## Antarctic Ice Sheet: past and present

#### An educational module for high-school and introductory-college students focused on changes in the Antarctic Ice Sheet from 20,000 years ago to present.

*Developed by Leigh Stearns (University of Kansas; stearns@ku.edu) and Lauren Simkins (University of Virginia; lsimkins@virginia.edu) as part of NSF Office of Polar Programs Grant 1745055.*

The Antarctic Ice Sheet is one of the two existing ice sheets today; however, about 20,000 years ago during a time period called the Last Glacial Maximum, more ice sheets existed and both the Antarctic and Greenland ice sheets were much larger than they are today.

The 1.5-hour lesson you are about to begin is interactive using Google Earth and Google Sheets and will introduce you to multiple subject areas including glaciology, geomorphology, and climatology. You will gain experience identifying surface features in Antarctica, mapping glacial landforms preserved on the seafloor, calculating retreat rates of parts of the Antarctic Ice Sheet, and critically thinking about why changes in ice-sheet extent happen.

##### Getting started

After completing the pre-lesson assignment per your instructor’s guidance prior to the lesson, you are ready to move on to thinking about why the Antarctic Ice Sheet is changing today, what it was like in the past, and what its future might be in a warming world. Your instructor will ask you and your peers to discuss the pre-lesson assignment before you move on to the lesson. You will need an internet connection on a cell phone, tablet or computer to complete the lesson, but preferably a tablet or computer. Go ahead and navigate to the Google Earth map for the lesson: [Antarctic Ice Sheet: past and present](https://earth.google.com/earth/d/1DAaO1QL_obwFFtW7nO9KDOe3koHsK6KZ?usp=sharing), where the sites mentioned in the lesson can be found.

##### Part 1: The Antarctic Ice Sheet today

The Antarctic Ice Sheet today is losing ice quicker than new snow and ice is being gained. Watch this video by the National Aeronautics and Space Administration (NASA), Jet Propulsion Laboratory, and California Institute of Technology on Antarctic ice mass loss from 2002-2020

([Video: Antarctic Ice Mass Loss 2002-2020 – Climate Change: Vital Signs of the Planet](https://climate.nasa.gov/climate_resources/265/video-antarctic-ice-mass-loss-2002-2020/); **Image 1;** Site 1 in Google Earth map).

[INSERT IMAGE 1]

You will notice the units of ice loss are in a mass of Gt (gigatons) in the plot and in a change of ice thickness in meters water equivalent. An important reference is how many gigatons of ice lost raises sea level by 1 millimeters (mm) across all of Earth’s oceans. 1 mm of sea level rise spread across the oceans is equivalent to 362 Gt of ice loss (or -362 gigatons).

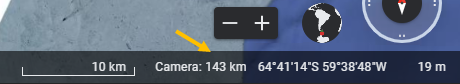
Image 1

**Question 1.1.** Determine the approximate cumulative (total) ice loss in gigatons between 2002 and 2020. How much (total) has the Antarctic Ice Sheet contributed to sea level since 2002 in mm? From 2002-2020, what is the average rate of sea level rise coming from the Antarctic Ice Sheet in mm per year? Show your work, include units, and round answers to the nearest tenth.

[INSERT IMAGE 2]

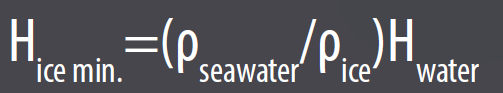
**Question 1.2.** The parts of the ice sheet that are losing the most ice since 2002 are the Antarctic Peninsula, West Antarctica (see Google Earth map), and a few places in East Antarctica. Two major reasons ice is being lost are a warming ocean that is directly in contact with ice shelves and ice-sheet grounding lines, where ice goes from rest on the land or seafloor to floating in the ocean, and, in some cases, the disintegration of ice shelves that act as physical barriers for any marine-terminating glacial systems (**Image 2**). Melting of ice due to relatively warm ocean water and collapse of ice shelves leads to accelerated ice-sheet flow into the ocean. And when ice flow speeds up, sea level rises even more than before. Being important for understanding the health of the Antarctic Ice Sheet today, let’s explore some ice shelves now.

