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Climate change

Edited by
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Climate change

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Earth and its Resources

About this collection

Our Climate refers to the types of weather we expect at different places around the world – some places are hot or cold, or dry or wet. But we know that our climate is changing, and this is having an effect on all of us.

Sometimes these changes are caused by natural things like volcanoes, but we know that most of the climate change we see is caused by humans making pollution. This pollution changes the gases in the air and traps in the sun's heat. This makes our world warm up – sometimes called "global warming".

Climate change will affect all areas of the world – on the land, in the oceans and in the air. This will have impacts on people, animals and plants all over the world. This collection describes lots of different aspects of climate change, why it is happening and what we can try to do about it.

This Climate Collection brings together a set of core articles on climate science so that young people can understand the implications of new findings. It covers the basic elements of climate and climate change and enable children to be fully informed about what is happening to their world.

We have seen a growing youth movement passionate about protecting our planet. This collection helps support such goals by ensuring objective science knowledge is made accessible to this next generation.

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WHAT DO WE MEAN BY "CLIMATE" AND "CLIMATE CHANGE"?

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YOUNG REVIEWERS:

COLÉGIO MAXI – MIZZOU ACADEMY

AGE: 12

Climate change is all over the news. But what exactly do we mean by "climate" and "climate change?" The word "climate" describes the average state of the atmosphere. It is a result of the composition and interactions between the natural elements: the air, oceans, plants and animals, ice and snow, and rocks. There are several different climate zones around the world. The state of the global climate is described by the average global air temperature. This temperature depends on how much heat the Earth receives from the Sun and how much of this heat is sent back to space. If the amount of heat received through the sun's rays or the composition of one or several of the natural elements changes, the amount of heat taken up by the Earth changes. All elements are connected and constantly interacting, and this has consequences for the whole planet: climate change.

CLIMATE IS NOT WEATHER

You might have heard or read about climate change or global warming in the media. Scientists from all around the world say that the Earth is warming and Earth's climate is changing. They predict that these changes will probably continue over the coming decades to centuries. But, if scientists cannot predict the weather over more than a couple of days, how can they know what the temperature on Earth will be in several years?

WEATHER

Current state of the atmosphere (what you see when you look out of the window). If it is a rainy or sunny day, for example.

Such predictions can be made because *weather* and *climate* are different things. In scientific words, **weather** is the *current* state of the atmosphere and **climate** is the *average* state of the atmosphere. For example, the clothes you wear today or tomorrow are a response to the weather you see when you look out the window. On a rainy, cold day, you will wear something different than you would on a sunny, warm day. Climate, on the other hand, describes the typical weather conditions in a region for a very long time—30 years or more. That is how we define seasons—for example, in summer, the climate is hotter than it is in winter. So, in winter, we know that we must wear warmer clothes than we do in summer. Climate describes the average characteristics of the weather over a long time at a specific place.

CLIMATE

Average state of the atmosphere, meaning typical weather conditions a in region for a very long time.

THE CLIMATE SYSTEM

Weather, and therefore climate, is a consequence of interactions between the atmosphere and the environment around us: the oceans, lakes, and rivers (also called the hydrosphere); the vegetation and animals (biosphere); the mountains, volcanoes, and ocean floor (lithosphere); and the ice and snow surfaces (cryosphere). These components continuously exchange things like heat, water, or gases. Together, these elements form the **climate system** (Figure 1A). These elements influence the average weather and are important to understand if we want to understand what climate is and how it can change.

CLIMATE SYSTEM

Interactive system consisting of five major components: atmosphere, hydrosphere, biosphere, lithosphere, and cryosphere.

The components of the climate system are constantly interacting. Because the atmosphere covers the whole globe, it is an important means of transport for heat, water, and gases between different regions. When transported, these components affect the state of the atmosphere and influence the average weather. As an example, let us look at how water (Figure 1B) and carbon dioxide (CO_2) (Figure 1C) are exchanged within the climate system.

The oceans are the largest water reservoir on Earth. Every day, due to the heat reaching the Earth from the Sun, water from the oceans, lakes, and rivers evaporates to become water vapor in the atmosphere. The clouds and the moist air are then transported by winds to other regions of the Earth. At some point, the water vapor cools down and falls back

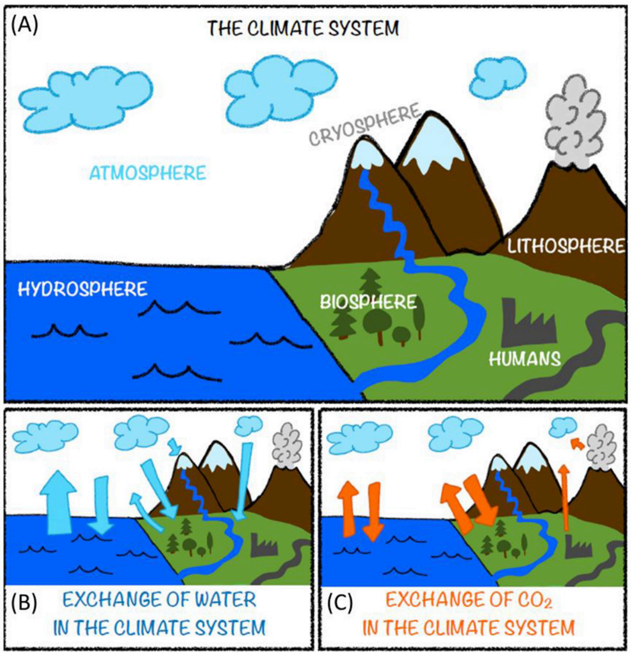

Figure 1

Figure 1

(A) The climate system includes the atmosphere, the hydrosphere (oceans, rivers, and lakes), the biosphere (vegetation and animals), the lithosphere (mountains, volcanoes, rocks, and the ocean floor), and the cryosphere (ice sheets, glaciers, and snow). **(B)** The water cycle: Water is exchanged between the five components of the climate system, mainly between the hydrosphere, the biosphere, the atmosphere, and the cryosphere. **(C)** The carbon cycle: CO_2 is exchanged between the five components of the climate system, mainly between the hydrosphere, the biosphere, the atmosphere, and the lithosphere.

to Earth. If this happens in a cold region over land, it falls as snow and accumulates either on the ground or on glaciers and larger ice sheets. If rain falls over a region covered by vegetation, the water will be taken up for plant growth. Part of the rain also falls directly into rivers and the ocean. Additionally, plants "sweat" and "breathe." Through these processes, plants release water vapor into the atmosphere. The exchange of water between the hydrosphere, atmosphere, biosphere, and cryosphere is called the **water cycle** and it is one example of the interactions between the various elements of the climate system.

WATER CYCLE

Regular exchange of water between the hydrosphere, atmosphere, biosphere, cryosphere, and lithosphere.

The atmosphere is a thin layer of gas surrounding the Earth. It contains the oxygen we breathe and other gases, including CO_2. CO_2 is a **greenhouse gas**, which means that it helps keep the planet warm enough for us to live on. But CO_2 is not only present in the atmosphere—large amounts of carbon are stored in the oceans and in vegetation and are constantly exchanged with the atmosphere in the form of CO_2. This is called the **carbon cycle**. But human activity is throwing this balance off. Every year, as we burn fossil fuels, we release large amounts of CO_2 into the air. The large amounts of CO_2 that we continually release make it very difficult for the exchange between the atmosphere, ocean, and vegetation to readjust and find balance. The excess CO_2 accumulates in the atmosphere, which causes Earth's temperature to rise and results in climate change.

GREENHOUSE GAS

Gas that traps heat and makes the planet warm enough for us to live on.

CARBON CYCLE

Regular exchange of carbon between the atmosphere, hydrosphere, biosphere, cryosphere, and lithosphere.

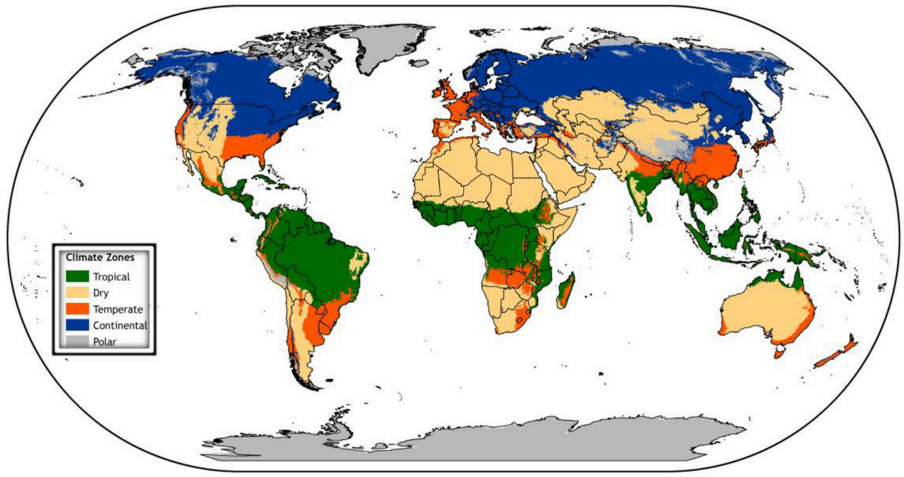

Figure 2

Figure 2

The five main climate zones around the world, as defined by Wladimir Köppen. The zones are in various colors, explained in the key on the left [1].

CLIMATE ZONES

The climate is different all around the world. Scientists have classified the regions that have similar patterns of temperature and rain into **climate zones**. The scientist Wladimir Köppen defined five main climate zones (Figure 2).

CLIMATE ZONE

Regions around the world that have similar patterns of temperature and rainfall.

The tropical climate, found around the Equator, is warm and wet year-round. The dry climate, such as that of deserts, is usually warm, with large variations of temperature between day and night, and has very low rainfall. The temperate climate, such as that of Western Europe, typically has warm summers and mild winters, without a dry season; but for some places, like the Mediterranean, the summers are dry. The continental climate, seen in Russia and Canada, has cooler summers and very cold winters, without a dry season; but in areas like northeastern China, the winters are dry. Finally, the polar climate, seen at the North and South Poles, is very cold year-round.

HOW CAN CLIMATE CHANGE?

The evolution of the global climate is usually monitored by measuring the average global air temperature. This temperature is obtained by measuring the temperatures at various locations worldwide. The average global air temperature represents the amount of heat trapped near the Earth, and it is determined by how much heat from the Sun reaches the Earth and how much heat the Earth releases back to space (Figure 3). Climate has been changing continuously since the formation of the Earth, due to changes in three factors: the position of the Earth compared to the Sun; interactions within the climate system near the Earth's surface; and the gases in Earth's atmosphere. Let us look a little closer at each of these factors.

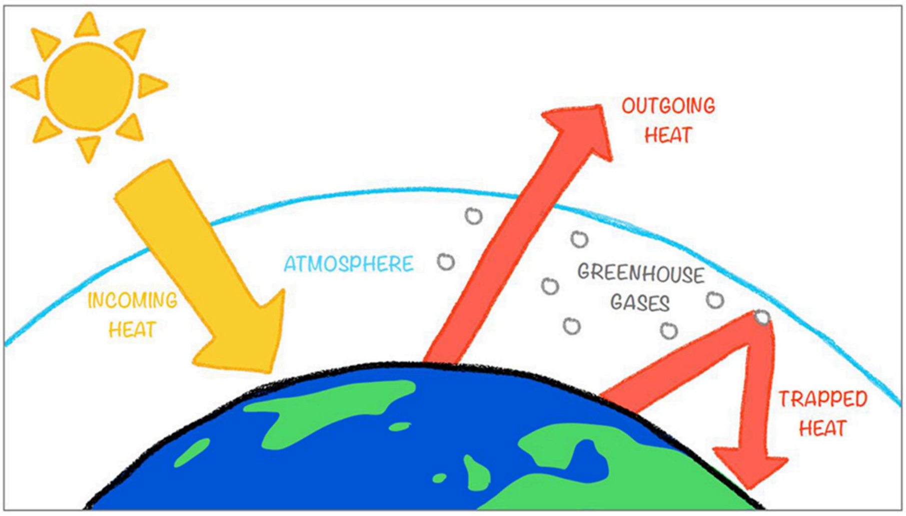

Figure 3

Figure 3

Heat from the Sun reaches the Earth's surface and warms it. The Earth emits heat back into space. Some of that heat is trapped by greenhouse gases and sent back to the Earth's surface. This is the "greenhouse effect" and makes Earth warm enough to live on.

The Position of the Earth Compared to the Sun

Although it is about 150 million kilometers away from the Earth, the Sun provides the Earth with huge amounts of heat. Over the course of the past 4.5 million years, the Earth has sometimes moved a tiny bit closer to the sun, and sometimes a tiny bit further away from it, or has changed its angle toward the Sun very slightly. These small positional changes led to small variations in the heat that reached the Earth. These tiny heat variations were enough to cause ice ages or hot periods.

Interactions Within the Climate System Near the Earth's Surface

When reaching the Earth's surface, some of the Sun's heat is reflected and bounces back into space. But the majority of the heat is absorbed by the natural elements at the Earth's surface. This heat powers the exchange of water and gases between the components of the climate system (atmosphere, hydrosphere, biosphere, lithosphere, and cryosphere), as described earlier.

The Gases in Earth's Atmosphere

The Earth's surface also emits heat back to space. If all the heat released by the Earth's surface were lost to space, it would be too cold for us to survive on Earth! This is where the Earth's atmosphere comes into play. The greenhouse gases in the atmosphere—water vapor, CO_2, and methane—absorb some of the heat released by the Earth's surface on its way to outer space and send that heat back toward the Earth's surface. This way, the Earth stays warm enough for us to live on. The warming caused by the heat trapped by greenhouse gases is what we call the **greenhouse effect**. It is a natural phenomenon that has always happened. By emitting more CO_2 into the atmosphere, humans are currently making the greenhouse effect

GREENHOUSE EFFECT

Warming process caused by the heat trapped by the greenhouse gases. It is a natural process but can be enhanced by the increase of greenhouse gases in the atmosphere.

stronger. These processes are described in more detail in other articles in this Climate Collection.

IN SUMMARY

Climate describes the average characteristics of the weather and it can be quite different all over the planet. Although we describe weather by the current state of the atmosphere (whether it is a sunny day or it is raining, for example), weather is strongly influenced by the cryosphere, hydrosphere, biosphere, and lithosphere. There is continuous exchange of water, heat, and gases between the various components of the climate system. Changes in these processes lead to changes in the average properties of the atmosphere and therefore in weather and climate.

The average global air temperature helps us to monitor the evolution of Earth's climate over time. This temperature describes the difference between the incoming heat from the Sun and the heat released into space. Changes in the average global air temperature, like global cooling or global warming, can be due to changes in Earth's position compared to the Sun, changes in interactions between the elements of the climate system, or changes in the amounts of greenhouse gases in the atmosphere. Such changes have happened in the past and are happening right now. Because all components of Earth's climate are linked, changes in the average global air temperature affect all other parts of the climate system. This is how we define and detect climate change.

ACKNOWLEDGMENTS

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REFERENCES

1. Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., and Wood, E. F. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data*. 5:180214. doi: 10.1038/sdata.2018.214

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YOUNG REVIEWERS

COLÉGIO MAXI – MIZZOU ACADEMY, AGE: 12

For this review a small group of Middle School students within the Mizzou Academy program at Colégio Maxi worked together to complete the review. Our program is an opportunity for students to experience an American classroom experience without leaving Brazil. We had lots of fun learning about climate, weather and how the scientific process works.

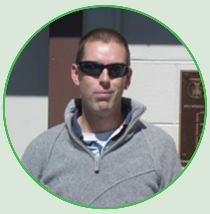
AUTHORS

PEDRO REGOTO

I am currently a PhD student in atmospheric sciences (meteorology). My main interest is in climate, with a focus on climate extremes in precipitation and temperature. I have been working on climate change detection for South America, but mainly in Brazil. One of my main professional goals is to understand more about the causes of climate extremes, like extreme precipitation and temperature events, which affect our daily lives. *pedro.regoto@yahoo.com.br

CLARA BURGARD

I am a climate scientist particularly interested in the climate of cold regions, where there is a lot of ice and snow, like the Arctic and the Antarctic. Particularly, I like to investigate the interactions between ice floating on the ocean and the ocean underneath. To better understand the consequences of climate change on the ice and the ocean at the poles, I use calculations done by large supercomputers and pictures taken by satellites from space.



CHRIS JONES

I am a climate researcher at the Met Office Hadley Center in Exeter in the UK. I have over 25 years of experience in writing computer programmes to model how climate affects our natural ecosystems and how the carbon cycle helps reduce the amount of CO_2 pollution in the atmosphere. I lead a research programme with partners in Brazil and have visited research sites in the Amazon rainforest. The photo here is on top of the Mauna Loa volcano in Hawaii, where CO_2 is measured.

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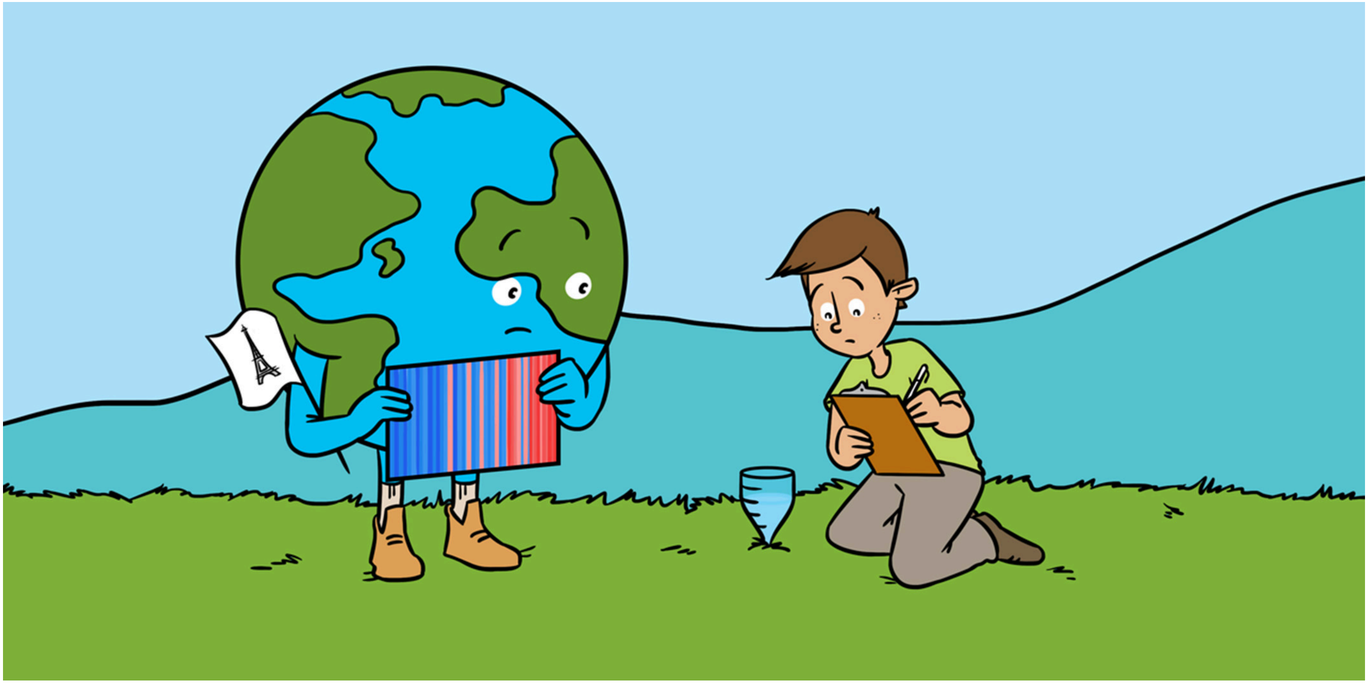

HOW HAS OUR CLIMATE CHANGED ALREADY?

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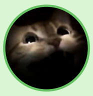

KAZIM
AGE: 13

PRICE
AGE: 14

PROVIDENCE
AGE: 10

It is easy to recognize that Earth's climate is changing. Scientists agree that the climate changes they observe are mostly caused by humans, primarily due to the greenhouse gases emitted by the burning of fossil fuels. Climate change has severe consequences—it leads to glaciers melting; sea levels rising; increased numbers of dangerous heatwaves, wildfires and droughts; decrease yields from food crops; and loss of ecosystems. We can monitor changes in Earth's climate by tracking the global average temperature. In this article, we will introduce the concept of climate and discuss how Earth's climate has changed in the past decades. We conclude with an explanation of the Paris Agreement, a treaty that nations have created to work together to limit global warming and to avoid the most dangerous of its impacts.

CLIMATE VS. WEATHER

Many people think of climate change as something we must protect humans from *in the future*. But Earth's climate has *already* changed and will likely continue to change for years to come [1]. What kinds of changes will we continue to see? "Before jumping into the details, we must first explain what we actually mean by the terms "climate" and climate change". Earth's **climate system** has five main parts: the atmosphere, which is the air around and above us; the hydrosphere, which is the liquid water in oceans, rivers, soils, and lakes; the cryosphere, which is the snow and ice, including glaciers and sea ice; the pedosphere and lithosphere, which are the layers of soils and rocks beneath our feet; and the biosphere, which contains living things like animals, plants, and humans (Figure 1). See also this Frontiers for Young Minds article.

