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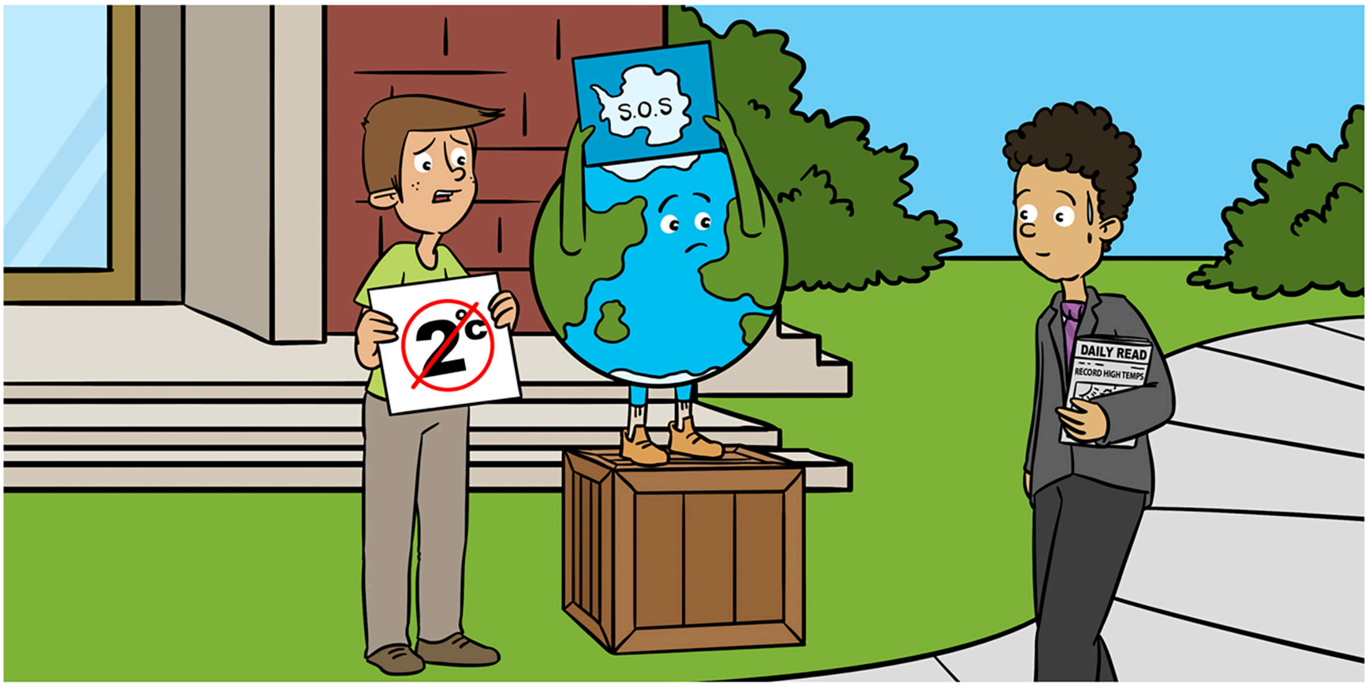

THE ANTARCTIC ICE SHEET—A SLEEPING GIANT?

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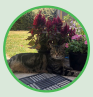
YOUNG REVIEWERS:


CHERYL
AGE: 9


PRICE
AGE: 13


PROVIDENCE
AGE: 10


SASYAK
AGE: 13

The coldest, the windiest, the driest: the continent of Antarctica is a place of extremes. Located at the South Pole, Antarctica is covered by a vast ice sheet, millions of years old and in some areas more than 4,000 m thick. If all this ice were to melt, sea levels would rise by roughly 58 m. Despite its massive size, the Antarctic ice sheet is vulnerable, losing more and more ice as the climate is warming. Most of this ice loss happens along the coast, where the ice sheet slowly flows into the ocean and forms ice shelves, which melt from below because of the comparably warmer ocean water. While the ice loss is still relatively slow right now, several processes could accelerate it and eventually even make it partly unstoppable. Wide-spread ice loss can only be prevented on the long-term if we manage to limit global warming to well below 2°C.

