The West Antarctic Ice Sheet and Sea Level Rise

Dustin Schroeder

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Introduction

The extent of global sea level rise during the next hundred years is of dramatic consequence for millions of people around the world. In addition to low-lying costal communities faced with the direct inundation, a large population of refugees displaced by rising seas will impact the entire global community. Accurate predictions of century-scale sea level rise will be essential in planning for and adapting to this feature of our changing climate. Despite this urgent need for accuracy, the most recent report of the international panel on climate change did not include the contributions of polar ice sheets (which contain 63.9 meters of sea level equivalent water) in its estimate for maximum sea level rise over the next century. [2] These tremendous sources of potential contribution to sea level were omitted from the IPCC report because its authors found the current ice sheet models could not produce predictions with sufficient accuracy. [2] Recent changes in the velocity structure and discharge rates of the Greenland and West Antarctic Ice Sheets have shown that their contribution to future sea level rise cannot be ignored. [7] In response to this situation, an international group of ice sheet modelers is working on the development of a Community Ice Sheet Model to incorporate physical processes that are insufficiently represented in existing models. [19] This and similar efforts will be integral in the production of more accurate and complete models in time for the next IPCC report in 2013. The West Antarctic Ice Sheet is the only remaining marine ice sheet from the last glacial maximum and has areas of recent negative mass balance and ice shelf thinning on its margins indicative of potential ice sheet collapse. [22]

The Cryosphere and Sea Level

Exceeding thermal expansion, which contributes approximately 0.5 mm yr^{-1}, the melting of ice in the cryosphere is the primary source of sea level rise. [1] The mass loss of glaciers and ice caps is estimated to have been 0.5 +- 0.18 mm yr^{-1} in sea level equivalent from 1961 to 2004 and 0.77 +- 0.22 mm yr^{-1} from 1991 to 2004. [2] Paleoclimate data has shown that past changes in CO_2 were correlated with changes in ice volume and global sea level as shown in Figure 1, below. [1]

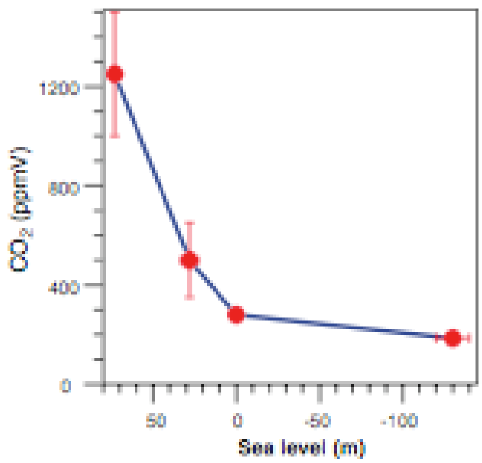

Figure 1: Relationship between atmospheric CO_2
and ice contribution to eustatic sea level [1]

During the deglaciation since the last glacial maximum, about 21,000 years BP, the rate of ice loss had an average value of 10 mm yr^{-1} with intermittent periods of "meltwater pulses" during which rates exceeded 50 mm yr^{-1} adding the equivalent of 1 to 1.5 Greenland Ice Sheets worth of ice over 1 to 5 centuries. [1] The plots of CO_2 level, sea surface temperature, and relative sea level during the last deglaciation in the left half of Figure 2 show the strong correlation of these variables. The right half of the figure shows those same variables for various projected global warming scenarios. Taken together, the data in Figures 1 and 2 indicate that contemporary global warming will likely be accompanied by significant sea level rise

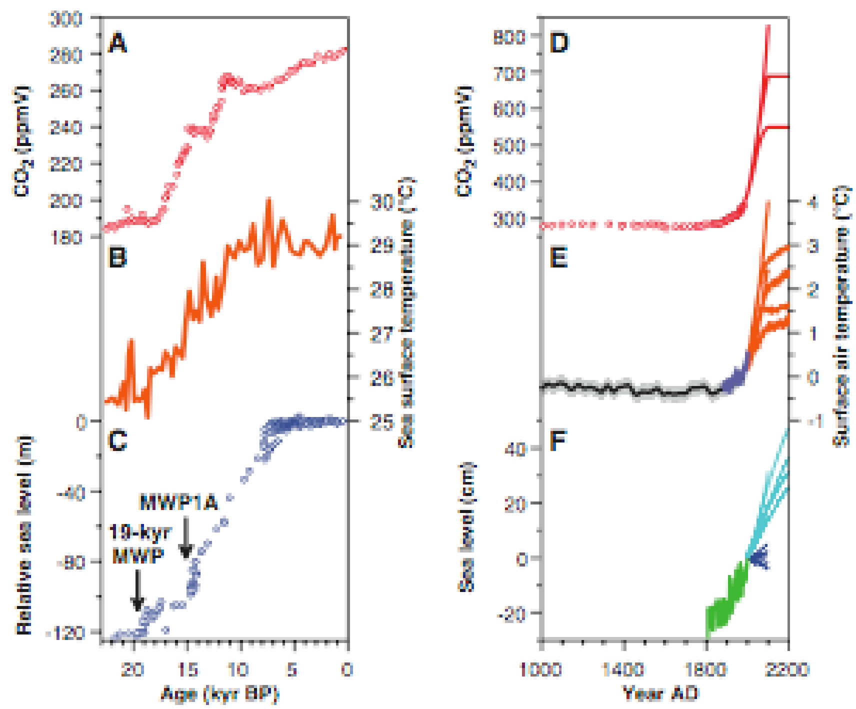

Figure 2: Time series of key variables during the last deglaciation (left) compared with scenarios of future global warming (right) [2]

Polar Ice Sheets and Climate Change

As shown in Table 1 and Figure 3 below, the polar ice sheets contain the vast majority of potential sea level rise in the Cryosphere. The Antarctic Ice Sheet would raise sea level by 56.6 meters if totally melted and the Greenland Ice Sheet would raise it by 7.3 meters. These values greatly exceed the sea level rise potential of approximately 0.6 meters for the rest of the cryosphere combined.

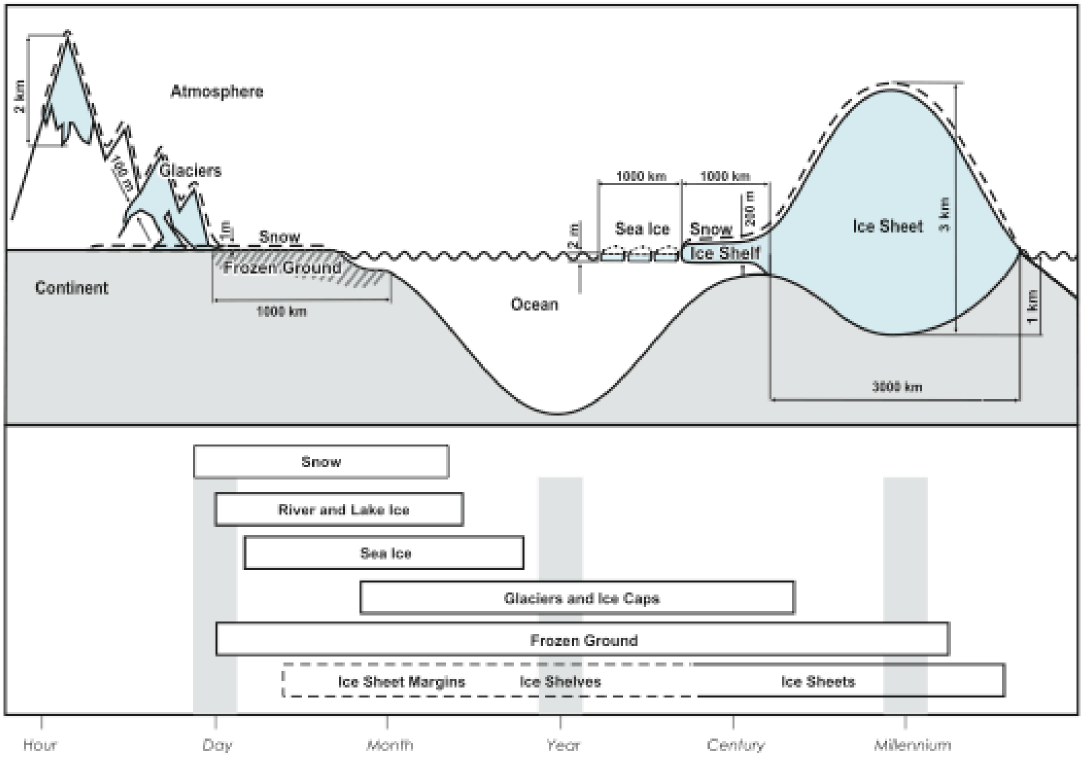

Figure 3: Components of the cryosphere and their timescales [2]