CLIMATE SYSTEM

The combination of all domains affecting our climate, including the atmosphere (air), hydrosphere (water), cryosphere (ice), lithosphere (soil and rock), and the biosphere (living organisms).

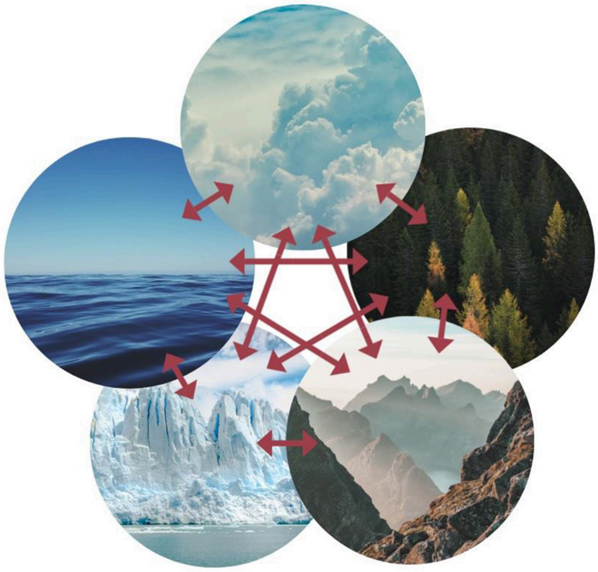

Figure 1

Figure 1

The Earth's climate system has several interacting parts. Emissions of greenhouse gases, no matter if from natural sources or human activities, consequently affect all parts of the climate system through their interactions (Image credit: Femkenilene, https://en.wikipedia.org/wiki/Climate_system#/media/File:Climate-system.jpg).

The parts of the climate system interact with each other. For example, clouds form rain (atmosphere) that hits the soil (pedosphere) and is then taken up by plants (biosphere). To get an idea of the condition of the climate system, scientists can measure properties of the climate, such as temperature, precipitation (rainfall, snowfall, hail, etc.), sea level, and glacier size. Any changes in the atmosphere that occur over hours or days are referred to as **weather**, while **climate** describes weather over longer time periods, typically in the range of 30 years or more. By comparing more recent measurements with data from the past, we can study **climate change**. Changes in climate can be natural, for example through volcanic eruptions, which can reduce incoming sunlight, or through changes in the Sun's activity or the Earth's distance to the Sun. But climate change can also be caused by humans. Humans change the climate by burning fossil fuels, e.g., with cars (fuel from oil), airplanes (fuel from oil), heating (using oil or gas), or power plants

WEATHER

The state of e.g., temperature, sunshine, rain, snow, and wind at the moment.

CLIMATE

The average of weather conditions over many years.

CLIMATE CHANGE

Changes in temperature, but also rain, wind, and sunshine, which happen slow but steady such that they can go unnoticed over some years but will become apparent after a few decades.

(using coal or gas). This burning releases gases such as carbon dioxide into the atmosphere, and these gases send back some of the radiation emitted by Earth like a heat-trapping blanket. This greenhouse gas effect warms our planet. In addition, changes in climate also occur naturally, for example through volcanoes, which can reduce incoming sunlight, or through changes in solar activity or the Earth's distance to the Sun. Scientists agree that the climate changes we have observed since 1850 are primarily caused by humans, not natural causes.

HOW CAN GREENHOUSE GAS EMISSIONS CHANGE THE GLOBAL CLIMATE?

Humans change Earth's climate by burning fossil fuels (oil, gas, or coal) in cars, airplanes, heaters, or power plants. Fossil fuels are made of two elements: hydrogen and carbon. Burning produces energy and releases **greenhouse gases**, including carbon dioxide, into the atmosphere. Greenhouse gases in the atmosphere trap heat and send some of it back to Earth, instead of letting it escape into space. This way, greenhouse gases warm our planet. Without carbon dioxide in the atmosphere, Earth would be frozen. So, greenhouse gases keep our planet warm enough for life!

GREENHOUSE GASES

These are components of the air which are invisible but minimize the heat loss from the Earth's surface into space.

However, as more and more fossil fuels are burned, carbon dioxide builds up in the atmosphere. Once carbon dioxide is emitted, it spreads across the whole atmosphere—it does not matter which countries released it. Carbon dioxide stays in the atmosphere for hundreds to thousands of years! Increasing carbon dioxide concentrations in the atmosphere causes the **global average temperature** (which is the average surface air temperature on land and the average temperature of the ocean surface) to increase. Global average temperature is calculated from measurements taken in many locations across the planet, and more recently from satellite observations. Global temperature increases causes stronger heatwaves, droughts, wildfires, and storms, as well as melting glaciers and decreased snowfall. This is a problem for the entire Earth—vegetation, animals, and people. Even if greenhouse gas emissions were reduced today, the long-lasting carbon dioxide in the atmosphere would keep the Earth too warm... and if we *continue* to emit carbon dioxide, climate change will continue to increase.

GLOBAL AVERAGE TEMPERATURE

The average of the surface air temperatures on land and ocean surface temperatures.

Interestingly, the climate system is dampening human-made climate change. Approximately half of the human-made carbon dioxide emissions remain in the atmosphere to contribute to rising temperatures while the rest is taken up by oceans and the biosphere. However, we cannot be sure that these "ecosystem services" will continue in the same way. For example, warmer ocean water stores less gases and vegetation is threatened by droughts and wildfires.

WHAT TEMPERATURE CHANGES HAVE WE OBSERVED?

The warming stripes in Figure 2 show the global average temperature (you can also look at warming stripes for your own region at https://showyourstripes.info/s/globe). The stripes are arranged from left to right, representing the years 1901–2020. The stripes in recent years are red, which shows that temperatures are much hotter now than they were at the beginning of the twentieth century.

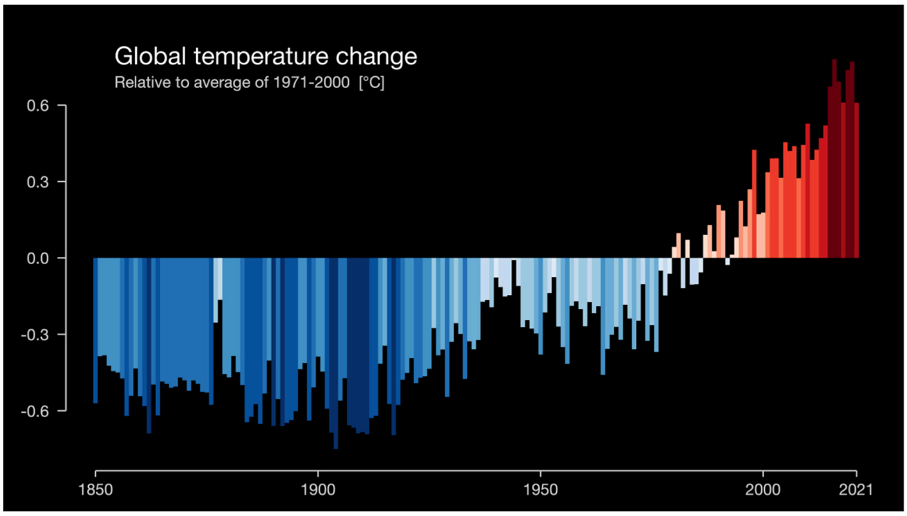

Figure 2

Figure 2

Earth's temperature is increasing. The colors of the stripes illustrate changes in global average temperature from 1901 to 2020, compared to a reference period from 1971 to 2000. The stripes turn from blue to red in more recent years, illustrating the increase in global mean temperature (Image credit: https://showyourstripes.info/c/globe).

The increase in global average temperature corresponds to the sharp increase in carbon dioxide emissions that began during the Industrial Revolution. In 2020, the global average temperature was around 1.25°C higher than it was from 1850 to 1900. Averaged over 30 years, today's global average temperature is currently around 1°C higher than it was in the mid-1800's.

WHY DOES AN INCREASE IN THE GLOBAL AVERAGE TEMPERATURE MATTER?

The increase in Earth's global average temperature due to greenhouse gas emissions has harmful consequences not only for the climate, but also for humans and nature (to learn more, see this Frontiers for Young Minds article). Every region of the globe is experiencing the impacts of climate change (Figure 3). For example, warmer air can hold more water vapor, which can lead to heavier rainfall, causing landslides and flash floods. On the other hand, some regions experience drier conditions, which can generate dangerous heatwaves and droughts. Hot, dry conditions can also cause wildfires, which have recently destroyed homes and habitats in southern Europe, the west coast of the US, and Australia. Increasing global average temperatures can also impact ecosystems, affecting fish migrations, coral reefs, forests, and more.

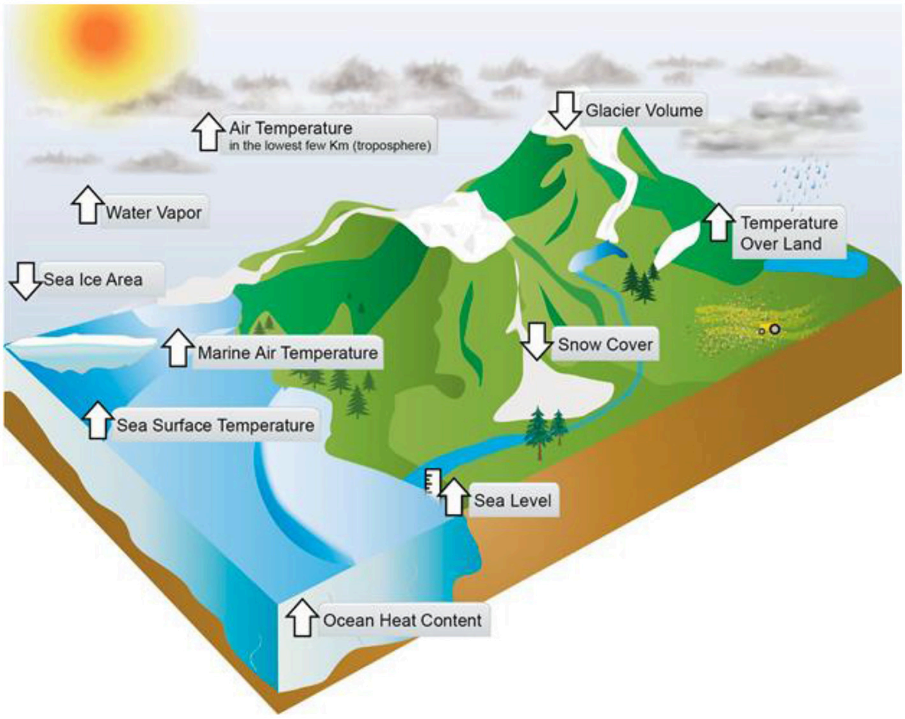

Figure 3

Figure 3

How Earth's climate system is changing. As temperatures increase in a changing climate, this leads to reduced snow, sea ice and glaciers and consequently more water in the oceans which increases their sea level. At the same time, higher temperatures provide more energy to evaporate water which increases the amount of water vapor in the air. Note that ocean heat content is a measure of the amount of warming in the ocean (Image credit: https://www.ipcc.ch/report/ar5/wg1/observations-atmosphere-and-surface/faq2-2-figure2-2/).

Unfortunately, when it comes to feeling the effects of climate change, some people are at higher risk than others. For example, people who live on islands or coastlines only a few meters above the sea (or even below sea level), could see their homes and livelihoods endangered. This is already happening on small island states in the Pacific Ocean and the Caribbean region, and in some highly populated delta regions in Asia. Also, people in sub-Saharan Africa, many of whom already suffer from hunger and poverty, will be more strongly affected by floods, droughts, heatwaves, and storms.

WHAT IS BEING DONE TO LIMIT GLOBAL WARMING?

Across the Earth, we are already observing the impacts of climate change. To avoid the most dangerous impacts of climate change, we must immediately reduce greenhouse gas emissions. It is also important that we prepare for climate-change effects that we cannot avoid, such as more heat waves and drier soils in summer, less snow cover in winter, and more intense storms throughout all seasons (to learn more, see this Frontiers for Young Minds article).

PARIS AGREEMENT

A contract signed by 196 countries from all over the world in 2015 in Paris in which these countries agree to try to take actions to limit global warming well below 2° increase of average global temperatures.

While there is no "safe" level of global warming, and *any* additional greenhouse emissions will increase warming and its adverse effects, 1.5 and 2°C of warming have become anchor points of the public discussion [2]. The **Paris Agreement**, which is a treaty between most countries of the world to limit global warming, set a goal to keep the global average temperature well below a 2°C increase over pre-industrial times, aiming for 1.5°C. To meet these temperature goals, the countries in the Paris Agreement must now implement solutions to reduce and eventually stop greenhouse gas emissions.

So, what difference can YOU make, and how much can one person's contribution even matter? Individual people make surprisingly large contributions to climate change. For example, let us look at the melting of sea ice due to global warming caused by carbon dioxide emissions. Each ton of emitted carbon dioxide (the weight of a small car) leads to the loss of 3 m^2 of Arctic sea ice [3]. The typical annual carbon dioxide emissions of individuals vary by country: 2.2 tons in Brazil, 5.5 tons in the UK, and 16 tons in the US. This means that, in the US, each person is "responsible" for 48 m^2 of ice melt per year—approximately the size of an apartment. By making small changes like (1) reducing car and airplane travel, or replacing it with bicycle and train rides, (2) replacing old electric devices which more efficient ones which consume less energy, and (3) use of heating and air conditioning only when needed and as much as needed, we can all work to protect Earth's climate—both by reducing our own contribution to greenhouse gas emissions and by being role models for others (to learn more, see this Frontiers for Young Minds article]. It is only by working together that we will be able to slow global warming, keeping the Earth safe for future generations.

ADDITIONAL MATERIALS

- https://ourworldindata.org/co2-emissions
- https://www.ncdc.noaa.gov/sotc/global/201913
- https://unfccc.int/process/conferences/pastconferences/paris-climate-change-conference-november-2015/paris-agreement

REFERENCES

1. Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y., et al. 2013. "Observations: Atmosphere and surface," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. Cambridge; New York, NY: Cambridge University Press. Available online at: https://www.ipcc.ch/assessment-report/ar5/ (accessed February, 2021).
2. Knutti, R., Rogelj, J., Sedláček, J., and Fischer, E. M., 2016. A scientific critique of the two-degree climate change target. *Nat. Geosci.* 9:13–8. doi: 10.1038/ngeo2595
3. Notz, D., and Stroeve, J. 2016. Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science*. 354:747–50. doi: 10.1126/science .aag2345

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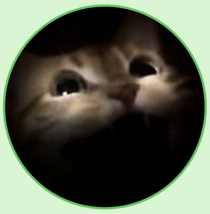
YOUNG REVIEWERS



KAZIM, AGE: 13
Kazim is a 13-year old student from Malaysia. His main interest is in gaming and digital technology exploration. Science, English, and Sports Education are his favorite subjects. He really enjoys street football.

PRICE, AGE: 14
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.

AUTHORS

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Ria Sarkar is a graduate student in the Department of Earth and Planetary Sciences at Rutgers University. Currently, her research is focused on studying the changes in how much ocean water sinks from the surface of the North Atlantic ocean into deeper depths North Atlantic Deepwater formation since the last ice age about 20,000 years ago, and how this water sinking may have caused other climate changes to happen since then. She also works as a tour guide for the Rutgers University Geology Museum and Rutgers Science Explorer bus. *rs1069@eps.rutgers.edu

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Rene Orth is a climate scientist interested in the interplay between hydrology, vegetation, and climate. He leads a research group on this topic at the Max Planck Institute for Biogeochemistry in Jena, Germany. In particular, he is interested in dry conditions where the soil moisture content influences plant functioning. In these conditions, the land surface can influence weather through the amount of evaporation and the amount of heat reflected. This is particularly relevant during heatwaves or droughts. He uses climate models and measurements to better understand these relationships.

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Martha M. Vogel is a climate scientist, lately worked for UNESCO's Man and the Biosphere Programme. She has expertise in temperature extremes and heatwaves. In particular, she is interested droughts, heat waves and their impacts and how they will change in a warming world. She advised UNESCO's climate change task force and worked on the effects of heat waves in biosphere reserves, as well as on spreading climate knowledge across citizens and politicians.

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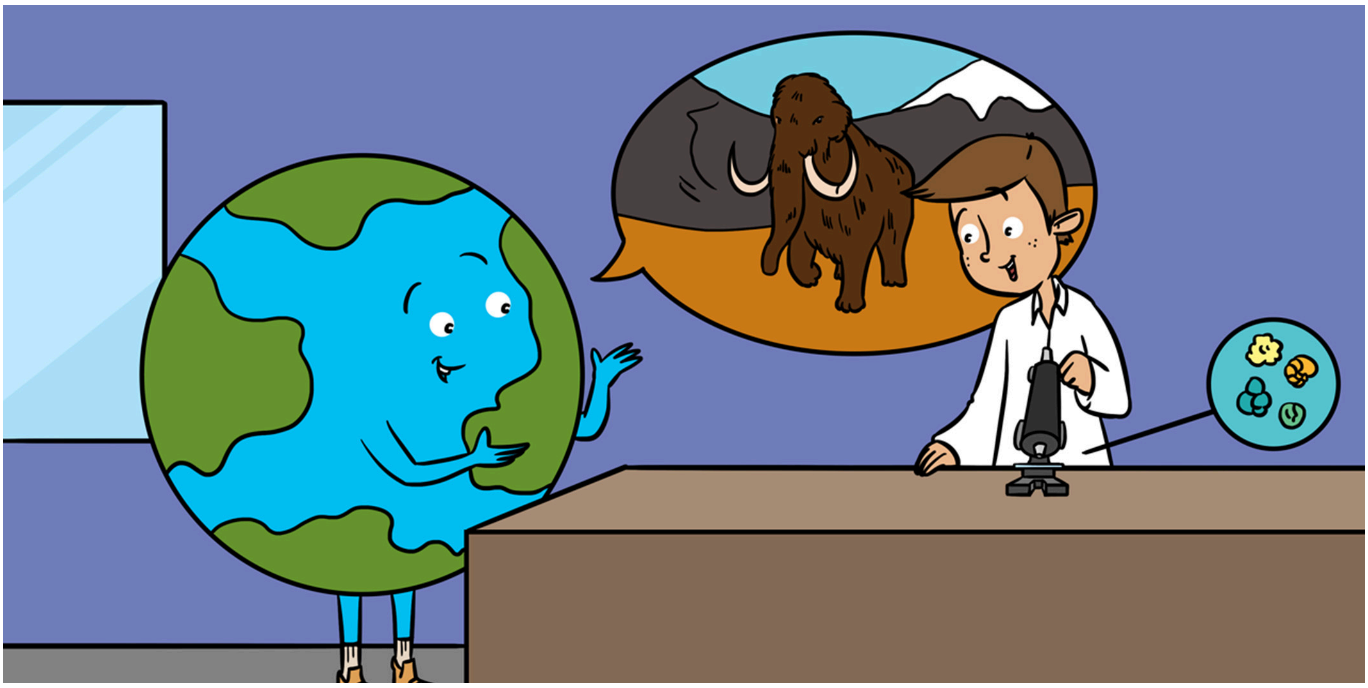

UNDERSTANDING THE CLIMATE OF ANCIENT EARTH

Edward Armstrong [1,2*], ***Alexander Farnsworth*** [2,3], ***Vittoria Lauretano*** [4] **and** ***Caitlyn Witkowski*** [3,4,5]

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YOUNG REVIEWER:

ETHAN
AGE: 9

The Earth has been around for a long time. Earth's climate history is called its paleoclimate, where "paleo" means old or ancient. In this article, we explain how studying paleoclimate helps us understand how and why the Earth (and the life on it) evolved over time. Scientists can study the fossils, chemicals, and minerals preserved in ice or ancient rocks. Using this information, as well as computer models of Earth's past climate, scientists can figure out climate changes going back millions of years. Understanding past climate changes helps us understand how Earth's climate is changing now, and how it might further change in the future.

WHAT WAS EARTH'S CLIMATE LIKE IN THE PAST?

The Earth is 4.5 billion years old—that is 4,500,000,000 years! It would take you over 1,000 years just to count to that number! Modern humans have only been around for about 200,000 years, so a lot of time passed before humans had an impact on the Earth.

Throughout Earth's history, the planet's **climate** has changed dramatically. The climate of ancient Earth is called its **paleoclimate**, and scientists study it to understand how Earth's climate might change in the future. In Figure 1, you can see how, in the past, Earth's climate was either much warmer or much colder than it is today. Over the past million years, there have been several ice ages, occurring approximately every 100 thousand years (Figure 1B). During the more recent ice ages, early humans started to evolve to what we are now. Thick ice sheets covered much of Europe and North America; in the UK, ice extended up to 1,000 meters above your head! Temperatures were much colder, but there were still big animals that were specially adapted to those icy environments, including wooly mammoths and saber-toothed tigers.

