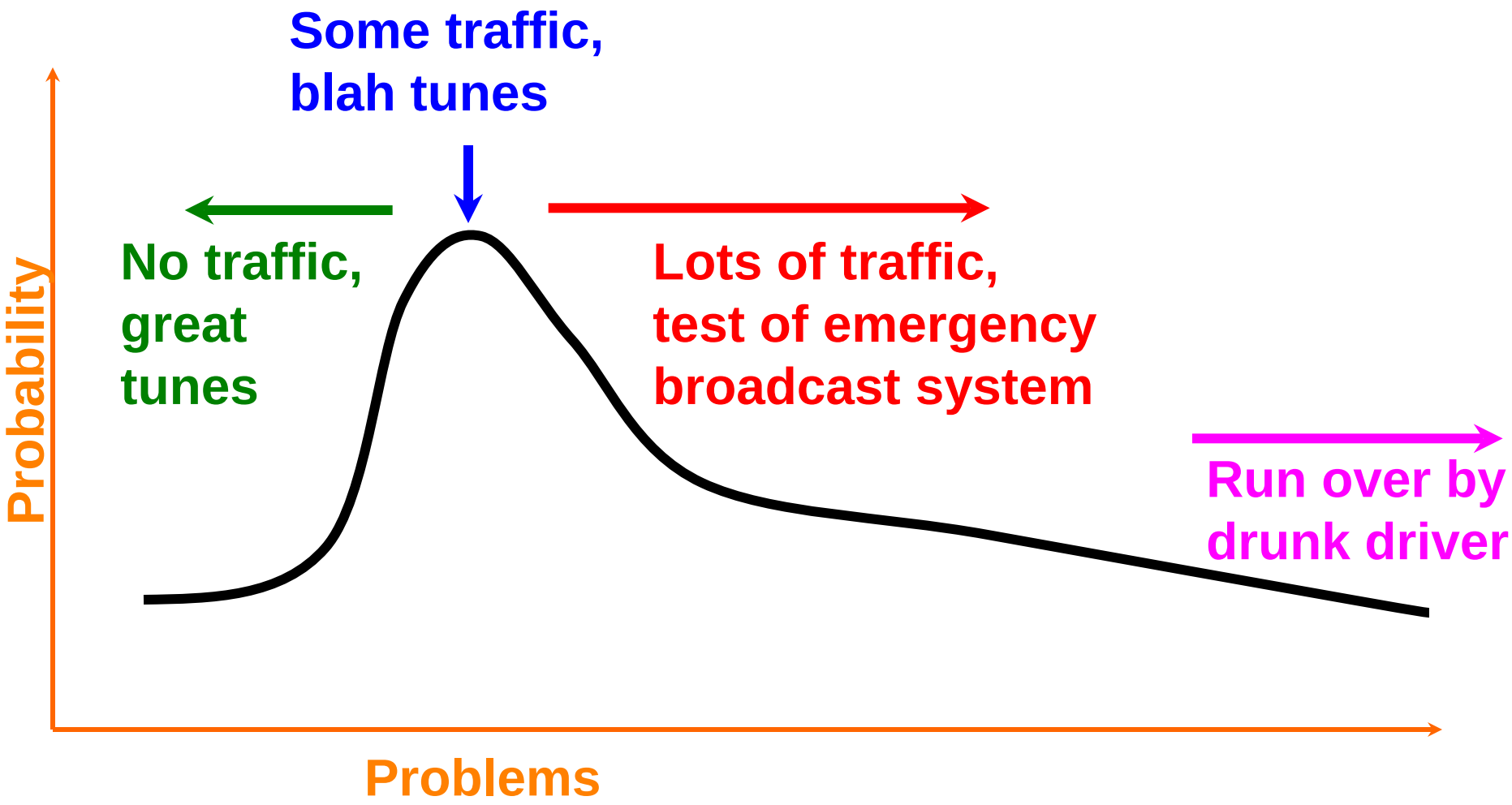


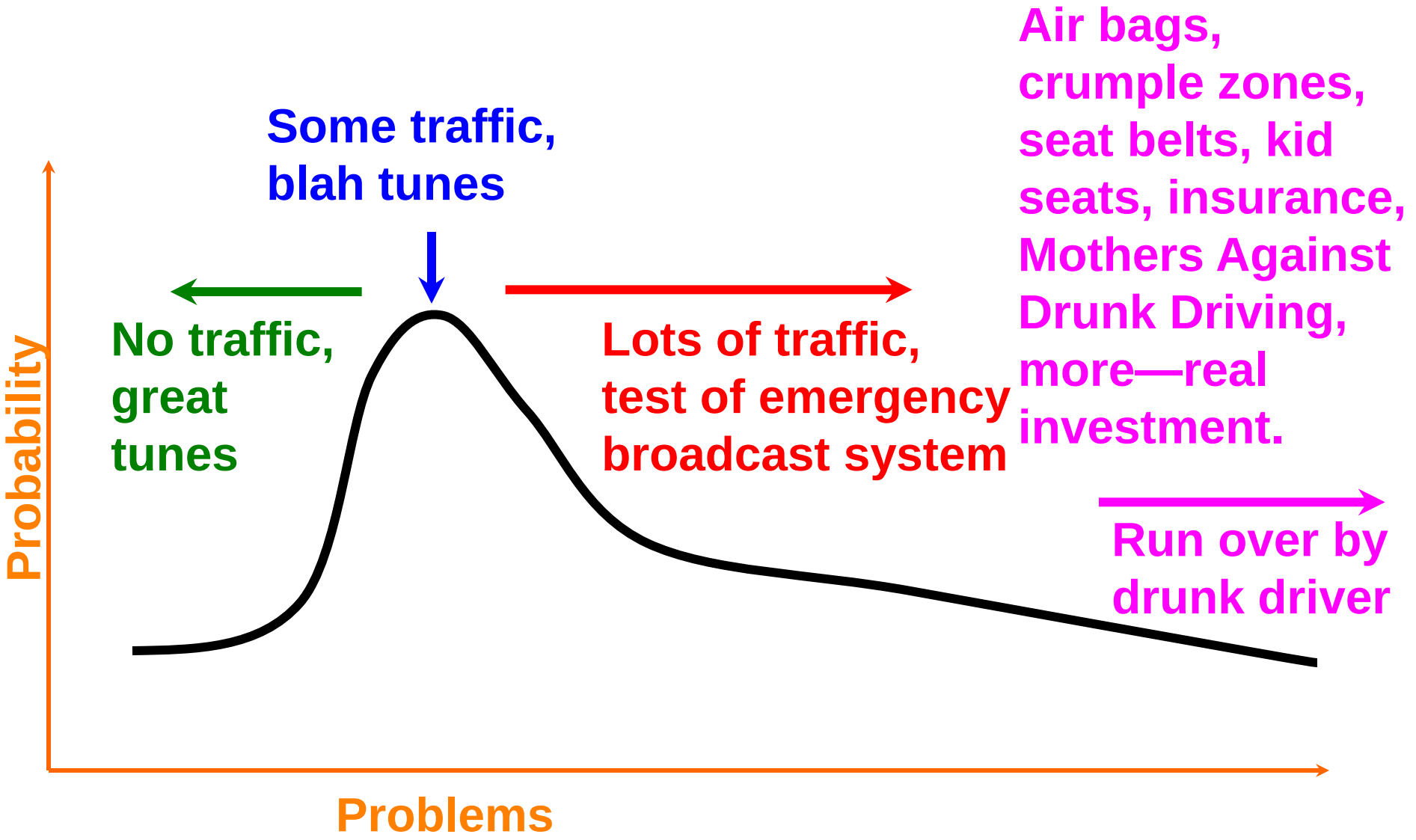
Suppose you have to drive somewhere. What are you likely to encounter, and what do you plan for?



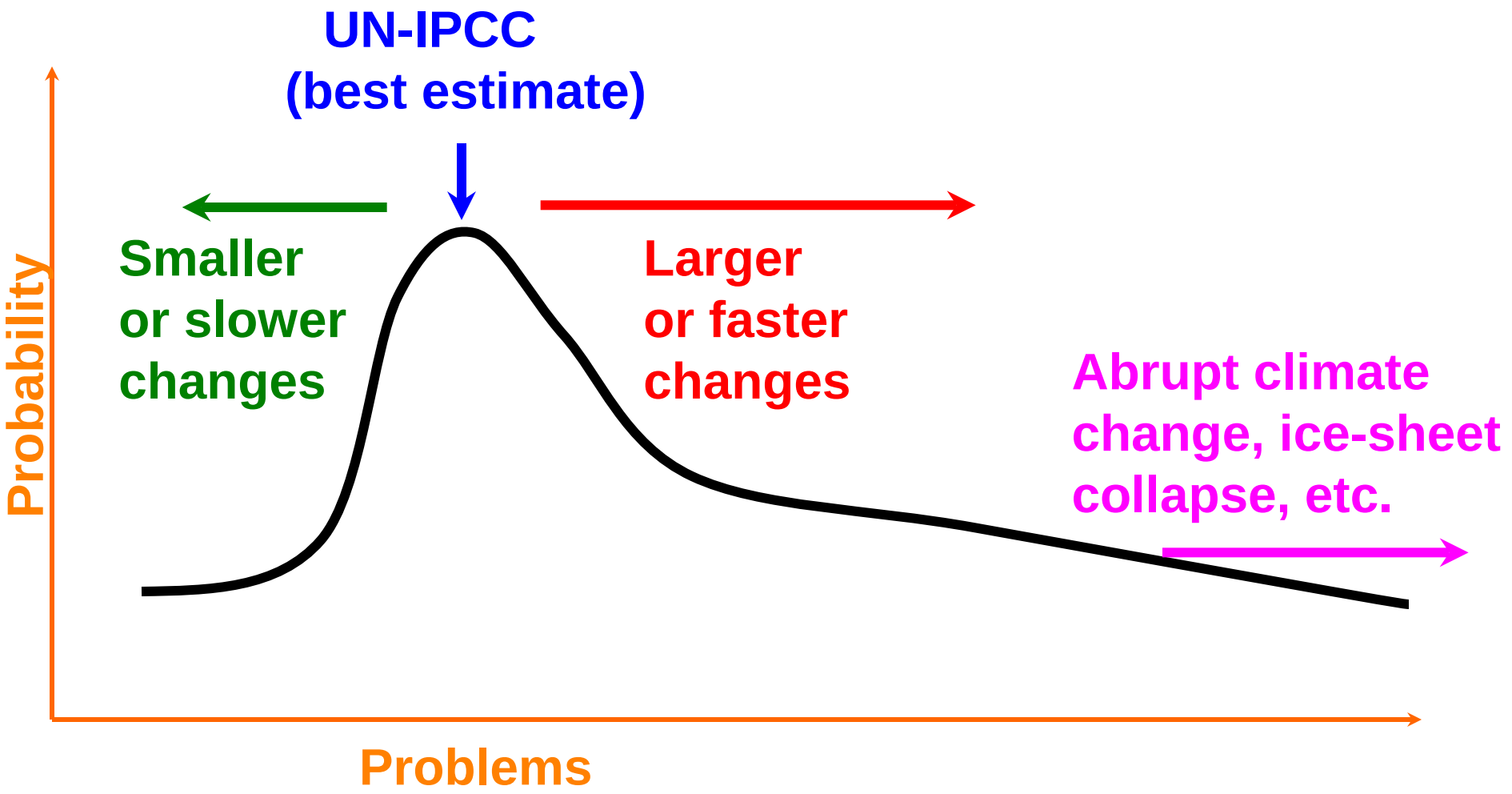
Suppose you have to drive somewhere. What are you likely to encounter, and what do you plan for?



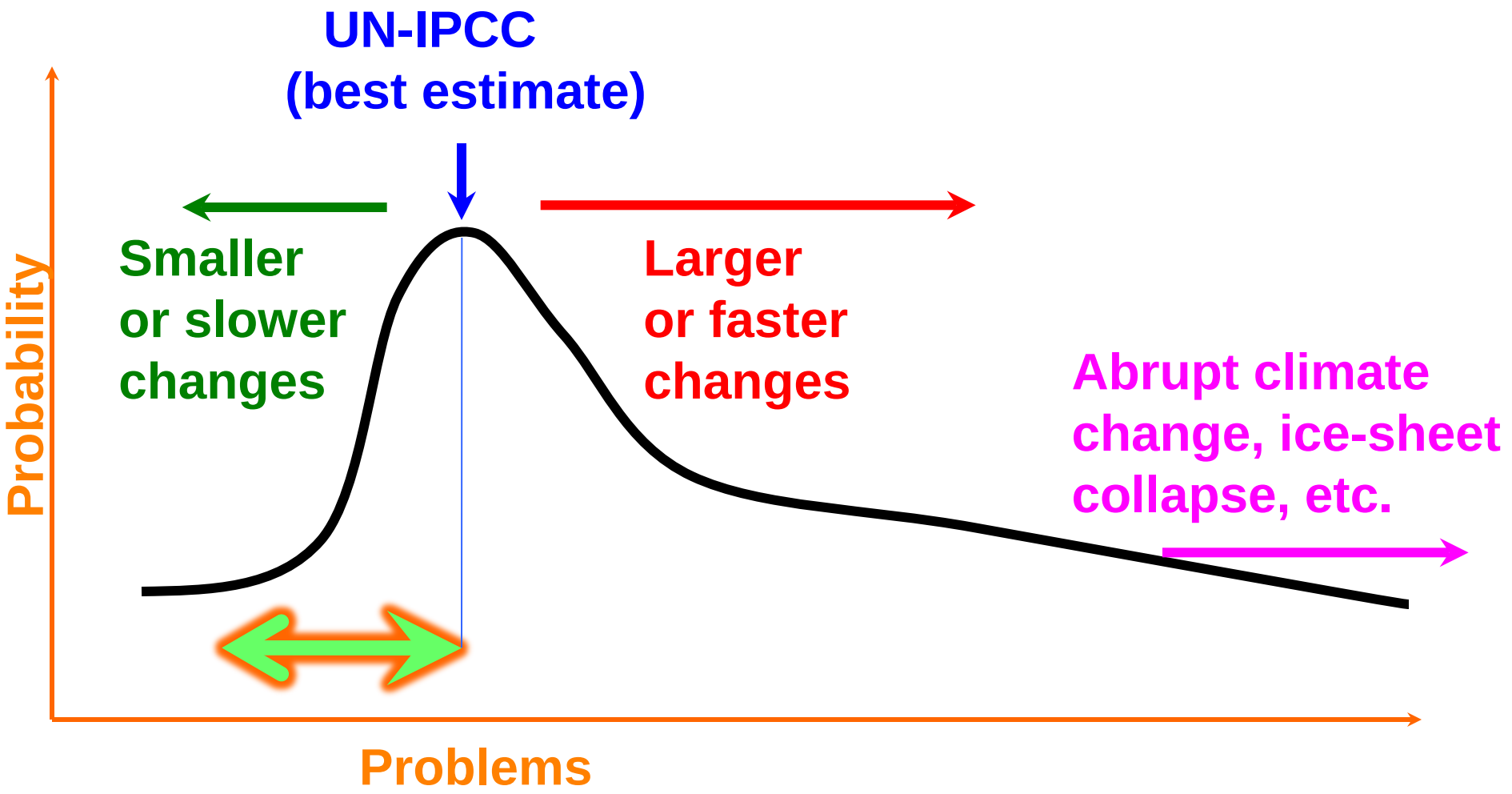
Suppose you have to drive somewhere. What are you likely to encounter, and what do you plan for?