Table 1: The area, volume, and sea level equivalent of cryosphere components [2]

Cryospheric Component	Area (10^6 km^2)	Ice Volume (10^6 km^3)	Potential Sea Level Rise (SLE) (m)[g]
Snow on land (NH)	1.9–45.2	0.0005–0.005	0.001–0.01
Sea ice	19–27	0.019–0.025	~0
Glaciers and ice caps			
Smallest estimate[a]	0.51	0.05	0.15
Largest estimate[b]	0.54	0.13	0.37
Ice shelves[c]	1.5	0.7	~0
Ice sheets	14.0	27.6	63.9
Greenland[d]	1.7	2.9	7.3
Antarctica[d]	12.3	24.7	56.6
Seasonally frozen ground (NH)[e]	5.9–48.1	0.006–0.065	~0
Permafrost (NH)[f]	22.8	0.011–0.037	0.03–0.10

Glaciers and mountain ice caps, though a much smaller total source of water, are currently melting at a much greater rate than the polar ice sheets. As a result, they actually represent the dominant component of current eustatic sea level rise as shown in Figure 4. [3] In fact, the glaciers on the Gulf of Alaska alone have represented a larger contribution to sea level rise over the last half century than the Antarctic Ice Sheet (Figure 5).

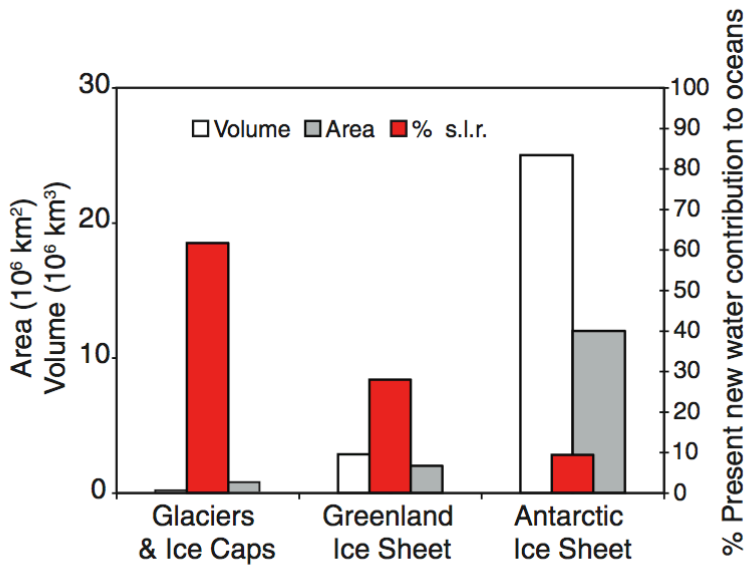

Figure 4: Volume, area, and sea level contributions of portions of the cryosphere [3]

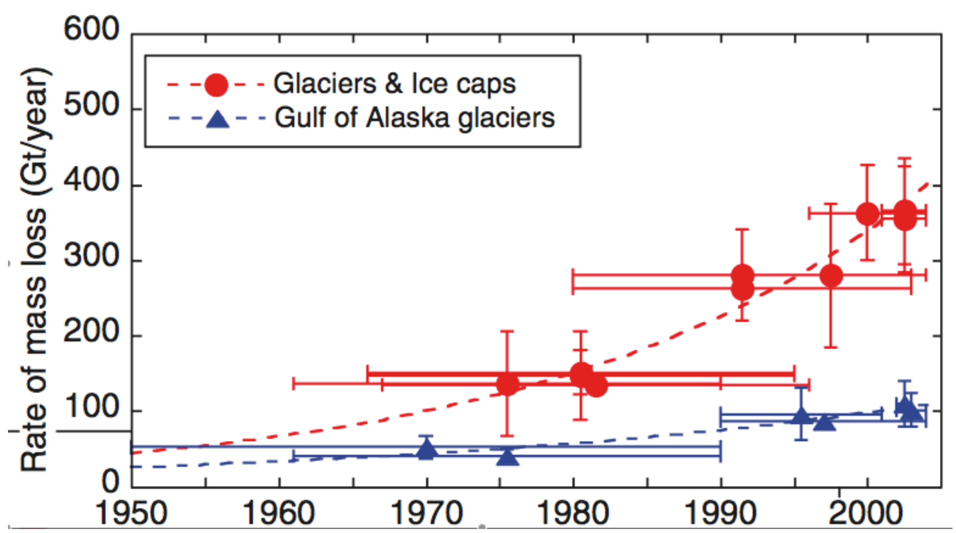

Figure 5: Contribution of Gulf of Alaska glaciers to total glacier and ice cap mass loss [3]

Marine Ice Sheets and Abrupt Change

Despite the current dominance of glaciers and ice caps in contributions to eustatic sea level, the West Antarctic Ice Sheet represents a significant threat of abrupt sea level rise because it is a marine ice sheet. [19] Current sea level predications assume that the primary mechanism of cryosphere contribution is surface melt-water. For every component of the cryosphere other that marine ice sheets, that is a reasonable assumption. Marine ice sheets however, can be susceptible to tributary acceleration and collapse if their buttressing ice shelf is lost. [4] The mechanism of the acceleration and potential collapse is shown in Figure 6.

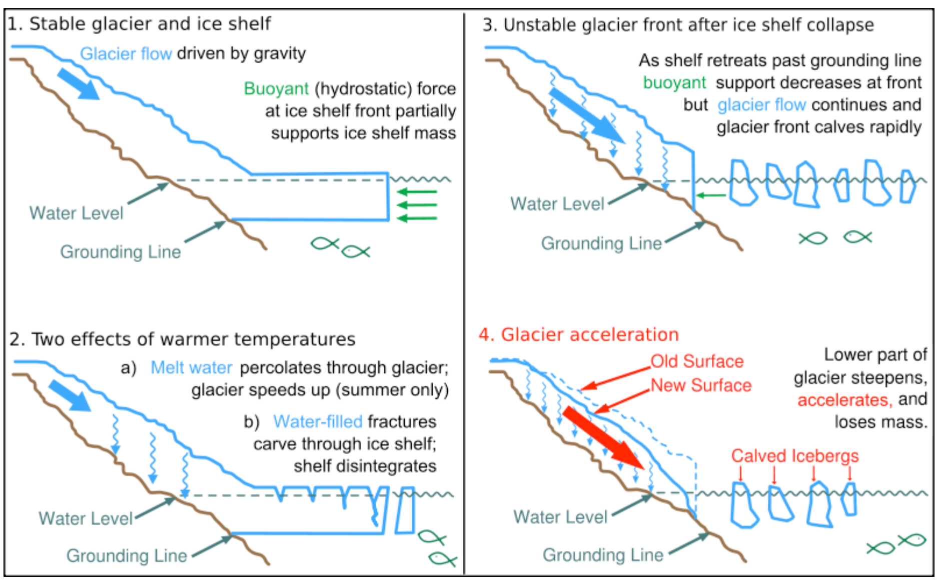

Figure 6: The mechanism of marine ice shelf collapse and glacier acceleration [4]

One such collapse occurred on the Antarctic Peninsula in 1995 when the Larsen B ice shelf collapsed over a period of days. Satellite images of the collapse, which were thought to have been caused by the warming ocean around near the peninsula, are shown in Figure 7.

