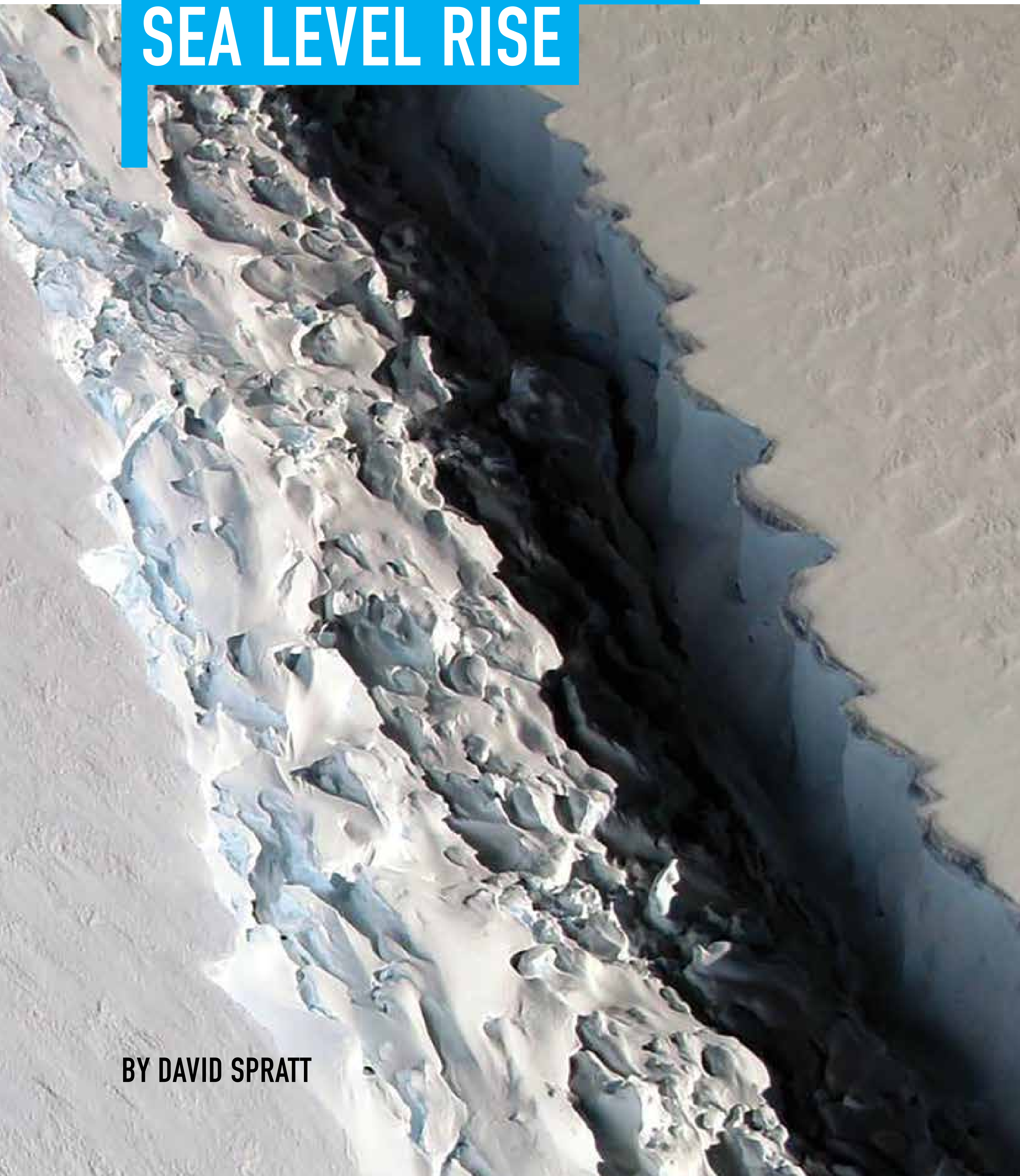
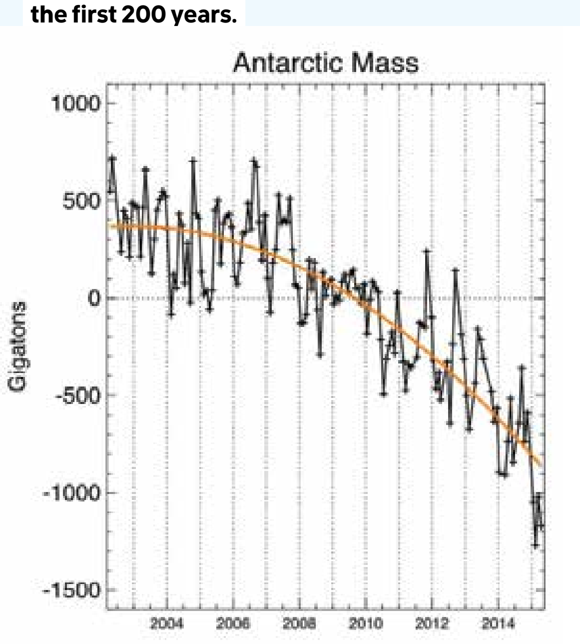
ANTARCTIC TIPPING POINTS FOR A MULTI-METRE SEA LEVEL RISE