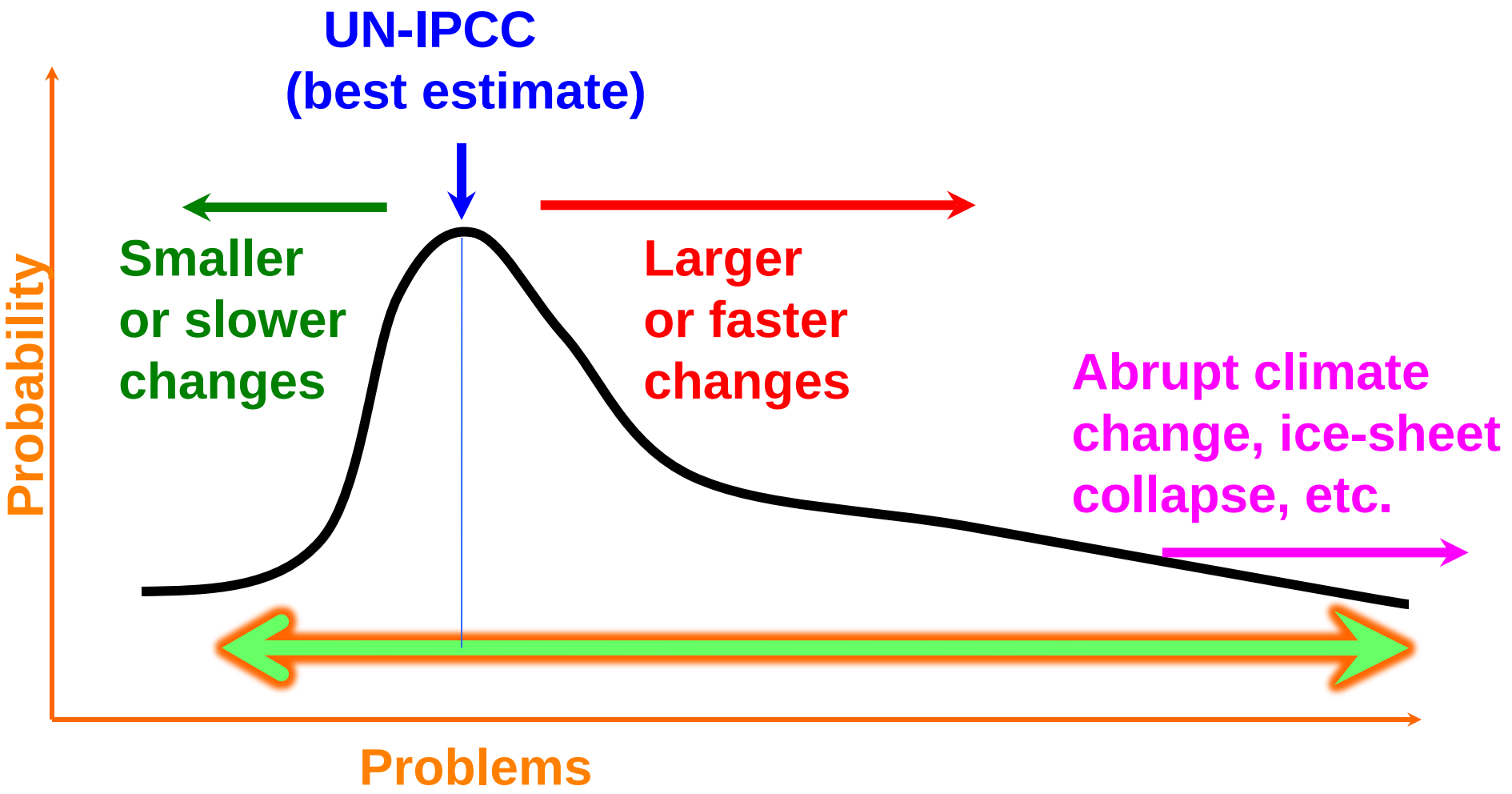
Suppose you have to drive somewhere. What are you likely to encounter, and what do you plan for?



My interpretation of probability of various levels of future problems.



My interpretation of views given greatest attention in recent Congressional hearings I've experienced.



Science is NOT “one side”; Science is the best we have, and the usual projections discussed are on the optimistic side of possibilities.

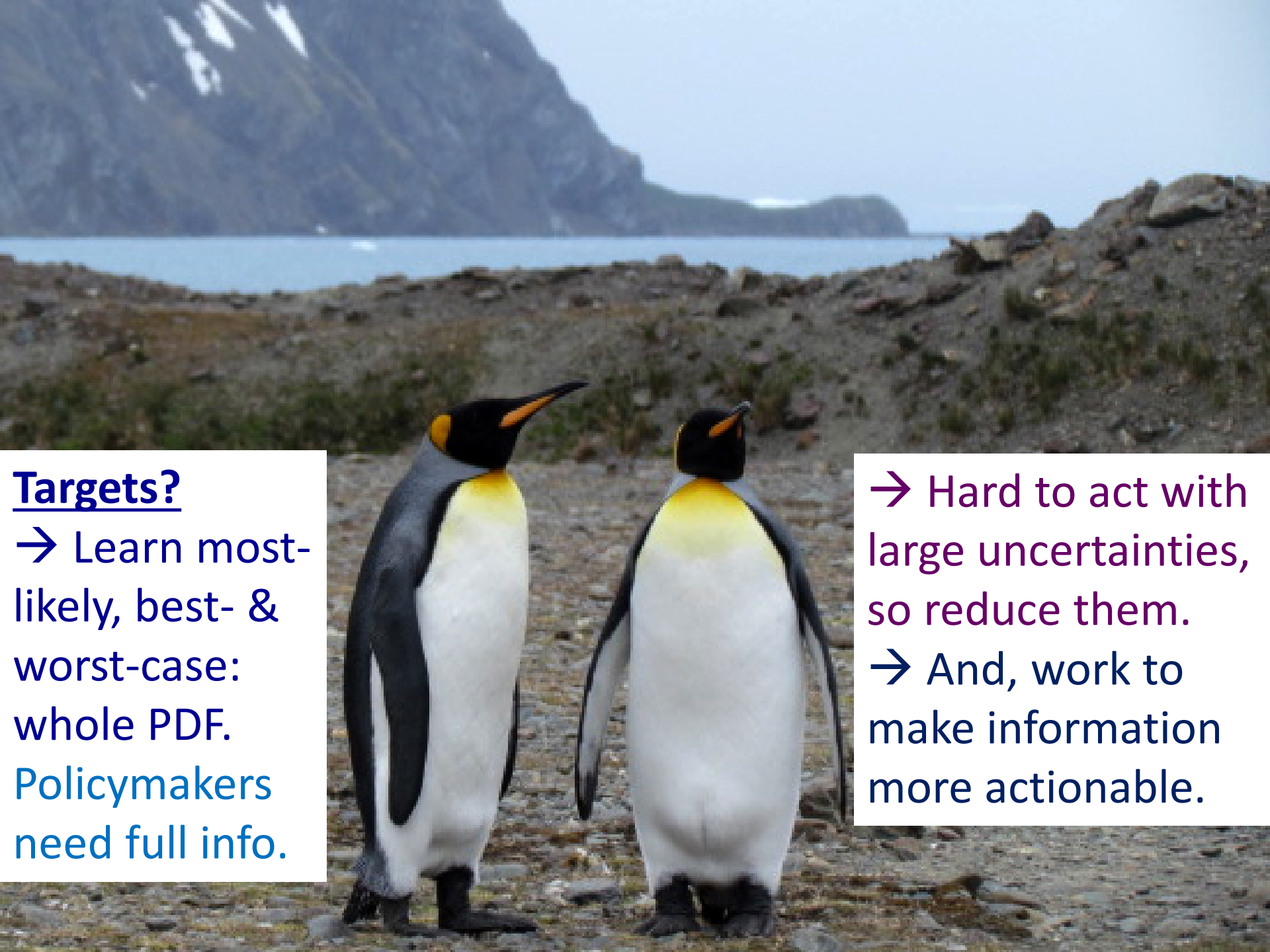

Properly used, knowledge saves lives & money
→ And that requires data
→ Data data data

And models

And data assimilation

Leading to understanding

You are important. Good data are essential, driving solid science. So keep doing what you do.



Targets?

→ Learn most-likely, best- & worst-case: whole PDF.

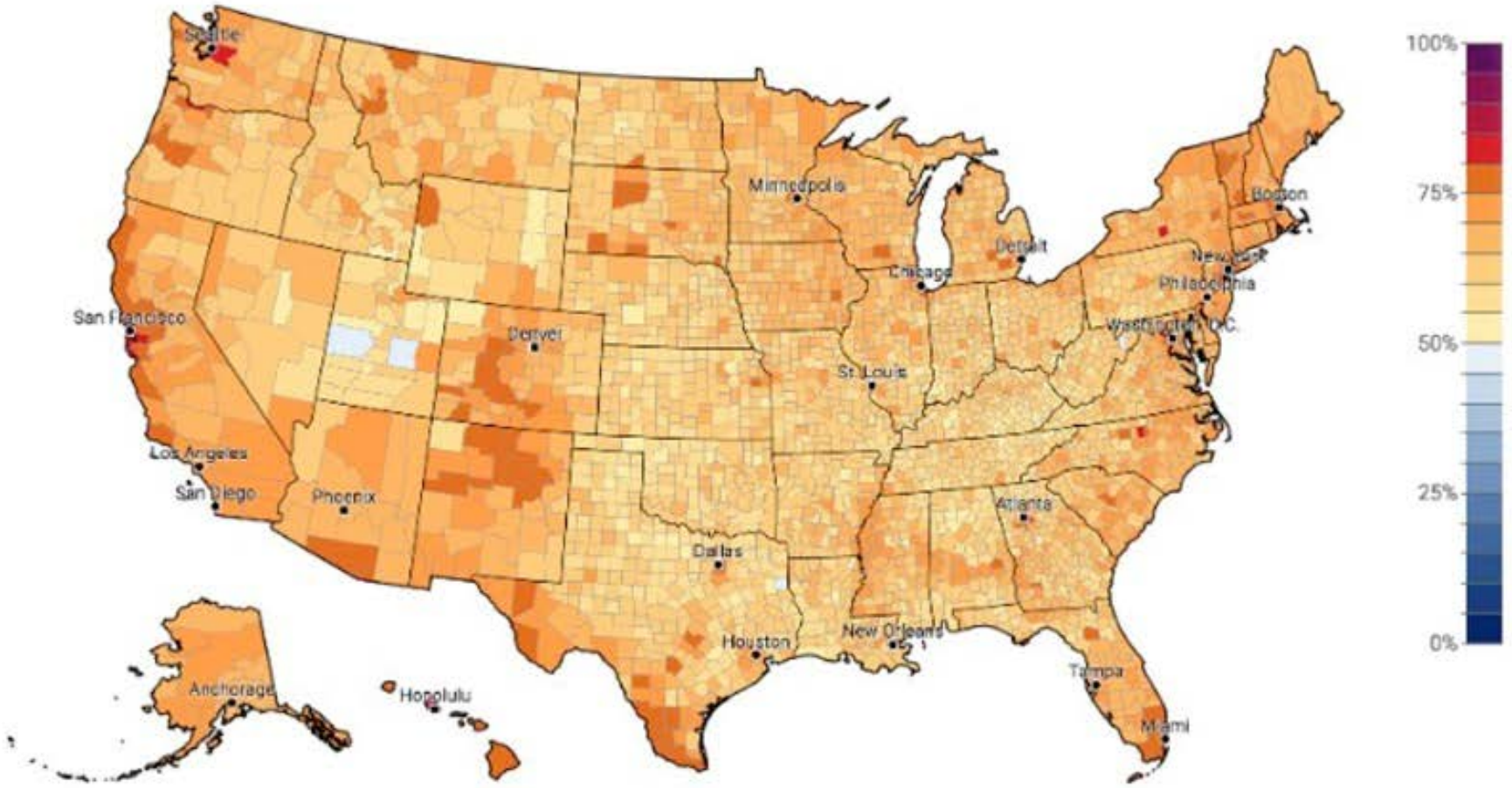
Policymakers need full info.

→ Hard to act with large uncertainties, so reduce them.

→ And, work to make information more actionable.