Following the collapse of the buttressing ice shelf, the tributary glaciers of the Larsen B ice shelf continued to accelerate and retreat as shown in Figure 8. [5]

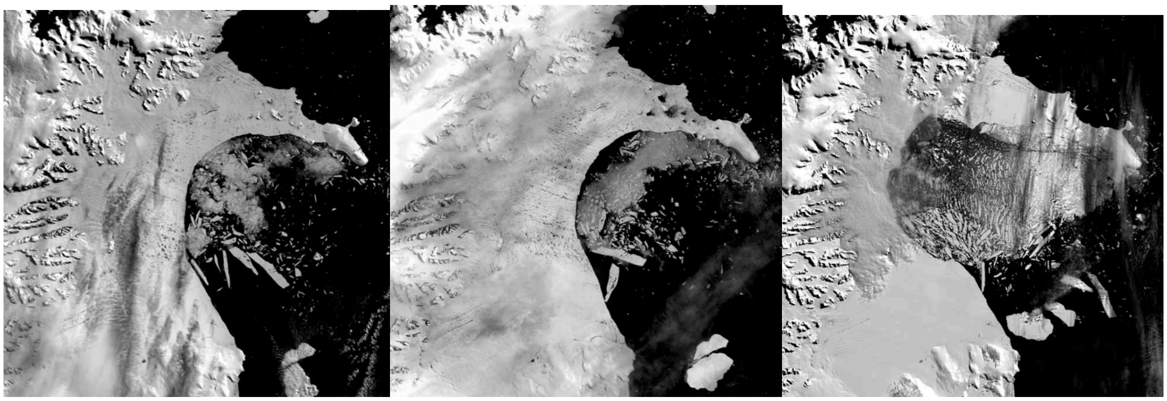

Figure 7: Satellite images taken of the Larsen B ice shelf collapse on February 17^{th}, February 23^{rd}, and March 3^{rd} 1995 [4]

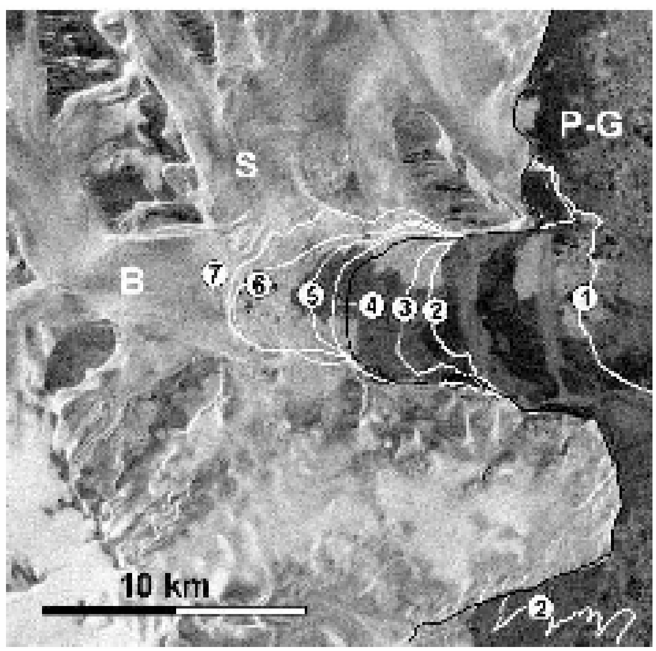

Figure 8: Post collapse retreat of the grounding line of a tributary glacier of the Larsen B ice shelf acquired on 1. 26 August 93; 2. 30 January 19 95; 3. 8 March 95; 4. 10 February 19 96; 5. 30 January 19 98; 6. 31 January 19 99; 7. 6 October 00. [5]

The Antarctic Ice Sheet

The Antarctic Ice Sheet is the largest component of the cryosphere and is comprised of the East Antarctic and West Antarctic Ice Sheets, which fall in the eastern and western hemispheres respectively and are separated by the transantarctic mountains. [8] The bed of the East Antarctic Ice Sheet (EAIS) is above sea level and the bed of the West Antarctic Ice Sheet is below sea level as shown in Figure 9. [6] With its bed below sea level, the WAIS is the final marine ice sheet remaining from the last glaciation.

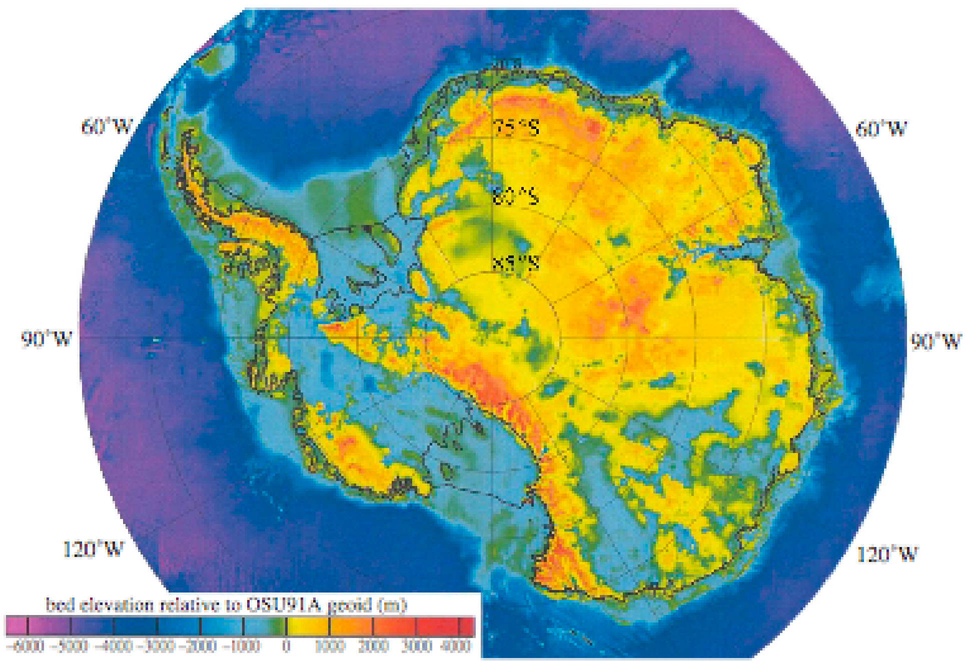

Figure 9: Bed elevation map of Antarctica [6]

Satellite observations using INterferometric Synthetic Aperture Radar (INSAR) to measure changes in elevation and surface velocity have produced detailed maps of the mass balance of the Antarctic Ice Sheet as shown in Figure 10. [7] This map shows that the WAIS has a large negative mass balance on the order of 60 Gt yr^{-1} and the EAIS has a positive mass balance. The positive mass balance in the EAIS is though to be the result of increased precipitation caused by ocean warming. [8] The negative mass balance on WAIS is greatest in the region of the

Amundsen Sea (AS), which is also thought to be the result of ocean warming. [11] More than simply contributing to sea level rise, the negative mass balance of the marine WAIS may also be the cause or early indication of an ice sheet collapse.

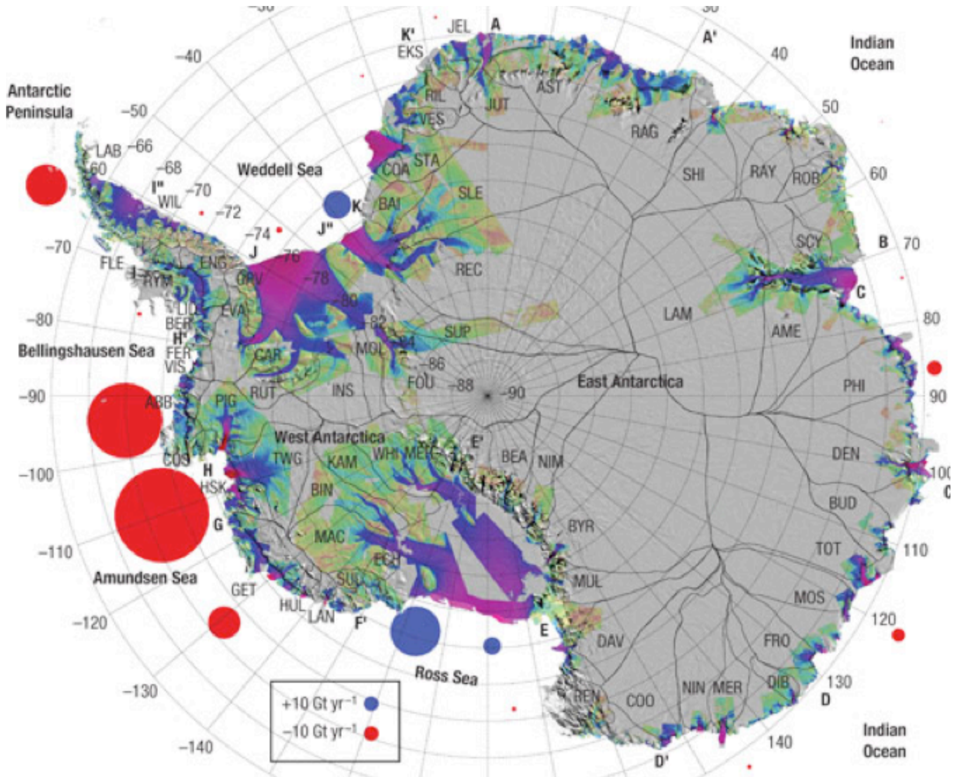

Figure 10: Mass balance map of the Antarctic Ice Sheet [7]

The West Antarctic Ice Sheet

The WAIS is comprised of three primary ice shelf drainage systems: The Ross Ice Shelf, the Ronne Ice Shelf, and the Amundsen Ice Shelf draining into the Ross, Weddell, and Amundsen Seas respectively as shown in Figure 11. [8] These systems contain fast-moving tributary ice streams that drain from their grounded catchments, over grounding lines, into the ice shelves. The high surface velocities (pink and purple in Figure 12) of the ice streams flowing into the Ross Sea had long identified those streams as possible candidates for ice sheet collapse initialization. [14] As the mass balance values in the more recent Figure 10 shows, however, the largest net ice volume loss occurs in the Amundsen Sea Embayment (ASE). The surface elevation change for the two primary outlet glaciers of the ASE, Pine Island Glacier (PIG) and Thwaites Glacier (TG) are shown in detail in Figure 13.

