THE ANTARCTIC AND SEA LEVEL RISE

By Gary Antonides

Antarctica is the highest, driest, coldest, and windiest of the seven continents. It is roughly the size of the United States and Mexico combined and is almost completely covered by a layer of ice that averages more than one mile in thickness, but is nearly three miles thick in places. This ice accumulated over millions of years through snowfall. Presently, the Antarctic ice sheet contains 90% of the ice on Earth and would raise sea levels worldwide by over 200 feet were it to melt. This description of Antarctica is found on https://lima.nasa.gov/antarctica/

Antarctica is made up of three regions. The 2000-kilometer Transantarctic Mountains separate the continent into a large sector in the east called East Antarctica, and a smaller sector in the west called West Antarctica. The Antarctic Peninsula is the most northerly region and is primarily a second mountain range.

The East Antarctic ice is typified by vast flat areas of polar desert, where it is too cold for much snow to fall, and frigid winds blow continuously. The West Antarctic ice sheet rests on a bed well below sea level and is drained by large outlet glaciers and ice streams that flow for hundreds of kilometers before reaching the ocean, often through large floating ice shelves.

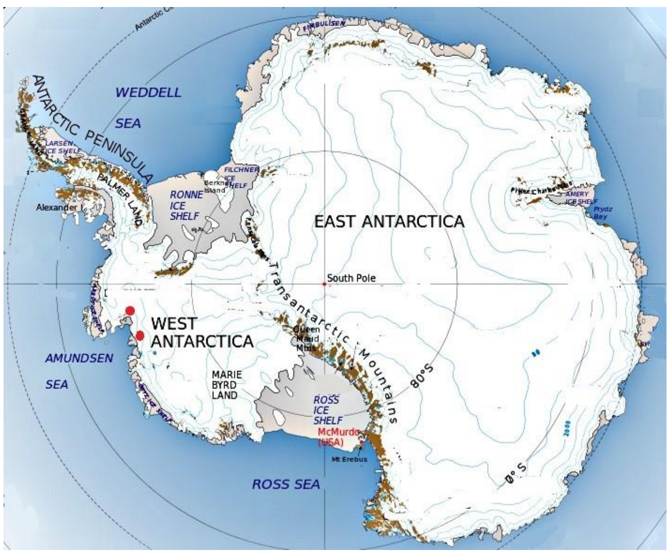

Figure 1.

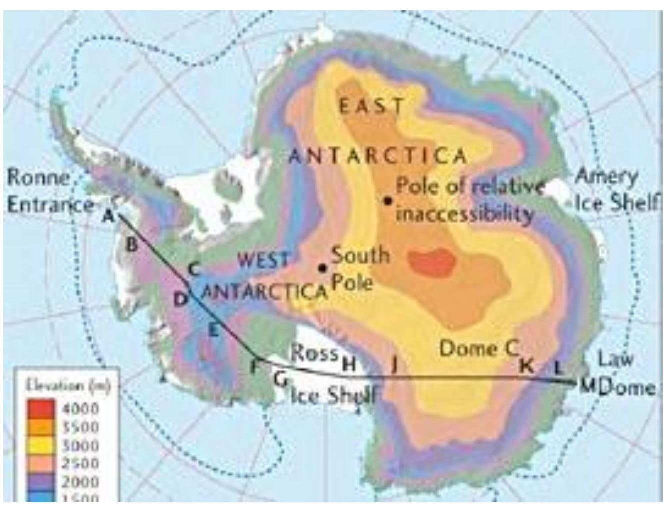

Figure 2. The elevation of the ice sheet shows the higher dome of the East Antarctic ice sheet.

The ground beneath the Antarctic ice sheet is a mixture of mountains, plains, and ocean basins. The tallest mountains extend above the ice sheet, the highest being 4,897 meters above sea level. The deepest known ice rests 2,555 meters below sea level, where the ice is over 4 kilometers thick. Gravity exerts sufficient force on the ice that the ice sheet moves. Flow rates increase toward the coast as faster moving glaciers are formed. Some glaciers flow into the ocean while others form large, thick floating ice shelves. The Pine Island Glacier (see upper red dot in Figure 1), flowing at over 10,000 feet per year, is believed to be the fastest Antarctic glacier. The largest ice shelf is the Ross Ice Shelf, roughly the size of Texas.