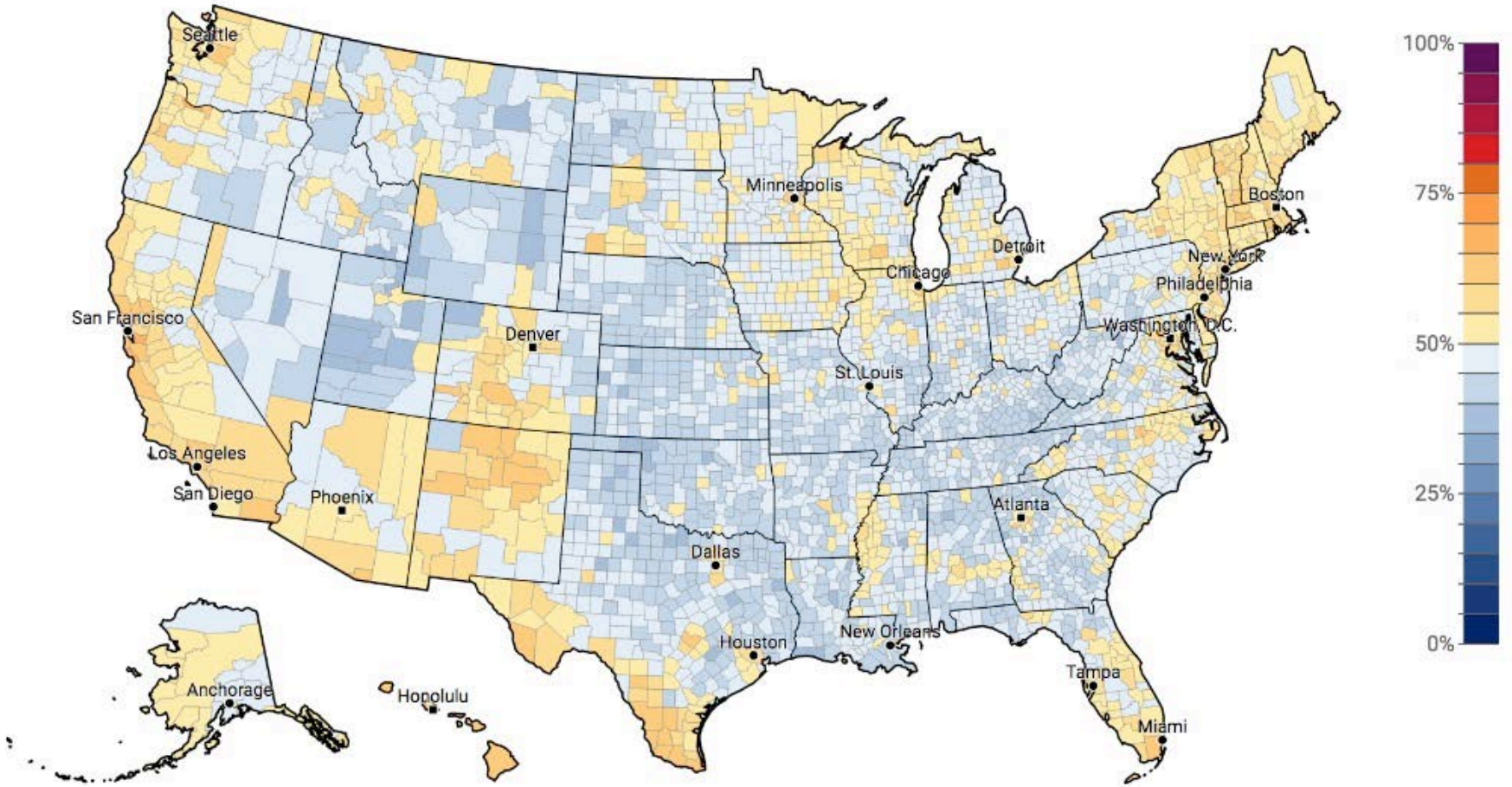
Thanks!

1. Climate change is real



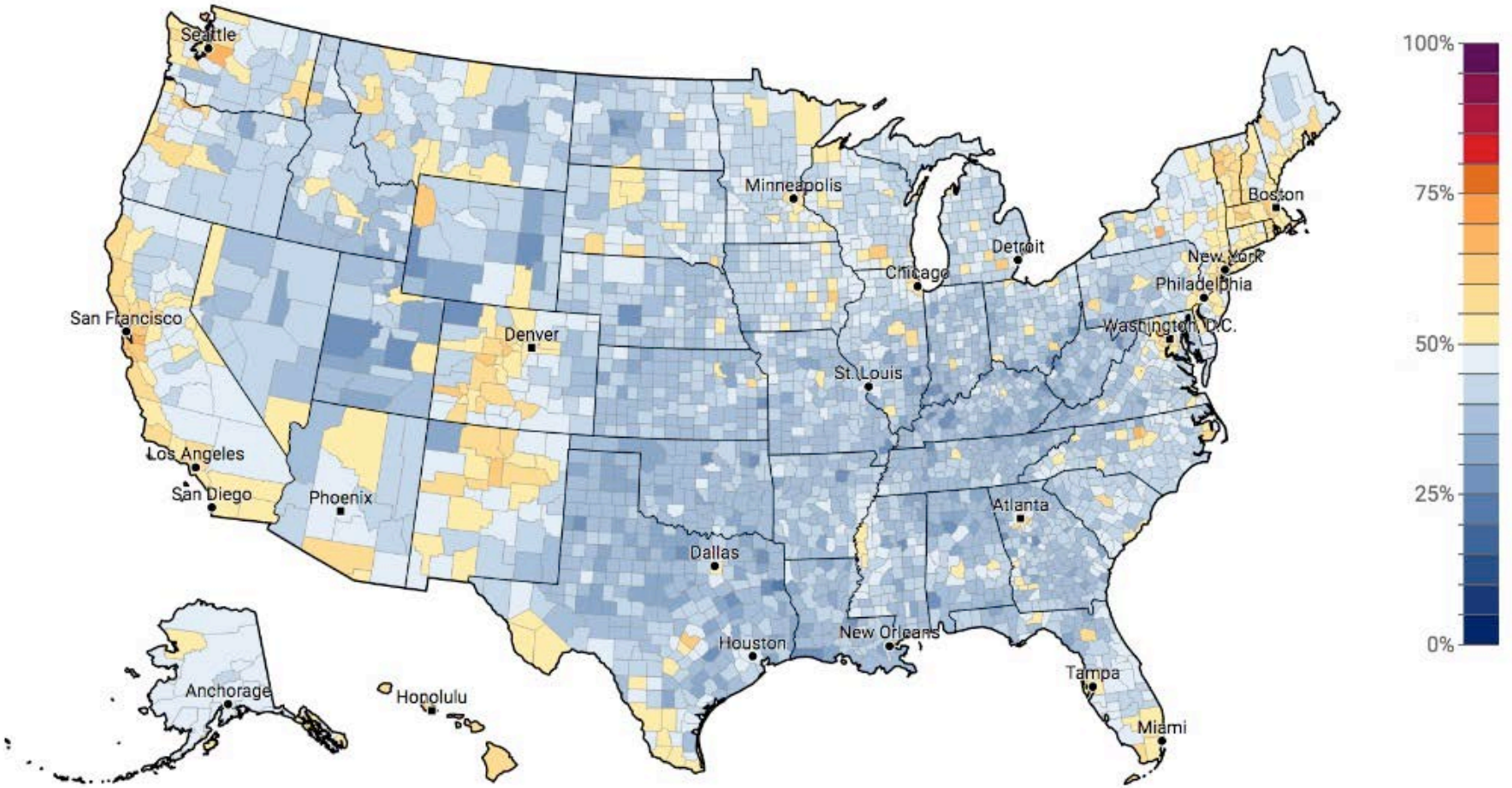
http://www.cnn.com/2017/02/28/us/sutter-climate-opinion-maps/index.html

2. Humans are causing the Earth to warm



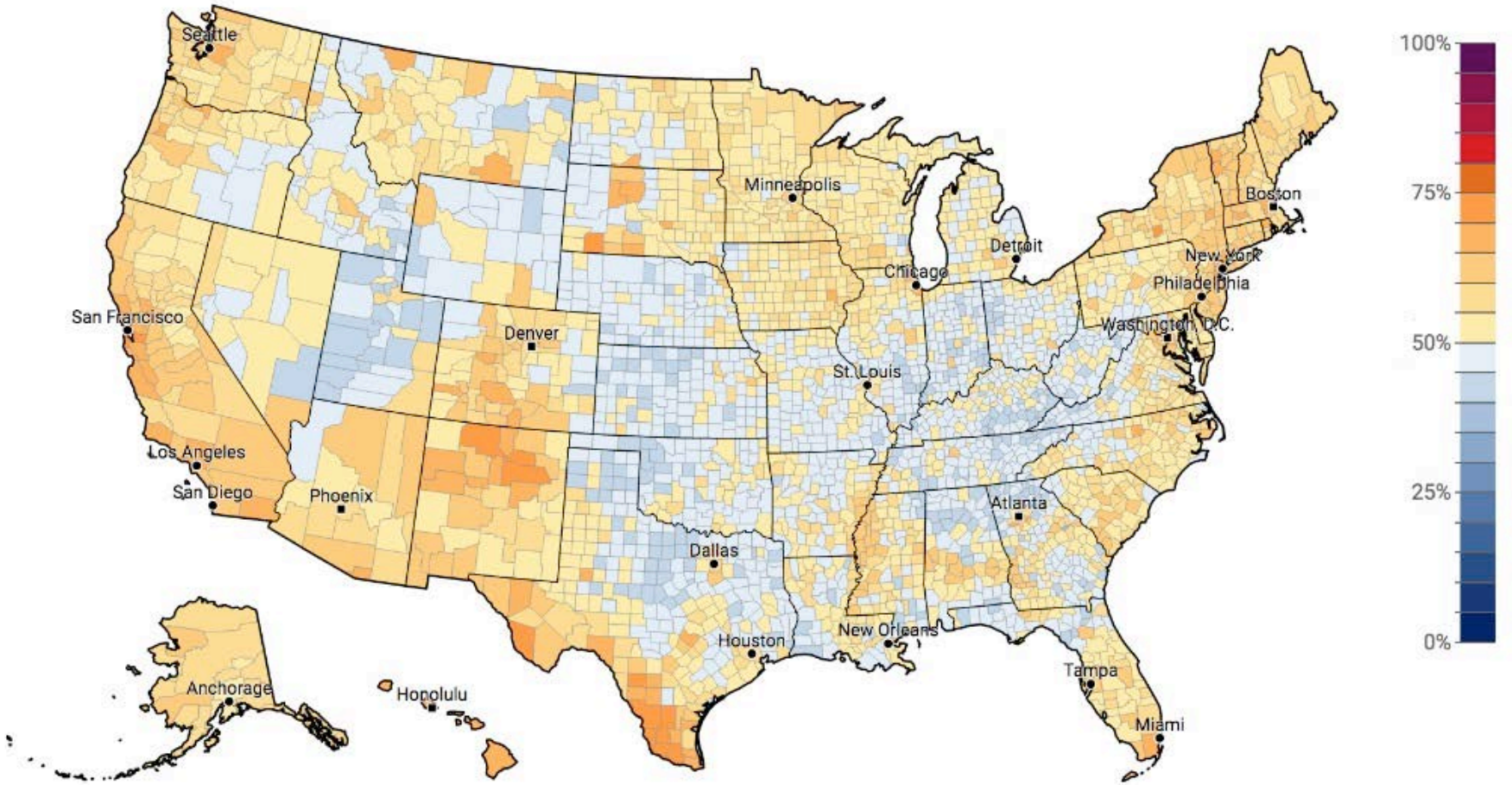
http://www.cnn.com/2017/02/28/us/sutter-climate-opinion-maps/index.html

3. Scientists agree on these points



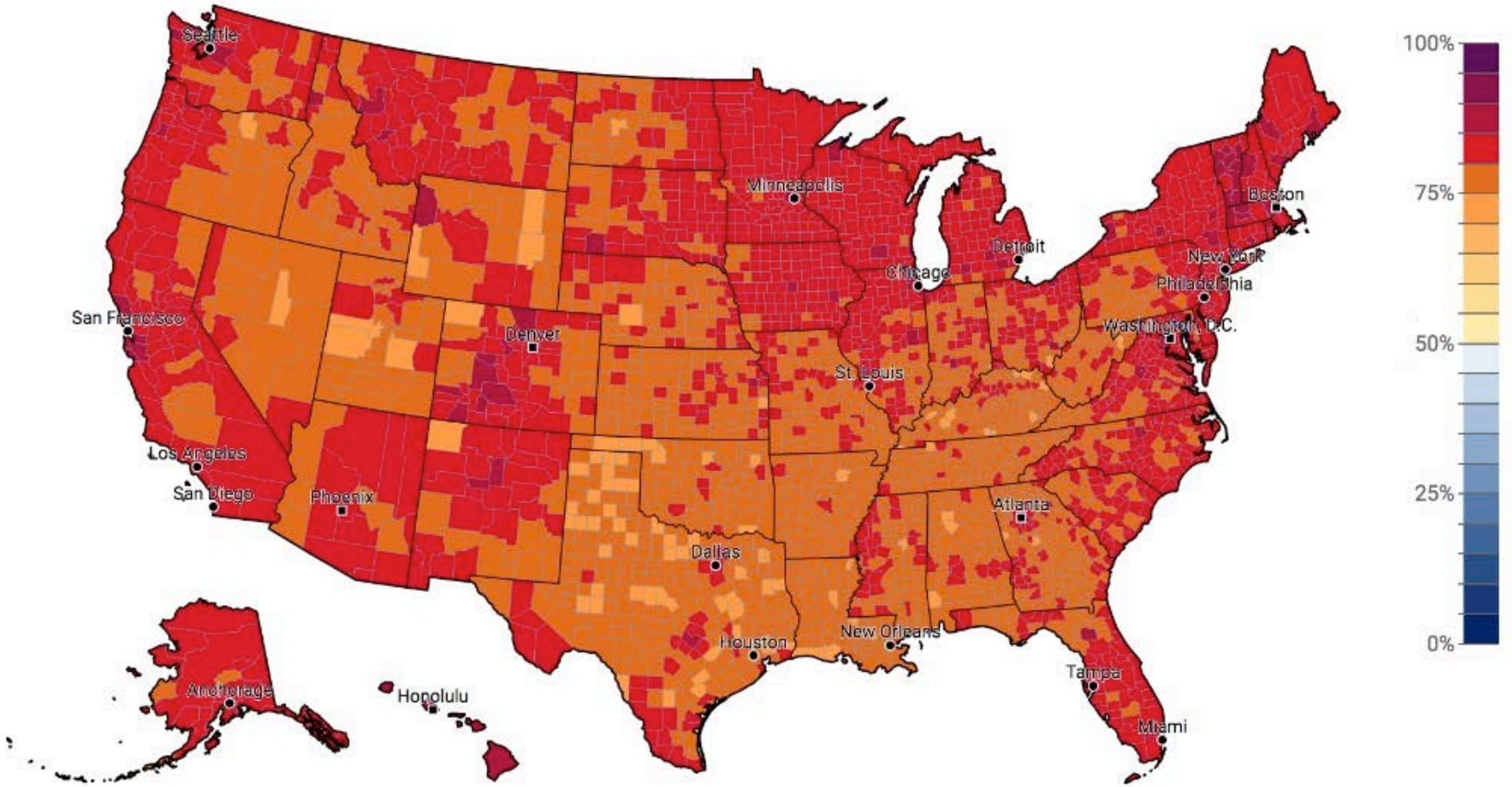
http://www.cnn.com/2017/02/28/us/sutter-climate-opinion-maps/index.html