CLIMATE

The average long-term pattern of weather in a region or across the Earth.

PALEOCLIMATE

The climate of the Earth at a particular time in the past, when direct measurements (such as from a thermometer) could not be taken.

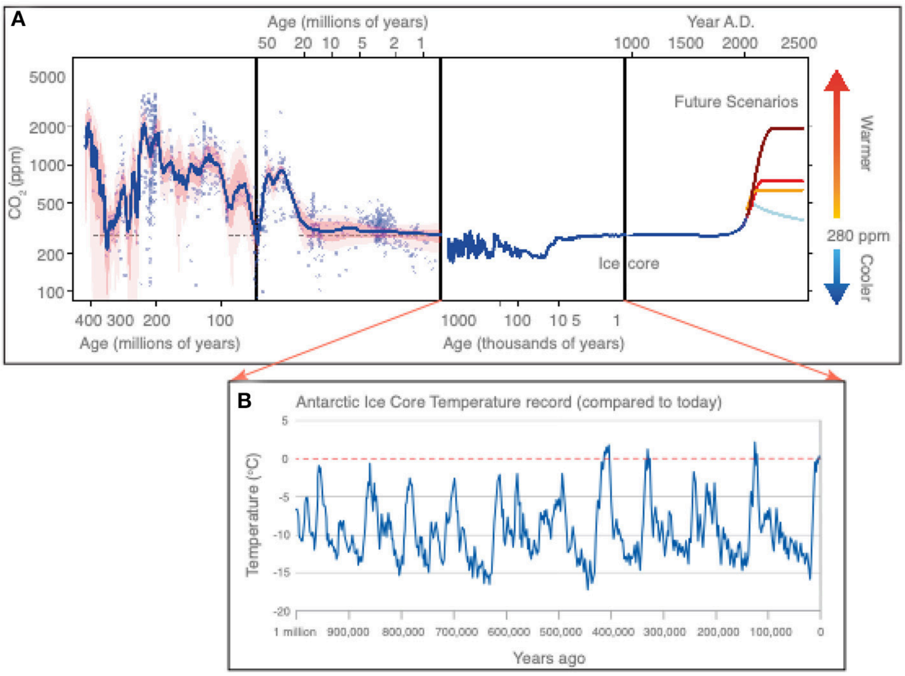

Figure 1

Figure 1

(A) Changes in Earth's carbon dioxide (CO_2) (left) and temperature (right) over the last 400 million years [1]. This is only a small section of Earth's 4.5-billion-year history. Notice how the x-axis changes. The red line shows the amount of CO_2 in the atmosphere before humans started burning fossil fuels. Future scenarios are dependent on how much CO_2 we release. **(B)** A more detailed view of temperature changes throughout the ice ages over the past 1 million years, constructed from Antarctic ice cores [2]. These show how much climate has changed naturally throughout Earth's history.

If we keep going further back in time, temperatures were much higher than they are today. During the Eocene (about 56–45 million years ago), there were no ice caps at all, and palm trees and crocodiles lived in the Arctic! Before then, between 150 and 80 million years ago in the Cretaceous period, dinosaurs lived on the Earth. Temperatures were even higher, more than 13°C warmer than today. A lot of the Earth was covered in tropical rainforests, including the UK. Antarctica was covered with forests, and those fossils tell us that cold-blooded reptiles lived there, similar to those that live in the tropics today.

If we continue to go back in time, around 600–700 million years ago, there was a period called the Cryogenian. During this period, the Earth was completely covered in ice, even at the equator. Scientists call this "snowball Earth." This may sound unpleasant, but these cold temperatures likely led to an explosion of life in the oceans, which was responsible for the start of most living things we see today. As you can see, humans are just a tiny part of Earth's history.

WHAT CONTROLLED PAST CLIMATES?

So what caused these big changes in climate? This is complicated because there are many different reasons, and they occurred over different timescales.

One major long-term controller of climate is the amount of **greenhouse gases** in the atmosphere. These gases include carbon dioxide (CO_2) and methane (CH_4), and they act like a greenhouse around the Earth by trapping heat energy from the Sun. More greenhouse gases trap more heat, so temperatures rise. The amount of greenhouse gases has changed slowly and naturally throughout Earth's history. There are lots of reasons for these changes, including the amount of volcanic activity, changes in ocean circulation, the types of vegetation, and complicated processes like weathering of rocks. More recently, greenhouse gases have been increasing dramatically due to human activity such as burning **fossil fuels**. A rapid increase in greenhouse gases is playing a major role in the climate change that is happening today [3].

GREENHOUSE GASES

These are gases that are in the atmosphere and trap heat from the sun. They include carbon dioxide and methane.

FOSSIL FUELS

Natural fuels that have formed underground over a long period of time from the remains of living organisms.

Another major controller of climate is the position of Earth's continents (Figure 2A). Continents move on very long timescales because blocks of land sit on a layer of molten lava called the mantle, which is moving them very slowly. Every 300–500 million years, Earth's continents join together into one massive continent. For example, around 175 million years ago, all of Earth's land was joined together in one supercontinent called Pangea. When Pangea broke apart, it changed wind and ocean currents, eroded land, and created big volcanoes. All these things had significant impacts on Earth's climate, partly by changing the amount of greenhouse gases in the atmosphere.

Earth's vegetation also influences climate. The first land plants evolved about 470 million years ago and began to suck CO_2 out of the atmosphere. These early plants may therefore have cooled the climate leading to "snowball Earth." Later, vegetation with dark green leaves (like ferns and trees) evolved. The dark colors absorbed the Sun's energy, which may have helped warm the planet.

The Sun's energy is the most important factor keeping the planet warm enough for life to exist—but the amount of energy we receive from the Sun is not constant. The way the Earth travels around the Sun changes

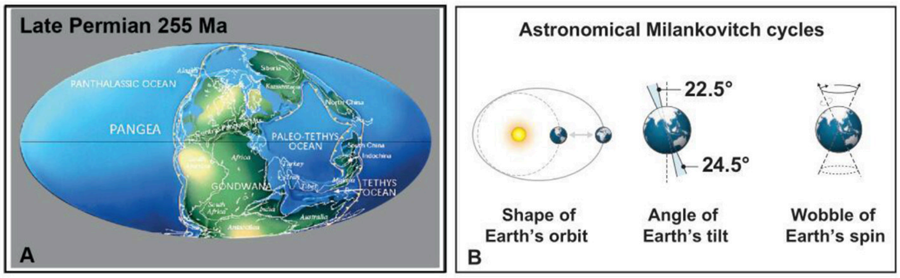

Figure 2

Figure 2

Natural processes that control climate. **(A)** The position of Earth's continents can change. In the past all of Earth's land was joined together in one super continent called Pangea [4]. **(B)** The Earth's orbit around the Sun changes through time [5]. These are called Milankovitch cycles, and they impact the amount of heat that reaches the earth, which can influence climate.

MILANKOVITCH CYCLES

Refer to natural changes in Earth's orbit around the sun that occur over long periods of time. These alter the amount of heat that reaches the Earth which impacts climate.

in cycles of hundreds of thousands of years. The amount of energy reaching Earth is controlled by how close the Earth is to the Sun, how much the Earth's axis tilts, and how much the Earth wobbles as it spins. These cyclic changes are called **Milankovitch cycles** (Figure 2B). These cycles impact Earth's climate and are responsible for the ice ages that occurred over the past 2 million years (Figure 1B) [5].

There are also short, explosive events that can impact climate, including meteorites, which are big rocks from outer space that hit the Earth. For example, the dinosaurs went extinct when a huge meteorite hit the Earth 65 million years ago. The impact released ash and soot high into the atmosphere, which reflected some of the Sun's energy back into space, away from the Earth. This cooled the planet; meaning plants and dinosaurs could no longer survive. However, seeds buried in the soil were preserved and grew again when the climate started to recover and warm.

HOW DO WE MEASURE PAST CLIMATES?

ICE CORES

A long cylinder of ice that is drilled out of an ice sheet or glacier. They can give scientists information about past climates.

Because we do not have a time machine to go back and measure Earth's paleoclimate, scientists must use creative methods to understand what climate used to be like. One way to look into the past is to drill and extract ice from the north and south poles. These **ice cores** can be up to 3,000 meters long! Scientists directly measure small air bubbles in the ice that still contain CO_2 from when they were formed, some as long as 800,000 years ago.

PROXIES

Preserved physical materials, such as fossils, minerals or molecules, which record past conditions and can be used to reconstruct past climate.

As we discussed, there were many times during Earth's history when there was no ice on the Earth. So, what do scientists do then? One method is to use **proxies**. Proxies are physical materials that record past conditions. Proxy materials can be fossils, molecules, or minerals found in ancient sediments (Figure 3). For example, fossils of animals and plants (including plant pollen) can tell us about the climate of the past. If sediments contain palm tree fossils, for example, the climate was probably hot and tropical in that location in the past.

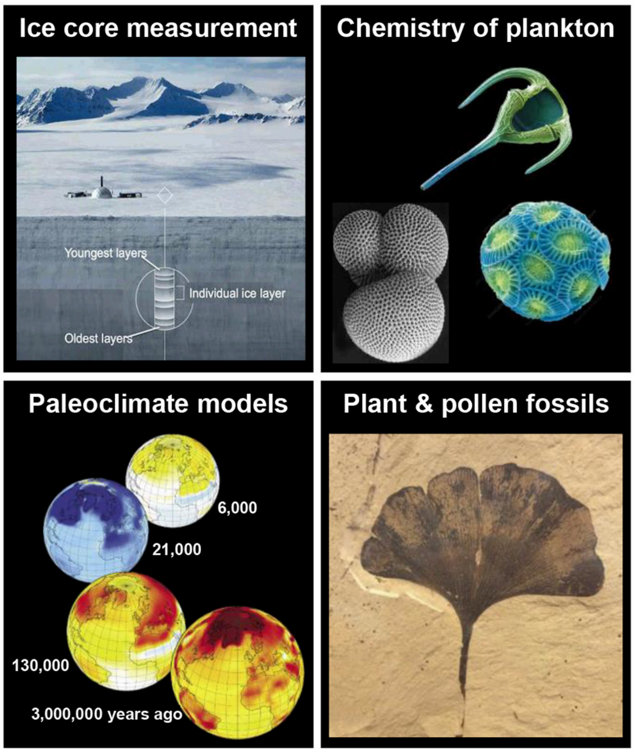

Figure 3

Figure 3

Scientists use ice cores, proxies like shelled organisms and fossils, and climate models to estimate past changes in paleoclimate.

One of the most useful proxies is found in the oceans—the remains of tiny, shelled organisms called plankton. During their lives, these tiny organisms built their shells from molecules in the surrounding water. When they died, their shells floated to the ocean floor and were buried. When scientists dig up these tiny shells, they can calculate the number of organisms and analyze the molecules in the shells. This helps them understand what the environment was like when those organisms were alive, including climate factors like CO_2 and temperature.

Another method to reconstruct the past is to use computers to build model worlds that simulate both past and future climate. These models use mathematical equations to represent the complex processes that make up the climate system. Scientists set up these models using information about the world today, which can then be changed to match the conditions found in the past. These models are very complex, so they need to be run on big supercomputers. Scientists can run simulations with the models to provide information about what the climate might have been like in the past.

Combining climate models with results from proxies gives scientists a powerful tool to more accurately understand paleoclimate.

WHY IS PALEOCLIMATE IMPORTANT AND HOW CAN IT HELP US UNDERSTAND THE FUTURE?

Studying paleoclimate is important for understanding Earth's past. It explains why the present-day Earth is the way it is, such as why certain animals and plants live where they do. Studying paleoclimate shows us how the Earth (and life on Earth) responds to change.

As you have seen, Earth's climate has changed a lot in the past, but these changes usually take many thousands of years. Right now, we are seeing climate change happening over just a few decades, making it difficult to know what will happen next. Therefore, it is also important to study paleoclimate to understand the future of our planet.

One of the most important things for scientists to understand is exactly how changes in greenhouses gases (like CO_2) affect temperature. This is known as **climate sensitivity**. Paleoclimate information can be used to help scientists better understand climate sensitivity. This information can be used to improve climate models, so scientists can more accurately predict how current changes in greenhouse gases might impact future climate. Climate affects all life on Earth, including plants, animals and us—so, understanding our past will help us prepare for our future.

CLIMATE SENSITIVITY

A measure of how sensitive the climate is to a change in greenhouse gases.

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REFERENCES

1. Foster, G. L., Royer, D. L., and Lunt, D. J. 2017. Future climate forcing potentially without precedent in the last 420 million years. *Nat. Commun*. 8:14845. doi: 10.1038/ncomms14845
2. Bintanja, R., and van de Wal, R. S. W. 2008. *Global 3ma Temperature, Sea Level and Ice Volume Reconstructions*. NOAA. Available online at: https://www.ncdc.noaa.gov/paleo/study/11933
3. Nogherotto, R., Burgard, C., and Jones, C. 2022. What is causing our climate to change so quickly now? *Front. Young Minds* 10:668763. doi: 10.3389/frym.2022.668763
4. Scotese, C. R. *Plate Tectonic Maps and Continental Drift Animations, PALEOMAP Project*. Available online at: www.scotese.com.
5. Hodell, D. A. 2016. The smoking gun of the ice ages. *Science* 354:1235–6. doi: 10.1126/science.aal4111

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YOUNG REVIEWER

ETHAN, AGE: 9

Ethan is a 9-years old boy that is currently in the fourth grade. He enjoys reading, writing, and studying math and history. During his free time, he plays basketball, tennis, and various other sports with his younger brother. He also loves exploring and learning about the nature and is currently a kid reporter. He lives in Virginia with his younger brother and parents.

AUTHORS

EDWARD ARMSTRONG

Edward Armstrong is a climate scientist who works at the University of Helsinki, Finland. He investigates climate over the Quaternary period (the past 2.5 million years), mainly focusing on the ice ages over the past 120 thousand years. He uses climate models to reconstruct climate over this period and uses the results to try and understand how ocean and atmospheric circulation have changed. He also investigates what may have caused rapid climate change events because a better understanding may help us more accurately predict future climate change. *edward.armstrong@ad.helsinki.fi

ALEXANDER FARNSWORTH

Since childhood, Alex has been fascinated with how the weather and climate behave—he wanted to be a storm chaser! Now he is fortunate enough to be a meteorologist and climate modeler at the University of Bristol, interested in monsoons, past environment reconstructions, and global extinction events such as the one that killed the dinosaurs. Instead of predicting what the weather will be like tomorrow, he modifies climate models to look at what the weather was like anywhere between 1 million and 300 million years ago, to better understand how the weather and climate will change in the future.

VITTORIA LAURETANO

Vittoria Lauretano is a postdoctoral researcher at the University of Bristol in the United Kingdom. After studying geology at the University of Chieti (Italy), she completed a Ph.D. in geosciences at the University of Utrecht (The Netherlands) in 2016, focusing on global warming events from the past (∼50-million years ago) using the shells of marine organisms. In her doctoral research, she studied how orbital cycles influenced the carbon cycle and deep-sea temperatures in past oceans. Currently, she uses organic geochemistry to reconstruct how temperatures changed on land over the past 66 million years, using fossil remains from bacteria.

CAITLYN WITKOWSKI

Dr. Caitlyn Witkowski received her bachelor's degree from Bryant University in the United States, her master's degree from Bryant University and China University of Geoscience, and doctorate from the Royal Netherlands Institute for Sea Research. Cait is currently a postdoctoral research associate at the University of Bristol in the United Kingdom. Cait's specialty is organic geochemistry, and she analyzes chemicals from organisms that died long ago and were buried in rocks (sometimes as long as 500 million years ago!). She loves uncovering the past to help us predict the future planet—especially changes in carbon dioxide (CO_2) and temperature.

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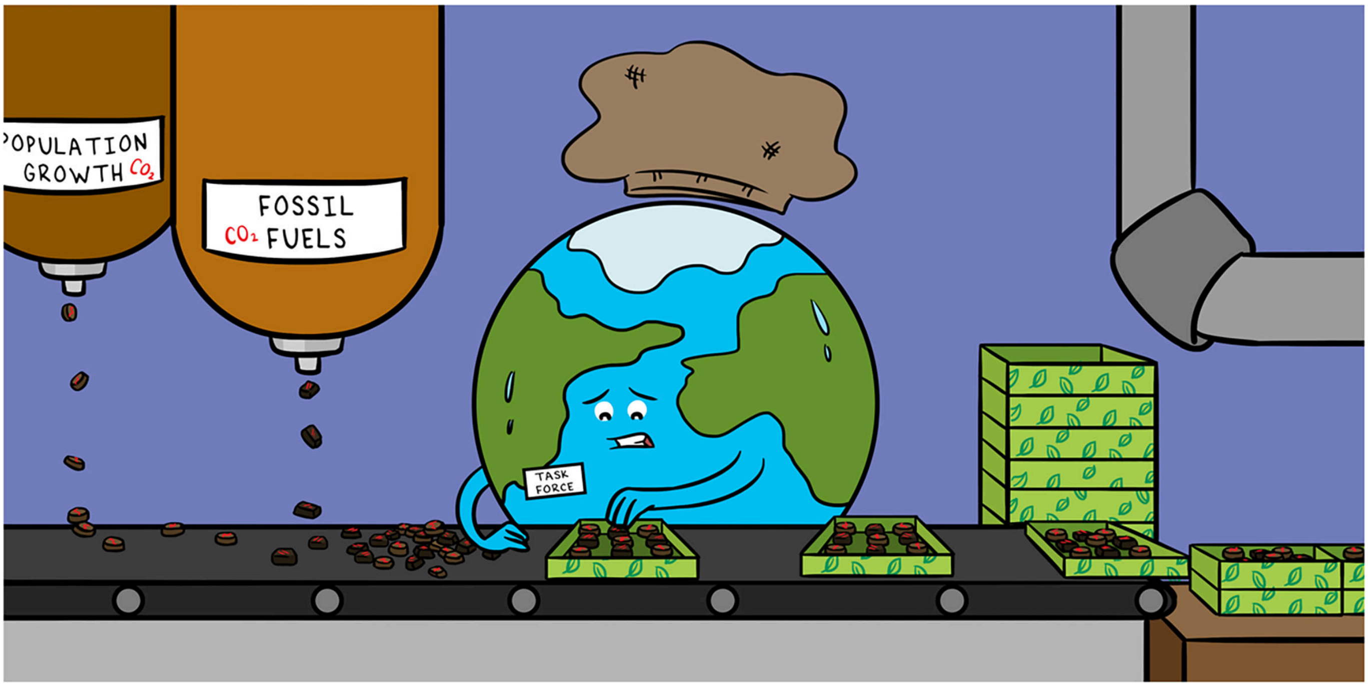

WHAT IS CAUSING OUR CLIMATE TO CHANGE SO QUICKLY NOW?

***Rita Nogherotto*[1,2*†], *Clara Burgard*[3†] *and Chris D. Jones*[4†]**

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YOUNG REVIEWERS:


ADDY
AGE: 13


TEDDY
AGE: 10

Our planet's climate has been warming much faster over the past 100 years than it has over the 10,000 years before that. In this article, we will explore how we know that the climate has changed so quickly in the last century, what carbon dioxide (CO_2) has to do with climate change, and why humans are responsible for the recent increase of CO_2 in the atmosphere. Understanding the problem is the best way to find a solution!

GLOBAL WARMING OR CLIMATE CHANGE?

It is about 1°C warmer today on Earth than 60 years ago. 1°C can seem like a very small change. After all, the difference in temperature between winter and summer can be 30°C in some regions! So why does **global warming** of a few degrees worry scientists so much?

GLOBAL WARMING
The warming we are experiencing due to the increased greenhouse effect.

Do you remember the last time you had fever? The usual human body temperature is around 37°C. When you have a fever, your body gets warmer by 1 or 2°C but you cannot concentrate well anymore, your body does not work as usual, and you need to rest. In the case of your body, it is a matter of a few degrees between being healthy and being sick. The effect of global warming on the Earth is like that of a fever: when the air at the surface gets warmer, the entire planet does not work as usual. The oceans warm as well. The thick ice melts away in cold and mountainous regions. All over the planet, living beings need to get used to new conditions or move to other regions. The warming of the planet affects everything within it, which is why we prefer to speak of **climate change** rather than of global warming. It is not only a problem of air temperature—there are changes in all elements of the environment around us.

CLIMATE CHANGE

The change of the Earth's climate due to the increased greenhouse effect causing warming of the Earth's surface.

CARBON DIOXIDE

A gas in the atmosphere that is created when we burn fossil fuels. CO_2 is a greenhouse gas and can stay in the air for many years. It is the main cause of climate change.

ATMOSPHERIC CO_2 CONCENTRATION

When measuring gases like carbon dioxide, the term concentration is used to describe the amount of gas in a given volume of air. It is usually measured in ppm (part per million), which is a way of expressing very dilute concentrations of substances. Just as per cent means out of a hundred, parts per million means out of a million.

GREENHOUSE GAS

A gas in the atmosphere which can absorb heat and cause the planet to warm up. These occur naturally, such as carbon dioxide and water vapor, but human activity is putting more greenhouse gases into the air leading to the planet getting warmer.