BY DAVID SPRATT

OVERVIEW

- **The Amundsen Sea sector of the West Antarctic Ice Sheet has most likely been destabilized and ice retreat is unstoppable for the current conditions.**
- **No further acceleration in climate change is necessary to trigger the collapse of the rest of the West Antarctic Ice Sheet, with loss of a significant fraction on a decadal-to-century time scale.**
- **Antarctica has the potential to contribute more than a metre of sea-level rise by 2100.**
- **A large fraction of West Antarctic basin ice could be gone within two centuries, causing a 3–5 metre sea level rise.**
- **Mechanisms similar to those causing deglaciation in West Antarctica are now also found in East Antarctica.**
- **Partial deglaciation of the East Antarctic ice sheet is likely for the current level of atmospheric carbon dioxide, contributing to 10 metres or more of sea level rise in the longer run, and 5 metres in the first 200 years.**



Antarctic ice mass 2002-2016, measured from NASA's Gravity Recovery and Climate Experiment (GRACE) satellites

FRONT COVER Rift in Antarctica's Larsen C Ice Shelf, photographed 10 November 2016 (NASA/John Sonntag)

INTRODUCTION

THE WEST ANTARCTIC Ice Sheet (WAIS), comprising more than two million cubic kilometres of ice, is under pressure from a warming climate, with scientists saying its break-up—and an eventual global sea-level rise of 3–5 metres—is not matter of if, but when.

The West Antarctic Peninsula is now the strongest-warming region on the planet, and WAIS glaciers are discharging ice at an accelerating rate.

Recent studies, surveyed in this report, suggest that WAIS passed a tipping point for large-scale deglaciation decades ago.

This should not be surprising, because such an event was foreseen almost 50 years ago. In 1968, pioneer glacier researcher John Mercer predicted that the collapse of ice shelves along the Antarctic Peninsula could herald the loss of the ice sheet. Ten years later, Mercer contended that "a major disaster—a rapid deglaciation of West Antarctica—may be in progress ... within about 50 years".

He said that warming "above a critical level would remove all ice shelves, and consequently all ice grounded below sea level, resulting in the deglaciation of most of West Antarctica". Such disintegration, once under way, would "probably be rapid, perhaps catastrophically so", with most of the ice sheet lost in a century. Credited with coining the phrase "the greenhouse effect" in the early 1960s, Mercer's Antarctic prognosis was widely ignored and disparaged at the time. Now in seems uncannily prescient.

Climate author Fred Pearce (in his 2007 book **"With Speed and Violence"** [4]) quotes the leading cryosphere scientist Richard Alley as saying a decade ago that there is "a possibility that the West Antarctic ice sheet could collapse and raise sea levels by 6 yards [5.5 metres]" this century. Pearce also interviewed NASA glaciologist Eric Rignot who has studied the Pine Island glacier in West Antarctica for decades, and concluded that "the glacier is primed for runaway destruction".

Although the much larger East Antarctic Ice Sheet (EAIS)—with potential for a 50-metre sea-level rise if all ice were lost—has generally been considered more stable than WAIS, recent evidence suggests some outlet glaciers there are displaying similar dynamics to those on West Antarctica.

- Rignot, Velicogna at al (2011) "**Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise**"[1], GRL 38: L05503-7
- Mouginot, Rignot and Scheuchl (2014) "**Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013**" [2], GRL 41:1576-1584).

- "**West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster**" [3], Nature 271:321-325