4. Climate change is bad



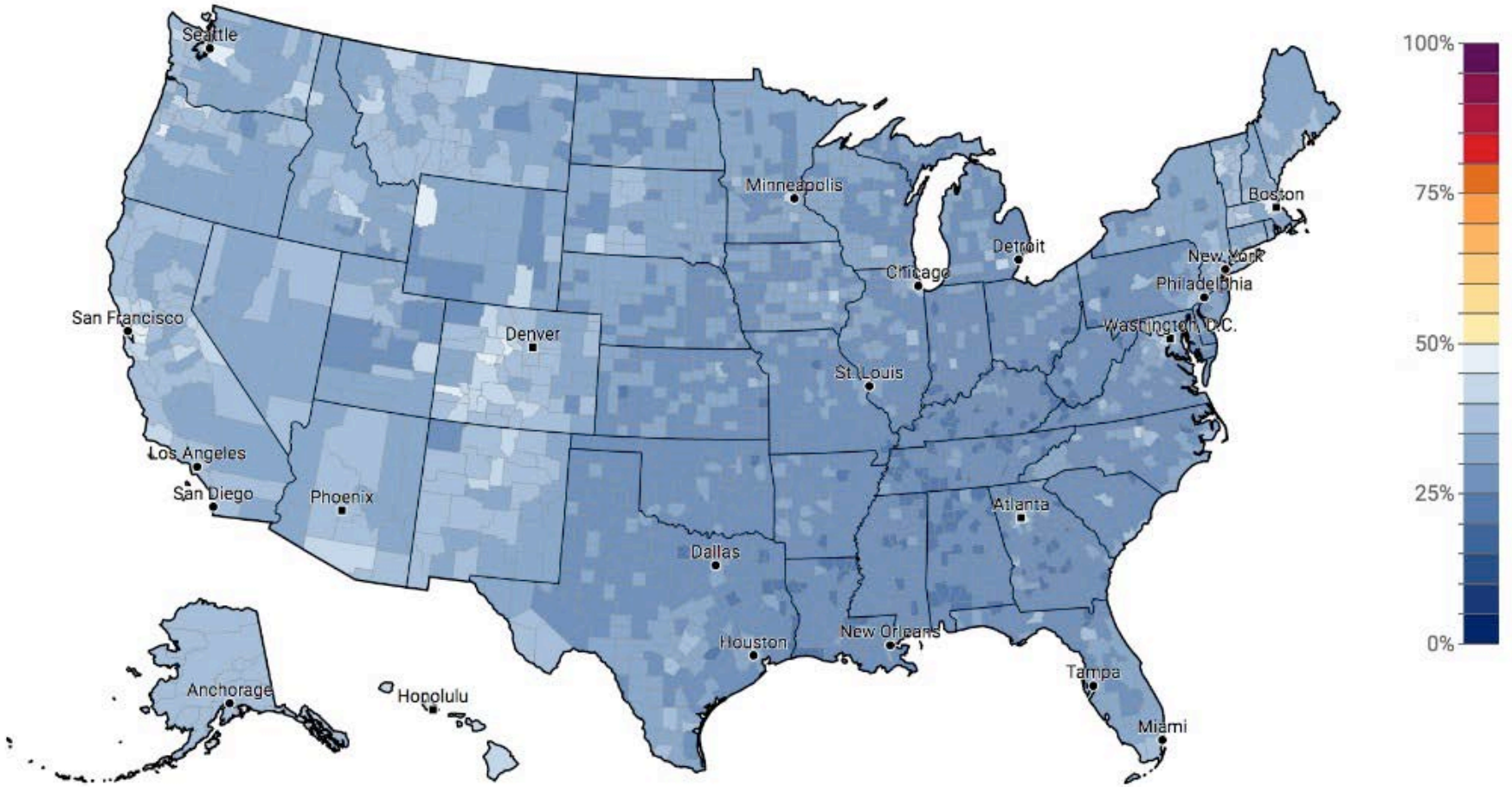
http://www.cnn.com/2017/02/28/us/sutter-climate-opinion-maps/index.html

5. There are smart ways to fix global warming

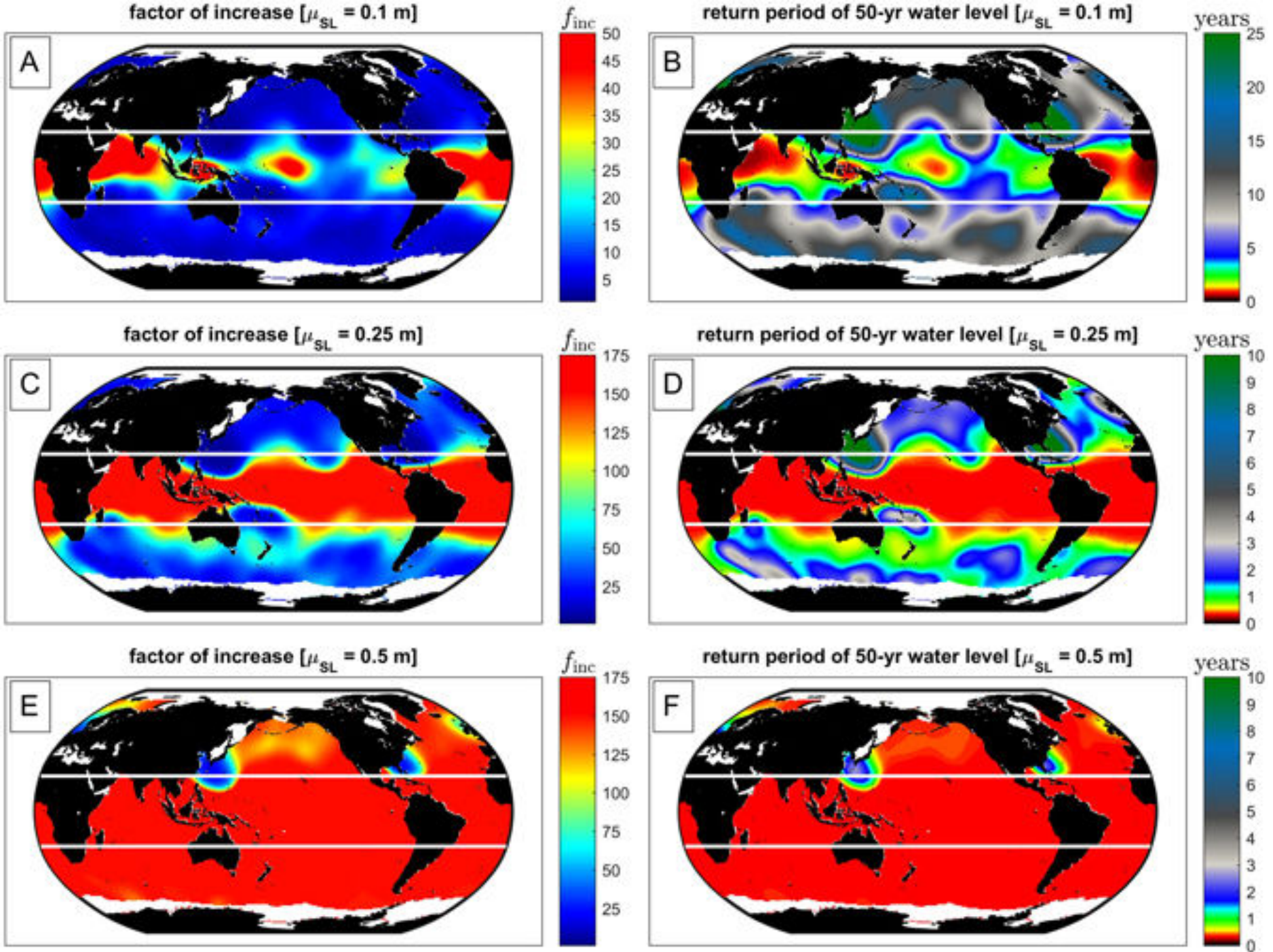


http://www.cnn.com/2017/02/28/us/sutter-climate-opinion-maps/index.html

Yet, almost no one talks about climate change



http://www.cnn.com/2017/02/28/us/sutter-climate-opinion-maps/index.html



Vitousek et al., 2017, Doubling of coastal flooding frequency within decades due to sea-level rise. Scientific Reports 7, DOI:10.1038/s41598-017-01362-7

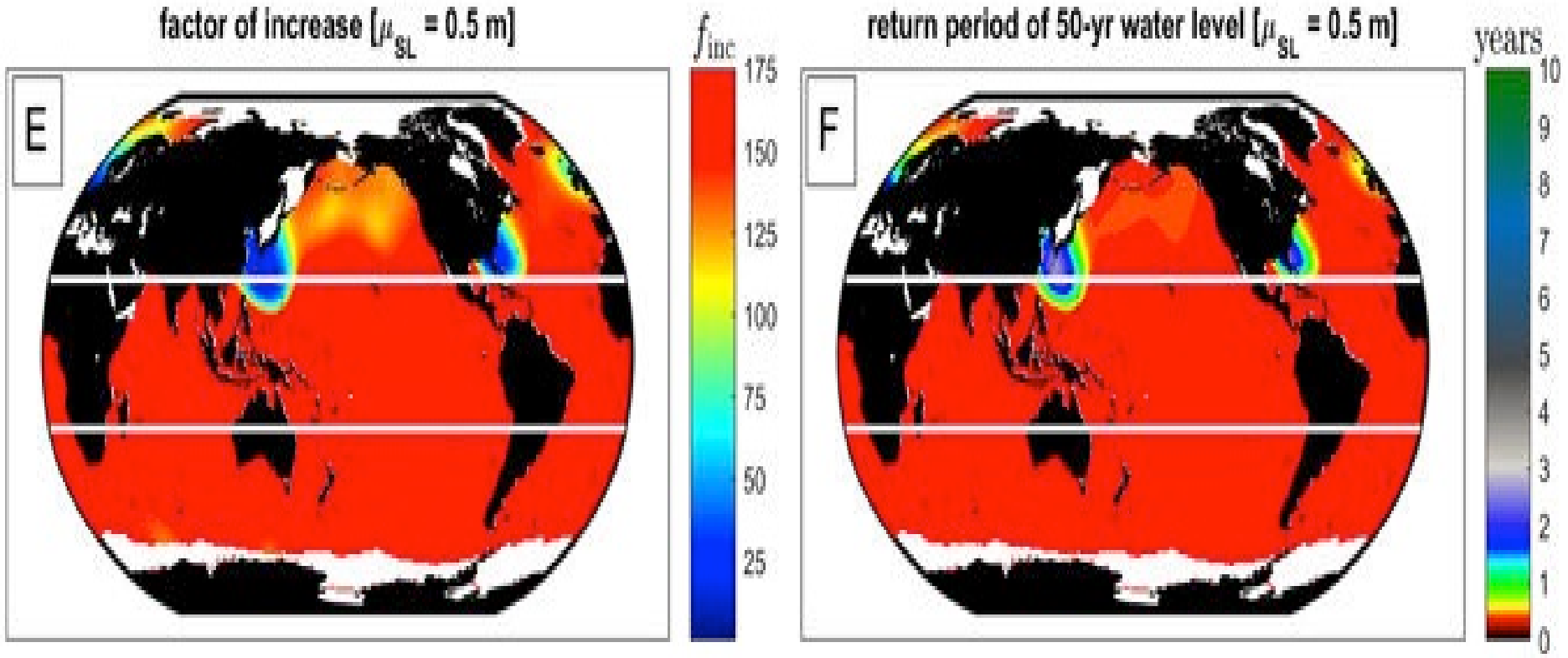
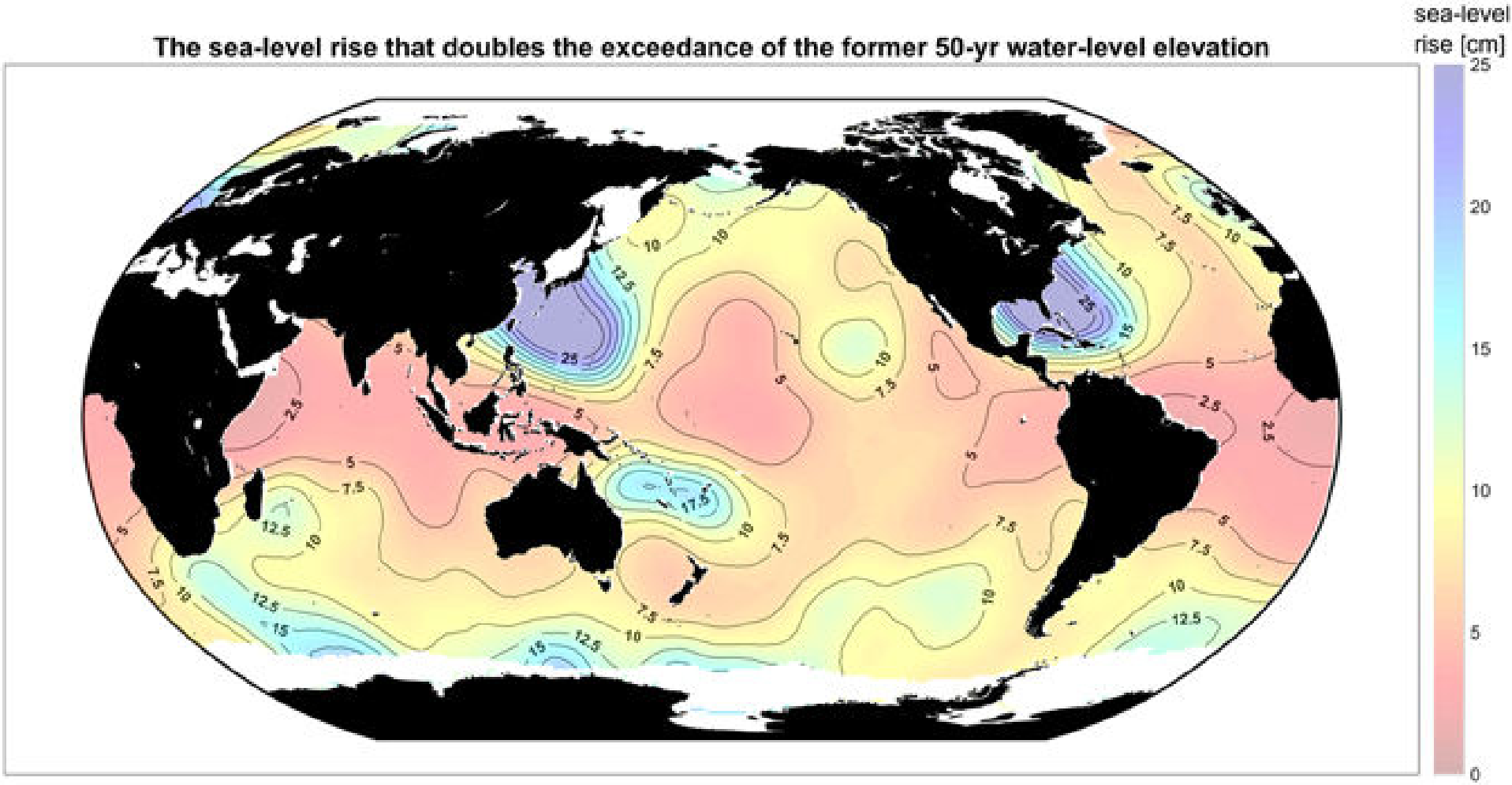