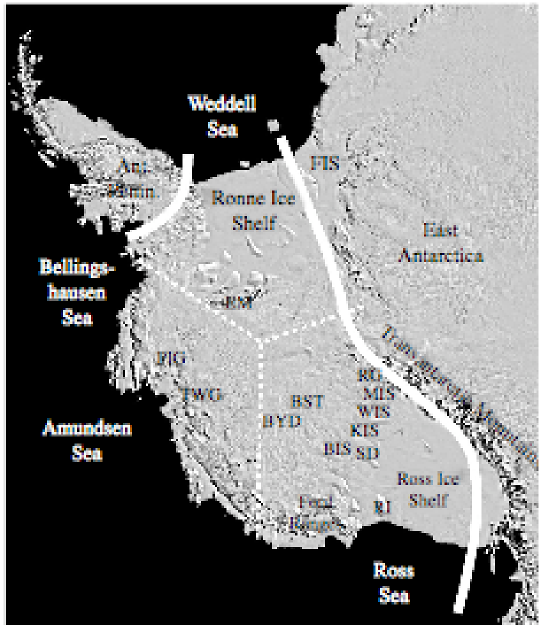

Figure 11: Geography of the West Antarctic Ice Sheet [8]

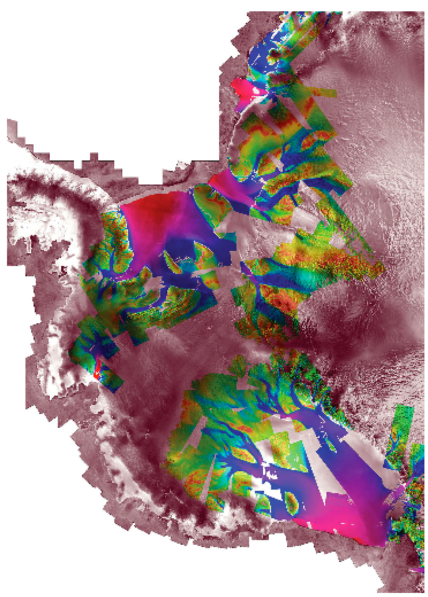

Figure 12: INSAR surface velocities for the West Antarctic Ice Sheet [7

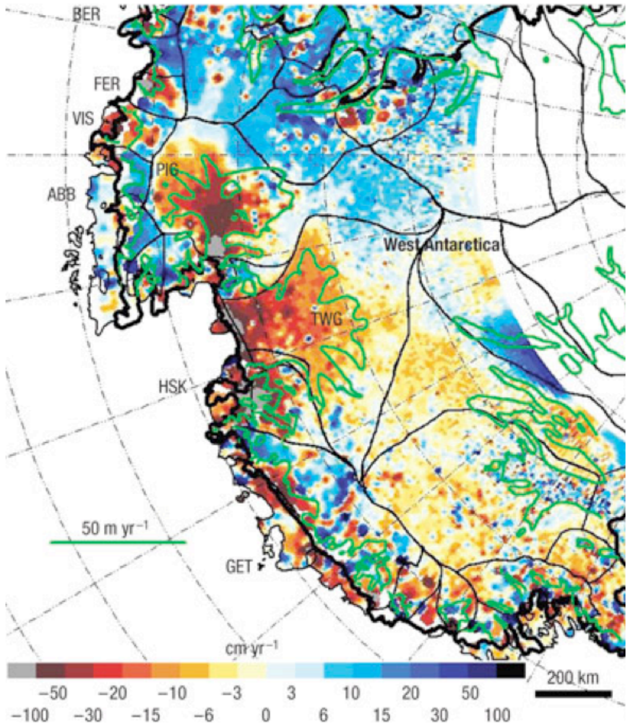

Figure 13: Map of surface elevation change for Pine Island and Thwaites Glaciers [7]

The Impact of a WAIS Collapse

The West Antarctic Ice Sheet contains sufficient water to raise global sea level by ~ 6 meters. The TG catchment alone contains 56 cm worth of water and the PIG catchment contains 24 cm in its northern basin and 28 cm its southern basin. [12,13] A WAIS collapse would freshen the surrounding ocean, potentially strengthening the Atlantic meridional overturning current and causing widespread warming. [1] The sea level rise induced by such a collapse would also have a dramatic effect on populations and economies that are disproportionately located near sea level (Figure 14). [9] Simulations of WAIS collapse scenarios with initialization in 2030 and end dates from 2130 to 3030 are shown in Figure 15 with populations on the order of tens of millions (Figure 14) displaced a few years after the onset of the collapse in most of the simulated scenarios.

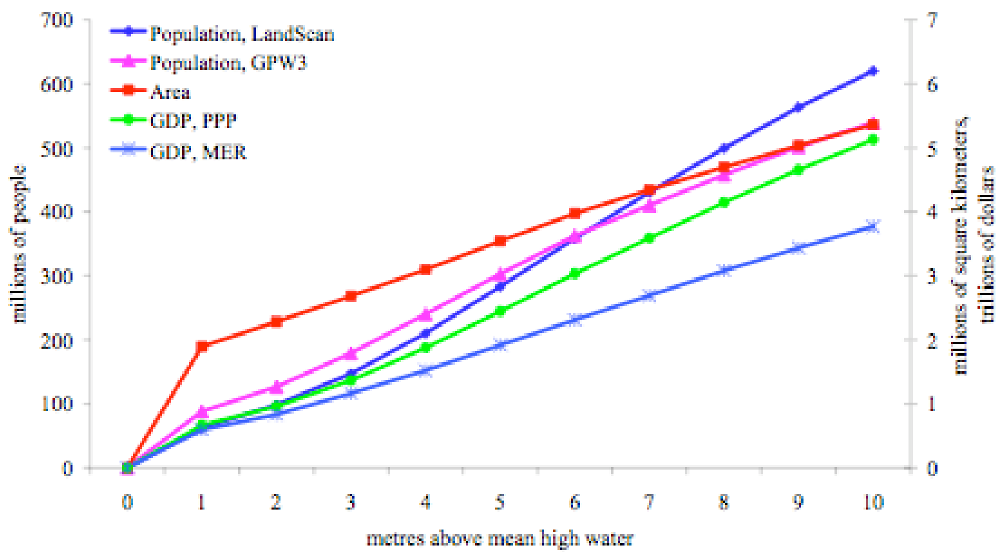

Figure 14: Distribution of people and capital about sea level [9]

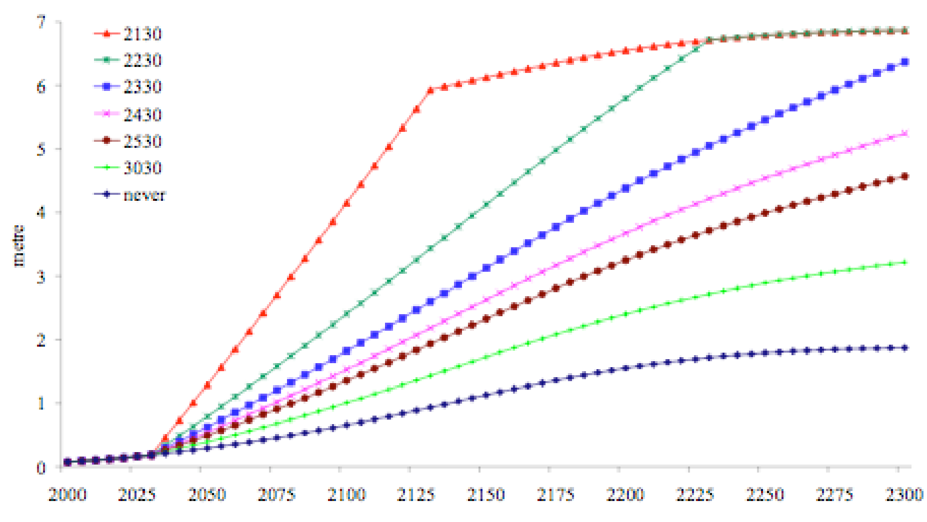

Figure15: Sea level rise profiles for several simulated WAIS collapse scenarios [9]

Oceans and Ice Sheet Forcing

The cause of the prodigious mass loss and recently perturbed discharge rates in the ASE are the result of the warming of Circumpolar Deep Water which is eroding the bottom the PIG and TG outlet glaciers. [11] The temperature profile for the water surrounding Pine Island Glacier, which is exhibiting the largest mass loss, is shown in Figure 17. The temperature at the base of the glacier is approximately 4 degrees above the freezing temperature. [10] A cross-section of PIG showing where the warm ocean water is reaching the base of the glacier is shown in Figure 18.