CLIMATE CHANGE AT PRESENT

In the past, the Earth has been warmer and colder than it is today. These temperature differences were due to changes in the Earth's position compared to the Sun, or to large natural events such as volcanic eruptions. These periods of warming and cooling occurred over several thousands of years. Nature and humans could therefore slowly adapt to the changing climate conditions.

This time it is different: climate change is happening very quickly. In Figure 1, you can see a reconstruction of the Earth's average surface temperature over the past 11,400 years. You can easily see that the temperature has risen much faster in the last decades compared to the temperatures that the Earth experienced previously. It only took 60 years to warm the Earth by around 1°C. Scientists have calculated that the Earth might be 3°C warmer—or even more—in 80 years, if we continue living like we are at the moment. Keep in mind that ice ages were only about 4°C cooler than today's temperatures, so this is actually a big deal! But…what is the difference between today's climate change and past climate changes? And what do humans have to do with it?

To answer these questions, let us go back some years in time. In the 1950s, a young scientist named Charles Keeling was wondering why the Earth had been warming so much over the past 100 years. He decided to measure the amount of **carbon dioxide** (CO_2) in the atmosphere, or what scientists call the **atmospheric CO_2 concentration**. Why CO_2? Charles knew that this gas is a **greenhouse gas**, meaning that it has a role in adjusting the temperature of Earth's atmosphere. The more CO_2 in the atmosphere, the more heat the atmosphere can absorb and send back to the Earth's surface, leading to global warming.

From that moment on, Charles measured the atmospheric CO_2 concentration every day—for years. Every year, he saw more atmospheric CO_2 than in the year before (Figure 2). This increase

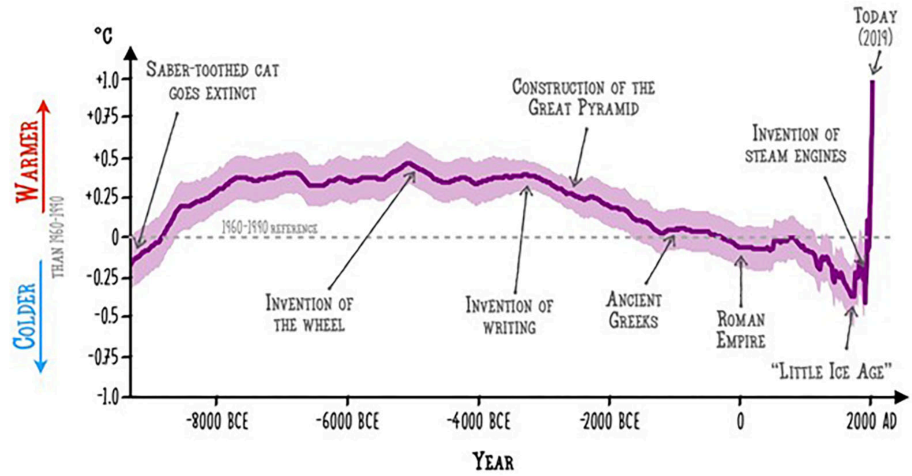

Figure 1

Figure 1

Variations in the Earth's average surface temperature over the past 11,400 years. The purple line is the mean and the shading around it is the uncertainty around the mean. BCE means before common era; AD means Anno Domini (Data until 1,900 compiled by [1]; data for 1900 to 2019 from [2]).

continues today: in 2019, atmospheric CO_2 concentrations were higher than they were at any time in at least 2 million years [4].

WHY IS THERE MORE AND MORE CO_2 IN THE ATMOSPHERE?

Charles discussed his findings with other scientists. They knew that more CO_2 in the atmosphere meant that the Earth was warming. And they knew that such warming could have dramatic consequences on the whole climate. They decided to find out what was causing this increase in CO_2. They hoped that tracking down the cause might help prevent more CO_2 from getting into the atmosphere.

As a first step, the scientists looked at the amounts of CO_2 in the atmosphere in the past. They found that, at least for the last 10,000 years (and probably for the last million years!), the amount of CO_2 in the atmosphere had never been higher than the amount Charles measured!

In the past, CO_2 was added and removed from the atmosphere through natural processes. Plants and oceans, for example, can store CO_2 and regularly exchange it with the atmosphere. Sometimes plants and oceans take up CO_2 from the atmosphere, reducing atmospheric CO_2 concentration, and sometimes plants and oceans release CO_2, increasing atmospheric CO_2 again.

These natural processes are very slow—they can take thousands of years to absorb or release large amounts of CO_2. This is why natural processes cannot possibly explain the rapid accumulation of CO_2 in the atmosphere during the last century. If the CO_2 is not coming from nature, then where is it coming from?

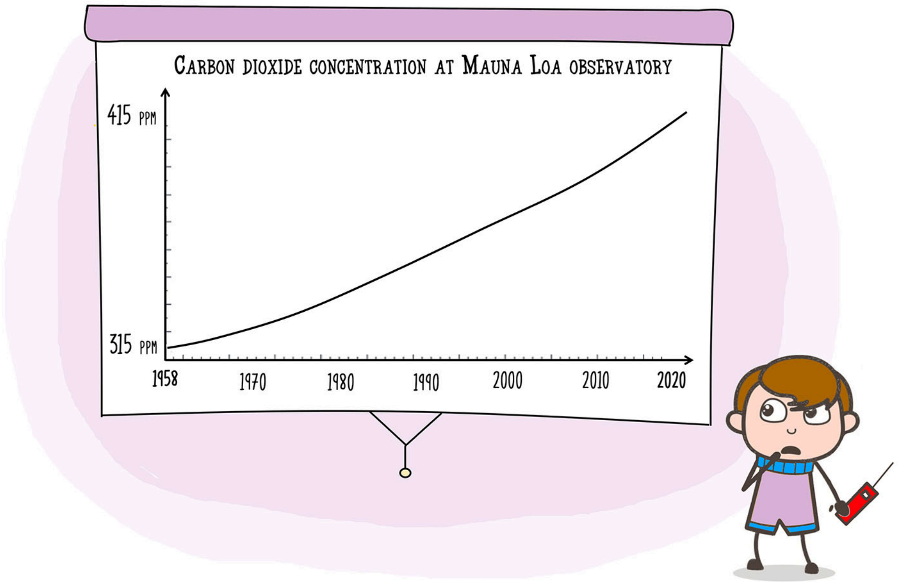

Figure 2

Figure 2

The atmospheric CO2 concentration, as measured on Mauna Loa, has been rising since it was first measured in 1958 (Data from [3]).

The CO_2 concentration started to rise very quickly around 150 years ago, when we started using machines to accomplish more work in a shorter time. To run these machines, we needed energy. We got this energy from burning oil, coal, and natural gas, which are called **fossil fuels**. When we burn fossil fuels, CO_2 and other greenhouse gases, including methane and nitrogen dioxide, are released (emitted) into the atmosphere.

FOSSIL FUEL

Fuels, such as coal, oil, and natural gas that were formed millions of years ago when plants and animals died and became buried. Burning fossil fuels creates CO_2, which goes into the atmosphere.

Over time, we needed more energy to power our cars, to heat our homes, to charge our smartphones, and so on. So, we burned more fossil fuels, leading to more greenhouse gas emissions. In parallel with industrial development, the human population has grown rapidly. To feed more and more humans, forests had to be cut down to create large fields for agriculture. As a result, less CO_2 could be taken up by trees. It is therefore we humans who were behind the fast increase in atmospheric CO_2 over the last century. And, since we have not yet stopped burning fossil fuels, we are still responsible for adding more and more CO_2 into the atmosphere!

The amount of CO_2 we emit is very small compared to that exchanged naturally between plants, oceans, and the atmosphere. So why does this small amount emitted by humans have such a big impact on our planet's temperature? Cannot plants and oceans just take up more CO_2? Let us take a sneak peek into the natural "CO_2-control task force" and how the atmosphere, plants, and the oceans divide the work between them.

HUMANS INTRODUCED AN IMBALANCE IN NATURAL CO_2 EXCHANGE

Nature likes a balance between different elements. For example, when you open your window in winter, cold air from outside and warm air from inside mix until they reach a common temperature—the indoor and outdoor temperatures are balanced. Over thousands of years, nature adapted to keep such a balance in the Earth's CO_2. If the amount of CO_2 in the atmosphere was higher than usual, the plants and the oceans would take up more CO_2 than usual, until CO_2 amounts were all in balance again. The atmosphere, plants, and the oceans form what could be considered a natural CO_2-control task force, because together they regulate the exchange of CO_2.

VICIOUS CIRCLE

A chain of events in which a change compared to the usual situation has the effect of creating new problems which then cause the original change to change more, creating new problems and more change again and again.

CARBON CYCLE

The movement of carbon through nature—plants absorb CO_2 from the air as they grow, and release it again when they die. The water in the oceans dissolves CO_2. This cycle is called the carbon cycle.

When humans started burning fossil fuels, more CO_2 started accumulating in the atmosphere in a short period of time. The change in atmospheric CO_2 was so fast that the CO_2-control task force could not keep up with establishing the balance. The fast rise in atmospheric CO_2 concentration and the resulting atmospheric warming put the plants and the oceans under pressure. The task force did not have time to adapt to higher amounts of CO_2, as it could in the past. As a result, the atmospheric CO_2 concentration increased even more, leading to more atmospheric warming, putting plants and oceans under even more pressure, and so on. This is what we call the **vicious circle** of the **carbon cycle** (Figure 3). This vicious circle has only a small effect compared to the human CO_2 emissions coming from the burning of fossil fuels, but it is expected to have a larger effect in the future! You should know that there are many such vicious circles in nature. For example, different vicious circles are responsible for the very fast warming in polar regions. Other greenhouse gases are also increased by human activity, although CO_2 is the biggest cause of climate change. Methane (CH_4) and nitrous oxide (N_2O) have also increased a lot since pre-industrial times because of the burning of fossil fuels and the increase in agriculture.

IN CONCLUSION

The amount of CO_2 that humans send into the atmosphere may appear small at first glance. However, it is enough to throw off the balance between the atmosphere, the oceans, and plants.

The good news is that Charles' measurements started a scientific investigation into the changes in atmospheric CO_2. Ever since Charles' first measurements in the 1950s, the crowd of scientists trying to understand climate change has grown. Today, we know much more than we knew in Charles' time. We know that it is humans who are behind the rise in atmospheric CO_2 concentration. And it is therefore also humans who will be able to *stop* climate change. By reducing CO_2 emissions, we can slow down climate change: every ton of CO_2 that

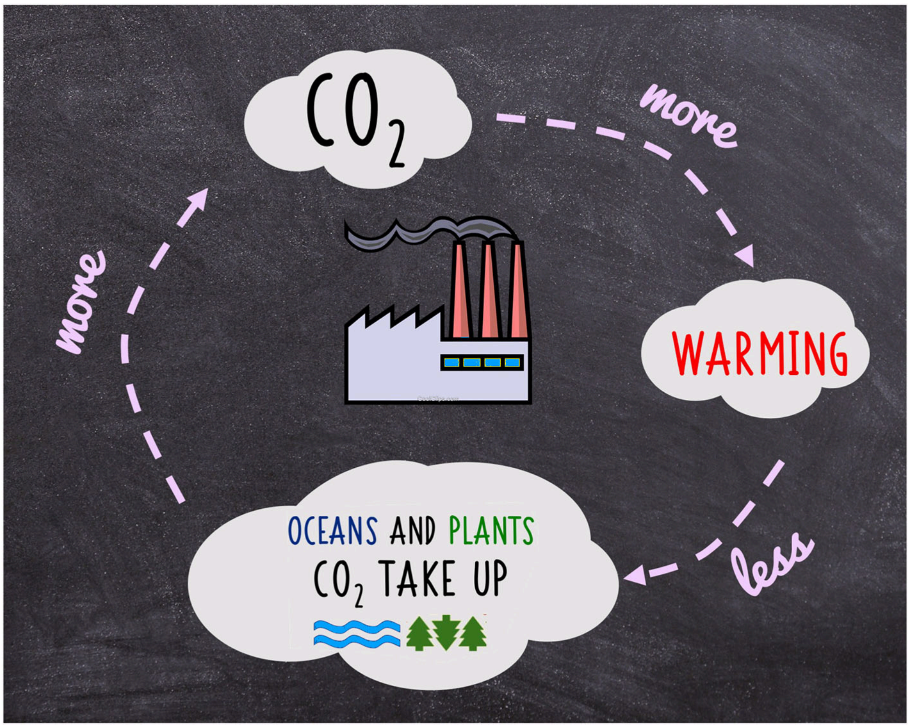

Figure 3

Figure 3

The vicious circle in CO_2 exchange. Humans add CO_2 to the atmosphere. This leads to atmospheric warming, putting oceans and plants under pressure. Oceans and plants take up less CO_2, which leads to more CO_2 in the atmosphere. This leads again to more warming, less CO_2 uptake, more CO_2 in the atmosphere, and so on.

does not go into the atmosphere means less warming. Our actions *now* are essential to avoid future climate change [5]! We need smart, creative, and hopeful people to think of new ways to live our lives! Maybe you will be one of those people?

BRIEF SUMMARY

Climate change: we hear about it almost every day now. We hear that our planet is warming and that this warming is caused by us. But why is that a problem? And what exactly are the mechanisms driving climate change at the moment? In this article we try to explain to a younger audience (8–11 years old) what are the causes of the recently observed changes in our climate. These changes are occurring faster than past changes. They cannot be caused by natural events only. Understanding the causes of climate change is crucial to figure out what is going on and what can be done to limit its consequences.

REFERENCES

1. Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C. 2013. A reconstruction of regional and global temperature for the past 11,300 years. *Science*. 339:1198–201. doi: 10.1126/science.1228026
2. Available online at: `https://climate.nasa.gov/vital-signs/global-temperature/`

3. Keeling, C. D., Bacastow, R. B., Bainbridge, A. E., Ekdahl, C. A., Guenther, P. R., and Waterman, L. S. 1976. Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. *Tellus*. 28:538–51. doi: 10.3402/tellusa.v28i6.11322
4. IPCC. 2021. "Summary for policymakers," in *Climate Change 2021 : The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Cambridge: Cambridge University Press).
5. Trascasa-Castro, P., and Smith, C. 2021. What can we do to address climate change? Front. Young Minds. 9:672854. doi: 10.3389/frym.2021.672854

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YOUNG REVIEWERS

ADDY, AGE: 13

I am in 7th grade and really enjoy volunteering at my local museum. I really like helping animals and I hope to become a veterinarian when I get older. My favorite class in school is my dance class (I am very flexible) and I love to travel.

TEDDY, AGE: 10

I want to be an engineer. I have really enjoyed trying and struggling to learn how to engineer and code things. I am dyslexic. I really love math (especially algebra and geometry). I like to travel. I bike 30 miles a week most weeks.

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I am a postdoctoral physicist. During my Ph.D., I worked on modeling the complex processes occurring inside the clouds. Their representation in climate modeling is very important and crucial to understand the future climate. I am now focusing on extreme events related to climate change, such as floods and fires. Science, travels, books, and small adventures are my passion. I also love to share the things I learn and to promote scientific thinking. *nogherotto@gmail.com †https://orcid.org/0000-0003-1718-542X

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I am a climate scientist particularly interested in the climate of cold regions where there is a lot of ice and snow, like the Arctic and the Antarctic. Specifically, I like to investigate the interactions between ice floating on the ocean and the ocean underneath. To better understand the consequences of climate change on the ice and the ocean at the poles, I use calculations done by large supercomputers and pictures taken by satellites from space. †https://orcid.org/0000-0003-3847-3172

CHRIS D. JONES

Chris D. Jones is a climate researcher at the Met Office Hadley Center in Exeter in the UK. He has over 25 years of experience of writing computer programmes to model how climate affects our natural ecosystems and how the carbon cycle helps reduce the amount of CO_2 pollution in the atmosphere. He leads a research programme with partners in Brazil and has visited research sites in the Amazon rainforest. The photo here is on top of the Mauna Loa volcano in Hawaii where CO_2 is measured. †https://orcid.org/0000-0002-7141-9285

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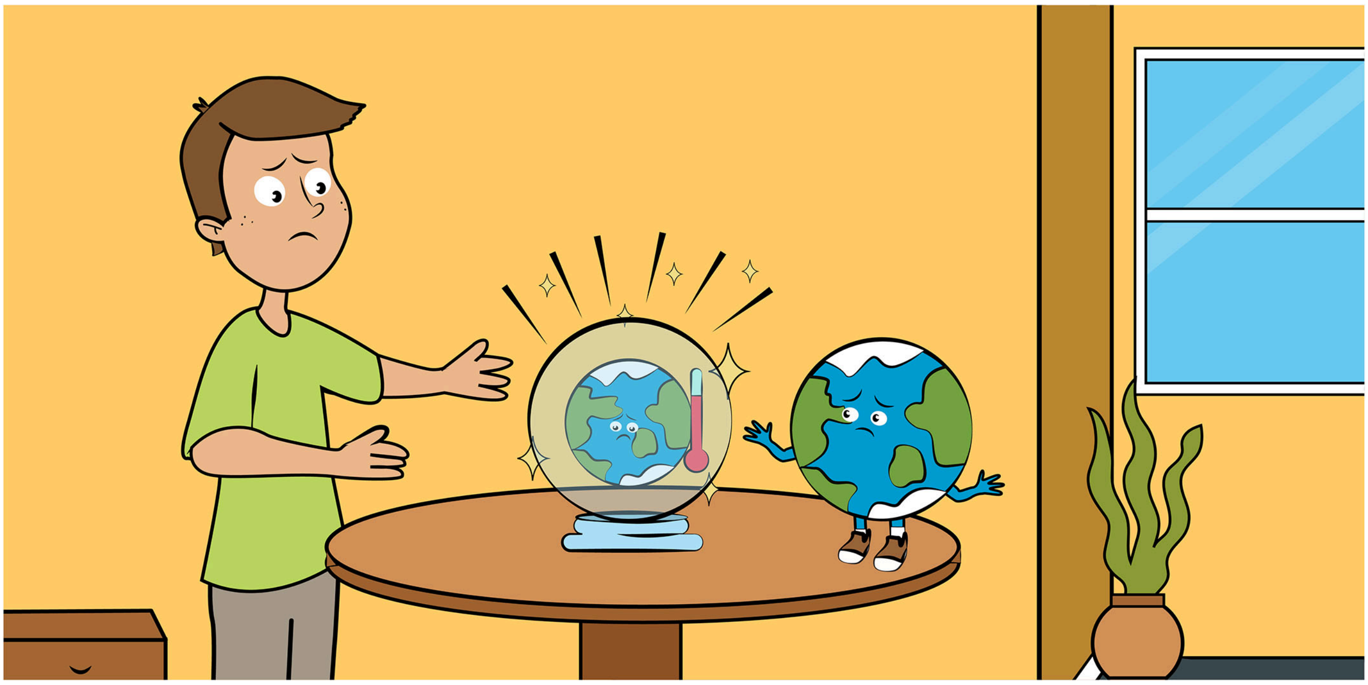

WHAT MIGHT THE FUTURE CLIMATE LOOK LIKE?

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YOUNG REVIEWER:

BEATRIZ
AGE: 12

Our planet's climate is warming rapidly, mostly because of greenhouse gases released by human activities. Earth's future depends on our actions, and getting a glimpse into the future could help us make smart decisions right now. A climate model is a computer-based twin of our planet's climate system, and many different climate models exist because there are many ways to describe the complex planet we live on. Scientists experiment with what the future might look like by changing the amounts of greenhouse gases and particles (pollution) in the computer atmosphere within a climate model. This way, we can figure out the amount of greenhouse gases we can safely emit to avoid dangerous climate change. Currently, climate models estimate that we will end up with a warming of 3°C by 2100, but this can still change depending on our actions.

WHAT ARE CLIMATE MODELS AND WHY DO WE USE THEM?

The Earth's climate has been changing a lot over the last 100 years, especially recently. Some of the changes, like the melting of glaciers, are visible to the naked eye. Others, like changes in how often it rains, are not as easy to see. Luckily, we do not rely only on our eyes to record changes. Scientists have installed instruments all around the globe that constantly measure changes in temperature, rain, wind, and sunshine. We even have instruments out in space on satellites, recording not just weather but climate-related properties of the ocean, the ice sheets, and the land all of which show the state of Earth's climate.

To better understand the reasons behind the observed climate changes, scientists need to do experiments. Let's say a climate scientist is curious to know what would happen if the Pacific Ocean suddenly had double the amount of sea salt as it has now. If the scientist tested this by releasing tons of sea salt into the ocean, the consequences could be catastrophic. Instead, scientists have created a digital copy of Earth on a computer. This copy consists of a computer atmosphere, a computer ocean, and computer land, almost like a video game [1]. This computer copy of Earth's called a **climate model**. In a climate model, it is safe to do experiments. Scientists can add a bunch of sea salt into the ocean or remove all the clouds, if they wish. Scientists use climate models to do both realistic and unrealistic experiments, to deepen their understanding of Earth's climate.