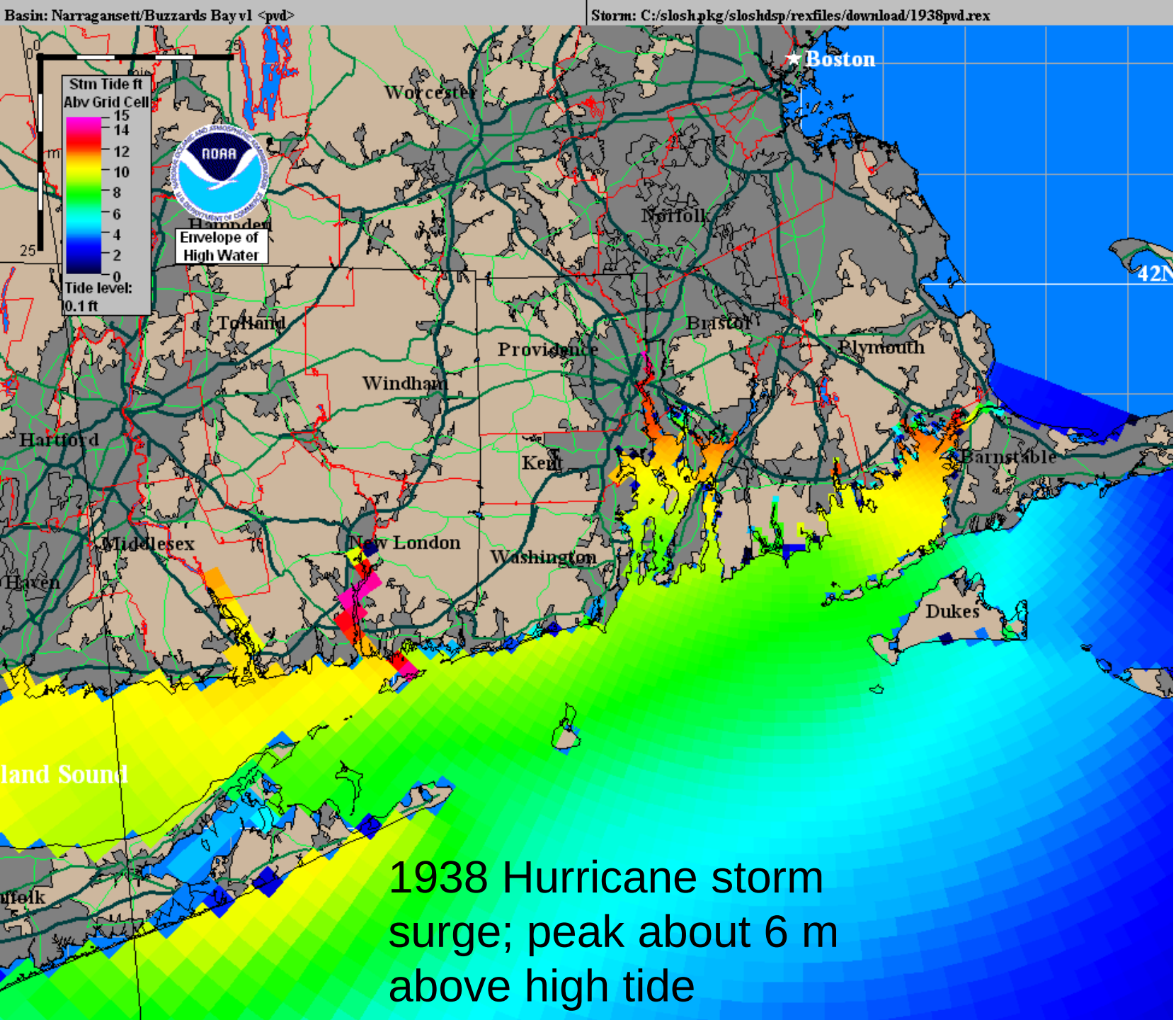
Figure 4. Global estimates of the expected factor of increase in exceedance probability, f_{inc}, and the future return period, T_R, of the 50-yr water level, for SLR projections: μ_{SL}=+0.1, +0.25, +0.5 m. We note that the estimated increase in flooding potential is purely due to SLR and not due to changes in climate or storminess. White lines indicate the Tropic of Cancer and Tropic of Capricorn.

Vitousek et al., 2017, Doubling of coastal flooding frequency within decades due to sea-level rise. Scientific Reports 7, DOI:10.1038/s41598-017-01362-7

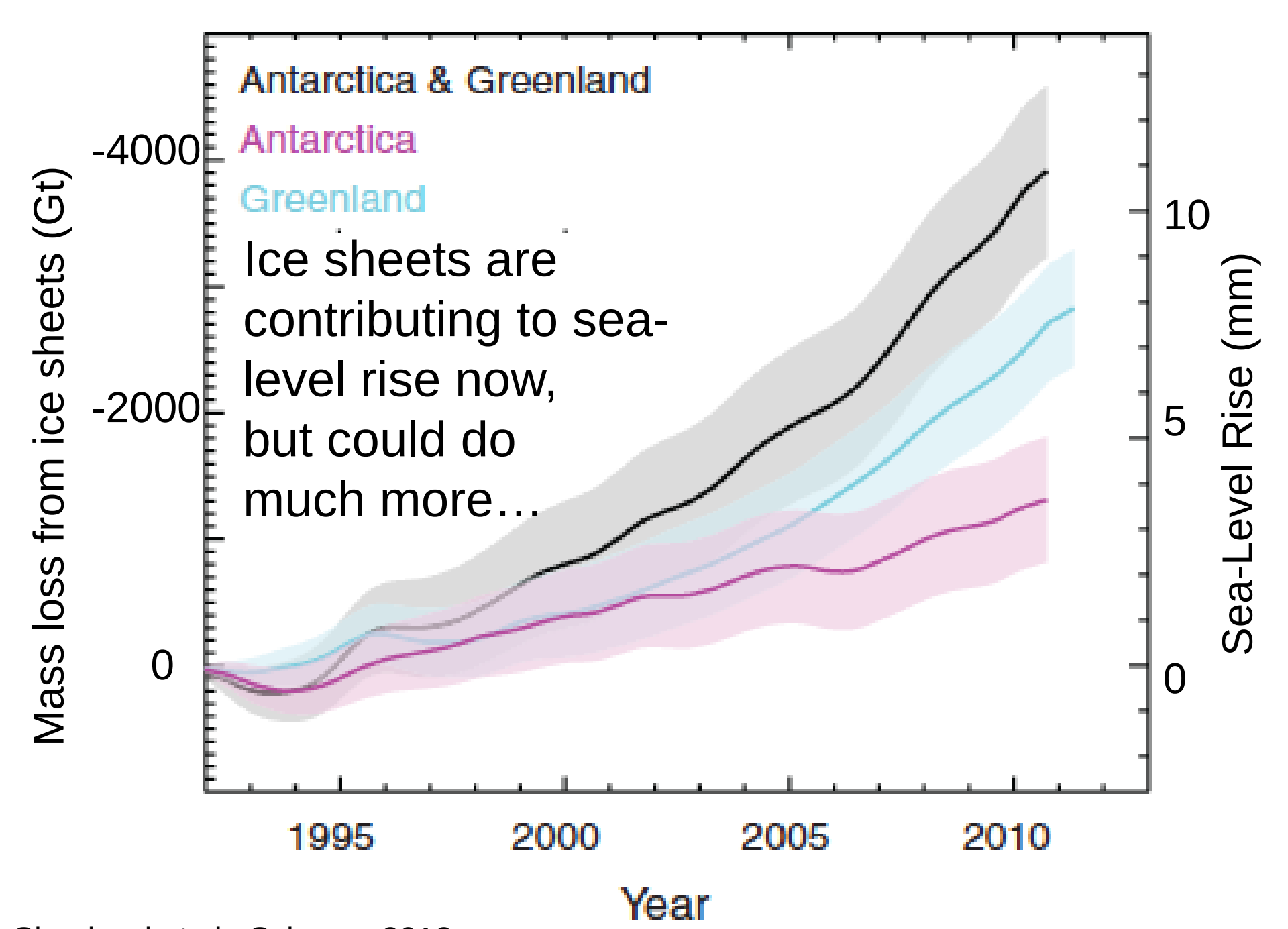


The upper bound of SLR that doubles the exceedance probability of the former 50-year water level. This SLR is the upper limit of a 95% confidence interval based on a Monte Carlo simulation of the GEV parameter estimates and their associated confidence bands. Red areas represent regions particularly vulnerable to small amounts of SLR.

Vitousek et al., 2017, Doubling of coastal flooding frequency within decades due to sea-level rise. Scientific Reports 7, DOI:10.1038/s41598-017-01362-7



http://www.nhc.noaa.gov/ssurge/HistoricalRuns



Shepherd et al., Science, 2012

UW & Penn State grad Kurt Cuffey. Wrote *The Physics of Glaciers*. Let's go over it…

Suppose you make a pancake. It is a pile or batter…

It tends to spread under its own weight.

Where you hold it back…

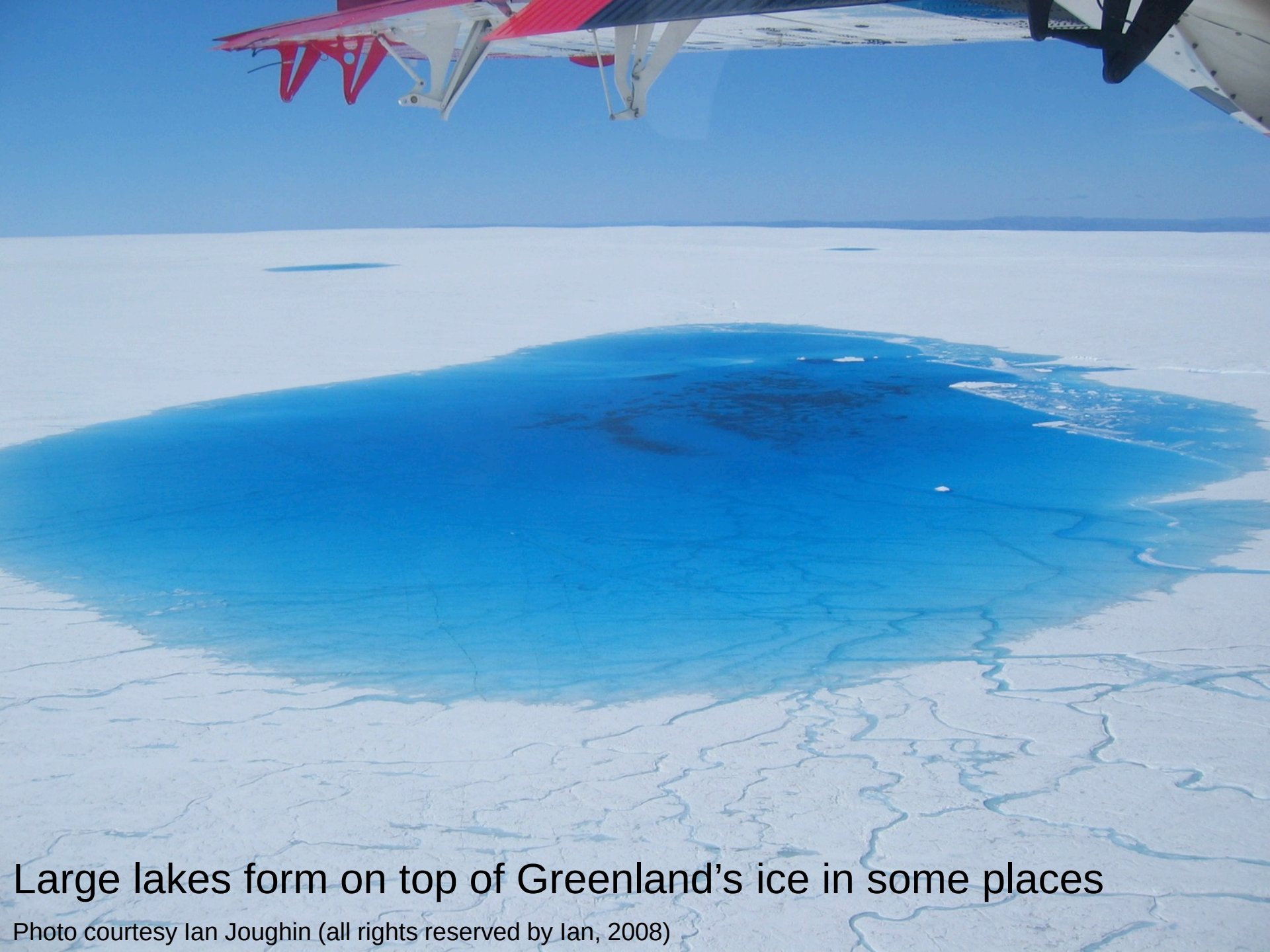
It doesn’t spread as fast.

When it gets stronger, it doesn’t spread as fast.

And on a rougher or bumpier bed…

It doesn’t spread as fast.