* The biggest ice shelf in the world is the Ross Ice Shelf. Navigate to site #2 “The biggest ice shelf in the world” in the Google Earth map that is on average 400 meter (m) thick and receives glacial ice from many marine-terminating glacial systems. Estimate the area of the Ross Ice Shelf by using the “measure distance and area” tool () in square kilometers (km2). How many of your home state or country would fit into the ice shelf? Name and state the area of your home state or country.
* Navigate to site #3 “Aftermath of ice shelf collapse” at a camera altitude of about 140 km (see screenshot below) by zooming in or out and to the site #4 “Crumbling ice shelf”. In these locations you see an ice shelf that has completely lost its integrity by breaking up into individual, freely floating icebergs and can no longer plug upstream grounded ice flow and an ice shelf that appears to be in a phase of imminent collapse. Explore “ice-shelf collapse” and “ice-shelf buttressing” by doing a google search. Based on what you found, why might ice shelves be vulnerable to collapse (i.e., entirely breaking apart) in a warming world and what impact might that have on Antarctica’s sea-level contributions in the future?



The shape of the land beneath the ice sheet (site #5), known as bed topography, is also extremely important in controlling how much grounded ice flows into the ocean and how quickly the grounding line retreats. Deep valleys can steer and accumulate ice flow developing fast-flowing rivers of ice called ice streams. Bumps in the bed topography, like the one shown at placemark “Ice flow bending around a bed bump” (site #6), can cause ice flow to change directions. And grounding line retreat is sensitive to bed topography in many locations where the land dips down toward the interior of the ice in what glaciologists called a retrograde bed.

**Question 1.3.** The Antarctic grounding line today is shown as the red line in the Google Earth map (site #7), but it is not fixed in place and can migrate temporarily (daily, monthly) and more permanently (years to thousand of years). When ice flow speeds up or when water depth increases by a rise in sea level or deepening of the seafloor topography, ice-sheet grounding lines can pop off the seafloor because the ice is no longer thick enough to counteract buoyancy of the ice (**Image 3**). A simple equation helps us determine the minimum ice thickness needed to keep ice grounded on the seafloor:



where minimum ice thickness (Hice min.) needed to keep a grounding line stationary is a function of water density (⍴seawater,1,026 kg/m3), ice density at the grounding line (⍴ice, 916.7 kg/m3) and water depth (Hwater).

Let’s say we have a grounding line at a water depth of 600 m.

* What is the minimum ice thickness in m needed to keep the grounding line in place and prevent it from floating off the seafloor? Show your work, include units, and round to the nearest one.
* We have a grounding line where the ice thickness is 690 m in a water depth of 600 m, but ice flow speeds up causing the ice at the grounding line to thin to 650 m - think like stretching silly putty, the same amount of material but stretched thinner by the extensional force of your hands. This thinning causes the grounding line to retreat inland, but the water depth deepens to 700 m, instead of 600 m, due to a landward-dipping, retrograde bed. What is the minimum ice thickness needed to get the ice to reground in 700 m of water. Is the now-thinned ice able to regain contact with the bed in this water depth or will it continue to float and retreat inland?

[INSERT IMAGE 3]

##### Part 2: Rewind to the ice sheet’s past

Ice Sheets in places like North America, Europe, Russia, Pakistan, Patagonia, and Antarctica have had a remarkable impact on the landscapes we see today (**Image 4**). Ice-marginal landforms that form by sediments piling up at glacial termini or, for marine-terminating glacial systems, grounding lines (**Images 1 & 4**) allow glacial geologists (glaciologists using geoscience tools) to determine patterns and magnitudes of glacial retreat in the past from the distribution and spacing of these landforms.

[INSERT IMAGE 4]

About 20,000 years ago during a time period called the Last Glacial Maximum, sea level was about 120 m lower than it is today because ice sheet volume on Earth was much greater due to the cooler air and ocean temperatures. During this time, the Antarctic Ice Sheet was much larger than today and, in many places around the continent, extended to the seaward edge of the continental shelf - a portion of a continent that is submerged under an area of relatively shallow water (**Image 5**). When the ice sheet retreated it left behind it’s footprint so to speak in the form of sediments and landforms that are preserved still today on the seafloor. We can study these glacial footprints by collecting seafloor sediment cores - tubes of sediment that have stacked up over thousands of years - and mapping the bathymetry which gives us very accurate water depths that allow us to visualize the shape of the seafloor and the preserved glacial landforms, including ice-marginal landforms that we are going to explore in this part of the lesson.

**Question 2.1.** The approximate maximum extent of the Antarctic Ice Sheet during the Last Glacial Maximum is shown as the yellow line in the Google Earth map (site #8). Remember that the red line is the approximate *current* grounding line of the Antarctic Ice Sheet. We can track the past extensions of contemporary ice streams by merging current ice flow direction with glacial landform and modeling observations. Where we can track past flow all the way to the contemporary ice streams, we call these “flowlines” - three of which are shown as purple lines in the Google Earth map (sites #9 - #11; Byrd Glacier, Siple Coast, and Pine Island flowlines).