GEOGRAPHY

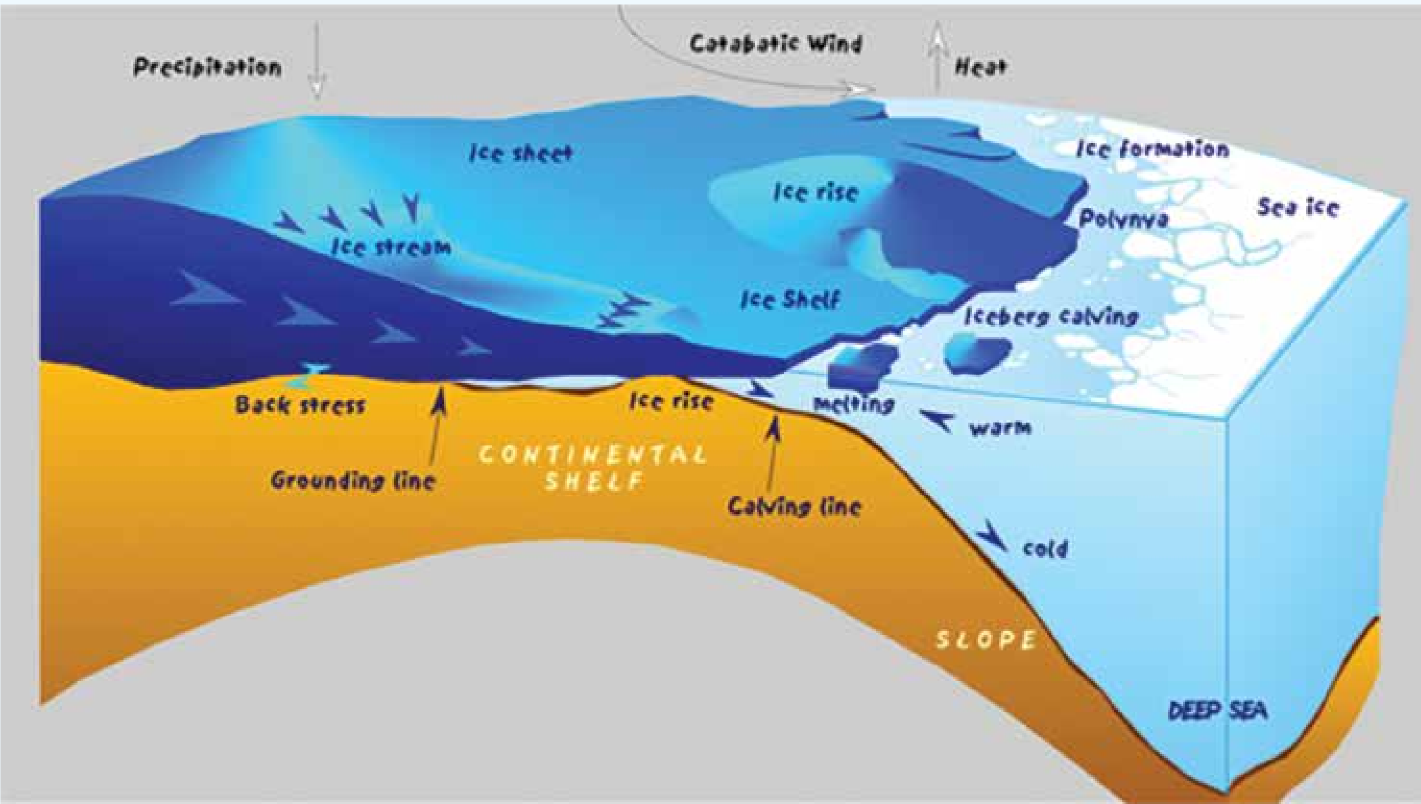
AN ICE SHELF is a floating sheet, or platform, of ice that is largely submerged and up to two kilometres in height, that abuts a land-based glacier, and extends into the ocean. The "grounding line" marks the boundary between grounded ice (glacier) and the floating ice shelf. Generally, an ice shelf will lose volume by calving icebergs from the seaward-facing edge, but it can also be subject to rapid disintegration events, in which cracking can dislodge very large sections of ice. The **formation of a huge crack**[5]—100 kms long, half a kilometre wide and a hundred metes deep—in the Larsen C ice shelf is one recent example.

Warming Antarctic waters are melting and thinning the underside of ice shelves, making them more susceptible to disintegration. An ice shelf acts as a "plug" that buttresses and slows the rate at which a glacier drains into the ocean, so the loss or diminution of the ice shelf will accelerate the pace of glacier movement and hence the rate of ice mass loss.

Because much of WAIS sits on bedrock that is below sea level (buttressed on two sides by mountains, and held in place on the other two sides by the Ronne and Ross ice shelves), melting of the submerged ice shelf allows warm ocean waters to proceed inland under the ice sheet. This creates hidden valleys of melting ice, puts pressure on the surface above, and contributes to large-scale rifting (cracking). This process also results in the grounding line being pushed further inland, in effect transforming the lower reaches of the glacier into an ice shelf.

Over the past 40 years, glaciers flowing into the Amundsen Sea sector of WAIS (including Pine Island, Thwaites, Smith and Kohler glaciers) have thinned at an accelerating rate, and observations and several numerical models suggest that unstable and irreversible retreat of the grounding line is under way.

Whilst it is traditionally considered that WAIS deglaciation would take a thousand years or more, some experts have suggested in could occur in a period as short as a couple of centuries because the rate of change in atmospheric greenhouse gases and in the global temperature are unprecedented.



Antarctic coast with glaciological and oceanographic processes

RECENT RESEARCH
WEST ANTARCTICA

Rignot, Mouginot et al (2014) **"Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011"** [6], Geophys. Res. Lett. 41:3502–3509

The researchers found that the "tipping point" has already passed for one of these "long-term" events. In the "Guardian" on 18 May 2014, lead researcher Dr Eric Rignot **explained**[7]: "We announced that we had collected enough observations to conclude that ***the retreat of ice in the Amundsen sea sector of West Antarctica was unstoppable***, with major consequences – it will mean that sea levels will rise one metre worldwide. What's more, its disappearance ***will likely trigger the collapse of the rest of the West Antarctic ice sheet***, which comes with a sea level rise of between three and five metres. Such an event will displace millions of people worldwide" (emphasis added).

This study, authored by some the world's best cryosphere scientists, stunned the research community. Malte Meinshausen, an IPCC lead author who also developed the RCP scenarios, **said**[8] this research is "a game changer, this is just one surprise with global warming of only 0.8 degrees of warming", and a "tipping point that none of us thought would pass so quickly", showing we are "committed already to a change in coastlines that is unprecedented for us humans".