(And, it makes cool patterns!you can probably see the Vashon Lobe flowing down Puget Sound and across Seattle in there…)



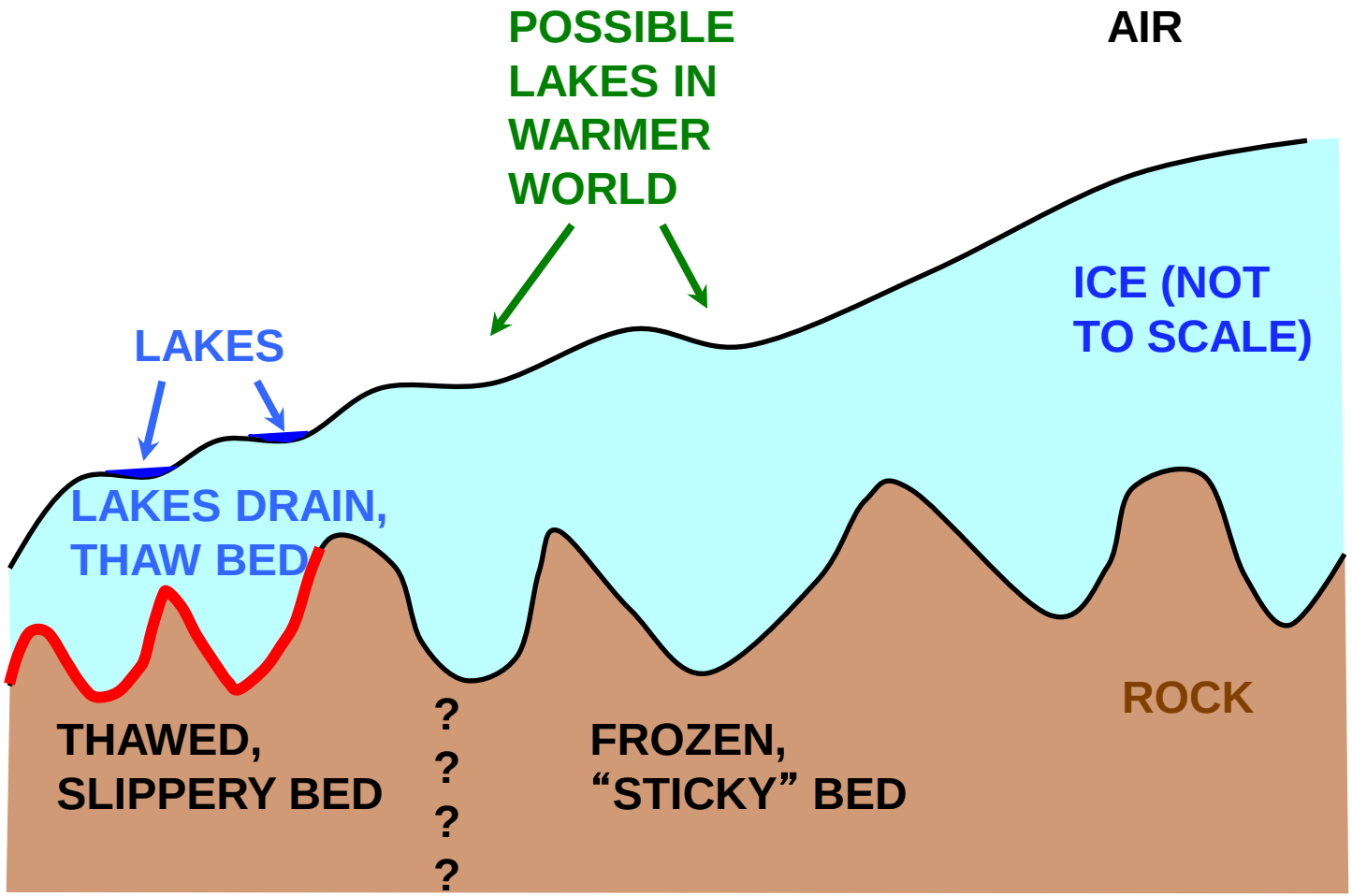
Large lakes form on top of Greenland’s ice in some places

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

Then break through, draining faster than Niagara

Photos courtesy Sarah Das (all rights reserved by Sarah, 2008)

This may speed ice loss, but the “waffle iron” keeps the ice from falling in the ocean

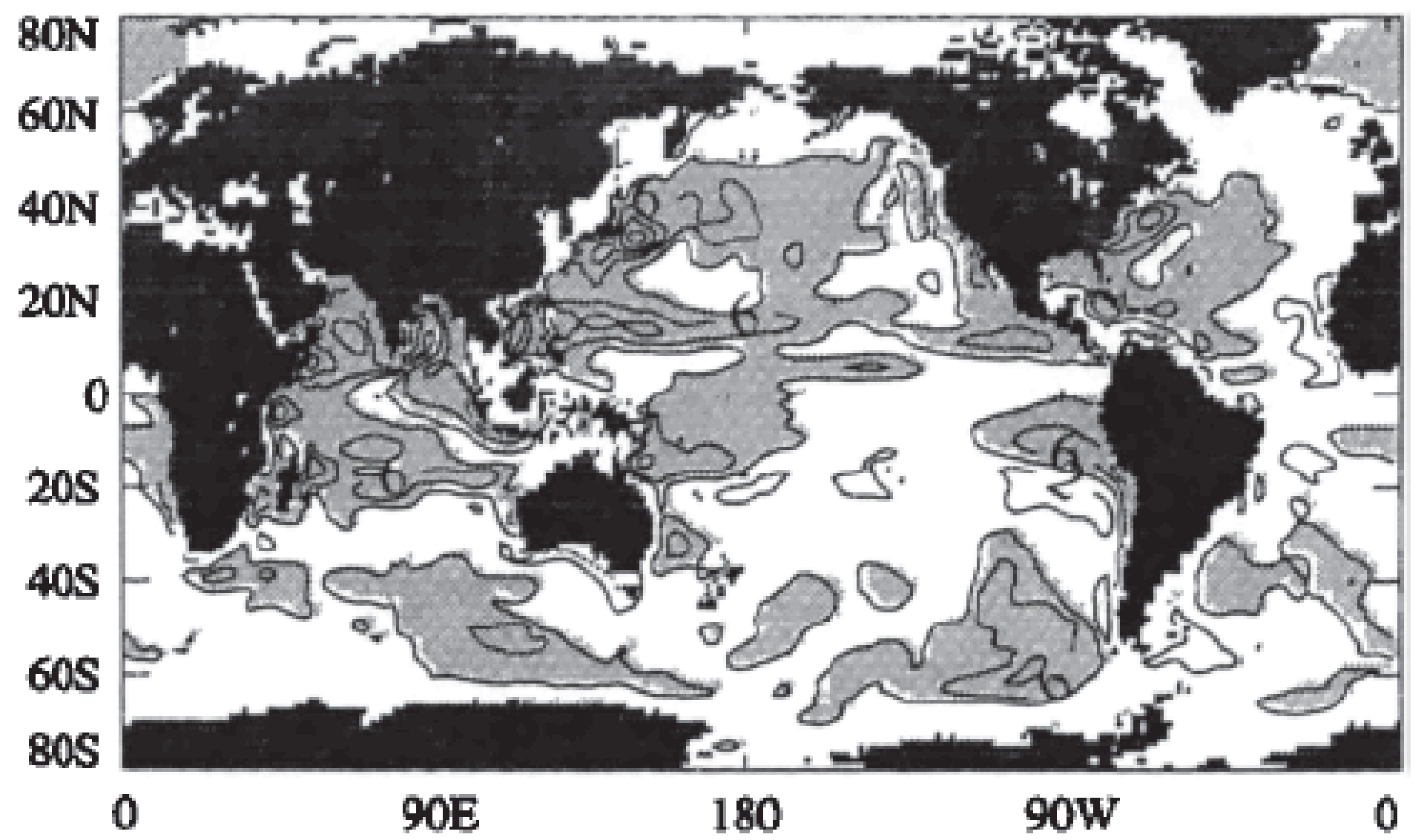


Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

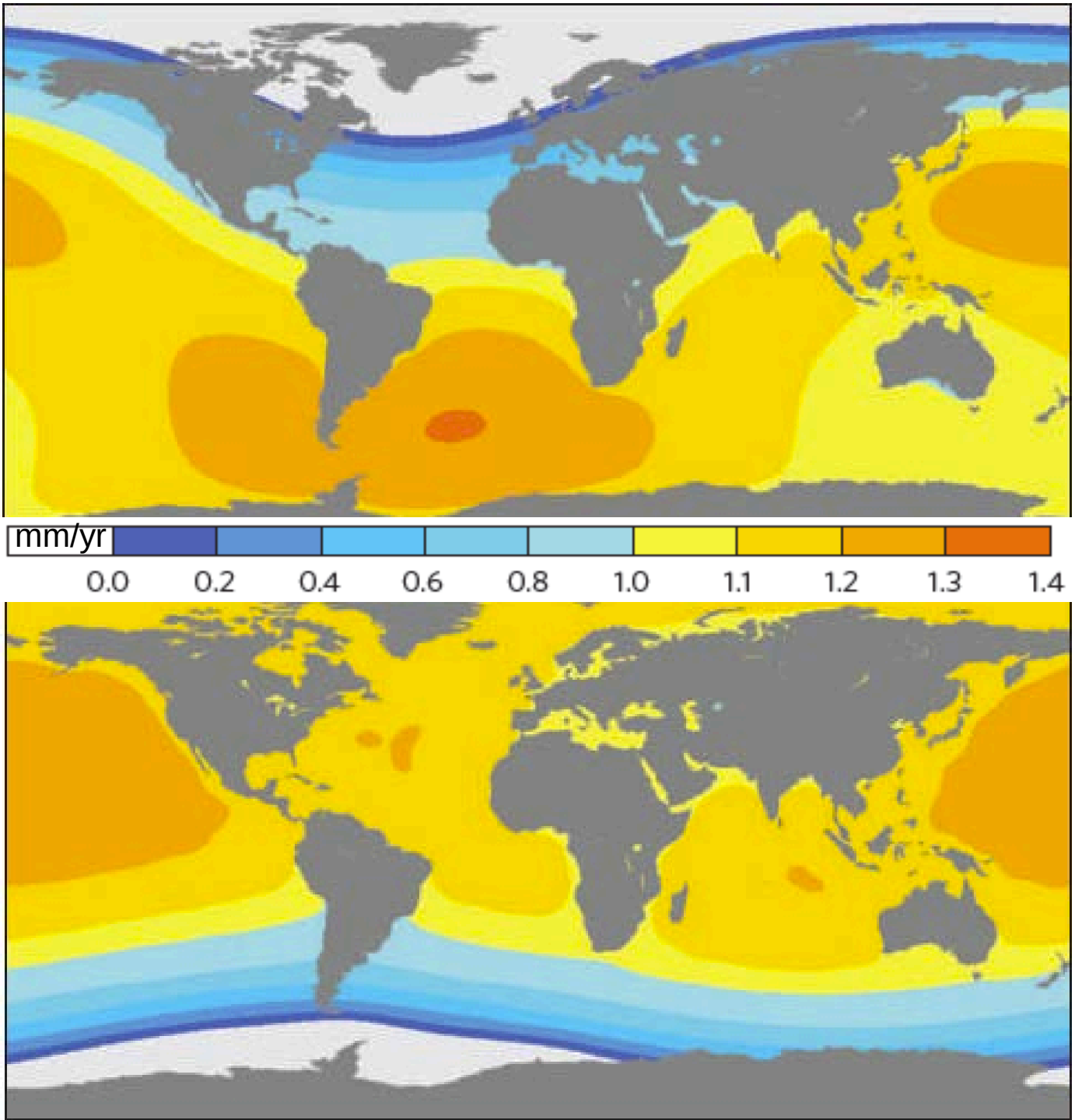
Science, 2014

Ian Joughin, Benjamin E. Smith, Brooke Medley

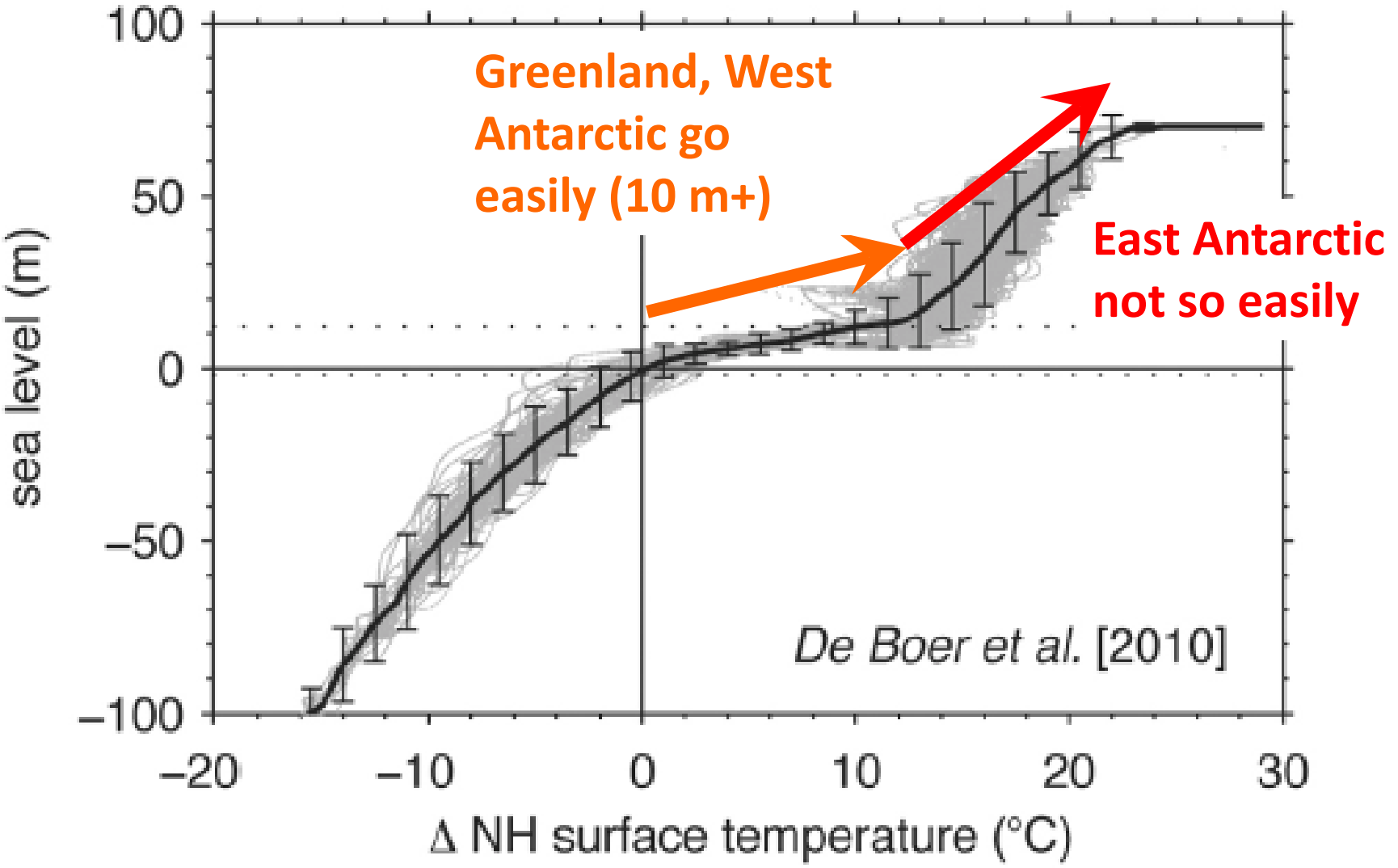
Our simulations provide strong evidence that the process of marine ice-sheet destabilization is already under way on Thwaites Glacier…although losses are likely to be relatively modest over the next century (<0.25 mm/year of sle), rapid collapse (>1 mm/year of sle) will ensue once the grounding line reaches the basin's deeper regions …undermining much of West Antarctica…unless CDW recedes sufficiently to reduce melt well below present levels, it is difficult to foresee a stabilization of the Thwaites system, even with plausible increases in surface accumulation. Although our simple melt parameterization suggests that a full-scale collapse of this sector may be inevitable, it leaves large uncertainty in the timing.



