Sea Level Rise Reference
Bruce Parker
September 21, 2017
http://ccdatacenter.org/documents/Sea Level Rise.pdf

Background

A recent article in Nature, "Contribution of Antarctica to past and future sea-level rise" (see review just below and Page 10 below) projects that the global sea level could rise this century could be more than a meter just from the melting of the West Antarctica sheet, and that the sea level rise by the middle of the next century could be more than a foot per decade (about 100 times what it is today). Although the timing of the seal level rise is far from certain, there appears to be growing consensus that sea level rise could be catastrophic for many coastal communities before 2100. And given the record-setting increase in global temperature in the last year, it would seem that prudent planning should take this into account.

Re: "Contribution of Antarctica to past and future sea-level rise"

The West Antarctic ice sheet sits in a sort of deep bowl that extends far below sea level, and if it loses its protective fringes of floating ice, the result is likely to be the formation of vast, sheer cliffs of ice facing the sea. These will be so high they will become unstable in places, Dr. Alley said in an interview, and the warming atmosphere is likely to encourage melting on their surface in the summer that would weaken them further.

The result, Dr. Alley suspected, might be a rapid shrinkage as the unstable cliffs collapsed into the water. Something like this seems to be happening already at several glaciers, including at least two in Greenland, but on a far smaller scale than may be possible in West Antarctica.

When Dr. DeConto and Dr. Pollard, drawing on prior work by J. N. Bassis and C. C. Walker, devised some equations to capture this "ice-cliff instability," their model produced striking results. In contrast to many prior attempts, it suddenly had no difficulty recreating the high sea levels of past warm periods.

They found that West Antarctica, which is already showing disturbing signs of instability, would start to break apart by the 2050s.

Vulnerable parts of the higher, colder ice sheet of East Antarctica would eventually fall apart, too, and the result by the year 2500 would be 43 feet of sea level rise from Antarctica alone, with still more water coming from elsewhere, the computer estimated. In some areas, the shoreline would be likely to move inland by miles.

The paper published Wednesday does contain some good news. A far more stringent effort to limit emissions of greenhouse gases would stand a fairly good chance of saving West Antarctica from collapse, the scientists found. That aspect of their paper contrasts with other recent studies postulating that a gradual disintegration of West Antarctica may have already become unstoppable.

http://www.nytimes.com/2016/03/31/science/global-warming-antarctica-ice-sheet-sea-level-rise.html Justin Gillis

This "Sea Level Rise Reference" was designed to provide background information on many of the aspects of sea level rise, hence acting as a handy reference. There is far too much information to include in such a short document, but the hope is that the most important aspects of sea level rise have been covered.

Because of the serious consequences of the likely sea level rise, it would be very helpful to have the following (and some of this might already be available):

1. An explanation of the "new findings" – what is it that will cause the sea level to rise so rapidly? (video and "short' description – importance of the "grounding line" and disintegration of "ice cliffs)
2. What are the various glaciers that might contribute to the sea level rise? Who is studying them? How might they collapse? What needs to be measured so that we will have an idea as to how far along the "collapse" is and how much sea level rise they might contribute in the next 10-50 years? Etc.
3. An "index" of scholarly articles on sea level rise (so that a new researcher does not have to find them)
4. An "index" of Web resources for sea level rise
5. A Web page that gives the likely range of expected sea level rise for the next 100 years (something that could be used for planning)

Reference

The sea level is rising for two reasons: as the oceans warm the water expands; and as the Earth's average atmospheric temperature rises land ice melts. Since 1993, global sea level has risen at an accelerating rate of around 3.5 mm/year. More recently the sea level rise has been 4.5 mm/year (see Figure 1).

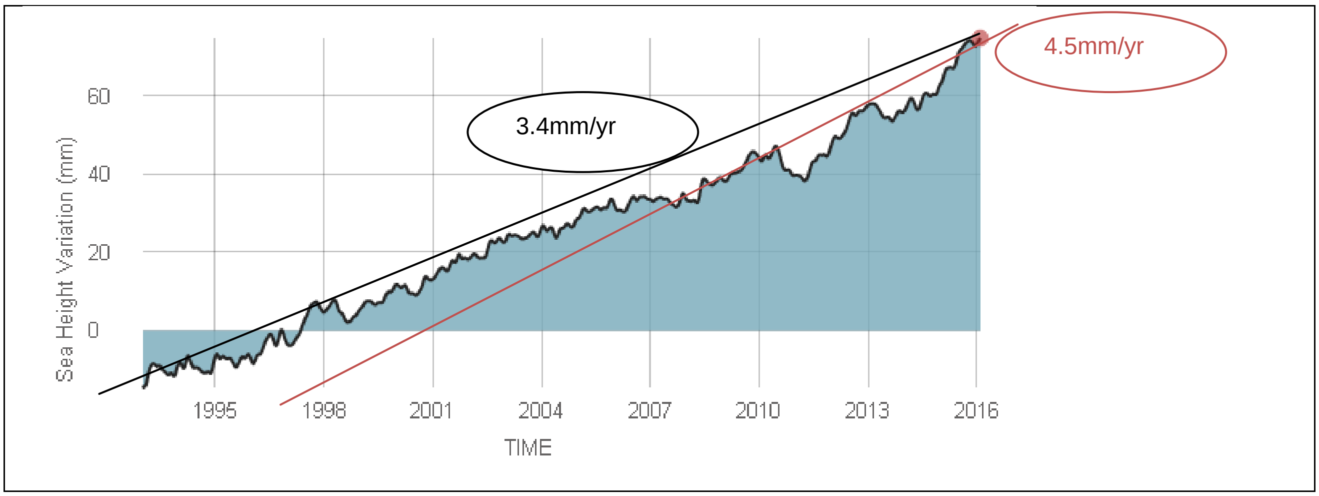
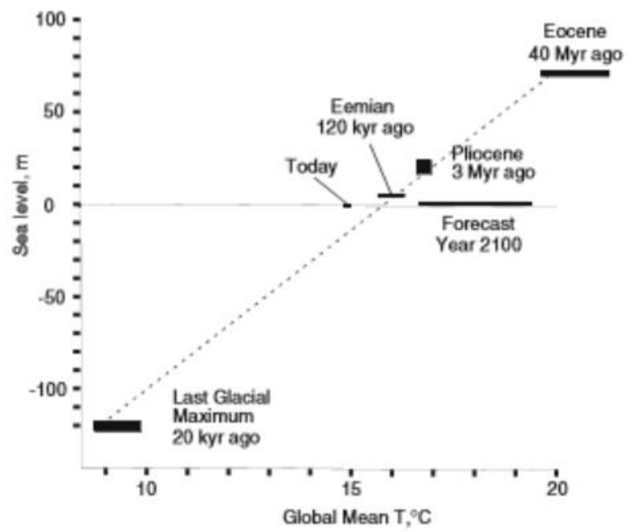


Figure 1 – Recent Sea Level Rise (http://climate.nasa.gov/vital-signs/sea-level/)

About 40 million years ago (during the Eocene), there were no significant glaciers on the Earth, so it seems reasonable to assume that if the Earth became as warm again as is was 40 million years ago (about 5° C warmer than today, or 6° C warmer than pre-industrial times – see figure 2) that all of the glaciers would eventually melt, raising sea levels about 70 meters (220 feet). So *on average* we should expect (and plan for) about 12 meters (40 feet) of sea level rise per degree C of warming (see Appendix A for additional information). With the Earth's average temperature increase already at about 1.25° C (and likely to reach at least 2° C this century), the future sea level will very likely be at least 20 meters (65 feet). Since even one meter of sea level rise is considered to be catastrophic, the relevant questions for planning for future sea level rise are (1) what can learn from paleoclimate sea levels?; (2) how fast is the sea level likely to rise?; and (3) what will be the impact on the expected rise of we can significantly reduce greenhouse gas emissions?