CLIMATE MODEL

A climate model is a model world built on a computer. Some climate models are more complicated than others.

Before trusting climate models, scientists want to check that the models work properly, so they simulate the recent past and compare the model results to actual observations. Such an experiment is called a historical simulation. This can be done by starting a climate model in the year 1850 and adding pollution (including greenhouse gases and small particles in the atmosphere) every year, stopping the experiment in the present day. Adding pollution is meant to represent human activity since the **Industrial Revolution**, which began in 1850. Using this historical model, we can compare climate change on our computer version of Earth to climate change on real Earth, as measured by our instruments on Earth and in space. If the changes are similar, we know our climate models are working properly, and that we have created a good model of Earth's climate. There are many climate models because there are multiple ways to describe the complex processes on Earth.

INDUSTRIAL REVOLUTION

The period beginning in 1850, when manufacturing processes started releasing greenhouse gases and small particles into Earth's atmosphere.

When we look at the results from a historical simulation, we often average the results of many models and present the data as one. For example, the red line in Figure 1 is based on 48 climate models! Figure 1 shows temperature change data from climate models, together with the real temperature change that has been measured by instruments, from the Industrial Revolution to 2014. The data from these models closely match the actual data and illustrate the temperature increase

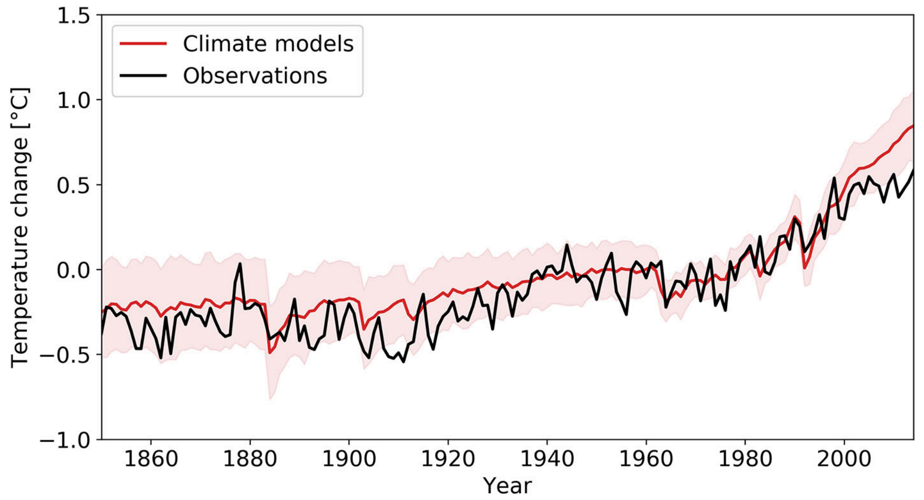

Figure 1

Figure 1

Historical development of global temperature as averaged from 48 climate models (red) and observations (black) from 1850 to 2014. The light red shading shows the uncertainty of the climate models, or in other words: how much the models are varying, since all 48 of them do not show the exact same temperature change.

GLOBAL WARMING

The measured temperature increase over the past 150 years, caused by an increased emission of greenhouse gases.

EMISSION

The release of something, in this case, into the atmosphere.

GREENHOUSE GASES

Greenhouse gases (GHGs) are ones which act to warm the air, causing global warming. The most well-known one is carbon dioxide.

SCENARIO

A potential story of how the future looks like. There are many scenarios for our future which depend on how much pollution we emit.

known as **global warming**. The red line is very close to the black line, so we can see that the models are doing a good job of representing the evolution of Earth's temperature. We can also see that the temperature increased over time, first slowly and then more rapidly. This is what is called global warming.

Accurate climate models can be used not only to *estimate* the future, but also to guide human actions in the future. Our future climate depends on our future actions, and scientists use climate models to help us prevent dangerous climate change from happening.

HOW DO WE ESTIMATE THE FUTURE WITH CLIMATE MODELS?

Climate change is mainly caused by an increased **emission** of **greenhouse gases**, specifically carbon dioxide (CO_2). A climate model is a great tool to assess future climate change since we can use it to experiment with varying levels of pollution that might occur in the future. It is impossible to know exactly how much pollution humans will emit in the future, but we can create different stories of what the future might look like. We call these stories **scenarios**. One scenario could be that the entire world collaborates to strongly reduce the amount of greenhouse gases we emit, maybe even capturing CO_2 from the air. This scenario is very hopeful, and we can call it a best-case scenario or, as many scientists, say, a low-emission scenario. The worst-case scenario is that humans continue to emit more and more CO_2 into the atmosphere in the future, just as we have done from 1850 until today.

Experiments using climate models are performed by changing the amount of pollution in the computer atmosphere for every year in the future, either decreasing pollution levels to examine the best-case

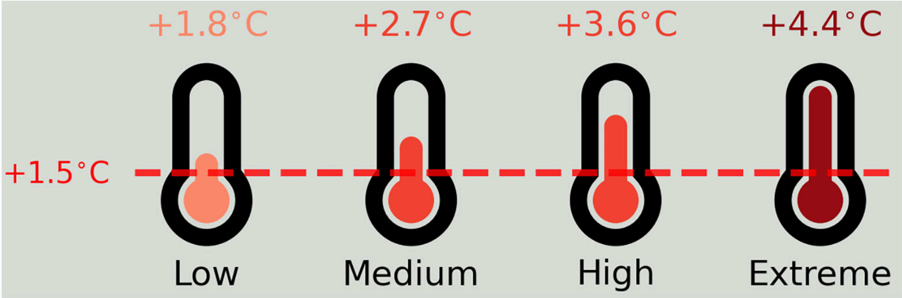

Figure 2

Figure 2

The amount of global warming Earth will experience in the future (up to 2100) depends on human emissions of greenhouse gases. 1.5°C of warming is the "safe" amount of warming agreed upon by politicians in Paris in 2016. "Low" refers to low emissions of greenhouse gases, in which we would end up with a warming of 1.8°C. On the opposite end we find "Extreme" which refers to a scenario where we emit extreme amounts of greenhouse gases, and the world would warm by 4.4°C in 2100.

HISTORICAL SIMULATION

A climate model experiment which starts in 1850 and ends in the present day, which includes emissions of pollution. A historical simulation is compared to observations.

scenario or increasing them to examine the worst-case. One difference between climate modeling and the **historical simulation** mentioned earlier is that the historical simulation starts in 1850 and ends in the present day, while modeling the future starts in the present day and might end in the year 2100. Since we do not have any real-world measurements from instruments in the future, this means we cannot compare our model Earth to real Earth when we look at the future, which is why just one scenario is not enough. We need a number of climate models so that we can understand the best-case scenario, the worst-case scenario, and scenarios that are in between. With this information, we can make the choices that will best shape the future.

WHAT DO THE CLIMATE MODELS TELL US ABOUT THE FUTURE?

Our computer models of Earth tell us that our planet will continue to warm over the upcoming decades. However, how hot Earth will get will depend directly on how we all live, which foods we eat, and how much we will continue to pollute our planet.

One thing that all our models tell us is that we need to reduce our pollution quickly (Figure 2). If all countries around the world start to reduce their CO_2 emissions today, Earth would only warm by 1.8°C by the end of this century. In this optimistic case, we would stop sea levels from rising too fast, so our coastal cities would not get flooded. Temperatures would not get too hot to grow our food, and we would also limit extreme weather events like heatwaves and droughts. However, this optimistic best-case scenario can only be achieved if humans reduce their emissions to a very low level, and ideally to zero.

If we continue polluting for a few more decades before we stop, Earth will certainly develop a high fever. In these medium- and high-emission stories of our future, model Earth would warm by 2.7°C or 3.6°C. Just like a fever in the human body, a temperature increase of just a few degrees makes Earth struggle. Glaciers in the mountains and in the Arctic would completely melt away. Many plants, trees, and animals and humans, too would struggle to adapt to this hotter world. We should certainly try to avoid such a story of our future.

In a worst-case scenario, we would not simply continue to pollute our planet at today is pace, but we would even increase our emissions. In such an extreme scenario, Earth would develop a massive fever and get very hot. Our model Earth would warm by 4.4°C, which would have catastrophic consequences for humans and animals.

The good news is that some countries have already started to reduce their emissions, so we will probably not follow such an extreme scenario. The bad news is that our models and observations tell us that the low-emission story the best-case scenario is getting increasingly unlikely, too. Our best current estimate is that we are heading for roughly 3°C [2] of warming in 2100. A 3°C degree warmer Earth would be above the safety threshold of 1.5°C of warming that politicians from all around the world have agreed on. However, our models also tell us that it is still possible for us to stay below 1.5°C of warming!

CONCLUSIONS

Climate models can be used for experiments that would not be possible in real life. These models can be used to estimate both the future and the past, but our future story depends on how much pollution humans will emit. Researchers have created several scenarios for future emissions. Climate models show that global warming could increase from 1.8 to 4.4°C by 2100. Currently, climate scientists estimate that we will end up with a global warming of roughly 3°C [2], and such a world will look very different from today's world. It is very important to remember that this estimated warming does not have to happen. There is still time to make changes that will limit climate change, even to the low-emission scenario of 1.8°C of warming. If we all work together for strong and rapid reductions in our greenhouse gas emissions, we can keep Earth healthy and habitable.

REFERENCES

1. Williams, J. 2020. Computing the climate: building a model world. *Front. Young Minds* 8:161. doi: 10.3389/frym.2019.00161
2. Hausfather, Z., and Peters, G. P. 2020. Emissions the business as usual story is misleading. *Nature* 577:618–620. doi: 10.1038/d41586-020-00177-3

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YOUNG REVIEWER

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I am a 12 years old girl, very curious about our planet and engaged in promote actions to take care of our world. I like reading, dancing and acting. I hope to support our planet with art and science!

AUTHORS

KINE ONSUM MOSEID
I am a Norwegian climate scientist interested in climate models. I am specifically interested in how small particles emitted by human activity affects how much sunlight reaches the surface of the Earth. When I am not researching I enjoy fishing and olympic weightlifting. *komoseid@gmail.com

STEFAN HOFER
I am an Austrian climate scientist. I am most excited about glaciers and ice sheets in the polar regions. Unfortunately, they are melting faster and faster. I also like to stare at clouds and ride my bicycle.

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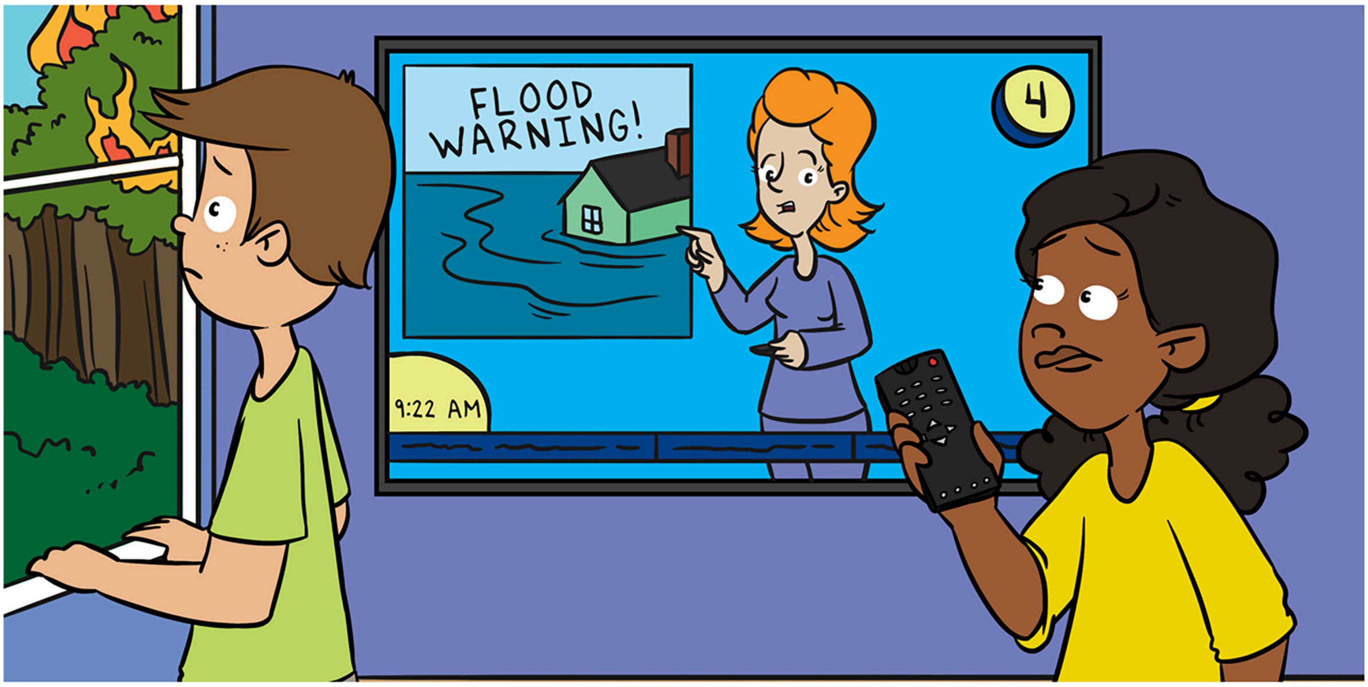

EXTREME CLIMATE AND WEATHER EVENTS IN A WARMER WORLD

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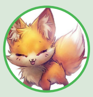
YOUNG REVIEWERS:


FARAH
AGE: 14


HAYTAM
AGE: 14


KATELYN
AGE: 13

Extreme climate and weather events are unusual and rare events that often cause a lot of damage both to nature and to people. They take place in the air (storms, tornadoes, heavy rain, atmospheric rivers), in the ocean (storm surges, marine heatwaves), and on the land (wildfires, heatwaves, floods, droughts). Many weather and climate extremes happen naturally, even without climate change. But Earth's changing climate *does* change where and how often some extreme events take place, and how strong those events are. What are extreme climate and weather events? Will new or stronger extreme events happen due to climate change? How is climate change impacting extreme events? These are the type of questions that our team of

climate and earth scientists from around the world will answer in this article.

WHAT ARE EXTREME EVENTS?

Extreme **climate** and **weather** events are defined as unusual and rare events. They are so intense or out of place that they get special mention. Heatwaves, extreme rainfalls, floods, thunderstorms, typhoons, hurricanes, tornadoes, tropical cyclones, hailstorms, storm surges, droughts, and wildfires are all **extreme events** (Figure 1).

Extreme events are important because they often cause damage, both to nature and to people. The damage caused by extreme events can cost individuals, businesses, and governments a lot of money. For example, the October–November 2019 wildfires in California (USA) caused $25 billion in damage [1]. Extreme events also cause health problems and can even cause the deaths of people and animals. However, not all extreme events bring damage, and some can bring good changes. For example, some extreme rainfall events in California bring a precious supply of water to the region. We cannot stop extreme events from happening, but we can prepare and protect ourselves from them, and learn how to better take advantage of them when possible.

Many weather and climate extremes happen naturally, but **climate change** *does* change where and how often some extreme events take place, and how strong those events are. Some extreme events are already happening more often, are more intense, and will continue to worsen.

TYPES OF CLIMATE AND WEATHER EXTREMES

Most of us have experienced at least one type of climate and weather extreme, and some of us have experienced many. Types of storms like tropical cyclones, tornadoes, hailstorms, and storm surges are well-known extreme events (Figures 1g,i,j). These storms can be very intense and often do a lot of damage. Another group of extremes is linked to floods, and includes extreme rainfall and **atmospheric rivers**, or "rivers in the sky" (Figure 1h). Extreme events also include droughts (Figure 1a), heatwaves, and coldwaves. Heatwaves are common and happen in many regions of the planet, including the oceans! Wildfires are also extreme events (Figures 1b,k). Wildfires have many names: forest fires, grass fires, peat fires, bushfires, or hill fires. While they can be very dangerous, wildfires are also a natural part of the environment and are needed to maintain healthy **ecosystems**.

MACKENZIE
AGE: 15

SOUNDOUSS
AGE: 15

CLIMATE

The pattern of weather over many years. Climate includes things such as clouds, temperature, wind, humidity, snow, and rain. Climate is like weather but over a long time.

WEATHER

A specific event, like a hot day or a storm, that happens over a few hours, days, or weeks. Weather changes daily.

EXTREME EVENTS

Unusual and rare weather and climate events that are particularly intense or happen in unexpected locations.

CLIMATE CHANGE

Over the past 150 years, gases released by human activities have trapped more heat on the Earth than in the past, resulting in increased temperatures, glacial melting, and sea-level rise.

ATMOSPHERIC RIVER

A long, narrow corridor of strong horizontal moisture flow in the air. Atmospheric rivers usually bring heavy rainfall or snowfall.

ECOSYSTEM

A biological community of living and non-living things (and their interactions) in an area.

Figure 1

Figure 1

Different types of climate and weather extremes and their impacts: **(a)** Drought conditions near Jaguari dam, Brazil (January 2014). **(b)** Smoke from the Williams Flat Fire (WA, USA, 8 August 2019). **(c)** The "Victoria's hailstone" in Villa Carlos Paz in Argentina (8 February 2018). **(d)** Paris during a heatwave (France). **(e)** New Jersey shoreline after a storm surge (USA). **(f)** Flooding following hurricane Eta (Central America, November 2020). **(g)** Four tropical cyclones across the Pacific Ocean (1 September 2015): Typhoon Kilo, Hurricane Ignacio, Hurricane Jimena, and Tropical Depression 14E. **(h)** Atmospheric river bringing moisture from the tropics to the Western U.S. (2018). **(i)** Thunderstorm off the coast of Byron Bay, Australia. **(j)** Tornado. **(k)** Wildfire and firefighters near Bilpin, Australia (19 December 2019). See the Author's Note section for photo credits.

STORMS: HOW THEY FORM AND THEIR FUTURE

Air, water, and heat are the three main ingredients that make the weather. Depending on the combinations of these ingredients, different types of weather form and some can create storms. Updrafts (warm air moving upwards in the atmosphere) create clouds, which are made of small water droplets. When clouds move higher, the droplets get colder and form ice particles. As the particles get bigger and heavier, they start to fall as snow or rain.

Thunderstorms are storms with lightning, thunder, and hail. In winter, freezing air temperatures associated with strong winds can create snowstorms (blizzards). Some really big and intense storms, called typhoons, hurricanes, or cyclones (different names in different regions), can form over the ocean. These storms can be up to 200 km wide and can cause ocean water to flood onto the land when approaching the coasts. This is called a storm surge. Tornadoes are rotating air columns about 150 m wide that link clouds to the ground, and they have winds between 100 and 500 km per hour (faster than a car)!

Some storms are quite rare and only develop under very specific conditions. However, as Earth's climate warms, storms are predicted to happen more often and they will be stronger [2]. Warming air is more unstable and has more winds and updrafts, creating more powerful thunderstorms, tornadoes, and blizzards. The ocean is also getting warmer and the extra heat can fuel big cyclones, which can create more extreme storm surges in coastal regions.

ATMOSPHERIC RIVERS AND EXTREME RAINFALL

Away from the equator and tropics, there are storms called extra-tropical cyclones. These cyclones transport heat and moisture away from the tropics. Some of these storms become extreme when they pick up a lot of moisture. All this moisture can be carried very long distances (more than 2,000 km) in narrow corridors (<500 km across), and can travel as far as the Arctic and Antarctic regions. Scientists named these long corridors of moisture atmospheric rivers because they are like rivers in the sky [3]. A typical atmospheric river can carry more than double the flow of the Amazon River!

As atmospheric rivers rise high into the air, they become colder and form clouds. This happens quickly, especially when the atmospheric rivers hit a coast or a mountain range, and the moisture transforms into intense rain or snow [3]. While rain is a key part of Earth's water cycle, extreme rain can cause too much water to fall in too short a time. We call rainfall "violent" when the ground receives more than 5 cm of water in 1 h. The most extreme rainfall in a day occurred in La Réunion, an island in the southern Indian Ocean, where 1.8 m of rain fell during the passage of Cyclone Denise over 2 days in 1966. Extreme rainfall brings severe risks to human health, the environment, and our economy. Impacts include flash flooding, landslides, damage to buildings and farmland, loss of livestock, and damage to lands and forests that increase soil erosion.

HEATWAVES AND DROUGHTS

Heatwaves are usually defined as times when temperatures are much higher than expected over a few days in a row. Heatwaves can happen everywhere—from Siberia to India. There are many reasons why heatwaves occur, including some weather patterns like anticyclones (also called "highs"), and climate patterns such as El Niño. Climate change also influences heatwaves. We know that the more the planet warms due to climate change, the more heatwaves we will experience, and these heatwaves will get longer and hotter [4]. Heatwaves like the European heatwave of July 2019 are now 100 times more likely to occur, due to climate change.

Droughts occur when there is low water availability over a period of a few months or longer. Although droughts occur on different timescales and for different reasons, droughts and heatwaves are linked. During droughts, we are more likely to experience heatwaves because dry conditions favor warmer temperatures. Also, when a heatwave occurs, the heat can increase the rate at which moisture evaporates from vegetation and the land, increasing the severity of drought.