CONTINENT OF SUPERLATIVES

Located at the South Pole, Antarctica is the coldest place on Earth. Temperatures there can drop to as low as −90°C, and it often feels even colder because of strong winds that can reach speeds of up to 300 km/h. Because of the low temperatures, snow falling over the Antarctic continent usually does not melt and has been collecting over millions of years to form a giant **ice sheet** (Figure 1). In some places, the ice cover is more than 4 km thick!

ICE SHEET

A huge body of ice that covers vast expanses of the polar regions. Currently, Greenland and Antarctica are covered by ice sheets.

The vast ice sheet contains an amazing record of Earth's past climate: as new layers of snow are added at the surface, the snow further down is slowly squeezed together and changes into ice, forming layers like tree rings. If we drill into the depths of the ice sheet, each layer takes us further and further back in time. Tiny air bubbles from the time of the initial snowfall remain trapped inside and allow us a glimpse into the climate of many thousands of years ago [1]. Ice up to 800,000 years old has been extracted from the depths of the ice sheet, and researchers all around the world are trying to find even older ice. This old ice helps us to understand how the climate evolved during past ice ages and during warm ages like the one we live in today.

A SEA-LEVEL GIANT

Whenever parts of the ice sheet drain into the ocean, this results in a rise in sea level. Because the oceans are so big, it takes a lot of melt water to raise sea levels by a large amount: 360 billion tons of ice loss cause a rise in global sea-level of merely 1 millimeter. Knowing this, can you imagine that all around the world, sea levels would be raised on average by an incredible 58 meters [2] if the Antarctic ice sheet were to melt down completely? This ice sheet truly is a sea-level giant!

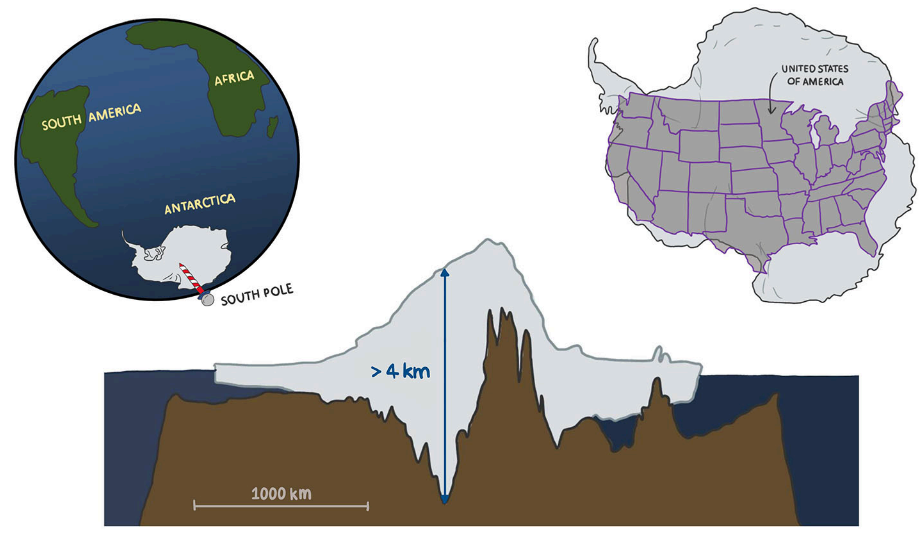


Figure 1

Figure 1

The Antarctic continent is located at the South Pole and is covered by a giant ice sheet. Antarctica is bigger than the USA and, in many places, the ice sheet is more than 4 km thick. Water from the melting ice sheet drains into the oceans and causes sea-level rise.