One of the authors of this paper was asked what conditions would be necessary to stop the loss of most of WAIS. The answer was that restoring the temperature of the 1970s might do it.

On the fate of West Antartica, Rignot **says**[9] "at the current rate, a large fraction of the (WAIS) basin will be gone in 200 years". Modelling studies indicate the retreat rate will increase in the future, so the process could be completed within a shorter period of time.

- Joughin, Smith and Medley (2014) **"Marine Ice Sheet Collapse Potentially Underway for the Thwaites Glacier Basin, West Antarctica"**[10], Science, 344:735–738

Another paper uses models which the "indicate that early-stage collapse has begun" of the Thwaites Glacier, and that ***no further acceleration*** of climate change and only modest extrapolations of the current increasing mass loss rate ***are necessary for the system eventually to collapse***. "The next stable state for the West Antarctic Ice Sheet might be no ice sheet at all," says the paper's lead author, glaciologist Ian Joughin.

- **"Briefing: Antarctic ice sheet mass loss and future sea-level rise"**[11], Proceedings of the Institution of Civil Engineers, 2014

Ted Scambos of the National Snow and Ice Data Centre and John Abraham of the University of St Paul explain: "For decades, it has been suspected that this region is particularly susceptible to rapid ice loss, through a 'runaway retreat'. The cause of the retreat is known to be increased frequency of warm ocean water intrusions onto the continental shelf, which appears to be a consequence of increased westerly circumpolar winds over the Southern Ocean. Models suggest that increased winds are a result of increased greenhouse gas forcing in the Earth system, and ozone loss effects on stratospheric/tropospheric circulation".

A note on timelines for collapse of WAIS

The papers surveyed here in general agree that the Amundsen Sea sector of the West Antarctic Ice Sheet has most likely been (or will soon be) destabilized and no further acceleration in climate change is necessary to trigger a collapse of a significant fraction of the rest of the West Antarctic Ice Sheet. However the timeline for significant collapse is contested. Rignot says that "at the current rate, a large fraction of the (West Antarctic) basin will be gone in 200 years" and the Pollard, DeConto and Alley model "accelerates the expected collapse of the West Antarctic Ice Sheet to decadal time scales, and also causes retreat into major East Antarctic subglacial basins", producing five metres in the first 200 years. And DeConto and Pollard say that "Antarctica has the potential to contribute more than a metre of sea-level rise by 2100", which would include a collapse of a significant fraction of WAIS this century. On the other hand, the Feldman and Levermann model says that the complete disintegration of WAIS is on "a millennial time scale". And the Joughin, Smith and Medley model says losses will be moderate over this century "with the onset of rapid (>1 mm per year of sea-level rise) collapse in the different simulations within the range of 200 to 900 years."

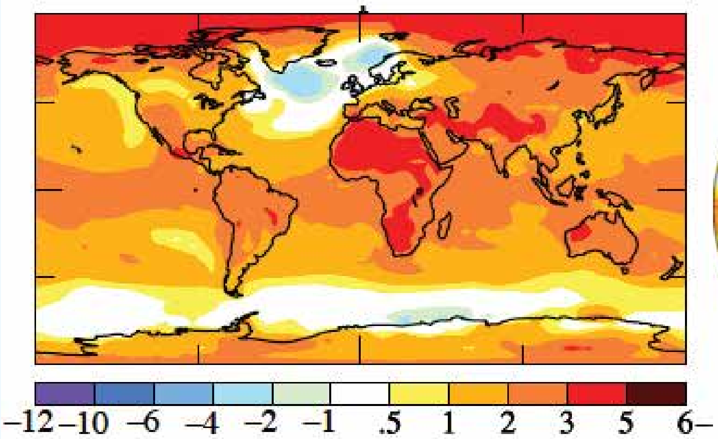
Feldman and Levermann (2015) "Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin"[12], PNAS 112;14191-14196

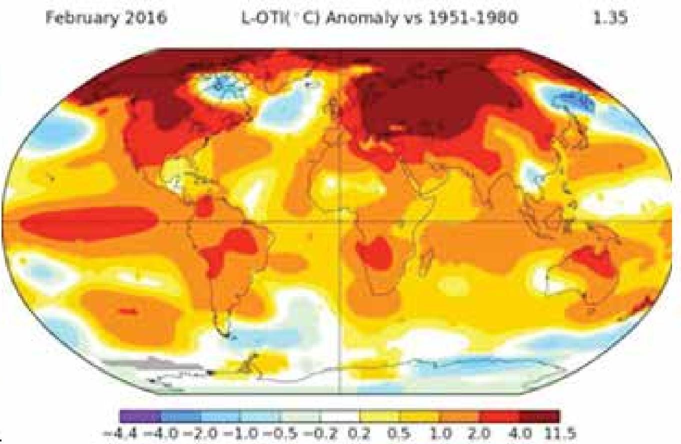
This modelling study of the Amundsen Basin finds that "a local destabilization causes a complete disintegration of the marine ice in West Antarctica... the region disequilibrates after 60 years of currently observed melt rates".. [Melt rates are observed to be continuing to accelerate, so the actual time line may be a good deal shorter.] However "whether this localized destabilization will yield a full discharge of marine ice from West Antarctica, associated with a global sea-level rise of more than 3 metre, or whether the ice loss is limited by ice dynamics and topographic features, is unclear." The significance of the study is given as: "The Antarctic Ice Sheet is losing mass at an accelerating rate, and playing a more important role in terms of global sea-level rise. The Amundsen Sea sector of West Antarctica ***has most likely been destabilized***. Although previous numerical modeling studies examined the short-term future evolution of this region, here we take the next step and simulate the long-term evolution of the whole West Antarctic Ice Sheet. Our results show that if the Amundsen Sea sector is destabilized, then ***the entire marine ice sheet will discharge into the ocean***, causing a global sea-level rise of about 3 metres. We thus might be witnessing the beginning of a period of self-sustained ice discharge from West Antarctica that requires long-term global adaptation of coastal protection" (emphasis added). The model in this study says that it will take about 2000 years to see the first metre of global sea-level rise from the WAIS collapse.