NATURAL VARIABILITY

Changes in climate caused by non-human forces. For example, changes in the sun, volcanic eruptions, and interacting climate patterns result in natural climate variability.

Understanding how climate change impacts droughts is trickier than it is for heatwaves. Decreased rainfall can be caused by several different climate patterns. Because of the **natural variability** of these patterns, it can be difficult to detect a long-term change in rainfall. However, some weather patterns that normally bring rainfall are shifting due to climate change, which can increase the likelihood of drought over these areas.

WILDFIRES

Fire is a natural and essential part of many ecosystems around the world. Fire is needed to regenerate and maintain healthy forests and grasslands. However, wildfires can also do a lot of damage, destroying homes, killing people, causing breathing illnesses from smoke, and impacting ecosystems, particularly fire-sensitive species and communities. Climate change increases wildfire risk by making Earth hotter, which dries out the vegetation and makes it more flammable. Fire seasons are starting earlier in the year and lasting longer.

Wildfires are occurring more often and burning larger areas in many parts of the world, such as the Amazon region, Australia, Siberia, and North America, but it is not always easy to determine how much of the increased wildfire activity is due to climate change. Other factors, like deforestation, expansion of agriculture, and short-term changes in weather and climate conditions, can also have a big influence on fire activity. However, the link between climate change and the recent increase in wildfires and area burned has been proven in Australia and North America [5, 6]. The 2019/20 Black Summer wildfires in Australia were unprecedented in their size, strength, and impact. Areas that burnt included parts of rainforests that would not normally have wildfires [7].

More severe wildfires are likely to occur in a hotter and drier world, increasing the risk of wildfires in areas where fires were not previously common. Wildfires lead to more wildfires, because wildfires release large amounts of carbon into the atmosphere, further increasing global warming and amplifying climate change.

WHAT DO CLIMATE EXTREMES LOOK LIKE IN THE FUTURE?

Climate change is increasing the frequency, severity, and impacts of some extreme events. The world has already warmed an average of 1.1°C since the late 1800s. Because of Earth's changing climate, we can expect hotter heatwaves, drier droughts, stronger storms, and more extreme rainfall (Figure 2).

Figure 2

Climate change has already increased the frequency, severity, and impact of some extreme events. Wildfires are more frequent and larger, and heatwaves happen more often and are hotter. In the future, we can expect drier droughts, stronger storms, more extreme rainfall, and more intense atmospheric rivers.

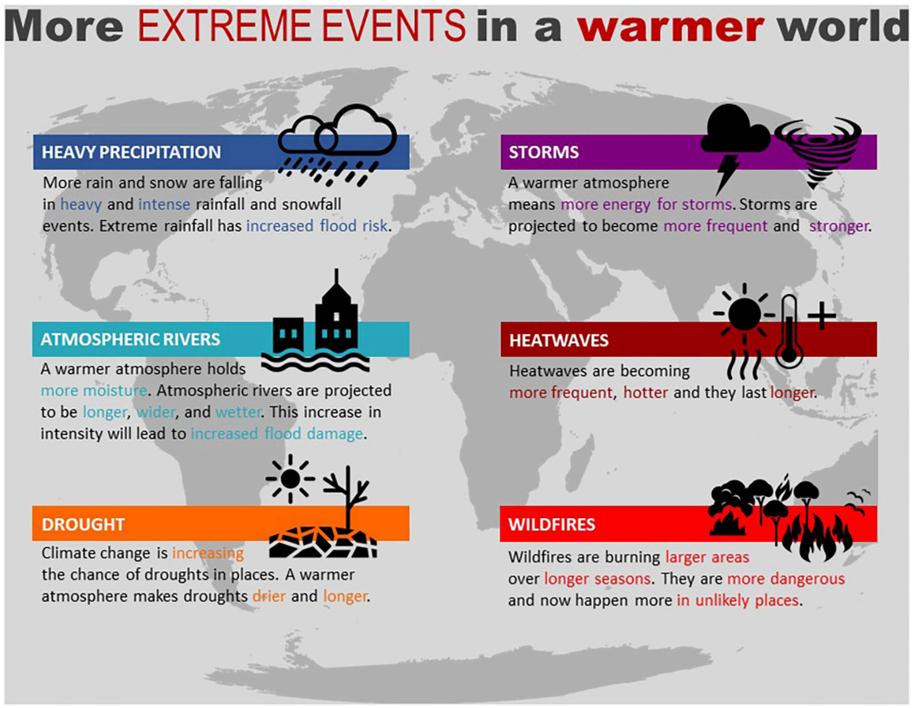


Figure 2

A warmer and wetter atmosphere can hold more water—about 7% more water for every degree of warming. The extra heat and water in the atmosphere mean that there is more energy for storms that generate intense rainfall. As a result, we expect more intense rainfall in the future, with increased floods and damage to structures like buildings and roads. Climate change also increases the risk of coastal flooding due to higher sea levels and more storms.

Some extreme events have already been affected by climate change. Wildfires are now more dangerous and fire seasons have lengthened. Climate change has also already increased how often heatwaves happen. If we want to protect ourselves and our planet from a future full of many more extreme events, governments around the world must plan to rapidly stop deforestation and the burning of coal, oil, and gas. These activities have been driving climate change over the past century and contributing to the increased risk of extreme events. The world must pull together to create a future in which extreme events, and the damage they cause, remain relatively rare.

AUTHOR'S NOTE

The credits and sources for the photos used in Figure 1 are **(a)** Nacho Doce, Reuters; **(b)** David Peterson, U.S. Naval Research Laboratory; **(c)** Victoria Druetta; **(d)** Beboy, Shutterstock; **(e)** N.C. DOT and U.S. DOT; **(f)** The Guardian; **(g)** NASA/NOAA GOES Project; **(h)** NOAA NESDIS;

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This article is dedicated to Dr. Rebecca Harris and her work. Rebecca was an outstanding and inspiring scientist and colleague, who very sadly passed away in December 2021. She worked tirelessly on climate risks and adaptation solutions for a better future. In addition to recognising Rebecca and her life's contributions to the field of climate science, we would like to thank the many other climate and earth scientists around the world, who are passionate about our planet and make understanding climate change and its impacts possible. This work puts together many results from this large research community. We also give a big thank you to the young reviewers for their time and effort; their commitment to improve science literacy is valued. AM and SP-K acknowledge support from the ARC Center of Excellence for Climate Extremes (CE170100023). IG thanks FCT/MCTES for support to CESAM [UIDP(UIDB)/500017/2020] and Project ATLACE (CIRCNA/CAC/0273/2019) through national funds. SP-K acknowledges funding from the Australian Research Council grant number FT170100106.

REFERENCES

1. National Academies of Sciences, Engineering, and Medicine. 2016. *Attribution of Extreme Weather Events in the Context of Climate Change (Report).* Washington, DC: The National Academies Press.
2. Steffen, W., Dean, A., and Rice, M. 2019. *Weather Gone Wild: Climate Change-Fuelled Extreme Weather in 2018*. Sydney, NSW: Climate Council of Australia Report.
3. Ralph, F. M., Rutz, J. J., Cordeira, J. M., Dettinger, M., Anderson, M., Reynolds, D., et al. 2019. A scale to characterize the strength and impacts of atmospheric rivers, *Bull. Am. Meteorol. Soc.* 100:269–89. doi: 10.1175/BAMS-D-18-0023.1
4. Steffen, W., Hughes, L., and Perkins, S. 2014. *Heatwaves: Hotter, Longer, More Often*. Sydney, NSW: Climate Council of Australia Report.
5. Abatzoglou, J. T., and Williams, A. P. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci. U.S.A.* 113:11770–5. doi: 10.1073/pnas.1607171113
6. Abram, N. J., Henley, B. J., Sen Gupta, A., Lippmann, T. J., Clarke, H., Sharples, J. J., et al. 2021. Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Commun. Earth Environ*. 2:8. doi: 10.1038/s43247-020-00065-8
7. Canadell, J. G., Meyer, C. P., Cook, G. D., Dowdy, A., Briggs, P. R., Knauer, J., et al. 2021. Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nat. Commun.* 12:6921. doi: 10.1038/s41467-021-27225-4

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YOUNG REVIEWERS

FARAH, AGE: 14

My name is Farah, I am 14 years old, my school level is the first year of high school, my favorite subjects are physics and mathematics, in my free time I read books and surf the net. As a social person, I like discussions on scientific phenomena and discoveries, my dream is to be an engineer.

HAYTAM, AGE: 14

My name's Haytam, I am 14 years old. My academic level is the third preparatory. My favorite subjects are: maths, physics, science, and English. My hobbies are: swimming, drawing and reading. I have practiced taekwondo for 2 years. I speak English and French fluently, I have previously participated in the Arab reading challenge and I participated in the math Olympiad too. My dream is to be a doctor or a vet.

KATELYN, AGE: 13

I am a 13 year old girl who enjoys reading and doing art. My favorite animal is a cat and I like to write short stories.

MACKENZIE, AGE: 15

My name is Mackenzie, and I enjoy music (both playing and listening), books (fantasy in particular), and sports (my favorite is tennis). I also enjoy science, math, and language, but the thing I enjoy most is backpack camping.

SOUNDOUSS, AGE: 15

My name is soundouss, I am 15 years old, my Academy level is first year in high school, my favorite subjects are Physics, French and English, my hobbies are swimming and reading, I speak Arabic and English, my dream is to become a bank manager, company manager, or a journalist.

AUTHORS

AMELIE MEYER

Dr. Amelie Meyer is passionate about climate change, polar science, and ocean circulation. Her work looks at how and why the polar oceans are changing. Amelie has spent several months both in the Arctic and in the Southern Ocean collecting data to answer these questions. She currently works for the ARC Center of Excellence for Climate Extremes based at IMAS, at the University of Tasmania in Australia. *Amelie.Meyer@utas.edu.au

HÉLÈNE BRESSON

Dr. Hélène Bresson has always been passionate about nature and science. She has studied many forms of severe weather such as thunderstorms, lightning, tornadoes, and tropical and polar cyclones. She loves traveling, experiencing different weather, and learning about weather's impact on our planet and our lives. Hélène is currently studying ice clouds with satellite and model data, to understand how they form and evolve and how they impact the weather and the climate. She is currently working at the Laboratoire d'Optique Atmosphérique, in the north of France.

IRINA V. GORODETSKAYA

Dr. Irina Gorodetskaya is a meteorologist who loves studying extreme environments, such as the Arctic and Antarctic regions, and extreme phenomena, such as atmospheric rivers. She believes that to understand these phenomena, we must measure them! She has been measuring and analyzing snow and atmospheric rivers in Antarctica for more than 10 years. She is one of the lead authors of the Intergovernmental Panel on Climate Change 6th Assessment Report, in which she explains how polar regions change. Irina currently works at the University of Aveiro, Portugal.

REBECCA M. B. HARRIS

Dr. Rebecca Harris was an outstanding and inspiring climate impact scientist. An ecologist by training, her work focused on the combined impacts of climate change and extreme events on natural and human systems. She recently contributed as a Lead Author to the Intergovernmental Panel on Climate Change Sixth Assessment Report, which gave her hope that governments around the world will make the changes needed to slowdown climate change and safeguard our future. Rebecca was not only a great researcher, but also a great leader, an inspiring lecturer, and a respected supervisor, both in and outside the School of Geography, Planning, and Spatial Sciences at the University of Tasmania in Australia where she worked. Alas, Rebecca Harris passed away in December 2021. She is greatly missed by the many people that knew and admired her.

SARAH E. PERKINS-KIRKPATRICK

Dr. Sarah Perkins-Kirkpatrick is a climate scientist who loves studying heatwaves. She has spent the last 10 years learning everything she can about them! Sarah's work has focused on how to measure heatwaves, what drives them, how they are changing, and how climate change may explain current and future heatwaves. She is also very interested in the health impacts they cause, and how these impacts may also be driven by climate change. Sarah currently works at the ARC Center of Excellence for Climate Extremes at UNSW in Sydney, Australia.

EARTH AND ITS RESOURCES
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POLAR AMPLIFICATION: STRONGER WARMING IN THE ARCTIC AND ANTARCTIC

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[2] Interdisciplinary Centre of Marine and Environmental Research (CIIMAR) of the University of Porto, Porto, Portugal

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YOUNG REVIEWERS:

FRANCESCO
AGE: 10

GIOSUÈ
AGE: 8

LORYAN
AGE: 10

MATTIA
AGE: 8

MIRKO
AGE: 9

During the past several decades, our planet has warmed because people have added a lot of greenhouse gases to the atmosphere. The warming in the polar regions (the Arctic, and parts of the Antarctic) has been much higher than in the rest of the world. Melting of snow and ice, disappearing glaciers, and rising global sea levels are evidence of the strong warming occurring in the polar regions. Various measurement techniques are used to discover how much the temperature, as well as sea ice and snow cover, have changed in the polar regions. In this article, you will learn how shrinking ice and snow, increasing clouds, and thinner ice help to warm the polar regions much more than other regions of the world.

SOFIA

AGE: 9

VITTORIA

AGE: 9

WHAT IS POLAR WARMING AMPLIFICATION?

Earth has two polar regions—the Arctic in the north, and the Antarctic in the south. The Arctic is a vast ocean with large areas covered by **sea ice**, even in summer. The Arctic also contains a huge island covered by ice, called the Greenland **ice sheet**. Northern regions of North America, Europe, and Asia also belong to the Arctic—they are covered by a lot of snow in winter and have **permafrost**, which is the permanently frozen ground. Antarctica is a huge ice sheet, which is surrounded by the Southern Ocean. Although the two polar regions have different characteristics, they have one thing in common: they are both covered by snow and ice year-round, because they are very cold. However, due to the recent warming of our planet, polar regions are also warming (Figure 1A), and their snow and ice cover is shrinking (Figure 1B). What is more, the Arctic and part of Antarctica have warmed more rapidly and strongly than other regions of the Earth. This phenomenon is called **polar amplification**.

SEA ICE

Ice that originates from freezing of ocean water.

ICE SHEET

A large body of ice that originated from compacted snowfall accumulating on rocky land over many years (currently there are two ice sheets—Greenland and Antarctic).

PERMAFROST

Ground that stays frozen throughout the year, even in summer.

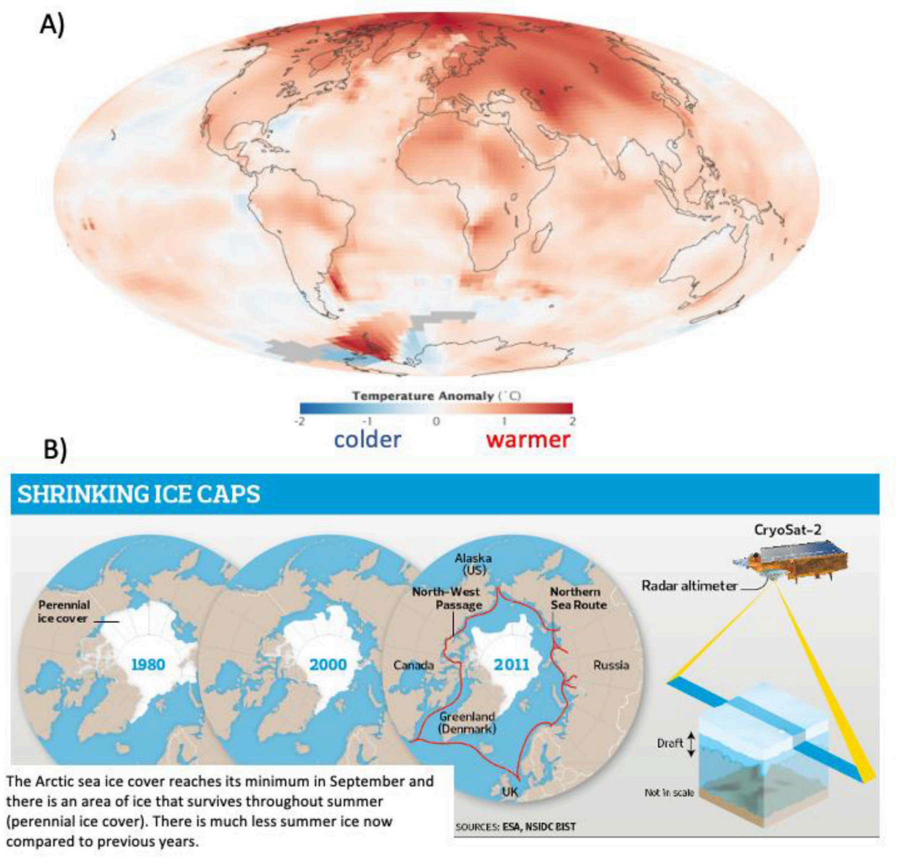

Figure 1

Figure 1

(A) Temperature changes between two periods: 2000–2009 compared with 1951–1980. Pink/red colors show where temperatures became warmer, and blue colors show where temperatures became colder. The entire Arctic and the Antarctic Peninsula have become 2°C warmer, which is much warmer than other regions (Image credit: National Aeronautics and Space Administration). **(B)** Shrinking summer sea ice in the Arctic, as measured from space by the CryoSat-2 satellite (Image credit: European Space Agency and National Snow and Ice Data Center). Radar altimeter is a sensor installed on the CryoSat-2 satellite measuring sea ice thickness above the water level (without the sea ice draft, which is below the water level).

WHY IS POLAR AMPLIFICATION IMPORTANT?

POLAR AMPLIFICATION

Greater warming near the poles compared to the rest of the world in response to global climate change.

The consequences of warming in the polar regions can be devastating: animals like polar bears lose their habitats; people living in those regions cannot continue their traditional lifestyles; and land that was frozen for thousands of years collapses, destroying buildings or roads built on it. The melting of snow and ice in the polar regions also has consequences around the world. For example, the melting of the Greenland and Antarctic ice sheets causes large amounts of water to flow into the ocean, which causes global sea levels to rise and may flood many islands and low-lying coastal areas around the world. Climate change in the polar regions also influences the rest of the Earth's weather. Thus, while someone may say that disappearing sea ice brings benefits like easier access to the Arctic sea routes (shown by the red line in Figure 1A), the bad consequences we listed above outweigh any economic benefits. Scientists are concerned about all these impacts, so they are investigating why the polar regions are warming so quickly, how much they will continue to warm in the near future, and what the local and global impacts of this warming might be.

MEASURING POLAR AMPLIFICATION

How do we know that temperatures have been changing in the polar regions? Scientists can measure the temperatures of the air, ocean, snow, and ice in these regions (Figure 2). Some stations have been measuring for more than 70 years, so we know how temperatures have been changing every year, month, and day since then. These stations need people to be present to take the measurements; but recently, scientists have been using automatic weather stations that need maintenance only once a year and thus can be installed at many more locations [1]. Scientists also take a lot of measurements during expeditions, when they study changes in the ocean, ice, snow, and atmosphere simultaneously [2]. Since 1979, there have been scientific satellites measuring Earth from space and giving a lot of information about changes in the polar regions and across the globe (such as the CryoSat-2 satellite shown in Figure 1B).

Long-term measurements show that temperatures in the polar regions have increased at twice the global average. Since humans started adding lots of greenhouse gases to the atmosphere at the end of the 19th century, the Arctic and parts of the Antarctic Peninsula have warmed on average by more than 2°C, while the global average temperature increase has been 1°C. Large amounts of snow and ice have also melted, and the air has become more humid and cloudier, which has increased the amount of precipitation. It often rains instead of snowing in the Arctic now.

Figure 2

Figure 2

(A) Weather stations where measurements are recorded by scientists living on-site at one of the Arctic stations (Image credit: Russian Hydrometeorological Service). **(B)** Automatic weather station installed near Princess Elisabeth station in East Antarctica (Photograph credit: Irina Gorodetskaya). **(C)** Measurements of the atmosphere using a weather balloon at the Escudero station in Antarctica (Photograph credit: Penny Rowe and Edgardo Sepúlveda). **(D)** Measurements of ocean temperature and salt content during the Antarctic Circumnavigation Expedition (Photograph credit: Irina Gorodetskaya). **(E)** Measuring the temperature and thickness of snow and ice (Photograph credit: Lianna Nixon) **(F)** A laser measuring changes in snow cover (Photograph credit: Esther Horvath).

FEEDBACK

A process that makes an initial change (such as a temperature change) stronger (positive feedback) or weaker (negative feedback).

ALBEDO

The amount of the sun's rays that are reflected (and thus not absorbed) by a surface (ex. 10% albedo means 10% of the rays are reflected and 90% are absorbed).

WHY ARE THE POLAR REGIONS WARMING FASTER AND STRONGER? LOCAL FEEDBACK!

Several processes are responsible for making the warming in the polar regions stronger than in other areas of the Earth. These are known as **feedback** processes [3], and they are processes that increase or decrease the original change (Figure 3). The processes that make warming even stronger are called positive feedback. And "positive" does not mean they are good! We will explain three of these positive feedback processes in more detail.