Sea-level variability (RMS, cm) (modeled with MOM 1.0, 2^{o} longitude, 1^{o} latitude (2 cm contours, >4 cm shaded) 12-hour, Fukumori et al., JGR, 1998

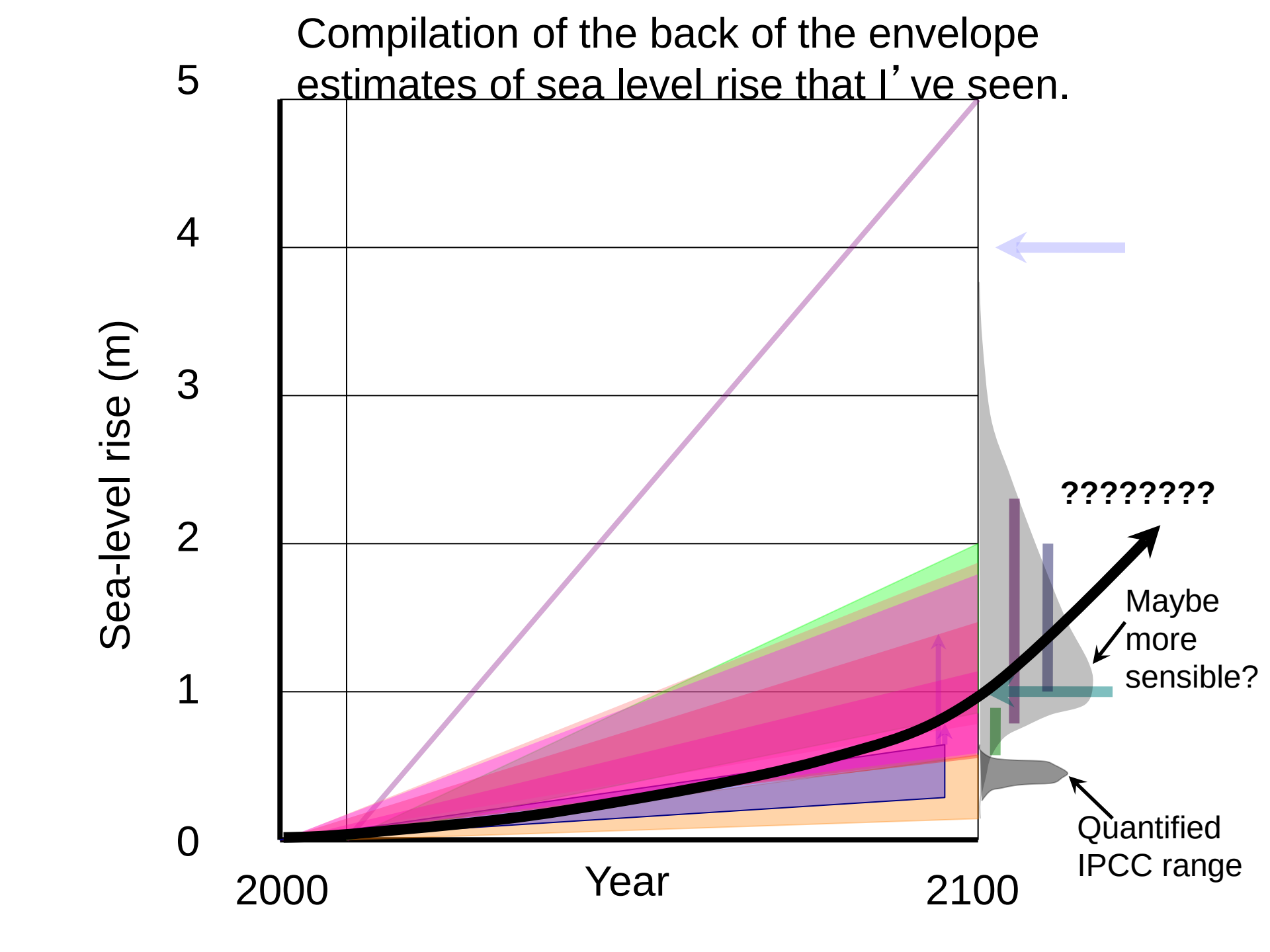


Sea-level rise from Greenland (top) or West Antarctic melt (bottom) at global average 1 mm/yr. Because gravity of an ice sheet attracts ocean water, melting raises sea level more farther away as the attraction shrinks. Most of US 0.6-1x Greenl., 1.1-1.2x WAIS Milne+ 2009 NatGeo



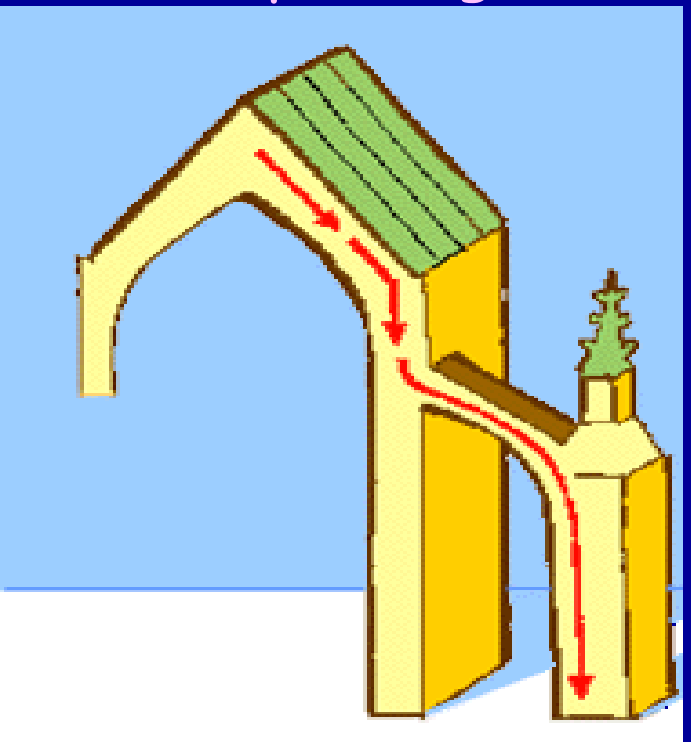
There are less-alarming versions of this curve…
But even those alarm some people.

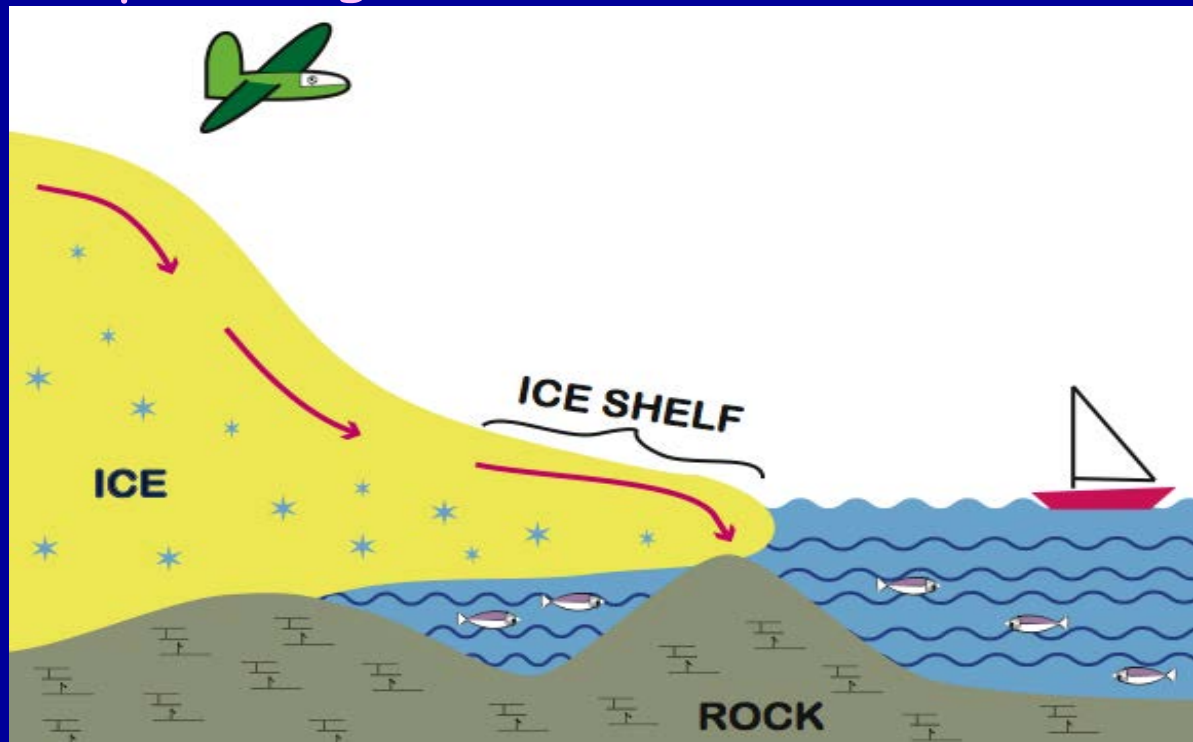
Gasson, E., M. Siddall, D. J. Lunt, O. J. L. Rackham, C. H. Lear, and D. Pollard (2012), Exploring uncertainties in the relationship between temperature, ice volume, and sea level over the past 50 million years, Rev. Geophys., 50, RG1005,Doi 10.1029/2011RG000358.

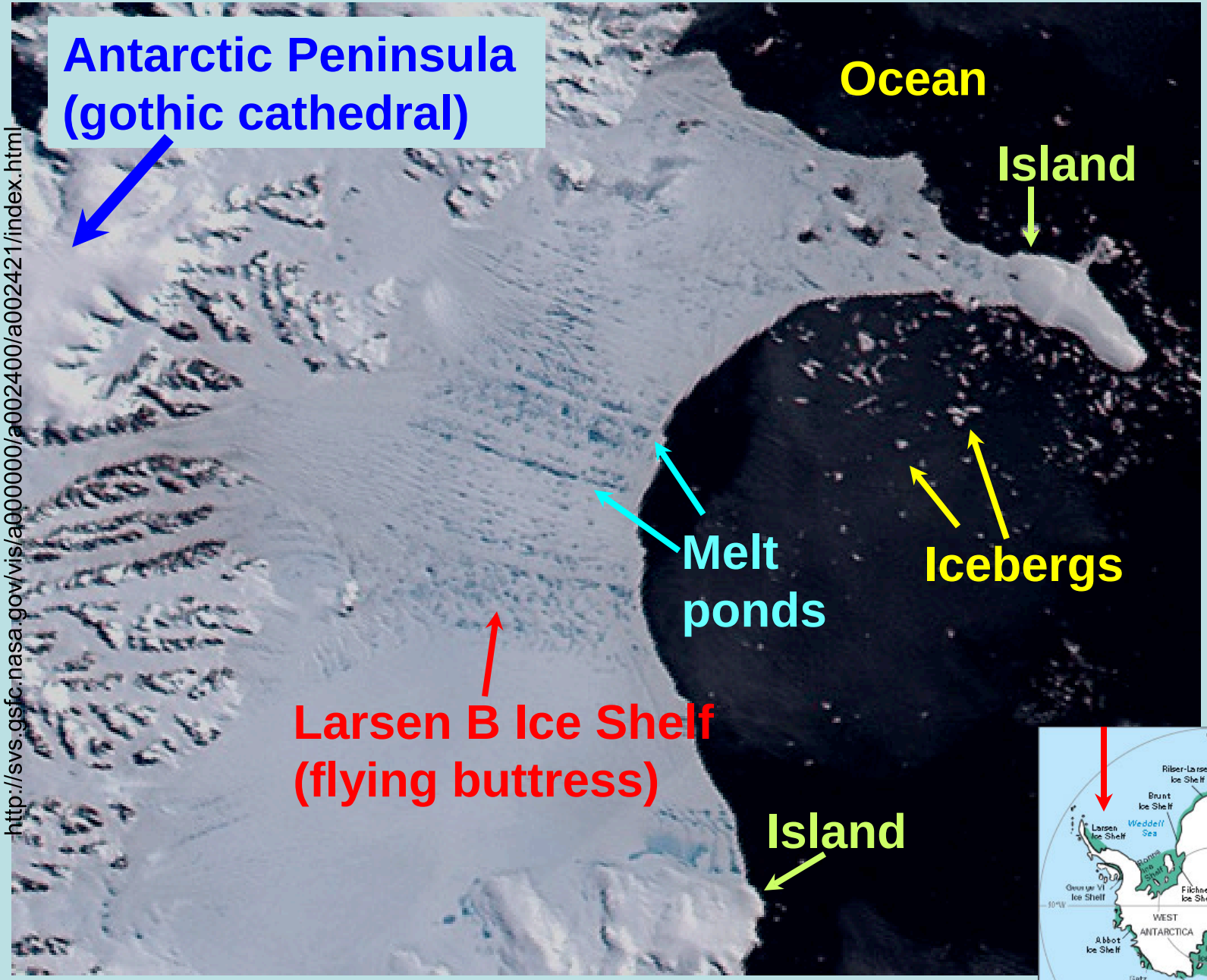

Compilation of the back of the envelope estimates of sea level rise that I've seen.
Sea-level rise (m)
0
1
2
3
4
5
2000
Year
2100
????????
Maybe more sensible?
Quantified IPCC range

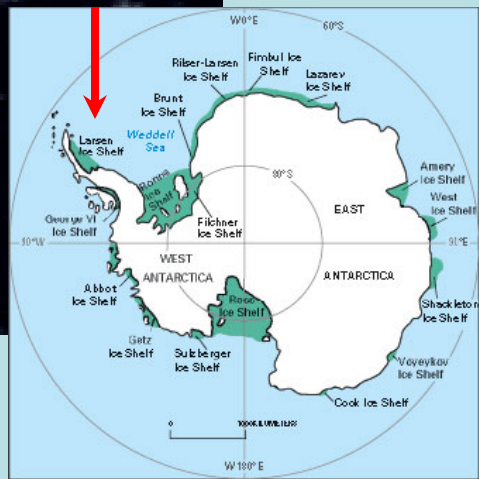
Ice sheets have "flying buttresses", too

- 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.