When talking about sea level rise, Antarctica must be considered since it contains about 90% of the world's ice, and, if it all melted, sea level rise would be about 200 ft. That won't happen, but the ice *is* melting, and we need to anticipate how much. The science involved is still a work in progress.

http://www.nationalgeographic.com/magazine/2017/07/antarctica-sea-level-rise-climate-change/ describes some of the recent studies with a disturbing headline: *"The Larsen C Ice Shelf Collapse Is Just the Beginning—Antarctica Is Melting. The massive iceberg that broke off the Larsen C Ice Shelf may be a harbinger of a continent-wide collapse that would swamp coastal cities around the world."* The story, by Douglas Fox, appeared in the July 2017 *National Geographic*, and was updated on line when a Delaware-sized iceberg broke off the Larsen C ice shelf. This does not raise sea levels since the ice shelf was floating, but ice shelves hold back glaciers that, when they reach the ocean and calve, do raise sea levels.

Antarctic Peninsula. Average warming here has been far greater than elsewhere on the continent. That explains why the huge iceberg broke off the Larsen C Ice Shelf and why, since 1988, four ice shelves on the east side of the peninsula have completely disintegrated into icebergs in the Weddell Sea. The Larsen C Ice Shelf may one day also disappear. Catching the winds and ocean currents that swirl around Antarctica, the peninsula gets slammed with warm air and water from farther north. Average temperatures on its west side have risen nearly 5ºF since 1950, several times faster than the rest of the planet. Winters have warmed an incredible 9ºF. Sea ice now forms four months a year instead of seven.

Warmer air helped trigger these collapses by forming meltwater ponds on the surface of ice shelves. The ponds drained into crevasses, making them deeper. As the shelves have vanished, the glaciers they once stabilized have accelerated to as much as nine times their original speed. They're relatively small glaciers and won't raise sea level much, but it raises concerns that the same thing might happen to the much larger glaciers along the Amundsen Sea.

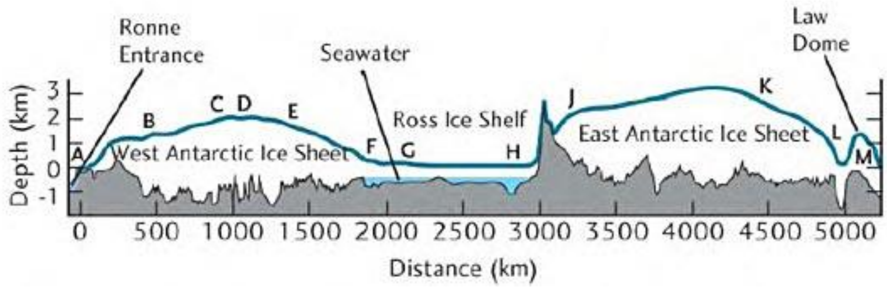

Figure 3. A vertical cross-section through Antarctica shows that the East Antarctic ice sheet is much higher than the West Antarctic ice sheet. Note that most of the ground along the cross section is below sea level but ice prevents the sea from intruding.

Pine Island Glacier. The Amundsen Sea lies a thousand miles to the southwest. The larger glaciers there, including the Pine Island Glacier, make the stakes far higher. Pine Island Glacier (upper red dot in Figure 1) is held back by the Pine Island Ice Shelf which is buckled and scarred by thousands of large crevasses. In 2015 and 2016 a 225-square-mile chunk of it broke off into the Amundsen Sea. The water there has warmed by more than 1ºF over the past few decades, and the rate at which ice is melting and calving has quadrupled. The Pine Island Ice Shelf, about 1,300 feet thick over most of its area, thinned by an average of 150 feet from 1994 to 2012.