Snow- and Ice-Albedo Feedback

The land and ocean in the polar regions can be covered in snow and ice. Snow- and ice-albedo feedback describes the relationship between the sun's rays and the snow and ice covering a surface (Figure 3A) [4]. The balance between the incoming sun rays and those reflected from a surface is called **albedo**. This feedback only occurs during daylight, so it cannot occur during the **polar night**—in winter, when polar regions do not receive any sunlight. If the sun's rays hit a bright surface like snow or ice, most of the rays are reflected back to the sky and are not taken up by the surface. This is called high albedo. Snow- and ice-free surfaces in the polar regions are darker and reflect fewer of the sun's rays. Instead, these rays are stored by the surface, which is known as low albedo.

So, as the polar air warms, snow and ice melt. Large parts of the ocean and land surfaces that were once covered by snow and/or ice become exposed and take up more sun rays. This warms the land surface and ocean *even more* and leads to *further* melting of snow and ice.

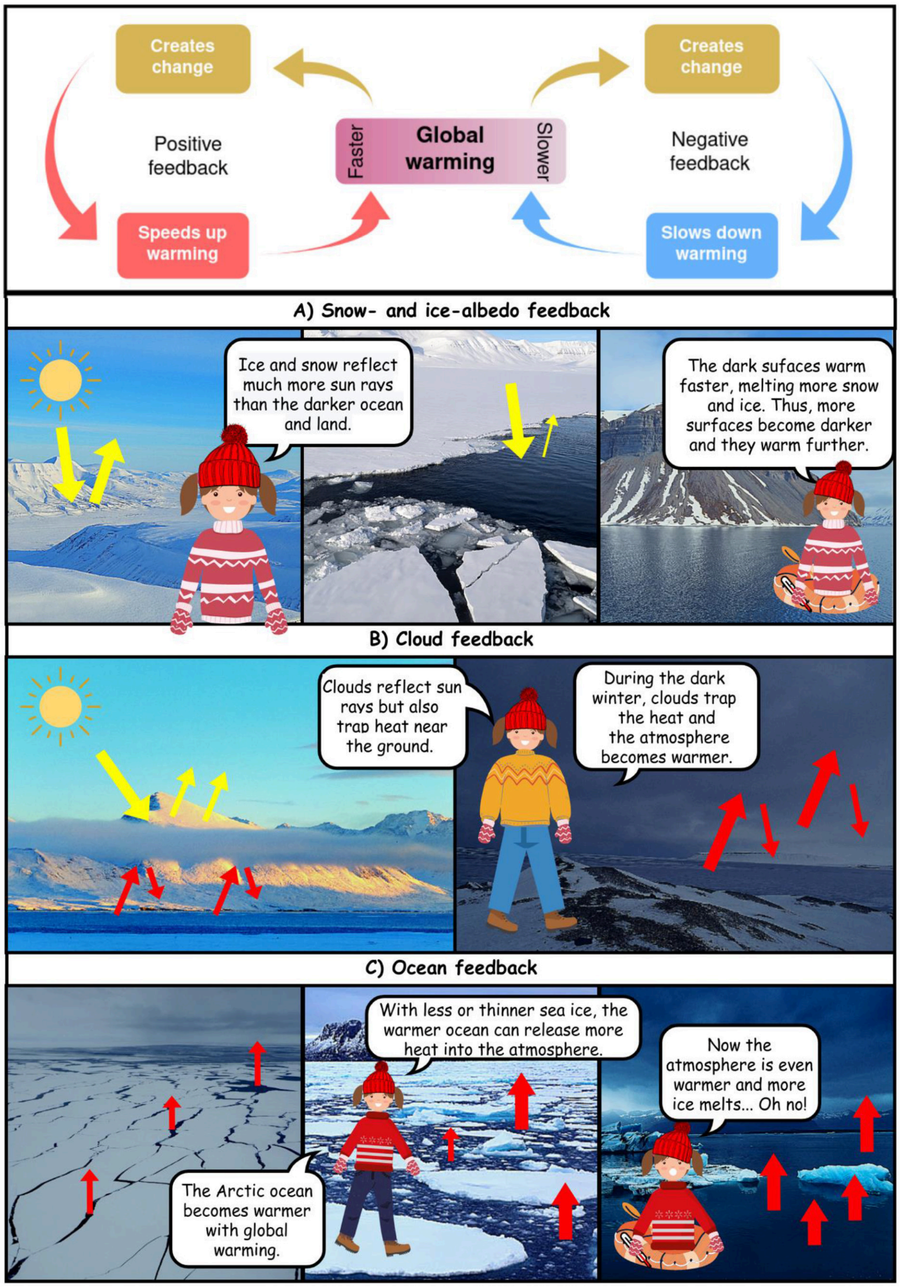

Figure 3

Figure 3

(TOP panel) Negative and positive climate feedback loops. Positive feedback speeds up warming, while negative feedback slows it down (Image credit: MetOffice, UK). **(A)** Snow- and ice-albedo feedback. **(B)** Cloud feedback. **(C)** Ocean feedback. In **(A–C)**, arrows represent the movement of heat from the ice/ocean/ground surface to the air above, and from the air to the surface (Photograph credits: A1–A3, B2 Melanie Lauer, B1 Vera Schemann, C1 Amelie Meyer, C2 northwestpassage2015.blogspot.com, C3 Emma Francis.

POLAR NIGHT

The winter period in the Arctic or Antarctic, when the sun does not rise and the night lasts several months.

This process will continue until all the snow and ice are gone from a surface.

Cloud Feedback

As the atmosphere becomes warmer, many processes happen that involve clouds—some lead to cooling and some to more warming. It is very complicated, and there are still many things we do not understand about these processes. Scientists measure clouds to understand their behavior, and they work with computer models to create virtual clouds, to study clouds' role in the climate system. One process that is being studied is called cloud feedback [2].

Clouds are made from little water droplets and/or ice crystals. Like ice and snow on the ground, clouds also have a high albedo and therefore reflect a large part of the sun's energy. However, in the polar regions, the sun does not shine during the polar night. During this time, the clouds block the energy emitted by the Earth's surface and send it back down, trapping it between the surface and the clouds. This energy warms the air (Figure 3B).

Warmer air contains more water vapor due to evaporation from the ocean, so it helps to form even more clouds…which increase the temperature even more. You can see that this is a positive feedback loop.

Ocean Feedback

Ocean feedback means that the ocean increases the warming of the air near the ocean surface [5], and this also interacts with other types of feedback (Figure 3C). First, because of increased ice/snow melting during the summer, the Arctic Ocean and land absorb more solar energy due to the snow- and ice-albedo feedback. Clouds warm the surface further, especially during the long polar winter, melting the ice and snow even more *via* cloud feedback. Scientists also found that global warming is causing increased inflow of warmer Atlantic water into the Arctic. All these processes warm the Arctic Ocean and melt sea ice, making it thinner and less abundant in winter. This is when ocean feedback starts to play a role: in winter, the Arctic Ocean is much warmer than the air above it, especially as the ocean continues to warm due to global warming. When there is less ice or thinner ice, the ocean can give more heat to the air, warming it even more. This is another positive feedback loop!

SUMMARY

During the past few decades, the entire Arctic region and parts of the Antarctic have warmed more than the rest of the world has. We know this thanks to long-term measurements and expeditions. This phenomenon is known as polar amplification, and it occurs because of various feedback processes, such as snow- and ice-albedo feedback, cloud feedback, and ocean feedback. Computer models of the climate system show that warming will continue in the future, with Arctic sea ice disappearing completely in summer over the next 20–30 years. Disappearing Arctic sea ice in summer harms indigenous people, as well as animals depending on ice and fragile ecosystems, while melting ice sheets raise global sea level. Although the current situation is dire, if all the countries of the world do their part by reducing greenhouse gas emissions, we can still slow down this warming and possibly even bring Arctic sea ice back!

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REFERENCES

1. Gorodetskaya, I. V., Kneifel, S., Maahn, M., Van Tricht, K., Thiery, W., Schween, et al. 2015. Cloud and precipitation properties from ground-based remote-sensing instruments in East Antarctica. *Cryosphere* 9:285–304. doi: 10.5194/tc-9-285-2015
2. Wendisch, M., Macke, A., Ehrlich, A., Lüpkes, C., Mech, M., Chechin, D., et al. 2019. The arctic cloud puzzle: using ACLOUD/PASCAL multi-platform observations to unravel the role of clouds and aerosol particles in Arctic amplification. *Bull. Amer. Meteor. Soc.* 100:841–71. doi: 10.1175/BAMS-D-18-0072.1
3. Stuecker, M. F., Bitz, C. M., Armour, K. C., Proistosescu, C., Kang, S. M., Xie, S.-P., et al. 2018. Polar amplification dominated by local forcing and feedbacks. *Nat. Clim. Change* 8:1076–81. doi: 10.1038/s41558-018-0339-y
4. Serreze, M. C., and Barry, R. G. 2011. Processes and impacts of Arctic amplification. A research synthesis. *Glob. Planetary Change* 77:85–96. doi: 10.1016/j.gloplacha.2011.03.004
5. Maslanik, J. A., Fowler, C., Stroeve, J., Drobot, S., Zwally, J., Yi, D., and Emery, W. 2007. A younger, thinner Arctic ice cover: increased potential for rapid, extensive sea ice loss. *Geophys. Res. Lett.* 34:L24501. doi: 10.1029/2007gl032043

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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

FRANCESCO, AGE: 10

Francesco is 10 years old and lives in Italy. He loves playing piano and devotes every spare moment to it. His favorite sport is basketball. As a book eater, he reads every night in bed for at least 1 hour. He also really likes Pokemon cards and has a nice collection. He loves nature and animals. He also likes fishing—then letting the fish free in water again. Among his favorite things are also drawing and cooking.

GIOSUÈ, AGE: 8

My name is Giosuè, I am eight and a half years old, I live in San Cesareo with my parents and my younger brother Leonardo who is almost 5 years old. I really like playing football and my role is the goalkeeper. Since last year I am at my new school and it helped me discover that I definitely like school. We have fun, laugh, run and above all we are always outdoors. I also really like pokemon cards, biking, scooter, overboard and skateboard.

LORYAN, AGE: 10

My name is Loryan and I am 10 years old. I live in Roma, I love football and music. I am very interested in all what concerns climate, pollution and planet Earth.

MATTIA, AGE: 8

Hi! I am Mattia, I like to skateboard and to draw comic strips. I think that scientific articles could be more interesting if they were written in cartoon bubbles. Maybe 1 day I will be a scientific cartoonist!

MIRKO, AGE: 9

Mirko is 9 years old and lives in Roma. He loves playing soccer with friends. He likes eating sushi very much and his favorite subject is history.

SOFIA, AGE: 9

Hi, I am Sofia, a young Italian girl and I am so curious!! I love my family and I love life! I like nature and sports. I go to school and my favorite subject is math, I like studying, but a little less than climbing trees. My favorite dish is my grandmother's meatballs and I really like cooking with her. When I grow up I would like to be a horsewoman or a violinist.

VITTORIA, AGE: 9

Vittoria is nine and a half years old, she likes drawing and painting, even writing and reading. Her favorite saga is "Harry Potter" and she is currently reading the third book; she has seen all the movies, and "The Hobbit" and "The Lord of the Rings." She is pretty good at doing impressions of Italian comedians as Teresa Mannino and Anna Marchesini. Ah, she loves popcorn!

AUTHORS

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Dr. Irina Gorodetskaya is a polar meteorologist who is passionate about Arctic and Antarctic environments, where she mostly studies clouds, snowfall, atmospheric rivers, and their roles in the polar warming amplification. She believes that to understand things better we must measure them! She has been doing measurements in the polar regions for more than 10 years. She has lived, studied, and worked in Russia, USA, France, Belgium, and now Portugal. She enjoys reading, music, rock climbing, and traveling with her family and friends. *irinag@ciimar.up.pt

MELANIE LAUER

Melanie Lauer is a Ph.D. student in meteorology at the University of Cologne in Germany. Even as a child, she was enthusiastic about the weather and nature, so she decided to study meteorology. During her studies, she got to spend a semester in the northernmost higher education institute, in Longyearbyen, Svalbard. Following her stay in Svalbard, she has focused on processes that contribute to Arctic warming. Now, she analyses atmospheric rivers and their influence on precipitation (snow and rain) in the Arctic.

THERESA KISZLER

Theresa Kiszler is a doctoral student at the University of Cologne, Germany, and works on a large project studying Arctic amplification. Their interests cover many topics, from cloud formation and what happens inside of clouds to large storm systems such as hurricanes. After studying meteorology, Theresa switched their focus and got more involved in computational sciences. Now they mainly work on running programs (atmospheric models) on huge computers, to find out more about clouds in the Arctic.

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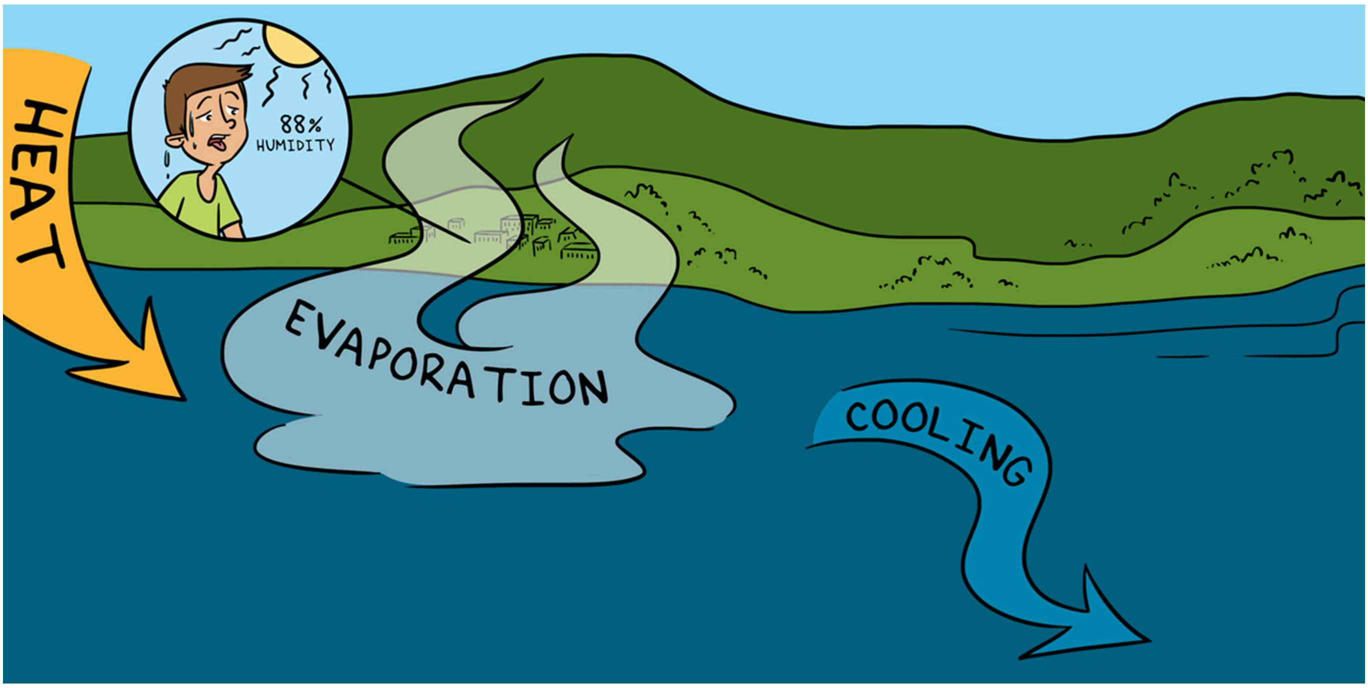

HOW MIGHT THE OCEAN CHANGE IN THE FUTURE?

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YOUNG REVIEWER:

AVIV
AGE: 9

The ocean is one of the main components of the climate system. It distributes and absorbs heat to regulate climate at different time scales. Temperature and salinity (saltiness) control the density of ocean water. Differences in water density are important for ocean circulation—they are responsible for generating some currents of water that move through the ocean. An important part of ocean circulation is called thermohaline circulation. Thermohaline circulation absorbs, stores, and transfers heat around the world. Changes in the temperature or salinity of ocean waters can affect thermohaline circulation, so climate change may also alter this circulation. Changes in water circulation also impact the ocean's chemistry and the organisms that live in the ocean. First, we will explain how ocean circulation happens, and then we will look at how climate change can affect it.

HOW DOES THE OCEAN WORK?

The ocean covers about 70% of the planet's surface and contains 97% of Earth's water. This water absorbs heat from the sun and transports this heat with the ocean currents. In addition to heat, ocean currents also transport carbon dioxide, nutrients, and organisms such as fish larvae all around the globe.

OCEANIC CIRCULATION

Large scale movement of waters made by ocean currents.

DENSITY

The ratio between the mass and volume of an object.

This transport is called **oceanic circulation**, and it has two major components. The first is the upper-ocean circulation, which is wind-driven and faster. It tends to happen only within a given ocean basin (the North Atlantic Ocean or the Indian Ocean basin, for example). Upper-ocean circulation helps to exchange heat and moisture between the ocean and the atmosphere. Therefore, changes in upper-ocean circulation can impact global and regional weather. The second component is the deep global circulation, which is slower and driven by differences in water **density**. It is the central part of the "global ocean conveyor belt". For more information see this Young Minds article: When Water Swims in Water, Will it Float, or Will it Sink? Or: What Drives Currents in the Ocean? [1]. Furthermore, the deep global circulation distributes heat and energy around the Earth across different ocean basins. Changes in the deep global circulation act over long timescales and can affect the local and global climate, as we have seen over the last 50,000 years. It is good to note that the difference between "weather" and "climate" is the time scale. When we talk about "weather" we refer to processes in the short time scale and climate, to the mean state of nature when averaging longer periods. For example, if it starts to rain in the desert, we can say that we are experiencing rainy weather. But for years, we have seen that it generally does not rain much in this region, so the desert has a dry climate despite the current rainy weather.

SALINITY

The amount of salt dissolved in a water body.

OCEAN STRATIFICATION

The division of ocean water into layers based on density.

WATER MASSES

Water parcels with formed at the same place that travels around with similar characteristics for properties like temperature and salinity.

How does the difference in water density drive the deep global circulation? The density of ocean water varies with **salinity** (saltiness) and temperature, so water density varies throughout the ocean. Different regions and depths will have different salinity and temperature, and thus different densities. The warmer liquid water is, the lighter and less dense it gets. But solid ice is actually less dense than liquid water due to the structure of the ice crystals. This is why ice floats on water, even though it has a lower temperature than the liquid water it floats in. Thus, areas of cold and salty water are denser than areas of warm and fresh water. In the ocean, denser water parcels flow beneath lighter ones. Water parcels in the ocean are layered according to their density, much like a birthday cake with several layers and fillings. This forms the **ocean stratification** illustrated in Figure 1.

Temperature and salinity ranges define a water parcel. These parcels are what we call **water masses**. By studying water masses, we can understand where they came from and where they are going, which helps us better understand and describe the ocean. Water masses

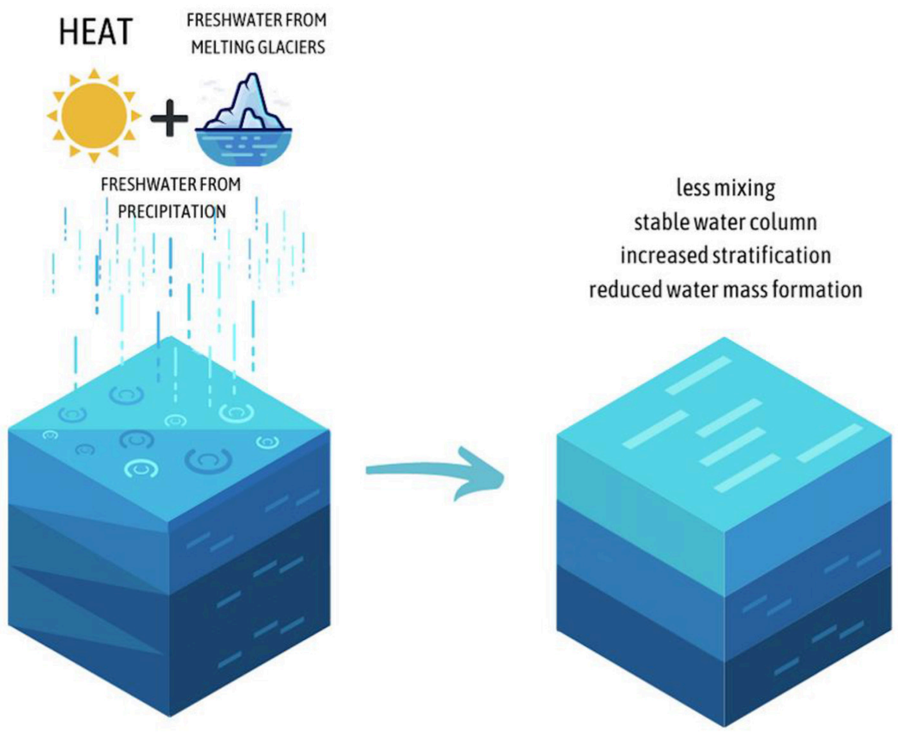

Figure 1

Figure 1

Ocean stratification is the separation of water into layers based on its density. Salinity (the amount of salt) and the temperature of the water contribute to density. When more rain falls or when glaciers melt, and when the sun heats the ocean water, the density of the water decreases (left panel). When water density decreases, this can create stable layers of water (right panel). Under these conditions, it is more difficult for water masses to form.

need the right combination of conditions to form. These conditions may include winds, solar radiation, and salt availability, which may only occur during specific seasons and in specific regions around the globe—in the North Atlantic or the Southern Ocean, for example.