(Figure 3 in "The millennial atmospheric lifetime of anthropogenic CO2" by David Archer & Victor Brovkin - Climatic Change (2008) 90:283–297; https://geosci.uchicago.edu/~archer/reprints/archer.2008.tail_implications.pdf)

There is a clear and strong correlation between long-term global average temperature and sea level in the geologic record. Sea level has the potential to change much more than is forecast for the coming century, and it has done so in the past. The slope of covariation from the geologic record has been 10–20 m/°C. (*Horizontal axis is atmospheric temperture in degrees C)*

Figure 2 "The relationship between sea level and temperature on geologic time scales. Data from (Alley et al. 2005)"

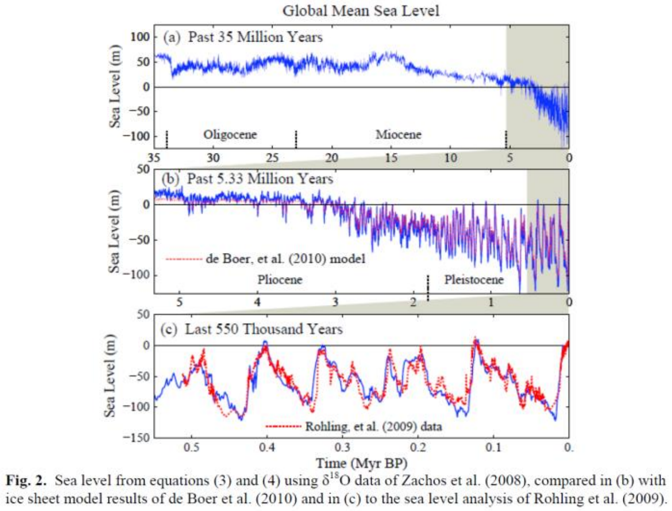
What can learn from paleoclimate sea levels?

The following table specifies the sea level relative to today for several time periods in the past.

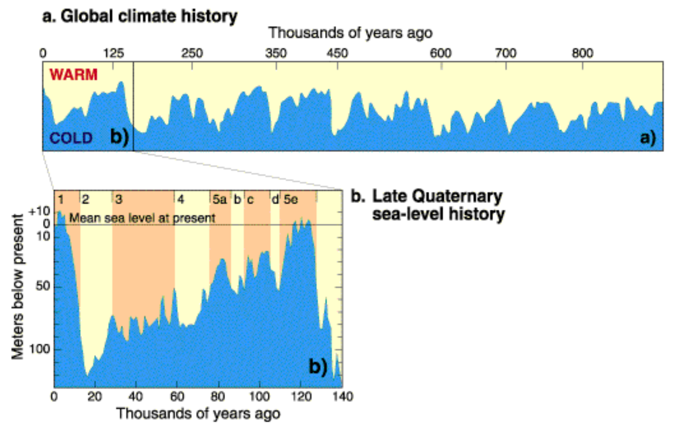
Years before present	Geologic Era/epoch	CO2	Temp relative to 1870 (pre-industrial)	Notes	Sea Level relative to today
54-34 million	Eocene	Thousands - 760PPM	6-14° C warmer	Antarctic ice free	70 meters higher
34 million	End of Eocene	760PPM	6-8° C warmer	Antarctic ice free	70 meters higher
34 million	Start of Oligocene	600PPM	4-6° C warmer	Start of Antarctic glaciation	70 meters higher
130,000-115,000	Eemian	300 PPM	2-3° C warmer		4-6 meters higher
18,000	Last Glacial Maximum	180PPM	8° C cooler		130 meters lower

1. Past 35 million years

The sea level has been no higher than about 10 meters over the current level for over 3 million years, and has been below the current level for almost all of that time (see Figure 3).



Climate Sensitivity, Sea Level, and Atmospheric CO2.pdf (James Hansen, Makiko Sato, Gary Russell and Pushker Kharecha)



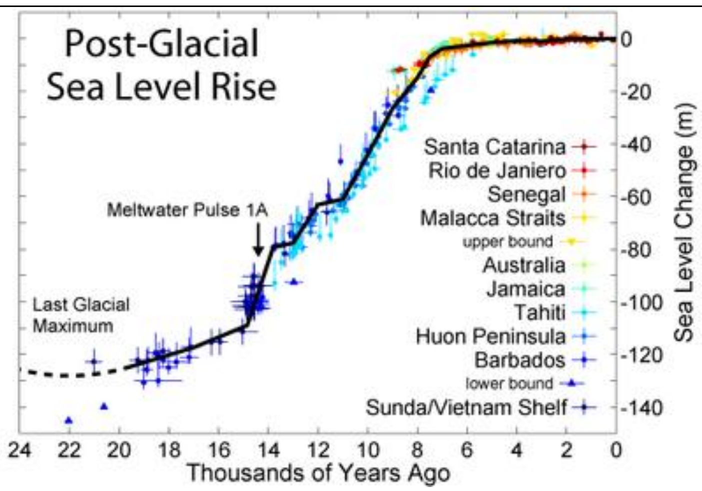
The relative temperature over the past million years and highlights how sea level has changed over the past 140,000 years.

http://www.ncdc.noaa.gov/paleo/ctl/clisci100k.html#sea

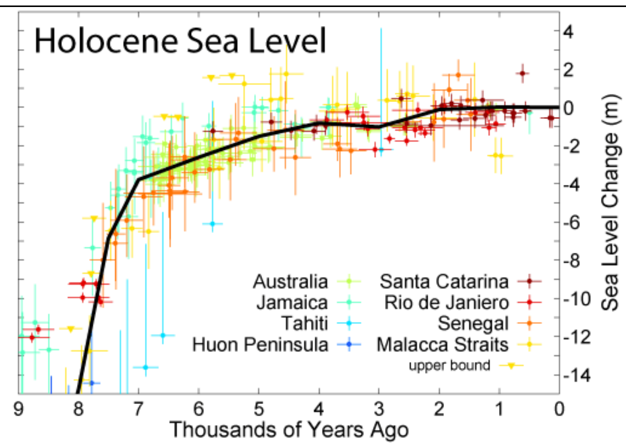
Figure 3 – Paleoclimate Sea Level

1. Past 20,000 years (the end of the last ice age to the present)

Since the end of the last ice age the sea level has risen about 120 meters (see Figure 4A) as the temperature increased about 8 degrees C. So the average sea level rise was about 15 meters (50 feet) per degree C (120/8 = 15). Coming out of the last ice age, the sea level changed an average of about 10 mm/year – about twice the current rate and three times the rate since 1993. There was a lot more ice to melt during that time, but the current temperature is rising about 20 times as fast, and the most of the recent increase has been in the last 40 year (see Table 1).