Hansen, Sato et al (2015) "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous"[13], Atmos. Chem. Phys. 16:3761-3812

This research surveys evidence from the previous warm Eemian interglacial period around 120,000 years ago. At that time there were rapid fluctuations in sea level, and the study identifies a mechanism in the Earth's climate system not previously understood, which points to a much more rapid rise in sea levels than currently anticipated. Increasing ocean stratification occurs when cooler surface layers from melting ice sheets trap warmer waters underneath, accelerating their impact on the melting of ice shelves and outlet glaciers. This in turn increases ice sheet mass loss, and generates more cool surface melt water in a positive feedback.

The consequences include the slowing or shutting down of key ocean currents including the Atlantic Meridional Overturning Circulation (AMOC), which Hansen **says**[14] would increase temperature differentials between tropical and sub-polar waters, and drive "super storms" such that "All hell will break loose in the North Atlantic and neighbouring lands". The projected cooling pattern of waters around Antarctica and the north Atlantic waters from the injection of fresh ice-melt water is already visible in the observed data (see diagram below), and is already contributing to a circulation decline of AMOC.





Above (left) the Hansen et al projection for 2065 of temperature with accelerated ice melt in both hemispheres; and (right) actual conditions in 2016 at the height of the 2015-2016 El Nino.

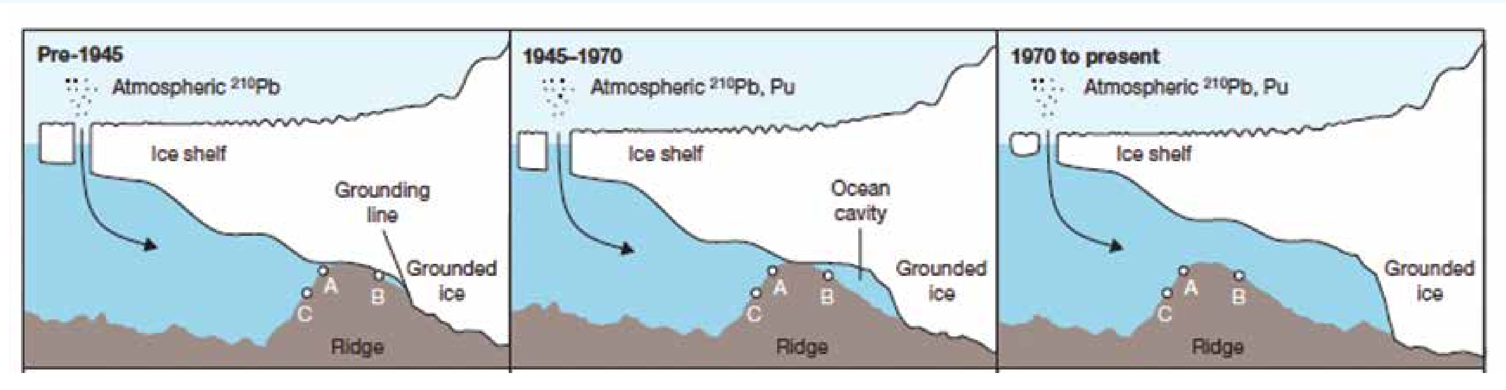
Smith, Anderson et al (2016) **"Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier"[15],** Nature, 23 November 2016, doi:10.1038/nature20136

This study finds that the present thinning and retreat of Pine Island Glacier in West Antarctica is part of ***a climatically forced trend that was triggered in the 1940s*** when an ocean cavity formed beneath the ice shelf, and followed a period of strong warming of West Antarctica, associated with El Niño activity. The final ungrounding of the ice shelf from the seafloor ridge occurred in 1970 (see diagram below).

It is interesting to compare this result with the view of researchers in the Rignot, Mouginot et al 2014 paper cited above that restoration of climate conditions of 1970s would be necessary to prevent widespread ice mass loss from WAIS.