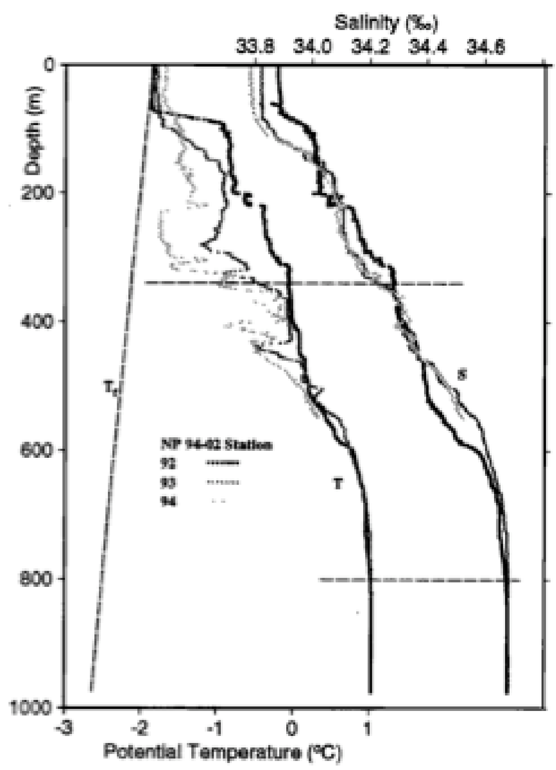

Figure 17: Salinity and temperature profiles for the Pine Island Bay [10]

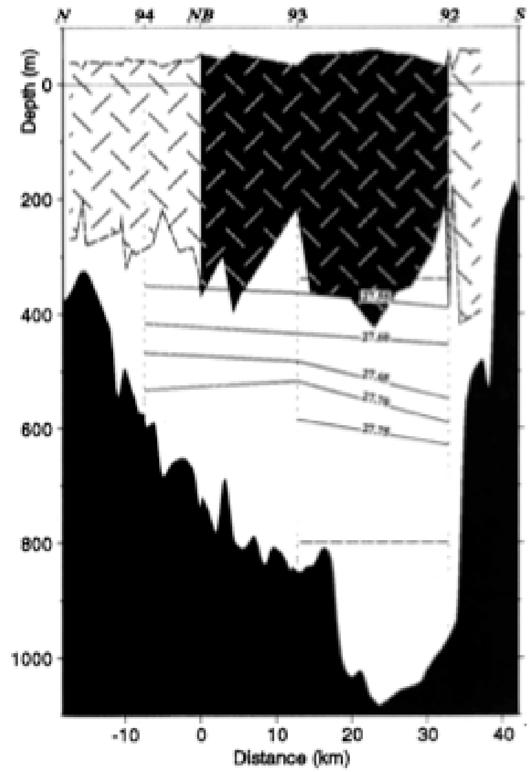

Figure 18: Cross-section of the base of the Pine Island Glacier [10]

Ice shelf elevation changes were estimated in 2004 to be on the order of -5 meters per year in the Amundsen Sea Embayment (Figure 10). [11] Improved satellite observations two years later (Figure 13) showed that the change was actually on the order -40 meters per year. Figure 20 plots these base melting rates against the temperature of the surrounding ocean for outlet glaciers in the West Antarctic Ice Sheet. [8] The largest melting rates (Pine Island Glacier and Thwaites Glacier) also correspond to the warmest surrounding ocean temperatures.

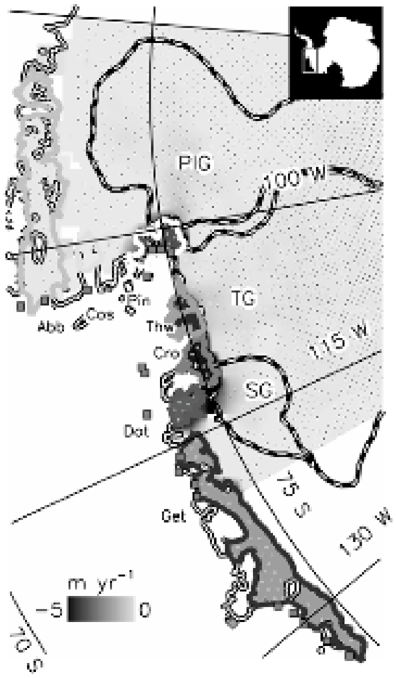

Figure 19: Ice shelf elevation changes estimated by Shepard in 2004 [11]

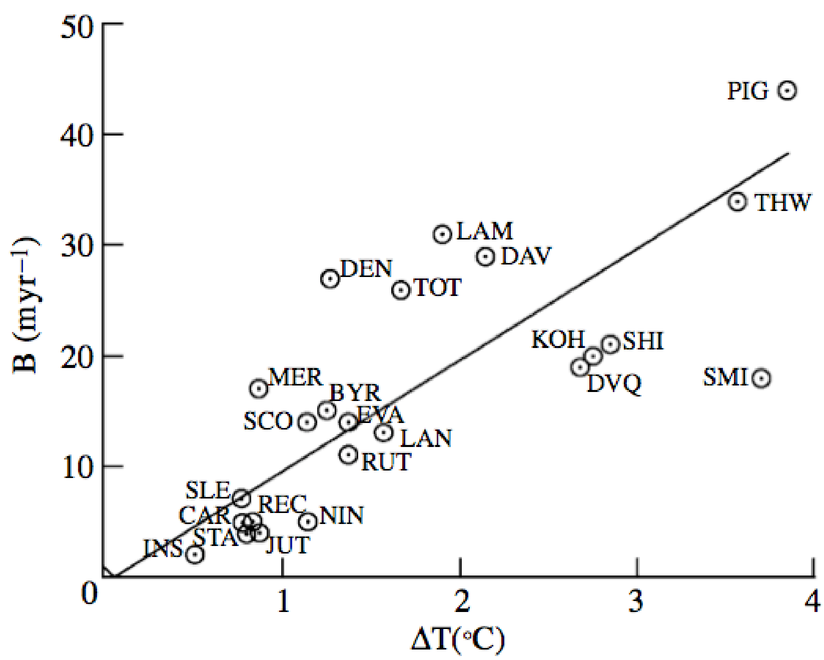

Figure 20: Base-melting values as a function of adjacent ocean temperature determined from satellite observations in 2006 [8]

Morphology and Ice Sheet Response

Although Pine Island Glacier exhibits both the largest negative mass balance and the largest rate of surface elevation change, the capacity of the glacier to initiate an ice-sheet-wide collapse of the WAIS is inhibited by its bed morphology. [12] The subglacial topography shown in Figure 21 was produced by airborne radar sounding and shows a range of subglacial mountains that separate its northern and southern catchments. In the event of a Pine Island Glacier collapse, these mountains would isostatically rebound above sea level, preventing the collapse from spreading to the southern basin or the rest of the ice sheet. [12] A PIG collapse would therefore be limited to the, still significant, 24 cm of sea level rise equivalent contained in the northern basin.