http://ossfoundation.us/projects/environment/global-warming/myths/images/sea-level/Post-Glacial_Sea_Level.png/view



http://www.globalwarmingart.com/wiki/File:Holocene_Sea_Level_png

Figure 4A – Post-Glacial Sea Level Rise

Figur4B – Holocene Sea Level Rise

Time Period	Description
20,000 -8,000 Years ago	From maximum ice extent in last ice age to about when the seas stopped rising
Last 7,000 years	Starting when the climate and sea level became relatively stable
Last 140 years	When CO2 concentrations began rising (also the first year on the chart for sea level rise)
Last 22 Years (1993-2015)	Reasonably accurate data is available from satellite observations

	20,000 -8,000 Years ago	**Last 7,000 Years to 1850**	**Last 140 years**	**Last 22 Years (1993-2015)**	**If all ice melts**
Sea Level Rise (SLR)	120 meters 400 feet	4 meters	230 mm 9 inches	70 mm 2.76 inches	70 meters 220 feet
Temperature Increase	8° C 14° F	0	1.0° C 1.8° F	0.25° C 0.45° F	6°C 11°F
SLR per degree	15 meters/°C 30 feet/° F	N/A	N/A	N/A	11 meters/°C 20 feet/° F
Average SLR/Year	10 mm .39 inches	0.57 mm 0.02 inches	1.8 mm 0.07 inches	3.38 mm 0.133 inches	
Temp increase/ 100 years	0.075 °C 0.135 ° F	-0.1 °C	0.71° C 1.28° F	1.5° C 2.7° F	
CO2 Concentration Change	100 PPM (180-280) (55% increase)	20 PPM (260-280)	125 PPM (275-400) (45% increase)	43 PPM (357-400)	
CO2 Average change/100 years	< 1 PPM < 1%	.29 PPM	90 PPM 32%	195 PPM 55%	

Table 1 – Selected Climate Parameters

2. *The prior interglacial period, the Eemian (about 115,000 - 130,000 years ago)*

The prior interglacial period, the Eemian, was at most ~2°C warmer than 1880–1920 (Fig. 3). Sea level reached heights several meters above today's level [78]–[80], probably with instances of sea level change of the order of 1 m/century [81]–[83]. Geologic shoreline evidence has been interpreted as indicating a rapid sea level rise of a few meters late in the Eemian to a peak about 9 meters above present, suggesting the possibility that a critical stability threshold was crossed that caused polar ice sheet collapse [84]–[85], although there remains debate within the research community about this specific history and interpretation. The large Eemian sea level excursions imply that substantial ice sheet melting occurred when the world was little warmer than today.

http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0081648

http://phys.org/news/2012-06-climate-cold-arctic-eemian.html

> The oceanic circulation in the north was reduced, and winter sea ice was more likely to form because of lower salinity. At the same time, this situation led to a kind of 'overheating' in the North Atlantic due to a continuing transfer of ocean heat from the south."

North Atlantic Ocean circulation was different in the Eemian – not as much heat transferred north, so the Arctic did not warm as much relative to the rest of the planet, so Greenland likely did not melt as much as it would with similar temperatures today, so the sea levels of "4 to 6m (13 to 20 feet) higher than today" are likely a lower bound and will likely be much higher for a similar temperature increase.

Atmospheric CO2 concentrations were about 300PPM during the Eemian, with temperatures a bit higher than today.

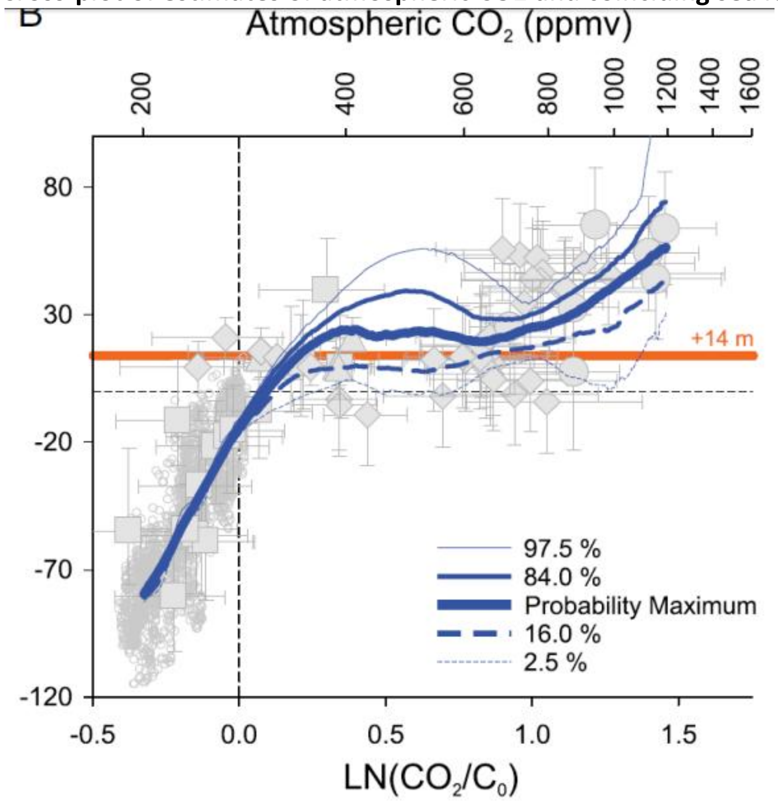
3. Early Pliocene (about 5 million years ago)

During the early Pliocene, which was only ~3°C warmer than the Holocene, sea level attained heights as much as 15–25 meters higher than today

http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0081648

4. Cross-plot of estimates of atmospheric CO2 and coinciding sea level

Cross-plot of estimates of atmospheric CO2 and coinciding sea level



" (B) Results from our probabilistic analysis of the data that fully accounts for uncertainty in both X and Y parameters … dotted lines denote the preindustrial conditions of 0 m and 280 PPM CO2. The horizontal orange line shows +14 m, which is the sea-level rise associated with the total melting of WAIS and GrIS (31). (WAIS= West Antarctic Ice Sheet, GrIS=Greenland Ice Sheet) Source: "Relationship between sea level and climate forcing by CO2 on geological timescales", Gavin L. Foster and Eelco J. Rohling, Sept 2012 – *(Vertical axis is meters of sea level rise)*

http://www.pnas.org/content/110/4/1209.figures-only

Figure 5.