Khazendar, Rignot et al (2016) **"Rapid submarine ice melting in the grounding zones of ice shelves in West Antarctica"[15a]**, Nature Communications 7 no. 13243

Researchers report the first direct observations (as opposed to satellite data) of ice melt from the floating undersides ***of glaciers in West Antarctica's Amundsen Sea sector***. They show that the amount of warm ocean water penetrating the undersides of the Smith, Pope, and Kohler glaciers at their grounding lines — the point at which a glacier's ice is anchored to the sea floor — and melting them from below has increased significantly between 2002 and 2014. These glaciers flow into the Dotson and Crosson ice shelves. Previous studies using other techniques estimated the average melting rates at the bottom of these ice shelves to be about 12 meters per year. However this research found ***stunning rates of ice loss from the glaciers' undersides*** with Smith, the fastest-melting glacier, losing between 300 and 490 meters in thickness from 2002 to 2009 near its grounding line, or up to 70 meters per year. Lead author Ala Khazendar said Smith's fast retreat and thinning are likely related to the shape of the underlying bedrock over which it was retreating between 1996 and 2014, which sloped downward toward the continental interior, and oceanic conditions in the cavity beneath the glacier. As the grounding line retreated, warm and dense ocean water could reach the newly uncovered deeper parts of the cavity beneath the ice shelf, causing more melting.



Ungrounding of the Pine Island Glacier (Smith, Anderson et al)

RECENT RESEARCH

EAST ANTARCTICA

DeConto and Pollard (2016) "Contribution of Antarctica to past and future sea-level rise"[16], Nature 531:591–597

In this research, climate models that better link atmospheric warming with the fracturing of buttressing ice shelves and structural collapse of their ice cliffs are used, calibrated against past warm-period climate events and sea-level estimates, and then applied to future greenhouse gas emission scenarios.

During the last interglacial (warm) period 130,000 to 115,000 years ago, the global mean sea level was 6–9.3 metres higher than it is today, at a time when atmospheric carbon dioxide concentrations were below 280 parts per million (the pre-industrial level, and 30% less than today), and global mean temperatures were only about 0–2°C warmer.

Under a high-emissions scenario, their model shows that rapidly warming summer air temperatures trigger extensive surface meltwater production and hydrofracturing of ice shelves by the middle of this century, with Larsen C the first ice shelf to be lost, and major thinning and retreat of Amundsen Sea outlet glaciers at the same time. (Note: The fracturing of the Larsen C ice shelf is a current reality!)

They conclude that: "Antarctica has the ***potential to contribute more than a metre of sea-level rise by 2100*** and more than 15 metres by 2500", doubling previous forecasts for total sea level rise this century to two metres or more.

This estimate of Antarctica alone contributing "more than a metre of sea-level rise by 2100" is consistent with the work of Hansen, Sato et al (above).

Pollard, DeConto and Alley (2015) "Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure"[17], Earth Planet. Sci. Lett. 412:112–121.

During the warmest part of the Pliocene (5.3 to 2.6 million years ago) atmospheric carbon dioxide concentrations were comparable to today's (~400 parts per million), temperatures were 1–2°C warmer than now, and some sea-level reconstructions are 10–30 metres higher. Because WAIS and Greenland can supply less than 10 metres of sea level rise between them, this means there was substantial ice mass loss from East Antartica. In this study, the authors model Pliocene conditions in the Antarctic by taking the current (and Pliocene) level of 400 parts per million carbon dioxide, and impose a 2°C ocean warming to represent maximum mid-Pliocene ocean warmth. Their model also incorporates mechanisms based on recent observations and analysis: "floating ice shelves may be drastically reduced or removed completely by increased oceanic melting, and by hydrofracturing due to surface melt draining into crevasses. Ice at deep grounding lines may be weakened by hydrofracturing and reduced buttressing, and may fail structurally if stresses exceed the ice yield strength, producing rapid retreat." The updated model "***accelerates the expected collapse of the West Antarctic Ice Sheet to decadal time scales*** (rather than century-to-millennial time scales), and also causes retreat into major East Antarctic subglacial basins, producing ~17 metres global sea-level rise within a few thousand years" and ***five metres in the first 200*** years (emphasis added).

[In the followup 2016 paper cited above, an updated model produces an 11.3-metre contribution to global mean sea level rise, reflecting a reduction in its sensitivity of about 6 metres relative to the formulation in this paper of ~17 metres, but within the range of plausible sea-level estimates.]

Phipps, Fogwill and Turney (2016) "Impacts of marine instability across the East Antarctic Ice Sheet on Southern Ocean dynamics"[18], The Cryosphere, 10:2317–2328

This research concludes that local melting from the Wilkes Basin in East Antarctica "could potentially destabilise the wider Antarctic Ice Sheet" as meltwater rapidly stratifies surface waters so, whilst the surface ocean cools, the Southern Ocean warms by more than 1°C at depth. "The temperature changes propagate westwards around the coast of the Antarctic continent with increasing depth, representing a positive feedback mechanism that has the potential to amplify melting around the continent… Thus, destabilisation of large sectors of the EAIS could arise from warming and melting in just one area." As well: "Our results suggest that melting of one sector of the EAIS could result in accelerated warming across other sectors, including the Weddell Sea sector of the West Antarctic Ice Sheet" (emphasis added).