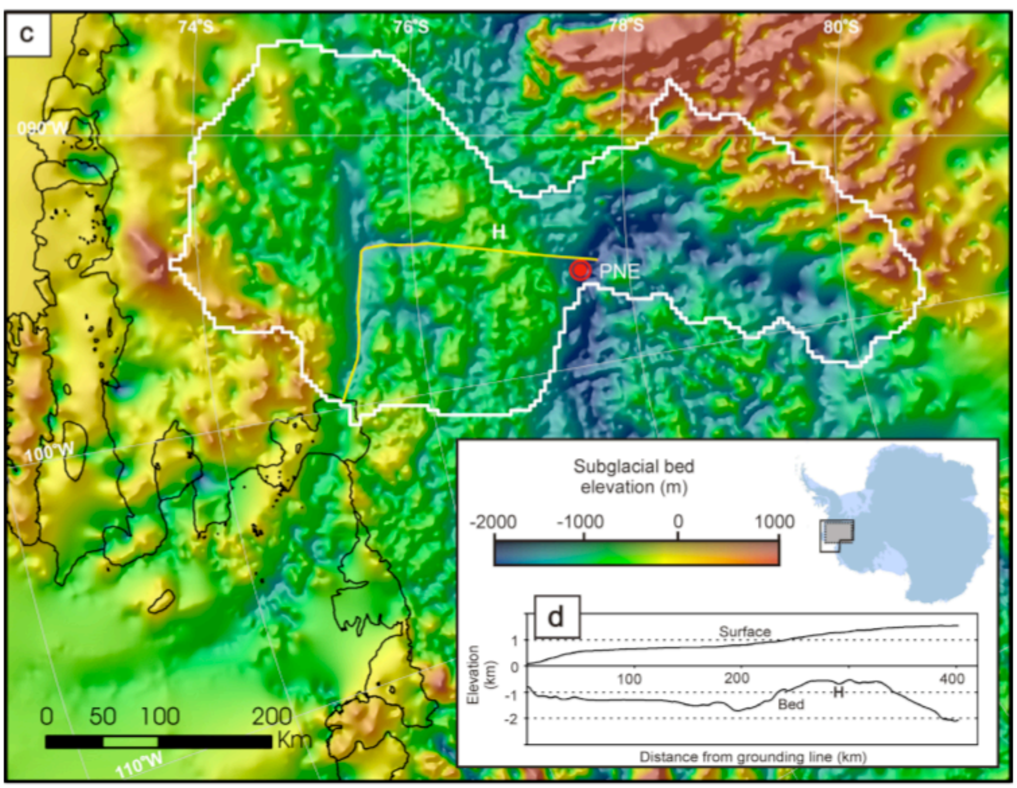

Figure 21: Subglacial topography of Pine Island Glacier [12]

The subglacial morphology of Thwaites Glacier (Figure 22), by contrast, slopes monotonically inward with no geological barriers preventing a TG collapse from spreading to the southern basin of PIG and to the rest of the WAIS. A TG collapse could, then, result in the contribution of its catchment's 56 cm of sea level equivalent water, the southern PIG basin's 28 cm, and possibly trigger the collapse of the entire 6m sea level equivalent WAIS. [13]

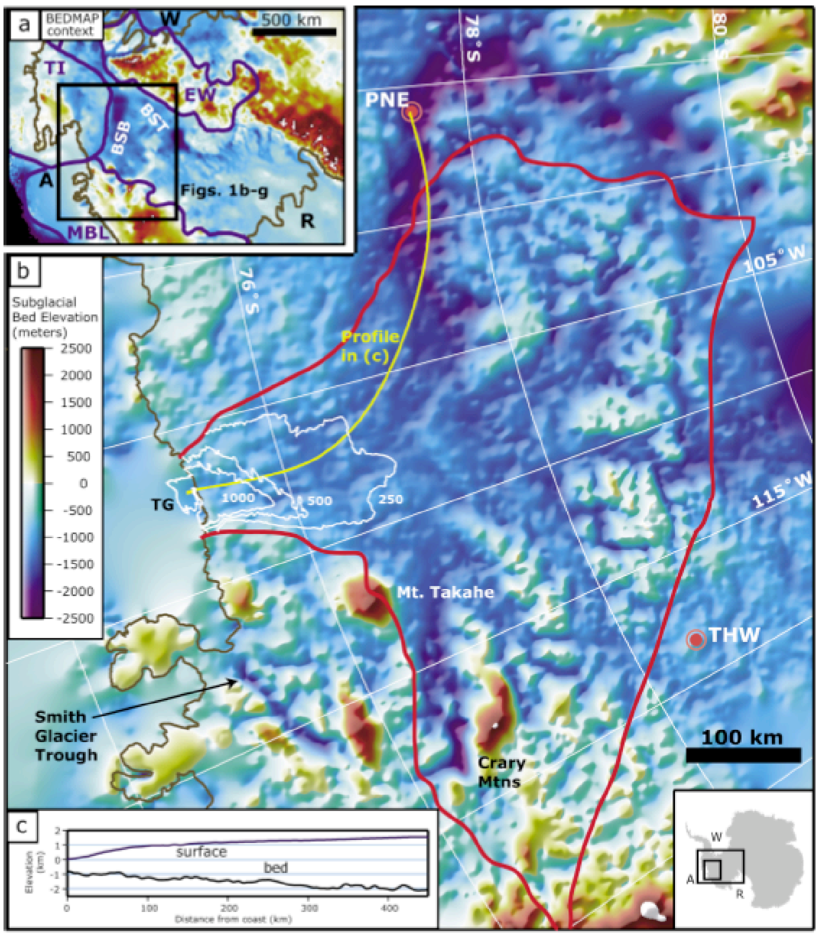

Figure 22: Subglacial topography of Thwaites Glacier [13]

Sediment and Ice Sheet Response

Whether or not a Thwaites Glacier collapse would spread to other areas of the West Antarctic Ice Sheet depends on the response of its tributaries and the retreat of its grounding line. The Larsen B collapse is a prime example of tributary acceleration and grounding line retreat in response to the loss of a buttressing ice shelf. [5] Previous studies on the conditions necessary to initialize ice streams in tributaries of the Ross Ice Shelf have shown that the presence of subglacial marine sediments to be a key conditions on determining the behavior of ice stream flow.[14,15] The subglacial topography in Figure 23 shows the onset of ice streams to correspond with the elevation at which marine sediments exist in the region.

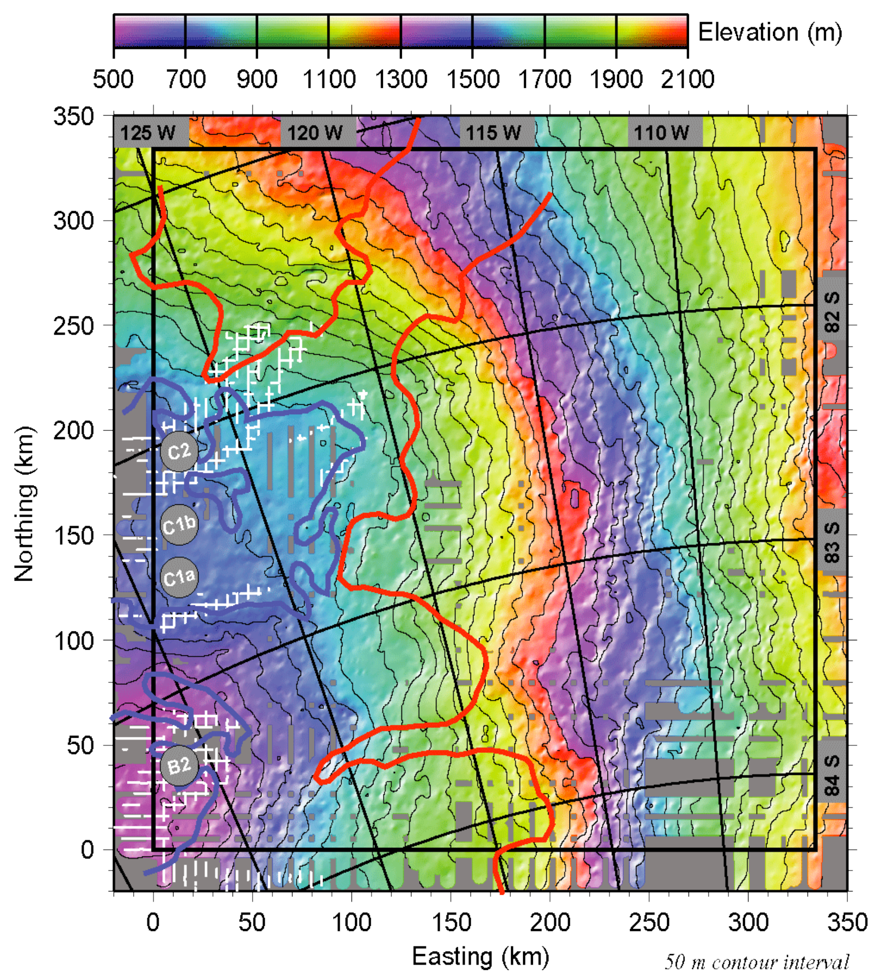

Figure 23: Subglacial topography near initiation of Ice Streams B and C [14]