How fast is the sea level likely to rise?

The National Climate Assessment has an excellent explanation of the expected sea level this century (see "*1. National Climate Assessment"* below*)*, which states that sea level will likely be between 1 and 4 feet (and could be more). This is a very large range, and while one foot would be "tolerable", four feet would be "catastrophic". However, combining a more recent study on the Antarctic (see *"7. Contribution of Antarctica to past and future sea-level rise"* below) with the expected sea level rise from thermal expansion and Greenland, scientists predict that sea levels will rise 1.5 to 2.1 meters by the end of the century if we are not able to limit the temperature increase to 2° C.

Based on reasonable expectations for global sea level rise, there is only a five inch difference in 2065 between a one percent annual increase and a four percent annual increase (see "*6. Pace of sea level rise"* below). So for a 50-year planning horizon, it seems to make sense to plan on a global sea level rise of 1.5-2.0 feet. (Note that the sea level rise any any specific region will likely be different due to local subsidence, topography, etc.) But the sea level rise in the following 50 years is apt to be another two to four feet.

A rapid thinning of one or more of the Greenland or Antarctic glaciers will likely be the cause of any significant increase in the rate of sea level rise. In order to provide as much warming as possible, it is critical that scientists measure the flows and topographies of any glacier that is large enough to possibly cause a significant problem (see *"8. Glacier Melt*" below).

1. *National Climate Assessment (from their Web site)*

Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100.

The key issue in predicting future rates of global sea level rise is to understand and predict how ice sheets in Greenland and Antarctica will react to a warming climate. Current projections of global sea level rise do not account for the complicated behavior of these giant ice slabs as they interact with the atmosphere, the ocean and the land. Lack of knowledge about the ice sheets and their behavior is the primary reason that projections of global sea level rise includes such a wide range of plausible future conditions.

Early efforts at semi-empirical models suggested much higher rates of sea level rise (as much as 6 feet by 2100)., More recent work suggests that a high end of 3 to 4 feet is more plausible. It is not clear, however, whether these statistical relationships will hold in the future or that they are appropriate in modeling past behavior, thus calling their reliability into question. Some decision-makers may wish to consider a broader range of scenarios such as 8 inches or 6.6 feet by 2100 in the context of risk-based analysis.

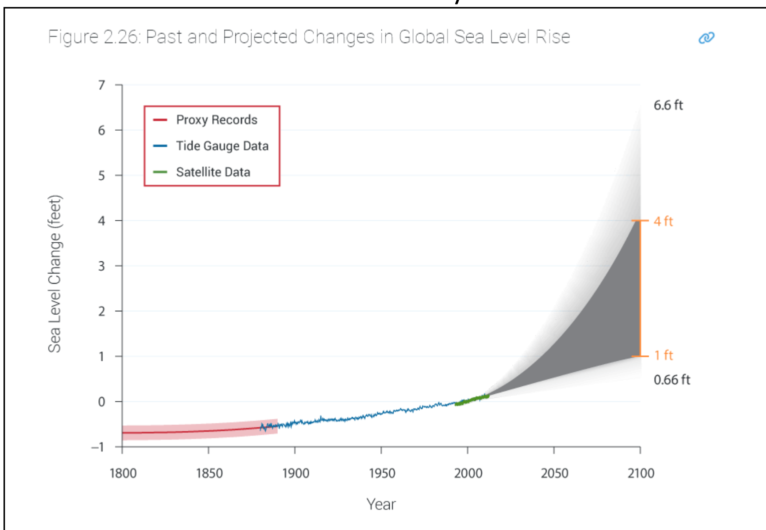
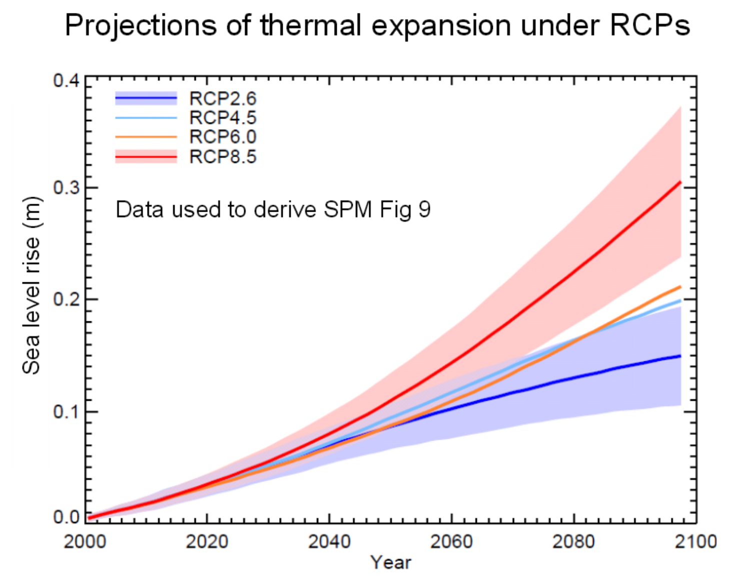


Figure 2.26: Estimated, observed, and possible future amounts of global sea level rise from 1800 to 2100, relative to the year 2000... The future scenarios range from 0.66 feet to 6.6 feet in 2100. These scenarios are not based on climate model simulations, but rather reflect the range of possible scenarios based on other scientific studies. The orange line at right shows the currently projected range of sea level rise of 1 to 4 feet by 2100, which falls within the larger risk-based scenario range. The large projected range reflects uncertainty about how glaciers and ice sheets will react to the warming ocean, the warming atmosphere, and changing winds and currents... (Figure source: Adapted from Parris et al. 2012 with input from NASA Jet Propulsion Laboratory).

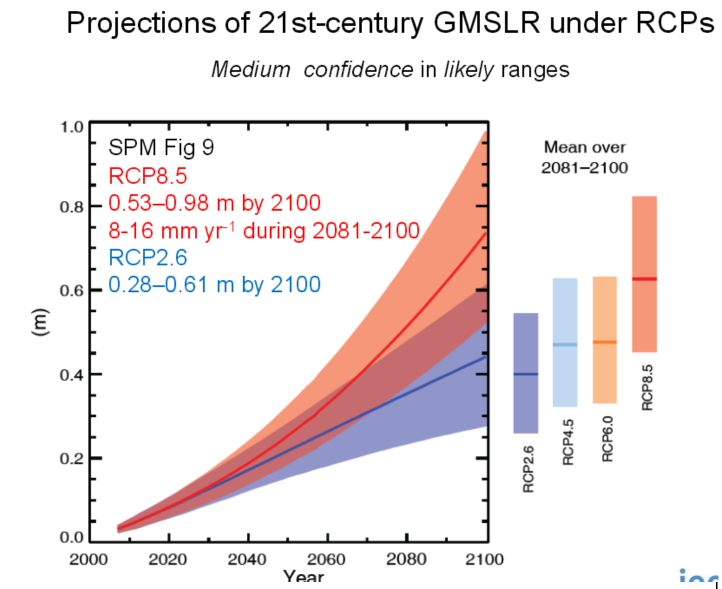
(National Climate Assessment- http://nca2014.globalchange.gov/report/our-changing-climate/sea-level-rise)

Figure 6. Sea Level Rise Estimate (National Climate Assessment)

2. IPCC



(High confidence)



Commitment to sea level rise and irreversibility

It is *virtually certain* that global mean sea level rise will continue for many centuries beyond 2100, with the amount of rise dependent on future emissions.