This paper is also consistent with Hansen, Sato et al in finding a process of water column stratification and warmer sub-surface waters as a positive feedback mechanism that has the potential to amplify melting.

Mendel and Levermann (2014) "Ice plug prevents irreversible discharge from East Antarctica"[19], Nature Climate Change 4:451–455

Substantial sectors of the EAIS, including Wilkes Basin, are underlain by extensive marine-based subglacial basins. This study shows that the removal of an ice plug (shelf) at the margin of the Wilkes Basin, that would cause less than 80mm of global sea-level rise, would destabilize the regional ice flow and leads to a self-sustained discharge of the entire basin and a global sea-level rise of 3–4 metres. As with the DeConto and Pollard papers above, this study also discusses the analogous situation of the the mid-to late Pliocene when "massive ice discharge occurred from the unstable margins of Adélie and Wilkes Land due to ice-stream surges that were linked to rapid grounding-line retreat during a warming climate".

Lenaerts, Lhermitte et al (2016) "Meltwater produced by wind–albedo interaction stored in an East Antarctic ice shelf"[20], Nature Climate Change 7:58-62

This study identifies a mechanism that triggers melting deep in the Roi Baudouin ice shelf in East Antarctica. Strong winds helped heat the air and cause white ice to melt out, exposing a layer of dark ice beneath, which in turns absorbs more sunlight, further expediting the melt. In these hotspots, surface glacial lakes form and meltwater pours into moulins, that funnel surface meltwater into the heart of the ice. As well, researchers found subterranean "englacial" lakes in the ice sheet. In total, 55 lakes on or in the ice shelf were identified. This means the ice shelf has many large pockets of weakness throughout its structure, suggesting a greater potential vulnerability to collapse through hydrofracturing, especially if lake formation continues or increases.

Fogwill, Turney et al (2017) "Antarctic ice sheet discharge driven by atmosphere-ocean feedbacks at the Last Glacial Termination"[21], Scientific Reports 7, article 39979

Antarctic ice mass loss during the end of the last ice age 14,600–12,700 yrs ago contributed several metres to sea levels which from various sources rose by tens of metres. At that time, changes in atmospheric-oceanic circulation led to a stratification in the ocean with a cold layer at the surface and a warm layer below. Under such conditions, ice sheets melt more strongly than when the surrounding ocean is thoroughly mixed. This is exactly what is presently happening around the Antarctic now. Research team member Michael E. Weber says, "The changes that are currently taking place in a disturbing manner resemble those 14,700 years ago."

A NUMBER of recent studies have focussed on the Totten Glacier in East Antartica. Several lines of evidence suggest possible collapse of Totten Glacier into interior basins during past warm periods, most notably the Pliocene epoch, and the glacier is again becoming vulnerable.

> **Totten has the largest thinning rate in East Antarctica, driven by enhanced melting of the ice shelf bottom, due to ocean processes. An ice-shelf cavity below depths of 400 to 500 metres could allow intrusions of warm water and an inland trough that connects the main ice-shelf cavity to the ocean. If thinning trends continue, a larger water body over the trough could potentially allow more warm water into the cavity, which may, eventually, lead to destabilization of the low-lying region between Totten Glacier and the similarly deep glacier flowing into the Reynolds Trough.**

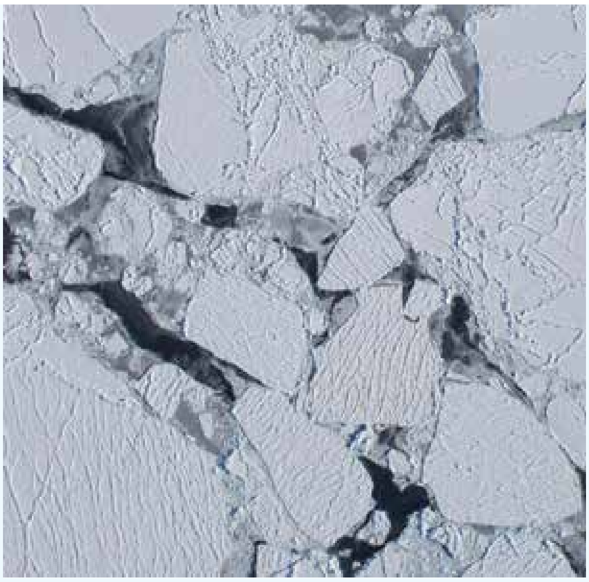
• Greenbaum, Blankenship et al (2015) **"Ocean access to a cavity beneath Totten Glacier in East Antarctica"[22]**, Nature GeoScience

> **Totten could become unstable if global warming continues at the present pace. As warm seas wash the ice shelf, the land-based mass of ice could begin to retreat, cross a critical threshold in the present century and then withdraw 300 kilometres inland.**

• Aitken, Roberts et al (2016) **"Repeated large-scale retreat and advance of Totten Glacier indicated by inland bed erosion"[23]**, Nature 533:385–389]

> **Totten is melting from below as warm ocean water flows inward powerfully towards Totten glacier, causing the ice shelf to lose between 63 and 80 billion tons of its mass to the ocean per year. Warm water enters a cavity beneath the glacier through a newly discovered deep water channel.**