* Use the “measure distance and area” tool () to determine the distance in km between the Last Glacial Maximum extent (yellow line) and the present grounding line (red line) for each flow line. Round your answers to the nearest hundred.
* Dating the timing of past retreat events is challenging. In many places, we don’t know when ice started to retreat from its Last Glacial Maximum extent and don’t know how long it took for the grounding line to reach its current position. Let’s explore some potential retreat rates by using different durations of retreat and the distance you calculated in the previous question. What is the retreat rate in m per year between the maximum and current extent of the flowlines if you use a total duration of 10,000, 15,000, and 20,000 years? Round to the nearest ten. How do your calculated retreat rates compare to current retreat rates in **Image 6** for the same regions?

[INSERT IMAGES 5 & 6]

**Question 2.2.** With technological advances, we can see smaller features and landforms on the seafloor around Antarctica, including ice-marginal landforms that allow us to better understand retreat rates and patterns, compared to the simplified approach we used in Question 2.2. Two examples of ice-marginal landforms marking a series of retreat events are shown as sites #12 - #13 “ Ice-marginal landforms 1” and “Ice-marginal landforms 2”.

* Make at least two observations about the bathymetry images and the elevation profiles across ice-marginal landforms shown at the two sites.
* What might control the differences in the shape and size of the ice-marginal landforms you see?
* Even though we don’t know exactly when the grounding line was situated at the locations of the ice-marginal landforms, the magnitude of retreat events is important information for potential magnitudes of retreat in the future. From the highest peaks of the individual ice-marginal landforms, determine the approximate average magnitude of retreat as the average spacing between ice-marginal landforms. Round to the nearest hundred.

Part 3: Putting it all together - using the past to help understand the future

We can learn a lot about how ice sheets change in a warming climate by studying how they retreated from the Last Glacial Maximum. Average annual temperatures were roughly 8°C colder than today during the Last Glacial Maximum.

**Question 3.1.** Grounded ice often stabilizes on bedrock bumps, since these bumps will prevent thinner ice from floating. On the Google Earth page, revisit the flowlines (Google Earth sites #9 - #11) to see how the grounding lines rest on these bedrock bumps. If ice along these flowlines continues to thin, what do you think will happen to the grounding line? Do any of the flowlines have a higher bedrock bump upflow that might prevent retreat?

**Question 3.2.** Now, revisit the Antarctic-wide bed topography (Google Earth site #5). Knowing that bed topography that gets progressively deeper inland is more susceptible to retreat, what parts of Antarctica are likely to undergo the most retreat in a warming climate?

**Question 3.3.** The ice-marginal landforms show us that the grounding line can actually stabilize on relatively flat beds as well - they don’t always need a big bedrock bump. Ice marginal landform 2 (Google Earth slide #13) shows this most clearly; successive grounding lines formed where topography varies less than 10 m. The ability for ice to stabilize on flat terrain is a key process to include in our numerical models of future Antarctic mass loss. Unfortunately, this process does not hold on negatively sloping beds (that get deeper inland), especially if they are steep.

The flowlines that extend across the Ross Ice Shelf (Google Earth slides #9 and #10) show that retreat occurred over a fairly flat bed. In addition, the ice marginal landforms show relatively small magnitude retreat - where the grounded ice “jumped back”. You calculated this magnitude in Question 2.3. The Pine Island flowline shows some rougher topography, with notable bedrock highs that likely stabilized grounded ice in the past. What is the approximate magnitude of retreat between the last few (3-4) pinning points?

[INSERT IMAGE 7]

**Question 3.4.** Data from Antarctic ice cores reveal how Antarctic temperatures have changed over time (**Image 7**). The oldest ice cores are used to understand how climate has changed over the past 800,000 years! When we focus on just the last 20,000 years, we see that most of the warming occurred between 17,000 and 11,000 years ago. In other words, 8°C of warming occurred over 6,000 years. Current warming trends are roughly 1°C every 50 years. The worst-case scenarios project 4°C warming in (less than) 100 years. During each time period, calculate how many years it took (will take) to warm by 1°C.

##### 

##### Answer here if you are completing the pre-lesson assignment by computer.

**Question 1.1.** [Answer here]

**Question 1.2.** [Answer here]

**Question 1.3.** [Answer here]

**Question 2.1.** [Answer here]

**Question 2.2.** [Answer here]

**Question 3.1.** [Answer here]

**Question 3.2.** [Answer here]

**Question 3.3.** [Answer here]

**Question 3.4.** [Answer here]