The Pine Island Glacier is one of several large glaciers that empty into the Amundsen Sea and drain a much larger dome of ice, the West Antarctic Ice Sheet, which is up to two and a half miles thick and covers an area twice the size of Texas. The ice sheet is draped over a series of islands, but most of it rests on the floor of a basin that dips more than 5,000 feet below sea level. That makes it especially vulnerable to the warming ocean. If all that ice were to break into pieces, and float away, as researchers increasingly believe it might, it would raise sea level by roughly 10 feet.

In December 2012, a Twin Otter plane landed on the Pine Island Ice Shelf, being very careful to avoid snow covered crevasses. A research team led by glaciologist Martin Truffer of the University of Alaska got out of the plane and set up camp, planning to spend two months on the ice shelf. No one had spent even a single night before. They wanted to bore holes all the way through the ice shelf and measure the heat eating at it from the seawater below. As they lay in their tents at night, they heard loud pops and bangs coming from the ice. Each morning they saw new cracks. During their five weeks there, the ice thinned by seven feet.

It has been very difficult for research ships to get close to West Antarctica's glaciers. In summer, in front of the ice shelves, fractured sea ice joins icebergs calved from the ice shelves. That normally keeps ships at least 100 miles from the ice shelf.
However, in March 1994, the U.S. research icebreaker *R/V Nathaniel B. Palmer* became perhaps only the second vessel ever to reach it. For a few days winds parted the ice floes, creating a narrow passage. Sonar showed a chaotic seafloor of canyons and sharp ridges. The *Palmer* would spend just 12 hours by the ice shelf before encroaching sea ice forced it to retreat. But that gave the crew enough time to make a disturbing discovery. Near the surface, a current was streaming out from under the ice shelf that was less salty than the sea around it because it was freshened by melted ice. And at depths of 2,000 to 3,000 feet, in a seafloor canyon that ran under the ice, warmer seawater was streaming in.

The warm water was coming from the South Pacific more than 200 miles north. It was heavy with salt so it was following the floor of the submarine canyon. The glacier itself had carved that canyon during the Ice Age, when it reached hundreds of miles out from its present-day position. Tens of miles inland, the warm water was finding the "grounding line": the place where the glacier lifts off the seafloor. Hitting that wall of ice, the warm water was melting it, producing a steady stream of less salty seawater, which, being less dense, rises above the incoming water and flows back out to sea just under the shelf.

By measuring the amount of this freshwater, the researchers estimated how much ice was being lost. Adrian Jenkins, a glaciologist from the British Antarctic Survey in Cambridge, calculated that the ice shelf was losing an incredible 13 cubic miles of ice per year from its underside. Near the grounding line, the ice was probably thinning up to 300 feet per year.
Over the next 13 years Jenkins tried three times to return to Pine Island, but sea ice blocked him. When the *Palmer* got back there in 2009, the melt rate had increased by about 50%. This time they came with a robotic submarine. On its first three dives, it discovered that the ice shelf had thinned enough to lift off a submarine ridge that had once supported and stabilized the ice shelf. That had opened a gap that was allowing warm water to flow in and melt the underside of the ice even faster.

The sub's sonar revealed that the bottom of the ice shelf was corrugated with many channels that cut as far as 600 feet up into it, and along the ceiling of each ran a gaping crack. These upside-down canyons had been carved by flowing water. The meltwater rising off the grounding line was still warm enough to melt more ice as it flowed for tens of miles along the underside of the ice shelf back out to sea.

The Amundsen Sea is farther south than the peninsula, and the air there is not as warm. The biggest threat to its glaciers is these deep submarine canyons that channel warm water from the north under the ice shelves, and the deep inverted canyons that warm the underside of the ice.

Last November, Ian Howat, of the Byrd Polar and Climate Research Center in Ohio, reported two new rifts spreading across the Pine Island ice shelf that threaten to prune it to its shortest length in recorded history. The "warm" water flowing underneath it from offshore is 4 to 6ºF above freezing. As the Pine Island Ice Shelf has weakened and the glacier behind it has accelerated, the ice has stretched and thinned for 150 miles inland from the coast. The destabilizing effects spread farther into West Antarctica every year.