Medium confidence that GMSL rise by 2300 will be less than 1 m for a radiative forcing corresponding to CO_2 concentrations below 500 ppm (as in RCP2.6), but 1 to more than 3 m for 700–1500 ppm (as in RCP8.5).

Larger sea level rise could result from sustained mass loss by ice sheets, and some part of the mass loss might be irreversible.

Sustained warming greater than a certain threshold above preindustrial would lead to the near-complete loss of the Greenland ice sheet (*high confidence*). The threshold is estimated to be greater than 1°C (*low confidence*) but less than 4°C (*medium confidence*) global mean warming with respect to preindustrial.

Rapid increase in ice sheet outflow

Only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the *likely* range during the 21st century.

Medium confidence that this additional contribution would not exceed several tenths of a metre.

Current evidence and understanding do not allow a quantification of either the timing of its onset or of the magnitude of its multi-century contribution.

https://www.ipcc.ch/pdf/unfccc/cop19/3_gregory13sbsta.pdf
(see also https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter13_FINAL.pdf)

Figure 7 – Sea Level Rise Estimate (IPCC)

Note: The IPCC itself does not do any climate change studies but relies on studies in the published literature. The estimates above are therefore based on the studies conducted before 2011 and do not reflect the latest thinking on glacier mass loss in Greenland or Antarctica.

3. James Hansen

It has been argued [97]–[98] that continued business-as-usual CO_2 emissions are likely to spur a nonlinear response with multi-meter sea level rise this century. Greenland and Antarctica have been losing mass at rapidly increasing rates during the period of accurate satellite data [23]; the data are suggestive of exponential increase, but the records are too short to be conclusive. The area on Greenland with summer melt has increased markedly, with 97% of Greenland experiencing melt in 2012 [99].

http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0081648
(See also Climate Sensitivity, Sea Level, and Atmospheric CO2 - https://arxiv.org/ftp/arxiv/papers/1211/1211.4846.pdf)

4. West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

In 1978 John Mercer, a US glaciologist, described how, in a warming world, a successive collapse of ice shelves extending down the Antarctic Peninsula might occur. He suggested that this would be a warning sign of a more significant sequence of events to come. The Antarctic Peninsula connects to an area of the Antarctic called West Antarctica, where the massive ice sheet sits on bedrock that is up to 2km below sea level. Mercer's concern was that if the successive collapse reached this far, the pressure of the warmer water at depth would lift the ice sheet, causing water to penetrate deeper and deeper below the ice, reducing friction between the ice and rock, leading to an unstoppable collapse. This would result in a rise in sea levels over time of many metres, as the total volume of ice in West Antarctica is equivalent to a six-metre rise.

http://www.nature.com/nature/journal/v271/n5643/abs/271321a0.html

5. Current sea level rise from Greenland and Antarctica Ice Melt

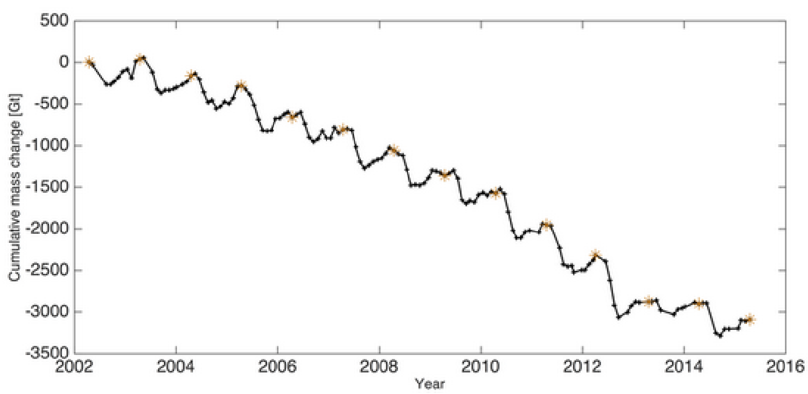


Fig. 3.4. Cumulative change in the total mass (in Gigatonnes, Gt) of the Greenland Ice Sheet between April 2002 and April 2015 estimated from GRACE measurements. Each symbol is an individual month and the orange asterisks denote April values for reference.

If the ice on Greenland continues to melt at the accelerating pace indicated by the graph at the left, the total ice mass loss by 2100 will be about 78,670 GT, raising global sea level by about 0.22 meters. Antarctica is currently contributing about one-third as much to sea level rise.