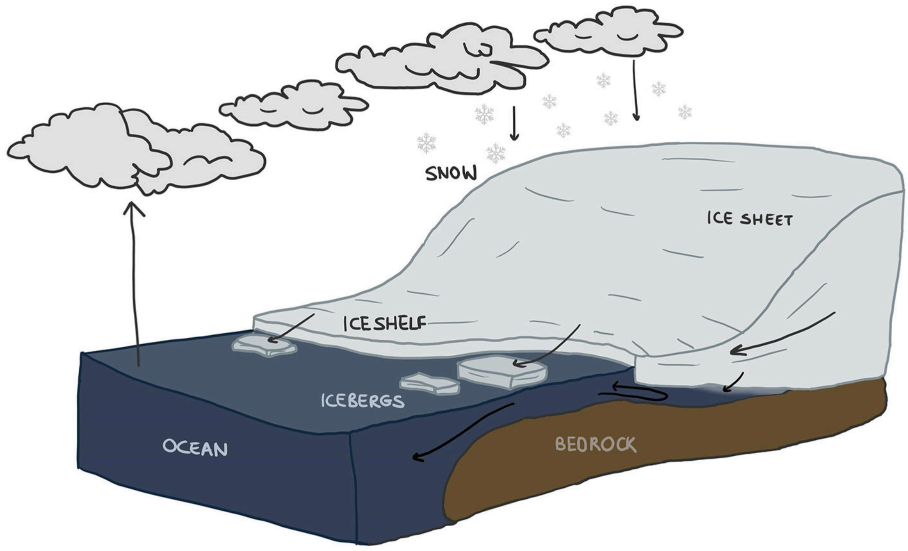


Figure 2

Figure 2

Key processes within the Antarctic ice sheet and its ice shelves. As the ice flows from the interior of the ice sheet into the ocean, it can form ice shelves, floating extensions of the grounded ice sheet. The ice sheet gains mass at its surface, through snowfall, and loses mass through faster flow toward its margins, through calving (the breaking off of icebergs) and through melting at its surface and, importantly, underneath the ice shelves where they are in contact with the surrounding ocean waters.

Even though Antarctica may seem far away, changes in its ice cover and the resulting sea-level rise have direct impacts around the globe, affecting millions of people. Forty percent of the world's population live less than 100 km away from the coast, with more than 600 million people in areas that are less than 10 m above sea level. If the Antarctic ice sheet continues to melt, more and more people are at risk of eventually being affected by the potential loss of their homes and the bridges, dykes, roads, and power plants that they depend on.

It is therefore important to monitor, understand, and predict changes in the Antarctic ice cover as accurately as possible. Over the past 25 years, Antarctica has lost roughly 3 trillion tons of ice [3]. What is more, some regions have lost much more ice in recent years than they did before, so that sea-levels are rising faster and faster. Eventually, ice loss from Antarctica might become the largest source of global sea-level rise.

WHY IS ANTARCTICA LOSING ICE?

POLAR DESERT

Polar regions with very little precipitation and low annual temperatures. Most of the interior of Antarctica is a polar desert, despite its thick ice cover.

To understand why Antarctica is losing ice, we must first look at how the ice sheet was created. Clouds that form over the ocean around Antarctica carry moisture toward the ice sheet, where it falls onto the ice as snow, building up the ice sheet layer by layer (Figure 2). Because the air is extremely cold, it cannot carry much moisture, which is why—maybe surprisingly—Antarctica is an extremely dry place or **polar desert**. It therefore took hundreds of thousands of years for this huge ice sheet to form.

Due to the high pressure that builds up in an ice sheet as massive as the one in Antarctica, the ice does not behave like a fully solid material as the ice cubes in your freezer. Instead, the glacial ice actually flows very, very slowly, from the interior of the ice sheet toward the coast. As the ice reaches the surrounding ocean waters it can start to float, creating extensions called **ice shelves**, which can be hundreds of meters thick. Every now and then, massive blocks of ice break off from these ice shelves to form icebergs. And where they are in contact with warmer ocean waters, ice shelves melt from below. Over the past decades, this so-called **sub-shelf melting** has increased, which in turn has led to faster flow of parts of the ice sheet further inland—one of the key reasons for the mass loss from Antarctica observed at present.

ICE SHELVES

Large platform of ice that forms where an ice sheet flows into the ocean and starts floating.

SUB-SHELF MELTING

Melting at the base of ice shelves, where they are in contact with the surrounding ocean waters.

HOW IS ICE LOSS CHANGING TODAY?