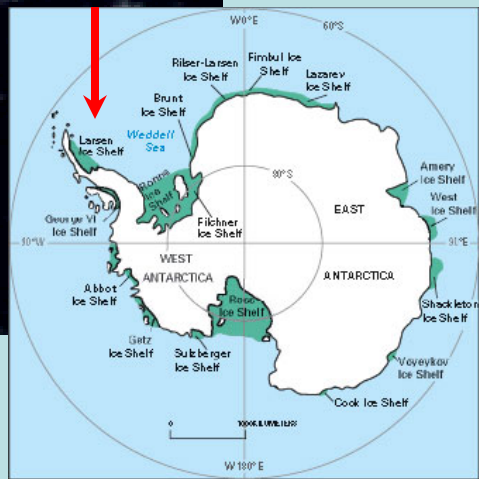




January 31, 2002

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

12 mi
20 km



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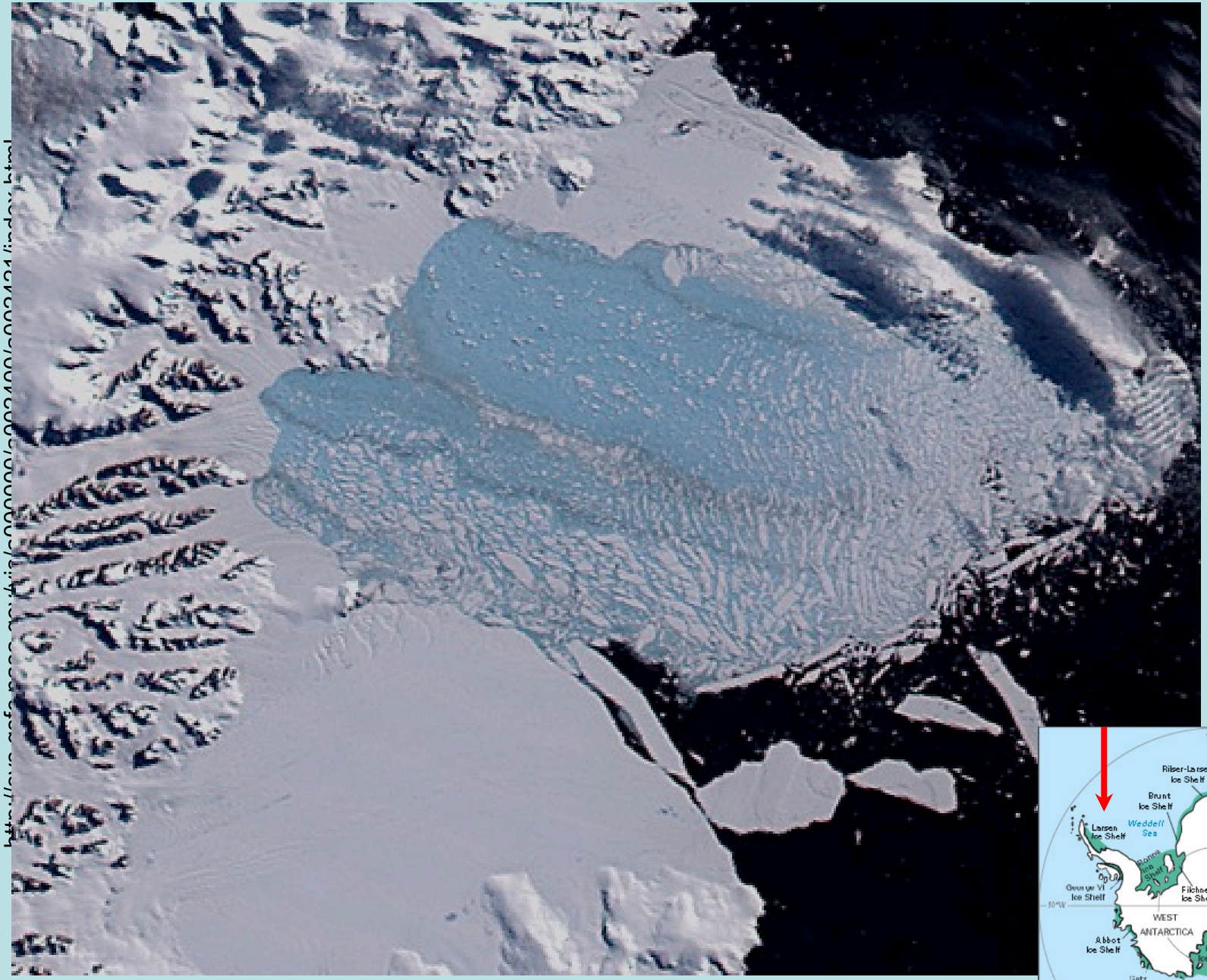
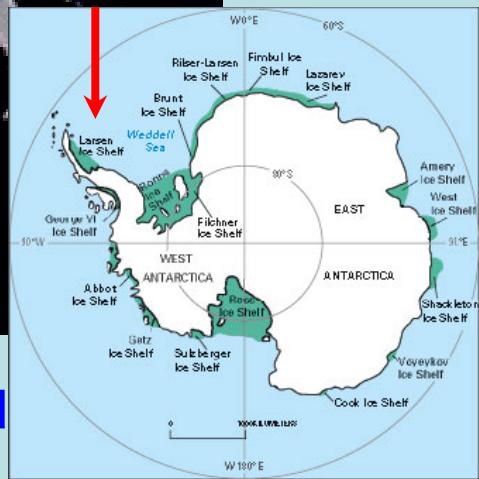
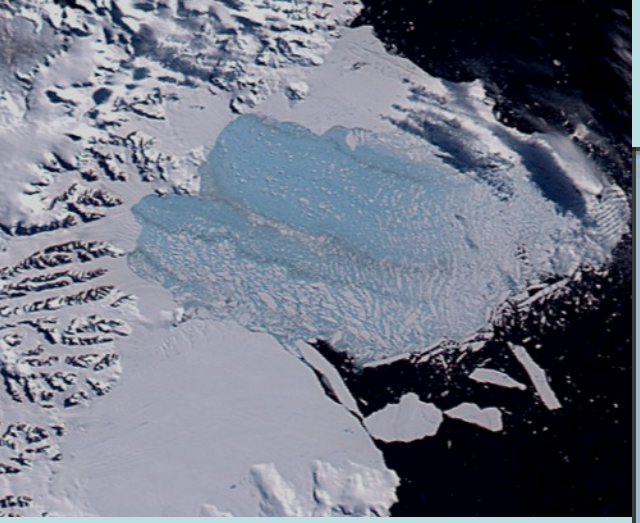


12 mi
20 km

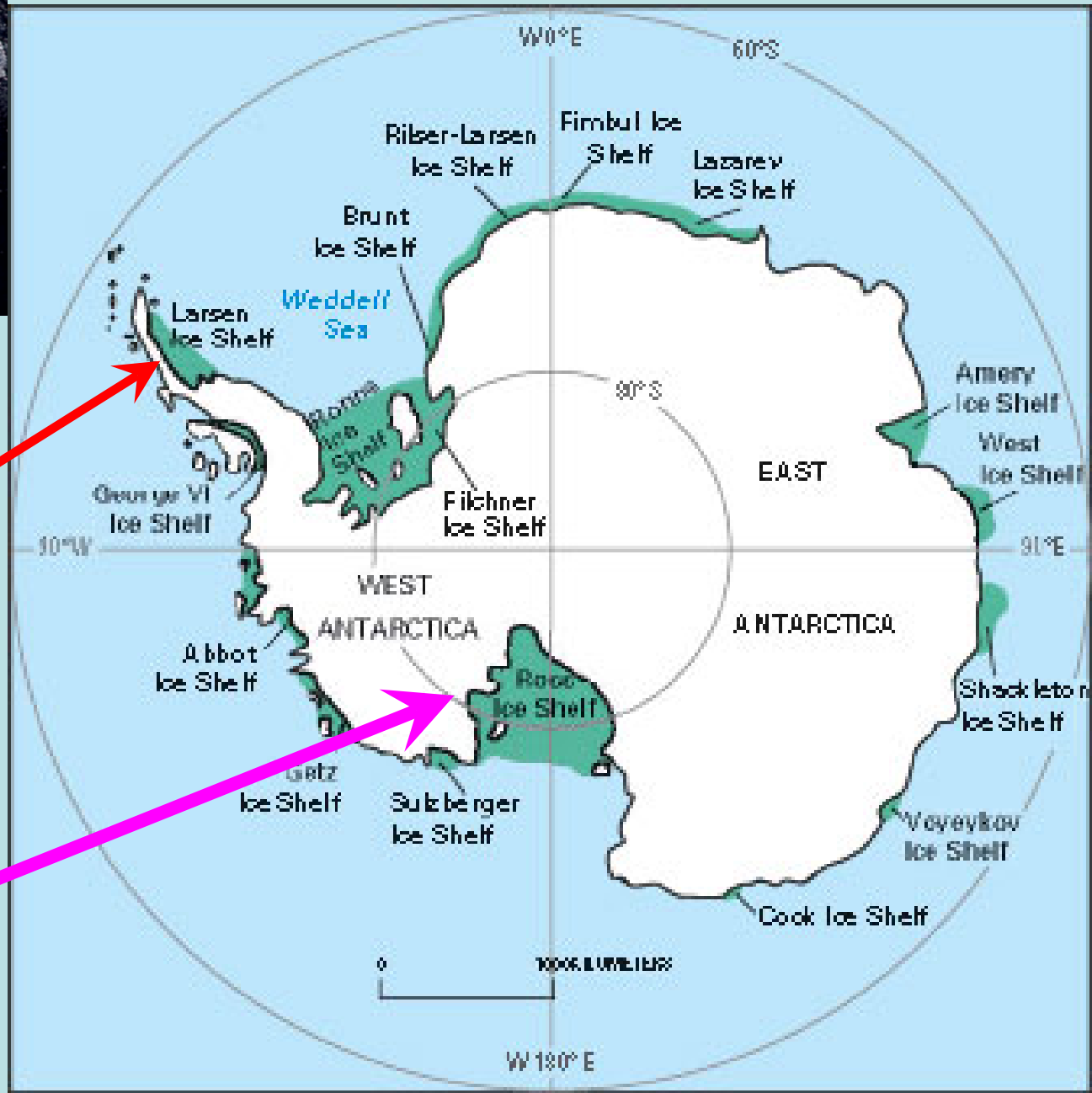


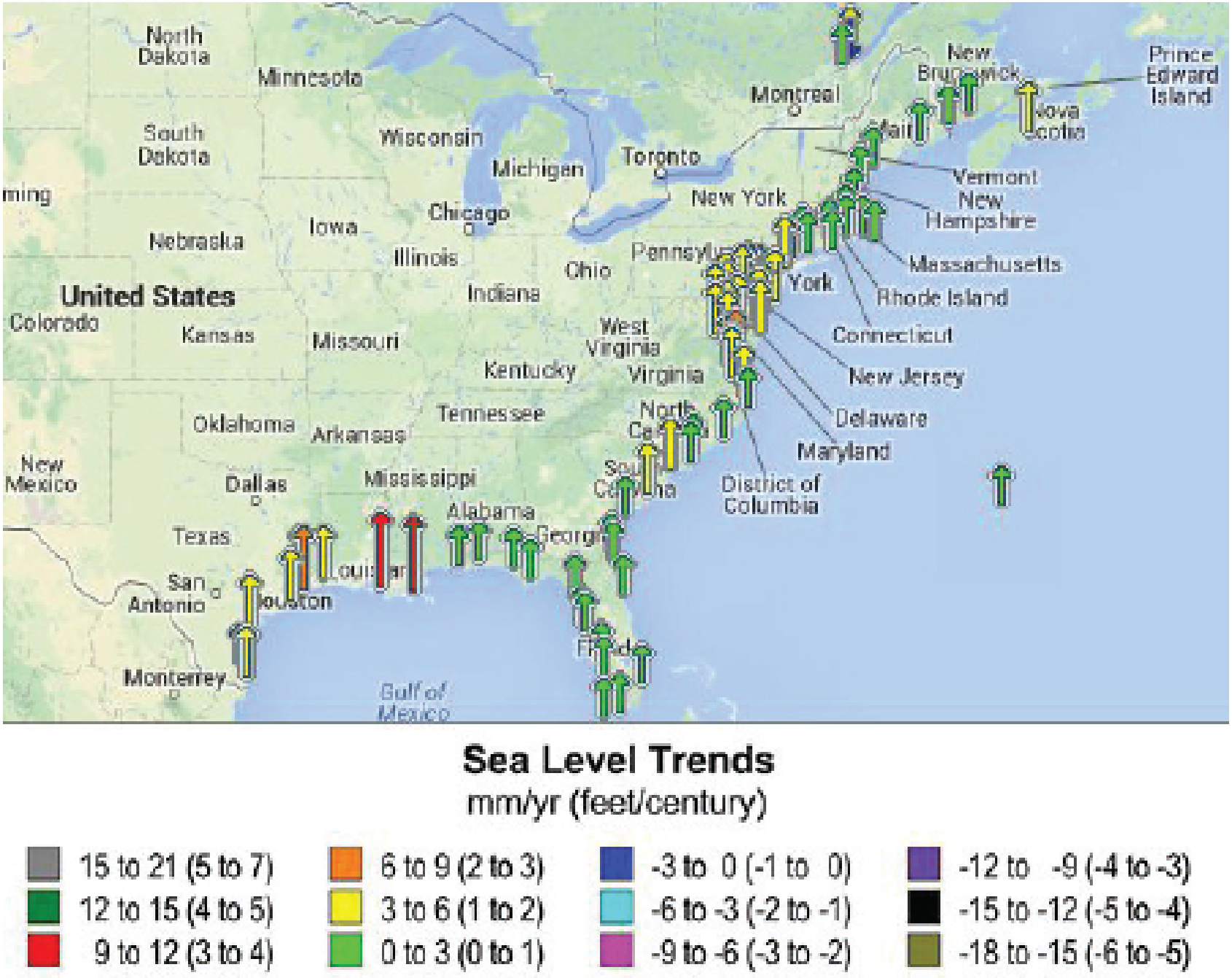
March 7, 2002. **8x tributary flow-speed increase followed**



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.





https://www.nap.edu/read/18811/chapter/3#17

FIGURE 1-2 Rates of relative sea level rise (mm/yr [ft/century])