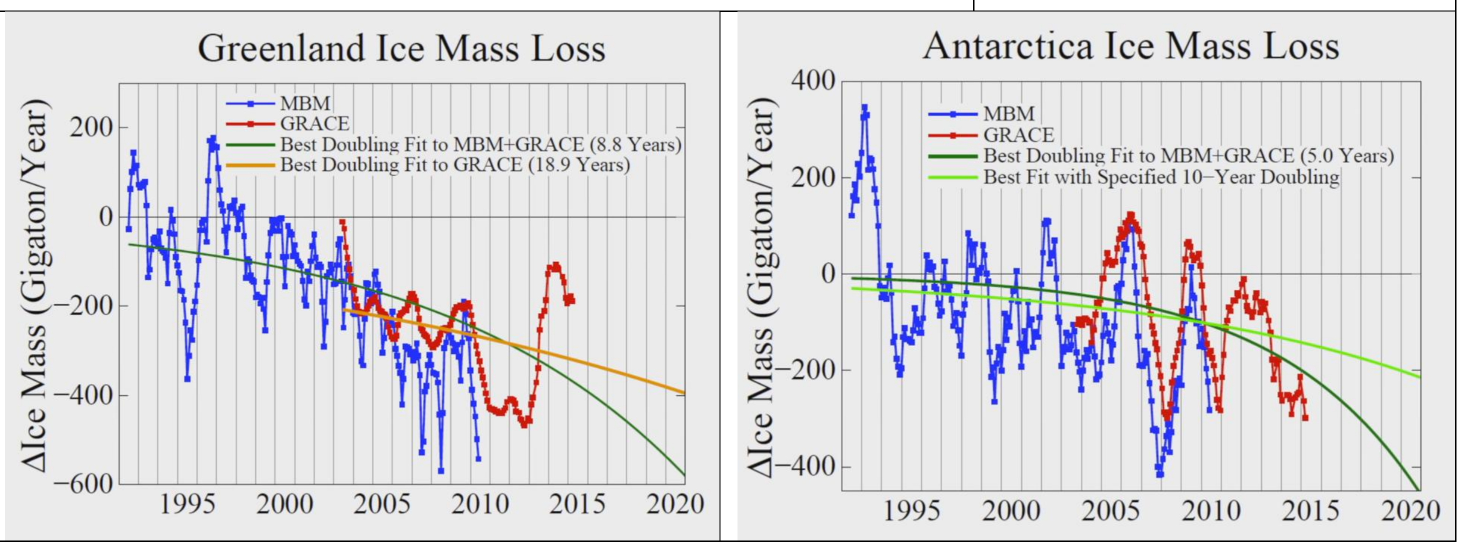
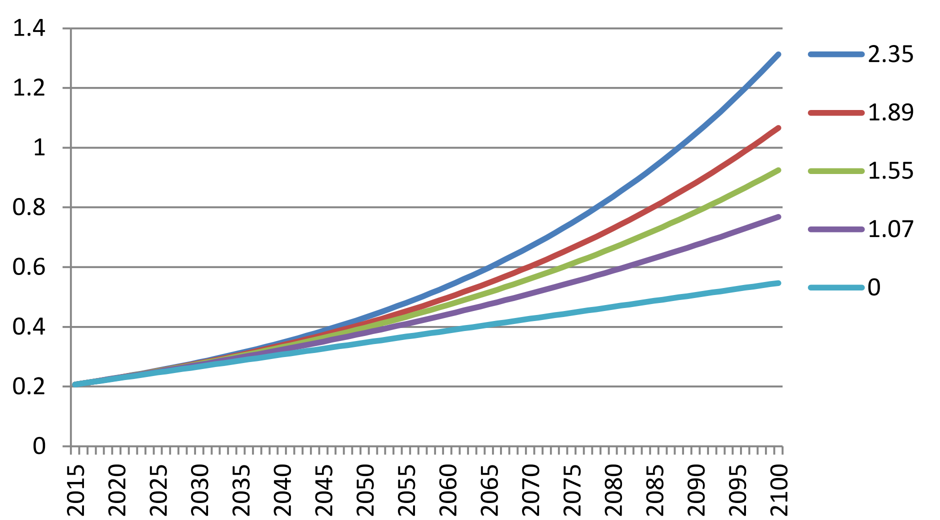


Figure 8 –Ice Mass Loss

6. Pace of sea level rise

The following table and graph provide an indication as to how much the sea level would rise by 2100 if the sea level were rising at the annual rate specified. Note that the sea level rise was about 10 mm/year coming out of the last glacial maximum. If sea levels were to rise at three times that rate then the total sea level rise by 2100 would about four feet and seas would continue to rise at about a foot per decade.

	Sea Level Rise in 2100		Sea Level Rise Per Decade In 2100		Total Sea Level Increase Through 2100	
%Increase/Year	**mm**	**Inches**	**Meters**	**Feet**	**Meters**	**Feet**
0	4.0	0.16	0.0	0.13	0.55	1.67
1.07	10.0	0.39	0.1	0.33	0.77	2.34
1.55	15.0	0.59	0.2	0.49	0.02	2.82
1.89	20.0	0.79	0.2	0.66	1.07	3.25
2.35	29.5	1.16	0.3	0.97	1.31	4.00



Total sea level rise (in meters) from pre-industrial times, assuming a 4mm annual increase in 2015 and the specified per cent increase per year through 2100. (For a 1.07 percent increase, the global SLR would be 1.24 feet in 2050 and 1.56 feet in 2065; for a 2.35 percent increase, the global SLR would be 1.41 feet in 2050 and 1.96 feet in 2065)

7. Contribution of Antarctica to past and future sea-level rise

Contribution of Antarctica to past and future sea-level rise

Robert M. DeConto & David Pollard
http://www.nature.com/nature/journal/v531/n7596/full/nature17145.html
Nature 531 30 March 2016
Polar temperatures over the last several million years have, at times, been slightly warmer than today, yet global mean sea level has been 6-9 metres higher as recently as the Last Interglacial (130,000 to 115,000 years ago) and possibly higher during the Pliocene epoch (about three million years ago). In both cases the Antarctic ice sheet has been implicated as the primary contributor, hinting at its future vulnerability. Here we use a model coupling ice sheet and climate dynamics - including previously underappreciated processes linking atmospheric warming with hydrofracturing of buttressing ice shelves and structural collapse of marine-terminating ice cliffs - that is calibrated against Pliocene and Last Interglacial sea-level estimates and applied to future greenhouse gas emission scenarios. Antarctica has the potential to contribute more than a metre of sea-level rise by 2100 and more than 15 metres by 2500, if emissions continue unabated. In this case atmospheric warming will soon become the dominant driver of ice loss, but prolonged ocean warming will delay its recovery for thousands of years.

Sea levels could rise twice as fast as previously predicted

Science News: Vol. 189, No. 9, April 30, 2016, p. 13

Antarctica's meltdown could spur sea level rise well beyond current predictions. A new simulation of the continent's thawing ice suggests that Antarctic melting alone will raise global sea levels by about 64 to 114 centimeters by 2100, scientists report in the March 31 *Nature*.

Adding Antarctic melt to other sources of sea level rise, such as the expansion of warming seawater and melting Greenland ice, the scientists predict that sea levels will rise 1.5 to 2.1 meters by the end of the century. That's as much as double previous predictions that didn't incorporate mechanisms that can expedite the Antarctic ice sheet's collapse, though uncertainties remain, says study coauthor David Pollard, a paleoclimatologist at Penn State.

Assuming that society takes no actions to curb greenhouse gas emissions, the simulation predicts that Antarctic melting will accelerate around 2050 as rising temperatures destabilize several keystone glaciers in West Antarctica. After 2100, Antarctica's contribution to sea level rise will exceed 4 centimeters a year — more than 10 times the current rate from all sources.

Such severe sea level rise would reshape most of Earth's coastlines, and the waters would rise even higher as time goes on, Pollard predicts. "Sea levels won't peak until around 3,000 to 4,000 years from now," he says. At that point, Antarctica will have raised global sea levels by about 20 meters.

https://www.sciencenews.org/article/sea-levels-could-rise-twice-fast-previously-predicted

A look at melting ice sheets and the threat to sea levels

April 8, 2016 by William Yardley, Los Angeles Times

The predictions only get worse. In 2007, a United Nations panel of scientists studying the rise of sea level related to climate change predicted that, if nothing was done to reduce greenhouse gas emissions, seas could rise by about 2 feet by 2100. By 2013, the panel had increased its forecast to more than 3 feet, which would put major cities at risk of flooding and storm surge.

Yet all along, the panel emphasized what it did not know. It expressed particular uncertainty about what could happen to the ice sheet in Antarctica. To help fill in the gaps, it invited outside scientists to contribute their own research.

Now the outside research is bearing fruit - and the news is not good.

A new study published in the journal *Nature* painted perhaps the most ominous picture yet. It showed that, by the end of this century, sea levels could rise 6 feet or more - again, if nothing is done to reduce emissions - potentially inundating many coastal areas, submerging nations and remaking maps of the world.