For thousands of years, the ice loss in Antarctica was largely equal to the amount of ice gained through snowfall, so the size of the ice sheet remained relatively constant—but this is changing now. Global warming, caused by greenhouse gas emissions from the burning of **fossil fuels** such as coal and oil, has already left its mark on Earth's polar landscapes. Unless kept in check, climate change will lead to further ice loss from the Antarctic ice sheet. At some point, the ice loss in certain regions could become irreversible.

FOSSIL FUELS

Fuels that formed underground many millions of years ago, like oil, coal, and natural gas. When we burn them to generate energy, they release carbon dioxide into the atmosphere.

The reason for this lies in a number of self-amplifying feedbacks between the ice, the surrounding air, the ocean, and the bedrock underneath the ice. One of these feedbacks is related to the outflow of ice in regions where it sits on bedrock below sea-level. This is the case for large parts of West Antarctica and certain regions in East Antarctica. In these so-called **marine ice-sheet** areas, if the bedrock becomes deeper as we move further inland, ice loss—once triggered—can become practically unstoppable: With increased calving or sub-shelf melting, the ice shelves lose some of their buffering effect on the nearby glaciers, causing them to flow faster. As a consequence, the **grounding line**—the boundary between the ice sheet sitting on land and the floating ice shelves—retreats further inland. As the ice further inland is thicker, and thicker ice generally leads to higher ice flux, this will cause the grounding line to retreat even further—and so on. In this way, an entire area of ice can fall into a vicious circle, in which ice loss causes more ice loss. This self-amplifying feedback only stops once a new stable position of the grounding line is reached, where the ice outflow is matched by the snowfall accumulation again.

MARINE ICE SHEET

An ice sheet sitting on bedrock that is below sea level, for example the West Antarctic Ice Sheet.

GROUNDING LINE

The grounding line separates the ice sheet, sitting on land, from the surrounding floating ice shelves.

Because of vicious circles like this one, we call Antarctica a "tipping element" in the climate system: once temperatures reach a certain level, a tiny amount of additional warming can start a chain reaction of ice loss that becomes difficult to stop. Such drastic ice loss would not happen overnight, though; in fact, it will likely take hundreds or even thousands of years. But while the consequences may unfold over very long timescales, some of these long-term changes could already be set in motion within the next few decades. As the planet continues to

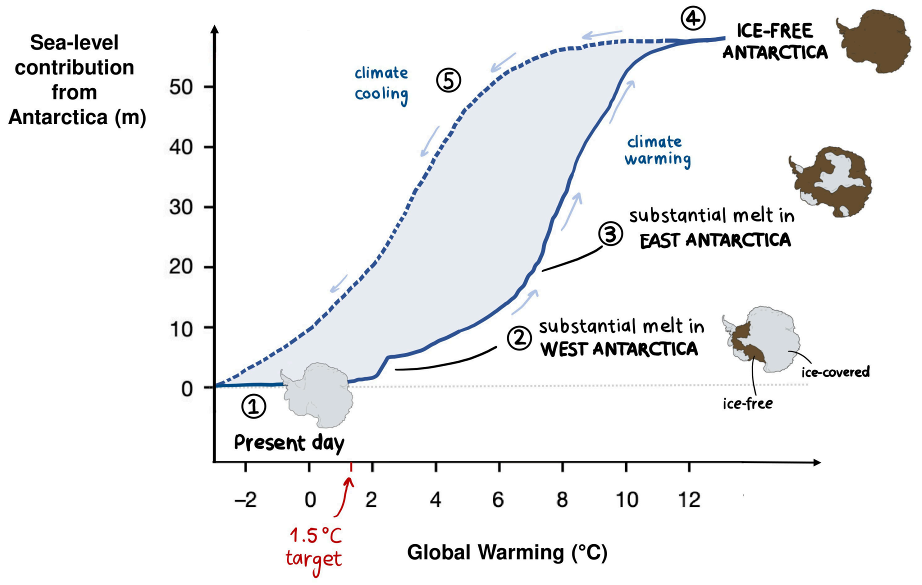


Figure 3

Figure 3

The future of the Antarctic ice sheet depends on the amount of global warming. The more the planet heats up, the more ice will eventually be lost. These changes are largely irreversible: once parts of the ice sheet are gone, they would only regrow if our climate became much cooler again.