The WAIS subglacial topography and sediment map shown in Figure 24 further established the correlation between tributary ice flow and the presence of marine sediment. [15]

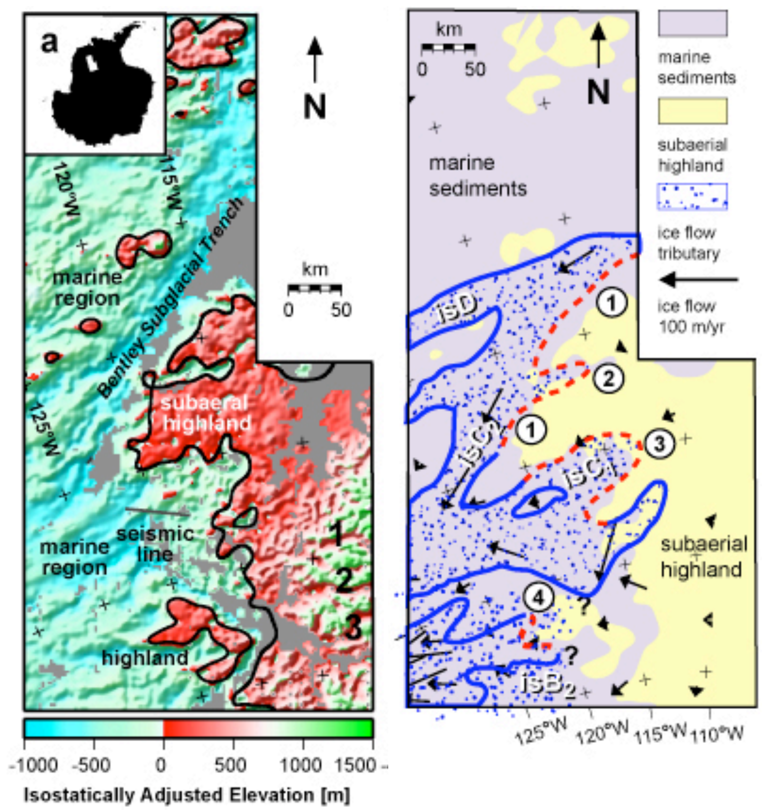

Figure 24: Subglacial topography, sediment mask, and ice stream initiation in WAIS [15]

Hydrology and Ice Sheet Response

Another key factor in determining the tributary level response of an Thwaites Glacier buttressing ice shelf loss is the subglacial hydrology. [19] In numerical models of the inception phase of glaciers in the northern hemisphere (Figure 25) the subglacial hydrology had a substantial impact on the extent, duration, and thickness of the simulated ice sheet. [16] The effect of sliding law exponent, which is a parameter representing subglacial hydrology, on simulated ice sheet thickness is shown in Figure 26.

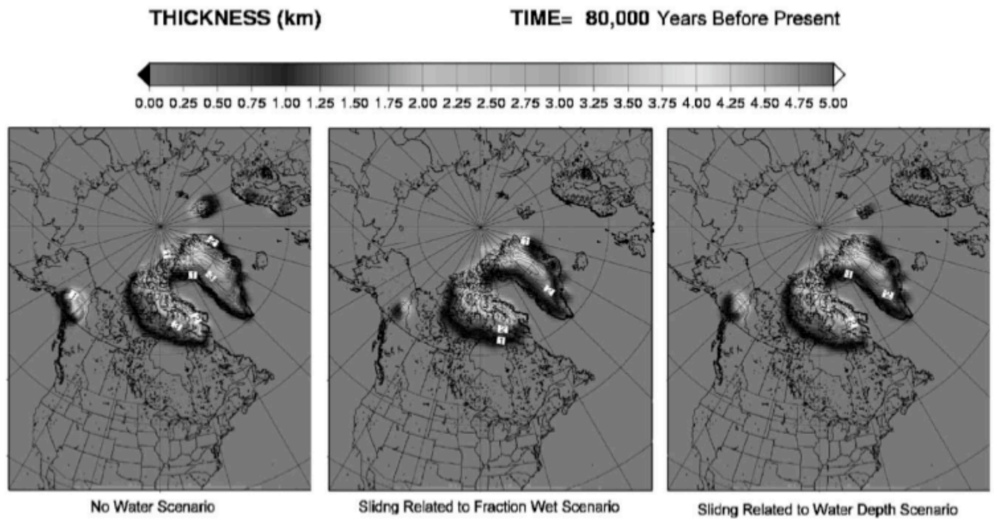

Figure 25: Modeled ice sheet thickness for different subglacial hydrology parameters [16]

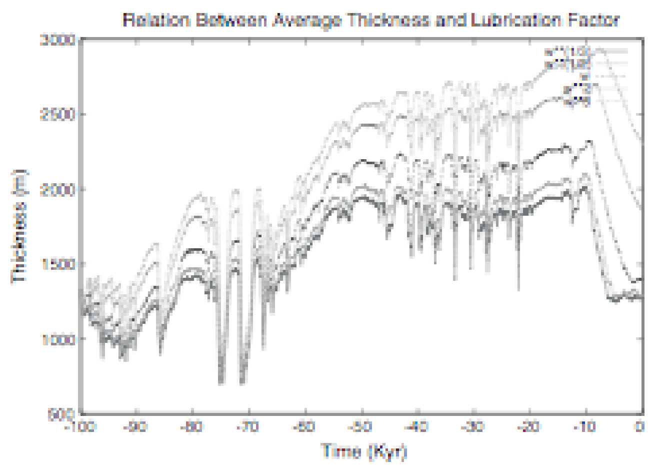

Figure 26: Sensitivity of average thickness to sliding law exponent in a NH ice sheet model [16]

Although the subglacial hydrology is difficult to observe beneath kilometers of ice numerous, interconnected subglacial hydraulic systems have been observed beneath the East Antarctic Ice Sheet (Figure 27) using airborne radar sounding as shown in Figure 28. [17] These systems of basal melt-water can be produced by both ice sheet motion and geothermal heat flux as shown in Figure 29.

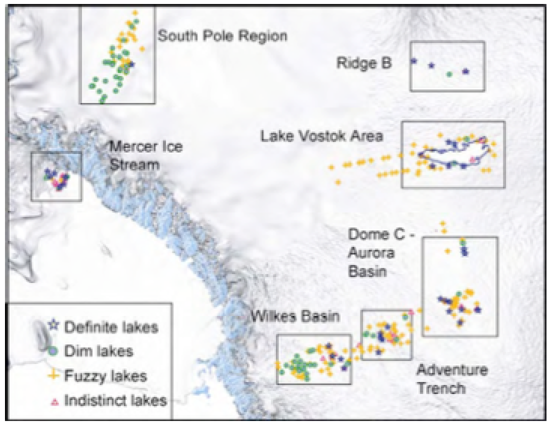

Figure 27: Subglacial lakes identified in the East Antarctic Ice Sheet [17]

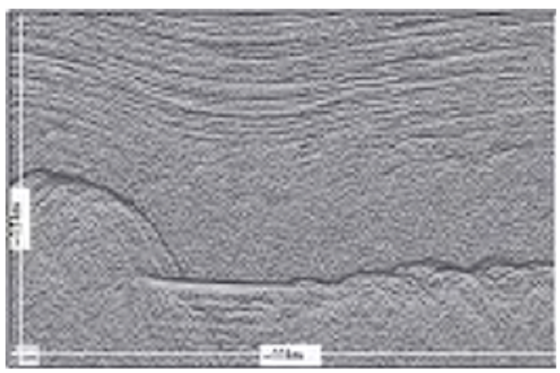

Figure 28: Radar-gram of a subglacial lake [17]