The study focused on one of the most elusive aspects of sea-level science: What will happen to the West Antarctic ice sheet?

Scientists have long believed the ice sheet would melt from climate change and contribute to higher sea levels. But they believed that the melting, and rising sea levels it would cause, could occur over many hundreds or even thousands of years.

The new study, by Robert DeConto, a geoscientist at the University of Massachusetts at Amherst, and David Pollard, a geoscientist at Pennsylvania State University, based its finding on models it developed from studying ancient sea level and temperature changes. The scientists found that drastic sea level rise could happen within a lifetime.

As alarming as the study may have seemed to the public and to policymakers, Benjamin Horton, a coastal geologist at Rutgers University in New Jersey who studies sea level, said it did not surprise many people in his field.

In 2013, Horton led a survey of almost 100 sea level scientists that concluded that seas could rise almost 4 feet by 2100 - higher than the United Nations panel's worst scenario. But within that group, 13 scientists said there was a 17 percent chance that sea levels would rise by 6.6 feet, a figure in line with the study.

Why has it been so hard to predict sea level change?

Predicting changes involves measuring and modeling several different factors that then have to be blended together, Horton said. Those elements include an increase in volume from expansion caused by warming water, the melting of glaciers in places such as Alaska and the melting of ice sheets in places such as Greenland and Antarctica. Measuring sea changes from the first two, he said, is much easier than measuring what the vast ice sheets are doing.

What has helped improved our understanding of how ice sheets melt?

Satellite technology and imagery had made it easier to understand what is happening above and below the West Antarctic ice sheet, Horton said.

"These ice sheets have this double whammy," he said. "They're heated at the surface from air temperature and they're heated at the base from ocean temperatures.

"They retreat and then they become unstable and they retreat even further. They have all these feedback mechanisms that keep on making the situation worse."

The process involves what is known as cliff collapse.

"Ponds of meltwater that form on the ice surface often drain through cracks," the article said. "This can set off a chain reaction that breaks up ice shelves and causes newly exposed ice cliffs to collapse under their own weight."

How much water do the ice sheets hold?

Horton said that the Greenland ice sheet contains enough ice to raise sea levels 6 meters, or more than 20 feet, if they completely melted. Antarctica holds much more ice, enough to raise seas 65 meters, or more than 200 feet. But this extreme scenario could happen only over thousands of years.

What can be done?

Even as the study released this week predicted potential catastrophe, it also emphasized that the West Antarctic ice sheet probably would cause little change in sea level if temperature increases can be held under 2 degrees Celsius. That is a central goal of the climate agreement reached in Paris in December, though it is far from clear that countries will achieve it.

The obvious solution, Horton said, is to move quickly away from burning fossil fuels that contribute to climate change and rapidly expand solar, wind and other renewable forms of energy.

"We have a choice right now," he said. "If we strongly mitigate against greenhouse gases, we can keep the sea level rise to a manageable level. These papers are not all doom and gloom. They are providing a warning and we as a scientific community are trying to stress the urgency on climate change.

"This is a dire warning, a dire prediction, but we can do something about it."

http://phys.org/news/2016-04-ice-sheets-threat-sea.html

The finding: Ice sheets in Antarctica could rapidly melt, causing seas to rise up to four times faster than current projections.

Why it made the list: Most high end sea level rise projections indicate if we continue on our current greenhouse gas emissions path, oceans will rise a little more than 3 feet by 2100. But research published earlier this year by James Hansen, NASA's former chief climate scientist, shows that number could be far too low. Instead, oceans could rise by as much as 16 feet due to the rapid melt of Antarctica.

While the odds of ice sheet collapse, especially in West Antarctica, are increasing, the timeline is still very much under scrutiny, which made these findings highly controversial. They also attracted debate for highlighting results that hadn't yet been through the peer review process. That's because the journal they were published in does public peer review,

putting the results through the independent scientific ringer for all to see. In the months since, it's received dozens of comments (see them all [here](#)) and is still under review by the journal. http://www.climatecentral.org/news/7-most-interesting-climate-findings-2015-19835?

8. Melting Glaciers - Interesting Web links

1.	NASA video of ice melt in Antarctica (2 minutes)	https://www.youtube.com/watch?v=6yLee8jBW0g	
2	With a collapsing West Antarctica, sea level rise may be twice as high as we thought	http://mashable.com/2016/03/31/antarctic-ice-sheet-melt-sea-level/#Z3lzgeCqumqk	March 31, 2016
3	Abrupt Sea Level Rise Looms As Increasingly Realistic Threat	http://e360.yale.edu/feature/abrupt_sea_level_rise_realistic_greenland_antarctica/2990/#.V0raHjFwJ6c.twitter	May 5, 2016
4	Scientists Are Watching in Horror as Ice Collapses (National Geographic)	http://news.nationalgeographic.com/2016/04/160412-ice-sheet-collapse-antarctica-sea-level-rise/	APRIL 12, 2016
5	Climate Model Predicts West Antarctic Ice Sheet Could Melt Rapidly (New York Times)	http://www.nytimes.com/2016/03/31/science/global-warming-antarctica-ice-sheet-sea-level-rise.html	March 30, 2016

9. Melting Glaciers – Journal Articles

We measure the grounding line retreat of glaciers draining the Amundsen Sea sector of West Antarctica using Earth Remote Sensing (ERS-1/2) satellite radar interferometry from 1992 to 2011. Pine Island Glacier retreated 31 km at its center, with most retreat in 2005-2009 when the glacier ungrounded from its ice plain. Thwaites Glacier retreated 14 km along its fast flow core and 1 to 9 km along the sides. Haynes Glacier retreated 10 km along its flanks. Smith/Kohler glaciers retreated the most, 35 km along its ice plain, and its ice shelf pinning points are vanishing. These rapid retreats proceed along regions of retrograde bed elevation mapped at a high spatial resolution using a mass conservation technique that removes residual ambiguities from prior mappings. Upstream of the 2011 grounding line positions, we find no major bed obstacle that would prevent the glaciers from further retreat and draw down the entire basin. © 2014. American Geophysical Union. All Rights Reserved.

A1. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011

The history of deglaciation of the West Antarctic Ice Sheet (WAIS) gives clues about its future. Southward grounding-line migration was dated past three locations in the Ross Sea Embayment. Results indicate that most recession occurred during the middle to late Holocene in the absence of substantial sea level or climate forcing. Current grounding-line retreat may reflect ongoing ice recession that has been under way since the early Holocene. If so, the WAIS could continue to retreat even in the absence of further external forcing.