GREENHOUSE GASES

Gases in the atmosphere that can warm Earth's climate. One of the most abundant and significant long-lived greenhouse gases is carbon dioxide. Other examples are water vapor, methane and nitrous oxide.

warm due to **greenhouse gases** produced from the burning of fossil fuels, the risk of triggering ice loss that will be unstoppable for many thousands of years is increasing.

WHAT WILL THE FUTURE BRING?

The amount of future ice loss therefore primarily depends on *our* actions. If we do not rapidly reduce the release of greenhouse gases, global temperatures will keep rising. Should they reach warming levels of 2°C compared to the temperatures we had 150 years ago, scientists expect that large parts of West Antarctica would become unstable (Figure 3). This could eventually result in more than 2.5 m of global sea-level rise through the processes and feedbacks described above [4] (see lower line in Figure 3).

If the planet continues to warm beyond 2°C, additional regions of the Antarctic ice sheet may also become unstable, leading to further sea-level rise. And once parts of the ice sheet are lost, they might be lost forever: even if temperatures eventually sank again, cooling well below today's temperatures would be required to regrow the Antarctic ice sheet to its present-day size (see upper line in Figure 3). These possible consequences for the Antarctic ice sheet and other parts of the climate system were one of the reasons why, in a 2015 meeting in Paris, world leaders agreed that we need to limit global warming to well below 2°C.

Over millions of years, much longer than we humans have existed, the Antarctic ice sheet has evolved, helping to form our global environment and today's landscapes. Now the fate of Antarctica—and that of the many people who will suffer from rising sea levels—lies in our hands.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

CHERYL, AGE: 9

Hi, I am Cheryl. I have a cat named Delilah and 2 little sisters called Tanya and Alice. I live in a small city of Canberra. I am sometimes pretty shy and sometimes pretty cheeky. I absolutely love icecream especially "Cookies 'n' cream." Love you all.

PRICE, AGE: 13

Price loves making up stories and has also written a book (Ms. Wasteson and the waste empire). She enjoys gymnastics, athletics, volleyball, and basketball. She is brave and bouncy. Price also enjoys quality time with family and is very creative. At her school, she is part of a "green team" that works to protect the environment. She likes debating and has a passion to study and become an activist against social injustices.

PROVIDENCE, AGE: 10

Providence is the youngest amongst her three sisters. She is playful and bouncy. Providence is curious, talkative, and likes asking many funny questions, that leaves others laughing. She loves making new friends and traveling. Providence loves science experiments. During this process, she may destroy, repair or recycle some household items. As part of this adventure, Providence repaired a spoilt speaker. But after weeks of action, she modeled the speaker wires into skipping ropes. She is passionate about music and sports including volleyball.

SASYAK, AGE: 13

Sasyak is a 13 year old student from India. He is an avid reader of several genres of books. He is a keen participant in quiz contests and olympiads, and is a spell bee champion. He attends football classes and enjoys cycling.

AUTHORS

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Ricarda Winkelmann is a Professor of Climate System Analysis at the University of Potsdam and the Potsdam Institute for Climate Impact Research (PIK) in Germany, where she leads the Working Group on Ice Dynamics, as well as the FutureLab on Earth Resilience in the Anthropocene. She will never forget the first time she set foot on Antarctic ice—a truly amazing experience! *ricarda.winkelmann@pik-potsdam.de

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Lena Nicola is a Master's student at the University of Hamburg in Germany. She focuses on cool topics like glaciers, polar regions, and snow. After studying for some time in the Arctic between glaciers and polar bears, she is now working on her thesis about snowfall changes in Antarctica.

DIRK NOTZ

Dirk Notz is a Professor of Sea-Ice Research at the Universität Hamburg and the Max Planck Institute for Meteorology in Hamburg in Germany. With his research group, he tries to understand how sea ice works and what we need to do to protect the fascinating polar landscapes for future generations. During his field work in both polar regions, he has spent many happy days standing on shaking sea-ice floes.