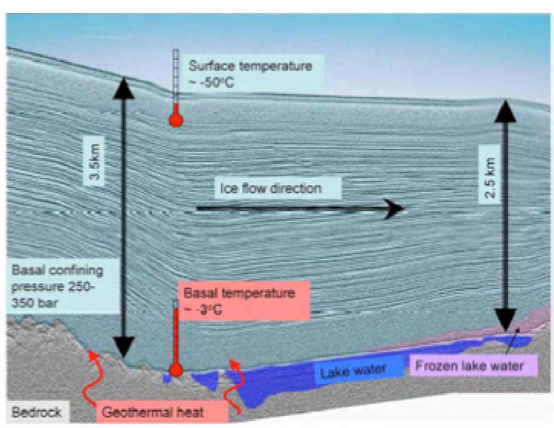

Figure 29: Anatomy of subglacial lake systems [17]

Geothermal Flux and Ice Sheet Response

The basal heat distribution of a glacier can be both a cause and effect of ice sheet motion. Geothermal heat flux, if of sufficient magnitude and heterogeneity, can be the dominant boundary condition in determining ice sheet behavior. [18] Figure 30 shows the difference in the basal heat distributions of two simulations of the Greenland Ice Sheet. The model on the left used fitted parameters and the model on the left assumed a uniform heat distribution (which is currently the most widely used boundary condition). The differences between these distributions as well as those produced from methods using gravity and magnetic anamolities show the large uncertainties in our knowledge this highly influential boundary condition. [23]

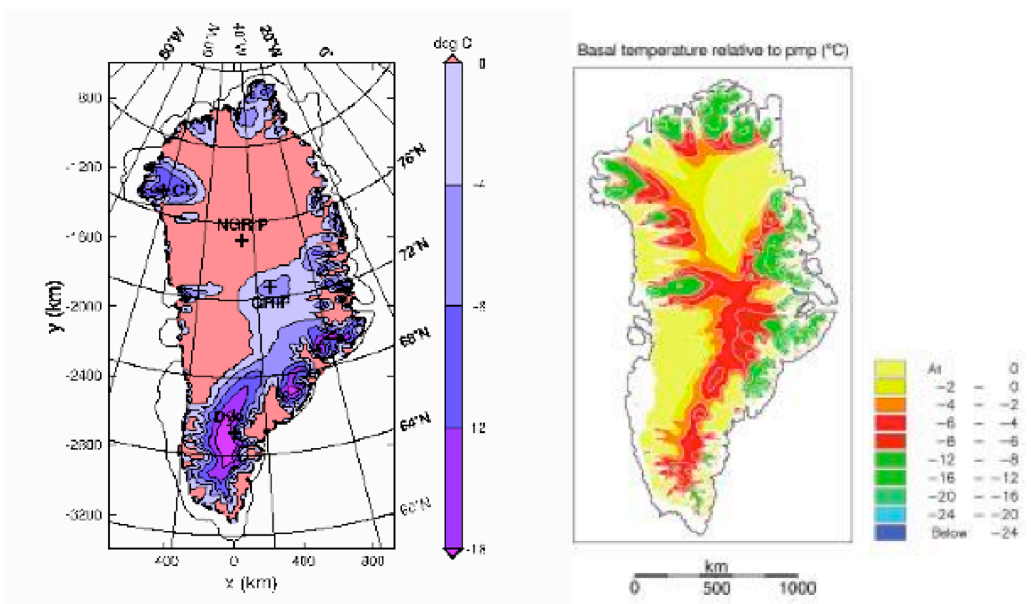

Figure 30: Modeled basal heat distribution from initial geothermal flux boundary conditions derived from fitted parameters (left) and a uniform assumption (right) [18]

In the specific context of the WAIS, there is the potential to use a similar technique with much higher resolution airborne gravity and magnetic measurements to constrain the geothermal heat flux. Figure 31 shows gravity and magnetic data collected in concert with topography determined by subglacial radar sounding. [14]

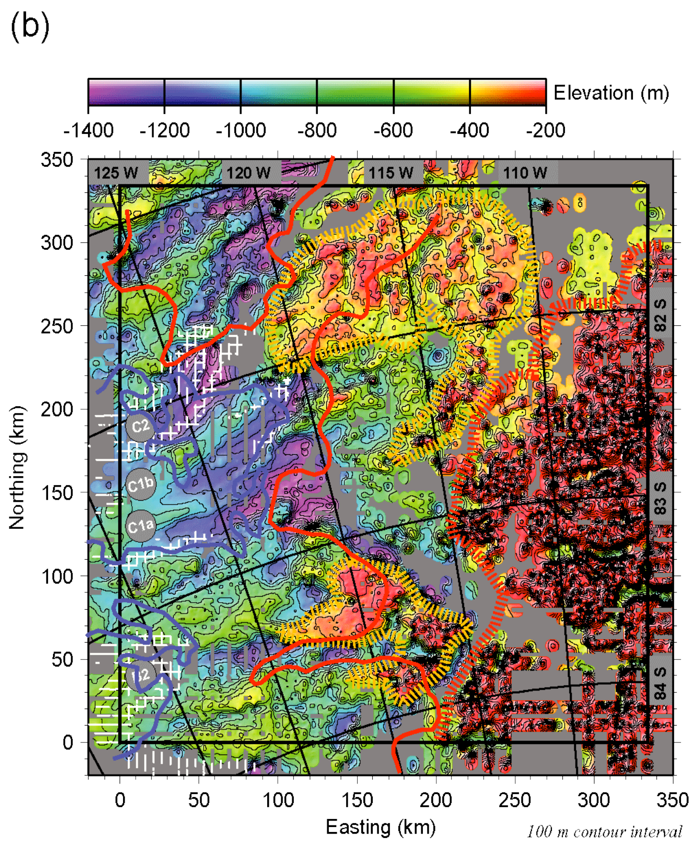

Figure 31: Airborne gravity and magnetic anomality observations over the WAIS [14]

Challenges in Modeling the West Antarctic Ice Sheet

A numerical model that accurately reproduces the governing dynamics of the Thwaites Glacier catchment in West Antarctic Ice Sheet will be essential in accurately predicting the possibility of WAIS collapse and/or its contribution to future sea level. The current state of ice sheet modeling in general and the integration of observational data and models for the Thwaites Glacier catchment in particular are impeded by several key challenges. [19, 24] Prominent among them are physical processes that are poorly represented (or not represented at all) in the current state-of-the art ice sheet models. These include: 1) ice-sheet/ocean interaction, 2) grounding-line migration, 3) ice-stream dynamics, 4) basal processes, 5) iceberg calving, and 6) higher order ice physics. [24] In addition to and perhaps resulting from these poorly represented physical processes, ice sheet models have produced highly divergent predictions for the stability of the WAIS, with some models predicting rapid retreat and others predicting stability even without a buttressing ice shelf. [20] A model of the Thwaites Glacier catchment is also faced with the challenge of integrating a set of observational boundary conditions produced from data that varies widely in kind, accuracy, and resolution. [13, 14] Finally, there has been no systematic study of the uncertainty in predictions from data constrained ice sheet models. A reduction and quantification in the uncertainty of sea level rise predictions for the West Antarctic Ice Sheet is essential if it is going to be included in the next version of the IPCC report.

Conclusion

Although its current contribution to eustatic sea level rise is small compared to even much smaller portions of the cryosphere, the West Antarctic Ice Sheet represents the dominant source of uncertainty in future sea level rise. The current and projected increases in CO_2 and mean global temperature are indicative of continued and possibly accelerated sea level rise. As the final remaining marine ice sheet, the WAIS is vulnerable to the same sort of abrupt collapse as observed on the Antarctic Peninsula with the Larsen B ice shelf. Large recent changes at the margins of the WAIS have suggested that the dynamic response of the Amundsen Sea Embayment is a likely candidate of that kind of remote change. Warming oceans eroding the bottom of the Pine Island and Thwaites Glaciers has been identified as the source of their accelerating discharge rates. Although Pine Island Glacier has exhibited the largest dynamic response, the subglacial topography of the ASE has singled out Thwaites Glacier as the 'weak underbelly' capable of initializing an ice-sheet scale collapse of the WAIS. If the buttressing ice shelf of Thwaites Glacier is eventually lost to warming seas, the resulting tributary acceleration and grounding line retreat will be determined, in part, by catchment sediment, morphology, hydrology, and geothermal heat flux. Implementing these boundary conditions from a diverse set of observational data and quantifying the uncertainty in predictions for the contribution to sea level rise will require significant advances in ice sheet modeling. Ultimately, reducing the uncertainty in the future of Thwaites Glacier will reduce the largest source of uncertainty in predicting the future of global sea level rise.

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