Other West Antarctic Glaciers. Research over the past few years indicates that the collapse of several major glaciers flowing into the Amundsen Sea is now unstoppable. Between 2002 and 2009 alone, the ice shelf in front of the Smith Glacier thinned by 1,500 feet in some places, the one in front of the Pope Glacier by up to 800 feet. The grounding lines of the Amundsen glaciers have retreated tens of miles in some cases. Each increment of retreat exposes a greater ice surface to warm ocean water. It's a runaway process—and scientists are urgently trying to figure out how fast it will proceed.

Most worrisome is the Thwaites Glacier (the lower red dot in Figure 1), which could destabilize most of the West Antarctic Ice Sheet if it collapsed. By itself it could raise global sea level four feet. Last fall the British and American science foundations announced a coordinated $20 million to $25 million field campaign that will deploy ships, planes, satellites, and underwater robots to assess the glacier's status.

"These are the fastest retreating glaciers on the face of the Earth," says Eric Rignot, a glaciologist at the NASA Jet Propulsion Laboratory in Pasadena, California. He believes the collapse of the West Antarctic Ice Sheet is only a matter of time. It may take 500 years or it may take less than a hundred.

Totten Glacier. To consider the long term worst case, we must consider East Antarctica, home to more than three-fourths of all the ice on Earth. This past January an old DC-3 from Australia's Casey Station made a series of flights along the East Antarctic coast. Over the Totten Glacier, a radar recorded the thickness of the ice. Another instrument found the topography of the seafloor under the glacier's floating ice shelf.

Until recently the East Antarctic Ice Sheet was considered secure. Much of it sits on high ground, but mapping with the ice-penetrating radar has revealed a low-lying region cut by glacially carved channels that drop as far as 8,500 feet below sea level. This is perfect for guiding warm ocean water deep into the heart of the ice sheet. The Totten Glacier is the largest coastal outlet in this region. If it collapsed, global sea level could rise 13 feet, just from that one glacier.

In 2015, the Australian icebreaker *Aurora Australis* became the first ship to reach the front of Totten. Like the *Palmer* at Pine Island in 1994, it found deep, warm water flowing under the ice shelf. The glacier is already losing a couple of cubic miles of ice per year. That's not much in Antarctic terms, but there is concern that it could increase dramatically. Totten will lose its ice much more slowly than West Antarctica. The worst case regarding sea level rise still seems to be centuries away.

Other Surveys. A satellite survey last year of many Antarctic ice shelves led by Ted Scambos of the National Snow and Ice Data Center in Colorado, and Helen Fricker of the Scripps Institution of Oceanography in San Diego revealed that melt canyons are common. They tend to steer water toward the edges of the shelves making the ice there thinner than the rest of the shelf. The ice there is crucial because it rubs against the stationary banks and slows the flow of the shelf and the glacier behind it. Fricker and her team have found that from 1994 to 2012, the amount of ice disappearing from all Antarctic ice shelves increased 12-fold, from 6 cubic miles to 74 per year.

Predictions. Sea level rise may not be disastrous for the next 30 to 40 years, but from 2050 to 2100 things could be different. The heat now hitting the Antarctic ice shelves comes from intensified circumpolar winds and currents driving water from further offshore onto the continental shelf and under the floating ice. That water is warmer than more local water, and the ocean in general is warming. These effects will continue to melt ice even if we begin to cut emissions.

For now, the best estimates suggest that Antarctica will melt enough ice to raise global sea levels by 1.5 to 3.5 feet by 2100. With Greenland and other rapidly melting glaciers around the world, average sea levels could rise 3 to 7 feet by 2100. But sea level won't stop rising in 2100. A complete collapse of the Greenland and West Antarctic Ice Sheets would raise sea level only about 35 feet, but if the East Antarctic Ice Sheet melts, the rise will be well over 200 feet.

Predictions of sea level rise due to glaciers melting cannot be reliable until the science is better understood and good models developed. An example of the type of difficulties in developing models is the study of sea ice in the Antarctic, which should be a simpler problem to assess. It is discussed in the next article.