• Rintoul, Silvan et al (2016) **"Ocean heat drives rapid basal melt of the Totten Ice Shelf"[24]**, Science Advances 2:e1601610



Antarctic sea ice, 2009 (NASA)

CONCLUSION

IN LATE 2015, a chilling report by scientists for the International Cryosphere Climate Initiative on **"Thresholds and closing windows: Risks of irreversible cryosphere climate change"**[25] warned that the Paris commitments will not prevent the Earth "crossing into the zone of irreversible thresholds" in polar and mountain glacier regions, and that crossing these boundaries may "result in processes that ***cannot be halted unless temperatures return to levels below pre-industrial***" (emphasis added). The report says it is not well understood outside the scientific community that cryosphere dynamics are slow to manifest but once triggered "inevitably forces the Earth's climate system into a new state, one that most scientists believe ***has not existed for 35–50 million years***" (emphasis added).

Ian Howat, associate professor of earth sciences at Ohio State University, **says**[26]: "It's generally accepted that it's no longer a question of ***whether*** the West Antarctic Ice Sheet will melt, it's a question of ***when***. This kind of rifting (cracking) behaviour provides another mechanism for rapid retreat of these glaciers, adding to the probability that we may see significant collapse of West Antarctica in our lifetimes."

The scientists I have communicated with take the view that Rignot, Mouginot et al. is a credible paper and, together with the evidence published since, it would be prudent to accept that WAIS has very likely passed its tipping point for mass deglaciation, with big consequences for global sea level rise (SLR). DeConto and Pollard project more than a metre of SLR from Antarctica this century. This tallies with the Hanse, Sato et al scenario, which is also consistent with the findings of Phipps, Fogwill and Turney.

The reality of multi-metre SLRs is not if, but how soon. "The natural state of the Earth with present CO_2 levels is one with sea levels about 70 feet (21 metres) higher than now" **says**[27] Prof. Kenneth G. Miller. Other research scientists **agree**[28] it is likely to be more than 20 metres over the longer term.

So how much could we expect sea levels to rise this century?

> **"Current estimates of sea-level rise range from 0.50 metre to over 2 metres by 2100", reported the November 2009 issue of *Science Update 2009* published by CSIRO and the Australian Bureau of Meteorology. "Sea-level rise ranging from 75 to 190 cm for the period 1990-2100", concluded Vermeer and Rahmstorf.**

• Vermeer and Rahmstorf (2009), **"Global sea level linked to global temperature"**, PNAS 106:21527-32

> **In 2012, the US National Oceanic and Atmospheric Administration (NOAA) reported "Scientists have very high confidence (greater than 90% chance) that global mean sea level will rise at least 8 inches (0.2 meter) and no more than 6.6 feet (2.0 meters) by 2100." NOAA provides four sea level rise scenarios to 2100, of which the highest of 2 metres by 2100 "reflects ocean warming and the maximum plausible contribution of ice sheet loss and glacial melting. This highest scenario should be considered in situations where there is little tolerance for risk" says Parris, Bromirski et al.**

• Parris, Bromirski et al (2012) **"Global Sea Level Rise Scenarios for the United States National Climate Assessment"**, NOAA Tech Memo OAR CPO-1, National Oceanic and Atmospheric Administration, Silver Spring, MD.

> **BREAKING NEWS An updated NOAA sea-level rise report[29] just released recommends a revised worst-case sea-level rise rise scenario of 2.5 metres by 2100, 5.5 metres by 2150 and 9.7 metres by 2200. It says sea level science has "advanced significantly over the last few years, especially (for) land-based ice sheets in Greenland and Antarctica under global warming", and hence the "correspondingly larger range of possible 21st century rise in sea level than previously thought". It points to "continued and growing evidence that both Antarctica and Greenland are losing mass at an accelerated rate", which "strengthens an argument for considering worst-case scenarios in coastal risk management".**

The general view amongst scientists I have communicated with is to expect a sea-level rise this century of at least 1 metre, and perhaps in excess of 2 metres in light of the work surveyed above. Scientists have found the business of putting a true upper limit on how much ice could melt—and how quickly—is a difficult one.

Among a myriad of devastating global impacts, a 1-metre sea-level rise would inundate up to 20% of the land area of Bangladesh and displace 30 million people, wipe out 40-50% of the Mekong Delta, flood one-fourth of the Nile Delta, and depopulate some coral atoll small states.

The only practical conclusion to be drawn is that climate warming has already gone to far, and the objective must be to achieve a level of greenhouse gases, and of global temperature, well below that currently prevailing.

FOOTNOTES

1. http://advances.sciencemag.org/content/2/12/e1601610.full
2. http://onlinelibrary.wiley.com/doi/10.1002/2013GL059069/abstract
3. http://www.nature.com/nature/journal/v271/n5643/abs/271321a0.html
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7. https://www.theguardian.com/commentisfree/2014/may/17/climate-change-antarctica-glaciers-melting-global-warming-nasa
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BACK COVER Pine Island Glacier 2002 (NASA/GSFC/METI/ERSDAC)

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