A2. Past and Future Grounding-Line Retreat of the West Antarctic Ice Sheet

The catastrophic break-ups of the floating Larsen A and B ice shelves (Antarctica) in 1995 and 2002 and associated acceleration of glaciers that flowed into these ice shelves were among the most dramatic glaciological events observed in historical time. This raises a question about the larger West Antarctic ice shelves. Do these shelves, with their much greater glacial discharge, have a history of collapse? Here we describe features from the seafloor in Pine Island Bay, West Antarctica, which we interpret as having been formed during a massive ice shelf break-up and associated grounding line retreat. This evidence exists in the form of seafloor landforms that we argue were produced daily as a consequence of tidally influenced motion of mega-icebergs maintained upright in an iceberg armada produced from the disintegrating ice shelf and retreating grounding line. The break-up occurred prior to ca. 12 ka and was likely a response to rapid sea-level rise or ocean warming at that time.

A3. Geological record of ice shelf break-up and grounding line retreat, Pine Island Bay, West Antarctica

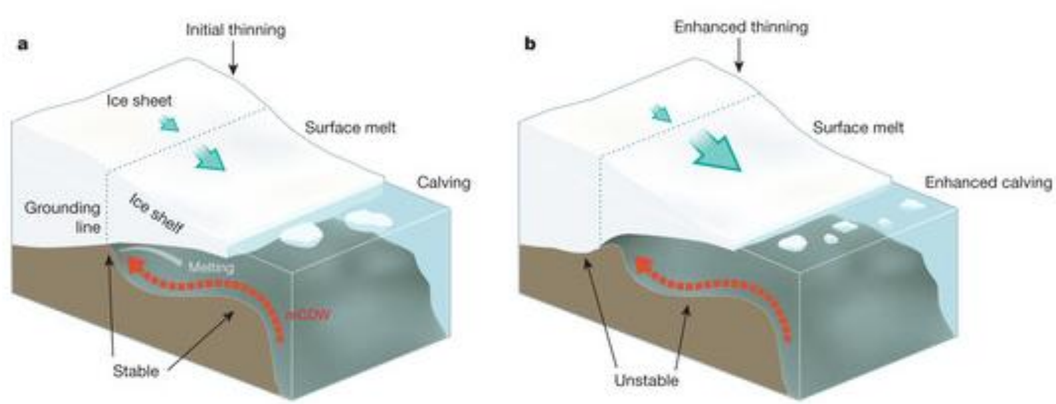
Marine ice sheets, such as the West AIS, rest on bedrock that lies below sea level. These grounded ice sheets are fringed by floating ice shelves. The grounding line is the contact of the ice sheet with the ocean where the ice mass starts to float by buoyancy. Ice from the grounded ice sheet is discharged across the grounding line into ice shelves, from where icebergs break off, through a process called calving (Fig. 3).

The migration of the grounding line is a result of the local balance between the masses of ice and displaced ocean water. The grounding line advances if previously floating ice becomes thick enough to ground, or retreats if previously grounded ice becomes thin enough to float. Theory has demonstrated that in order to simulate grounding-line migration, it is necessary to include (horizontal) stress gradients across the grounding zone[22] and in order to resolve this numerically, a high spatial resolution is needed, either by using a moving grid (following the grounding line directly) or by subsampling the grid around the grounding line to hundreds of metres (ref. 39). This high resolution is necessary to resolve horizontal stress gradients across a narrow boundary layer.

Ice discharge generally increases with increasing ice thickness at the grounding line. For a bed sloping down towards the interior this may lead to unstable grounding-line retreat, as increased flux (for example, due to reduced buttressing) leads to thinning and eventually flotation, which moves the grounding line into deeper water where the ice is thicker. Thicker ice results in increased ice flux, which further thins (and eventually floats) the ice, which results in further retreat into deeper water (and thicker ice), and so on (Fig. 3). This unstable retreat is referred to as the marine ice-sheet instability[22]. However, the grounding line is partially stabilized by the presence of ice shelves, which are either confined laterally through embayments or otherwise stabilized by locally grounded features which they enclose (for example, pinning points). Both geometries transmit a back-force, or 'buttressing', towards the grounded ice sheet, which may help to stabilize the grounding line against unstable retreat down inland-sloping bedrock[100].

Thinning of ice shelves reduces drag at the margins and over pinning points, leading to increased ice flow across the grounding line, causing grounding-line retreat until a new stable point (for example, upward sloping bedrock) is reached. The mechanisms described above rely heavily on a precise knowledge of the geometry of the ice–ocean contact, which explains why neighbouring outlet glaciers, in contact with the ocean, and subject to the same atmospheric and oceanic forcing, may exhibit contrasting behaviours[30].

Figure 3: Illustration of a marine ice sheet and its interaction with the ocean.



a, Warm modified Circumpolar Deep Water (mCDW) leads to melting at the grounding line, leading to ice-shelf thinning, grounding-line retreat, and initial thinning. **b**, Marine ice-sheet instability occurs when, in the absence of buttressi...

A4. Ice-sheet mass balance and climate change

	Journal	Authors	Publication Date	UIRL
1.	Geophysical Research Letters, 41(10)	Rignot, E; Mouginot, J; Morlighem, M; Seroussi, H; Scheuchl, B	05-01-2014	http://escholarship.org/uc/item/0wz826xt
2	*Science*	H. Conway, B. L. Hall, G. H. Denton, A. M. Gades, E. D. Waddington	08-09 1999	http://science.sciencemag.org/content/286/5438/280
3	Geology	Martin Jakobsson, John B. Anderson, Frank O. Nitsche, Julian A. Dowdeswell, Richard Gyllencreutz, Nina Kirchner, Rezwan Mohammad, Matthew O'Regal, Richard B. Alley, Sridhar Anandakrishnan, Björn Eriksson, Alexandra Kirshner, Rodrigo Fernandez, Travis Stolldorf, Rebecca Minzoni and Wojciech Majewski	May 2011	http://geology.gsapubs.org/content/39/7/691.short
4.	Nature	Edward Hanna, Francisco J. Navarro, Frank Pattyn, Catia M. Domingues, Xavier Fettweis, Erik R. Ivins, Robert J. Nicholls, Catherine Ritz, Ben Smith, Slawek Tulaczyk, Pippa L. Whitehouse & H. Jay Zwally	05 June 2013	http://www.nature.com/nature/journal/v498/n7452/full/nature12238.html#f3

10. Melting Glaciers

	Point of No Return	SLR	Time Period		
Antarctica					
Totten	within the next 100 years	more than 6.6 feet (2 meters)	Over the coming several centuries		
Pine Island					
Haynes					
Pope					
Smith					
Kohler					

10. How much could the sea level rise from the total melting of present-day glaciers?

Estimated potential maximum sea-level rise from the total melting of present-day glaciers.

[Modified from Williams and Hall (1993). See also http://pubs.usgs.gov/fs/2005/3055/. km^3, cubic kilometers; m, meters] (http://pubs.usgs.gov/fs/fs2-00/)

Location	Volume (km^3)	Potential sea-level rise, (m)
East Antarctic ice sheet	26,039,200	64.8
West Antarctic ice sheet	3,262,000	8.06
Antarctic Peninsula	227,100	0.46
Greenland	2,620,000	6.55
All other ice caps, ice fields, and valley glaciers	180,000	0.45
Total	32,328,300	80.32