OCEAN AND CLIMATE: HEAT TRANSPORT

The formation of deep-water masses is the fuel for what is called **thermohaline circulation**. The Atlantic Meridional Overturning Circulation (AMOC) is an important part of the thermohaline circulation. It is a north-south-oriented flow of water that transports heat in the Atlantic Ocean. Starting at the surface, the AMOC is composed of salty, warm waters from the low latitudes (near the Equator). Then, it flows toward the North Atlantic Ocean, where the ocean current called the Gulf Stream plays a key role. As the AMOC flows north, it slowly loses heat to the atmosphere because of the large difference in temperature between the air and the ocean. After losing heat, the water becomes denser and sinks, flowing back southwards (Figure 2).

THERMOHALINE CIRCULATION

Part of the large-scale ocean circulation driven by density gradients. Results from the combined effects of temperature (*thermo*) and salt (*haline*) on density. Also called the ocean conveyor belt.

At the same time, the warm, moist air above the AMOC current is taken by the winds. A similar thing happens when you forget about your cup of tea—it slowly starts to get cooler until it reaches room temperature. To achieve equilibrium, the hot tea must lose heat and moisture to the air just above your mug. But this warm, moist air does not stay

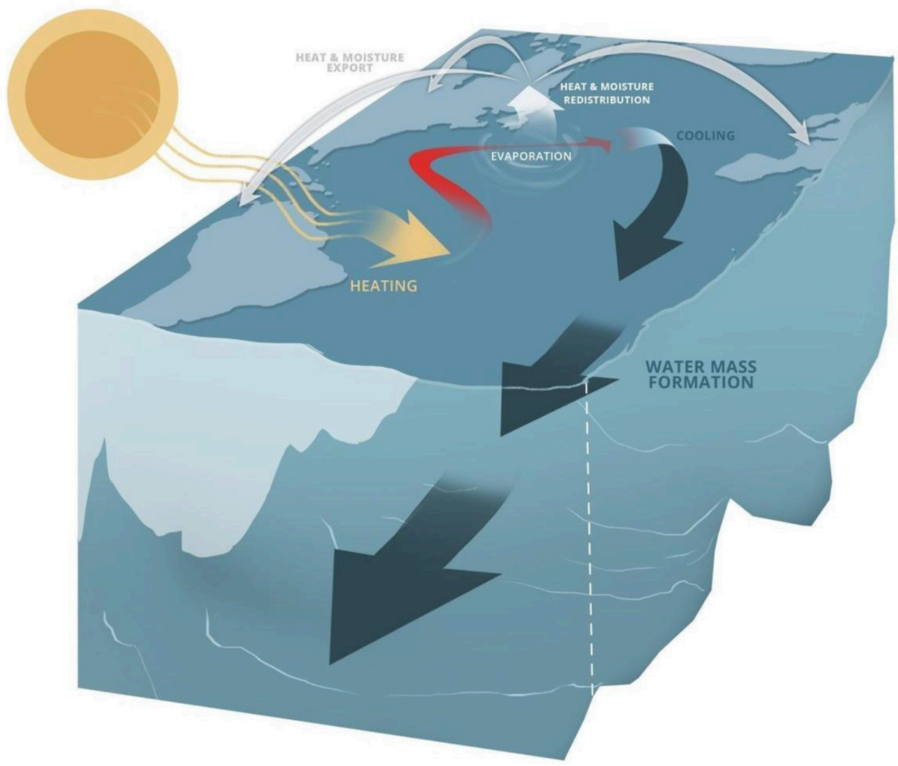

Figure 2

Figure 2

Heat circulation in the North Atlantic. The ocean absorbs heat from the sun near the Equator and transports it northwards. As it is transported, the water evaporates and cools down. Evaporation causes heat and moisture to be transferred from the water to the air above. The atmospheric circulation redistributes all this heat and moisture. As the current goes further north, it becomes much colder and saltier. Finally, it is mixed and creates a new water mass with a higher density that sinks to deeper layers and flows back to the south (Image credit: Thiago Sales).

concentrated around the cup forever. Instead, it is dispersed in the room until you cannot track it anymore. The warm, moist air from the AMOC is taken by the winds and travels very far, reaching cities as far away as London. This makes the weather in London warmer and more humid compared to other cities found at the same latitude.

Now you can see why the AMOC is an essential component of the Earth's climate system—because it plays a crucial role in heat transport. The AMOC is responsible for the relative warmth of the Northern Hemisphere [2].

BUT HOW WILL THE OCEAN CHANGE?

The ocean absorbs most of the sun's energy that hits Earth. Did you know that it also absorbs more than 90% of the CO_2 and excess heat that humans add into the atmosphere? But can the ocean keep absorbing heat and carbon forever? Probably not. Although the ocean changes all the time, it is currently changing much faster than scientists expected (Figure 3).

Every time we add something to the ocean that was not there before, like heat or carbon, we are causing the ocean to change. So, between climate changes and human impacts, what does the future hold for the ocean?

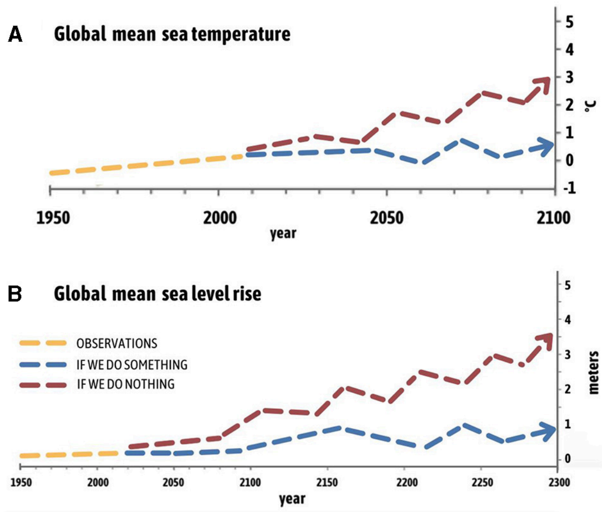

Figure 3

Figure 3

(A) The global mean sea surface temperature and **(B)** global mean sea level are projected to continue increasing into the future. If we work to reduce our CO_2 emissions, the changes will be lower (blue). But if we do nothing to reduce CO_2 (red), the ocean could get much warmer, and the sea level will rise substantially (Image adapted from [3]).

The mean ocean temperature is increasing. A warmer ocean will lead to a much more stratified ocean, meaning that there will be more still layers of water with less mixing. And it will be harder for water masses like we have today to be created because they need some mixing of the water to form. Changes in the formation of water masses will impact heat transport and, therefore, the Earth's climate. But some places will experience surface warming more than others. The Arctic, for example, will be more affected than other regions [4]. The problem is that the Arctic Ocean is one of the most critical water mass formation areas. If water masses do not form as readily in the Arctic, the ocean currents will probably get weaker. Researchers have already shown that the AMOC is becoming weaker, and they suggest that it is due to climate change [5].

THERMAL EXPANSION

When a substance is heated, molecules begin to vibrate and move more, increasing the distance between themselves. This increases volume and decreases density.

A warming ocean can also lead to the disappearance of some coastal cities and islands. This would happen because of **thermal expansion.** As the temperature rises, liquid water expands and occupies a larger volume, causing the sea level to rise. The sea level will also rise as liquid water shifts from land to the ocean, due to increased discharge from rivers or melting of glaciers. Melting of ice sheets as the temperature rises can also add volume to the ocean and contribute to local sea-level rise. Read more about it in Why Should We Worry About Sea Level Change? [6]. In the last few years, sea-level rise has already been observed, and it should be carefully studied, since it can impact many people around the world, especially coastal populations.

HOW CAN WE HELP?

Climate change studies teach us how and why the ocean will change if nothing is done to stop the process. If the global ocean temperatures continue to rise, there will be many harmful effects on ocean organisms and humans. The ocean is one of the main regulators of rain and oxygen production. It provides us with food and helps us to move around the Earth. We all depend on the ocean! So, we need to improve and spread our knowledge about the ocean and the danger it faces. To help do so, the United Nations created the Decade of Ocean Science for Sustainable Development, between 2021 and 2030. This initiative will help us to teach people what they need to do, individually and collectively, to better manage ocean resources. If we do not start to change our habits and improve our relationship with nature, climate change will intensify and the effects of ocean temperature rise will worsen.

But we hold the power to change! We can change our personal habits, such as being mindful about our use of water and energy and reducing the single-use of plastics, also playing a key role as citizens. Kids have a crucial role in raising awareness and shaping the future. By talking about climate change with our families and friends, we can draw people's attention to this subject. We can discuss how to support policies that protect the ocean and fight climate change. We can also demand that our governments and industries act responsibly and use natural resources wisely. The sooner we take action, the higher our chances of achieving a better and brighter future for the world's ocean—and for all the animals and humans that depend on it.

REFERENCES

1. Glessmer, M. S. 2019. When water swims in water, will it float, or will it sink? Or: what drives currents in the ocean? *Front Young Minds.* 7:85. doi: 10.3389/frym.2019.00085
2. Buckley, M. W., and Marshall, J. 2016. Observations, inferences, and mechanisms of the atlantic meridional overturning circulation: a review. *Rev Geophys.* 54:5–63. doi: 10.1002/2015RG000493
3. IPCC. 2019. "Summary for policymakers," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, eds H. O. Pörtner., D. C. Roberts., V. Masson-Delmotte., P. Zhai., M. Tignor., E. Poloczanska., et al. (IPCC).
4. Xie, S. 2020. Ocean warming pattern effect on global and regional climate change. *AGU Adv.* 1:e2019AV000130. doi: 10.1029/2019AV000130
5. Hu, S., and Federov, A. 2019. Indian ocean warming can strengthen the Atlantic meridional overturning circulation. *Nat. Clim. Change* 9:747–51. doi: 10.1038/s41558-019-0566-x
6. Siegert, M. 2017. Why should we worry about sea level change? *Front. Young Minds*. 5:41. doi: 10.3389/frym.2017.00041

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YOUNG REVIEWER

AVIV, AGE: 9

A huge Harry Potter fan! I love reading books! I spend many hours reading on my Kindle, especially Harry Potter—I have read the entire series 20 times! I also love jamming on my electric piano, jump-roping, and skipping when I am happy. I like eating salads and home cooked meals, but I also have a big sweet tooth—chocolate is yummy! As a vegetarian, I love nature–learning about it, protecting it, and enjoying it!

AUTHORS

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I am an oceanographer and I really like physics! Now, I am now trying to learn more about how the ocean is represented by climate models and how it will behave with climate change. I am currently finishing a Master's degree in meteorology at the Federal University of Rio de Janeiro (UFRJ). I work with a very interesting class of models that are meant to reproduce the main processes on Earth (Earth System Models). *denise.fukai@gmail.com

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I am an oceanographer with a Master's degree in environmental geosciences. Particularly, I am interested in understanding how the climate has changed over time, and how it can impact the future. I currently work with climate reconstructions in Antarctica and high mountain regions where we found ice and snow. For this, I use microscopic organisms such as diatoms as indicators of environmental and climatic changes, integrated with geochemistry and radiological analysis.

MAURO CIRANO
As a physical oceanographer, I have devoted the last 3 decades to understanding the circulation in coastal and oceanic regions, both based on the analysis of oceanographic data and through numerical modeling of circulation. I am an Associate Professor at UFRJ and the coordinator of two operational oceanography programs in Brazil. At UFRJ, I teach and supervise graduate and undergraduate students.

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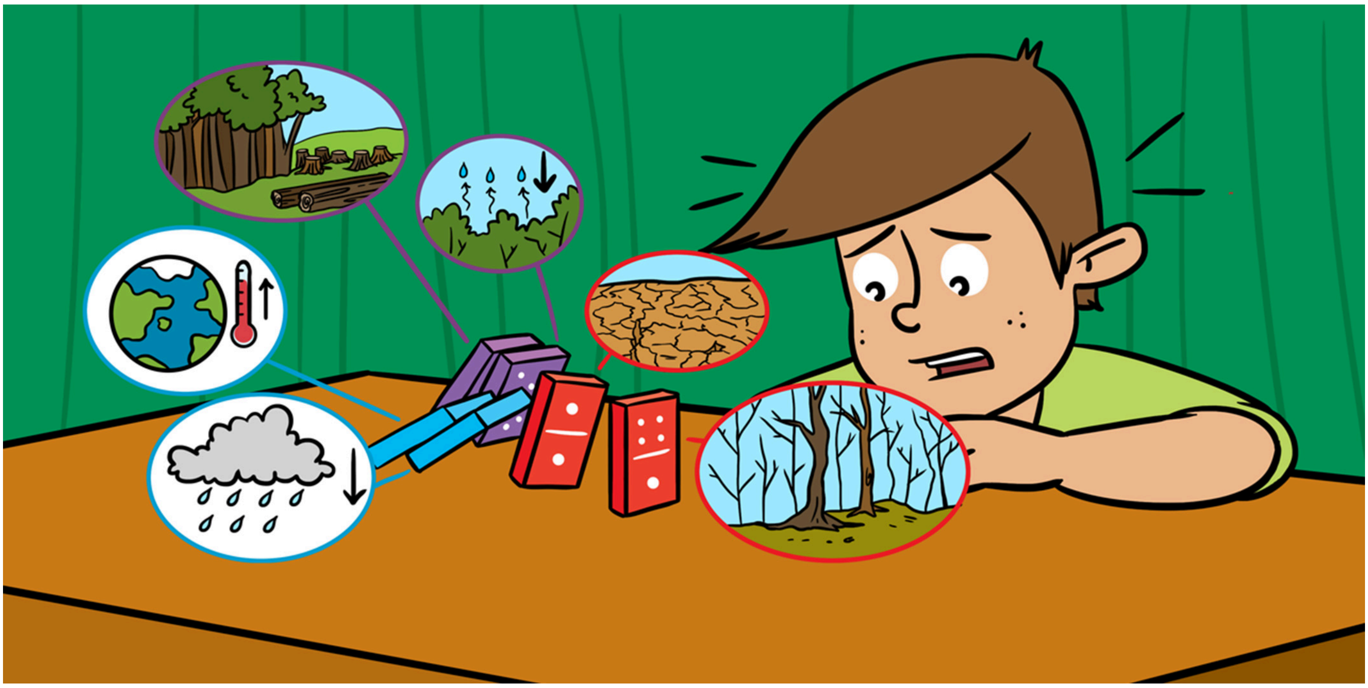

TIPPING POINTS: CLIMATE SURPRISES

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YOUNG REVIEWER:

DAVID
AGE: 11

We know that the more greenhouse gases are released, the more the world warms. But, at a certain point, could a *small amount* of extra greenhouse gas cause a *very big* change in the climate? And could this big change be irreversible? When a small change causes a very large (and long-term) effect, we call this a tipping point. Scientists are trying to understand whether tipping points exist in the Earth's climate system, and if so, what impact these could have.

WHAT IS A TIPPING POINT?

When a very small change causes a large, long-term effect, we call this a **tipping point**. In scientific language, we say that the system is pushed from one "state" to another. To understand this definition, let's look at an example of a tipping point from our everyday lives. Imagine riding a bike along the top of a hill (Figure 1). Each time you push the pedals, you move a little further forward, until one push sends you that crucial inch closer to the edge, and suddenly you are rolling irreversibly down the hill, all the way to the bottom. By making that last push on the pedals, you pass the **threshold** that takes you from one state—being at the top of the hill—to another state—being at the bottom.

TIPPING POINT

A threshold in a system which, when passed, results in large changes. The edge of a hill is an example of a tipping point—where passing the edge leads you from the top to the bottom.

Figure 1

When you ride your bike along the top of a hill, the last push of the pedals takes you past the tipping point, sending you irreversibly all the way down to the bottom.

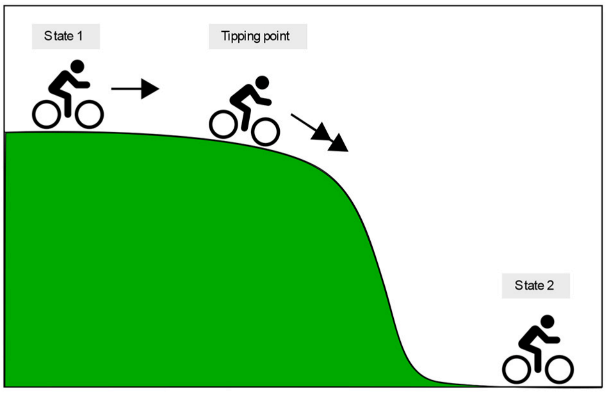

Figure 1

THRESHOLD

The value which must be exceeded for a system to move from one state to another.

Scientists are working to understand whether tipping points exist in the Earth's climate system, and if so, what sorts of global impacts tipping points might have in the future. We will now describe the parts of Earth's climate system where this threshold behaviour seems most likely to happen.

A TIPPING POINT FOR ICE SHEETS

The Earth has two big ice sheets: the Greenland ice sheet in the north, and the Antarctic ice sheet in the south. Let's take the Greenland ice sheet as an example.

The Greenland ice sheet is a relic from the last ice age—this means it did not form in the climate we have today but is instead left over from when the climate was much colder. The Greenland ice sheet is so thick that it reaches an altitude of over 2 km above sea level. At this height, the air is much colder than at sea level, helping the ice to stay frozen. In the past, the air has been cold enough to stop the ice from melting too quickly, allowing the snow falling on the surface of the ice sheet to replace any melting ice lost to the ocean. However, as more heat has been trapped in the Earth by greenhouse gases in the atmosphere, the air has warmed, melting the ice sheet faster than it can be replaced by the falling snow.

SELF-REINFORCING FEEDBACK LOOP

A process which gets stronger the more it happens. The melting and shrinking of the Greenland ice sheet is an example of a self-reinforcing feedback loop.

As the ice melts, the ice sheet shrinks—it gets smaller *and* shorter. At these lower altitudes, the ice sheet is exposed to warmer air. The more the ice melts, the shorter the ice sheet gets, which causes more ice to melt, lowering the ice sheet further, causing more heating, and so on (Figure 2) [1]. This is known as a **self-reinforcing feedback loop**—the more it happens, the worse it gets. At a critical point, scientists think the ice sheet will pass a threshold where it irreversibly moves from a state with permanent ice to a state without it—the ice sheet will pass a tipping point, after which it will inevitably disappear completely [2].

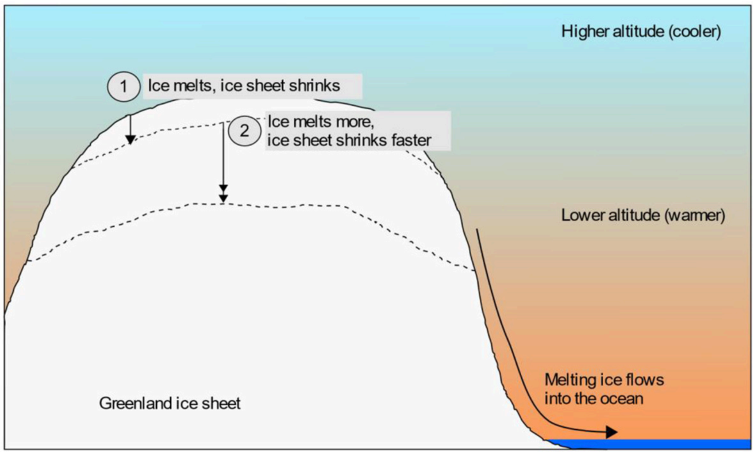

Figure 2

Figure 2

The melting of the Greenland ice sheet and an example of a self-reinforcing loop. As the climate warms, the ice sheet melts and gets shorter. At lower altitudes, the air is warmer, so the ice sheet shrinks even more. The tipping point would be the threshold where the ice will inevitably continue to melt until it completely disappears.

A TIPPING POINT FOR THE LAND

The Amazon rainforest is one of Earth's biggest natural ecosystems. The Amazon absorbs so much carbon dioxide that it is sometimes known as the lungs of the Earth. Without the Amazon, there would be a lot more carbon dioxide stuck in the atmosphere. As you might have guessed from the name, a rainforest requires a lot of rain. The Amazon is so enormous that it creates up to half of its own rainfall, just from the water evaporating from the plants and soil [3]. Without enough rainfall, the rainforest becomes vulnerable to big changes.

As the climate warms, patterns of rainfall change as well. Climate models predict a reduction in rain over the Amazon as global temperatures rise. To make matters worse, the Amazon is also shrinking due to deforestation (humans cutting down trees), which in turn reduces how much rain the rainforest can produce from its own evaporation. If there is not enough rain and the Amazon dries too much, this could cause the rainforest to die back, meaning the trees would die and not regrow. Instead, the rainforest would be replaced by grassland and savannah (Figure 3) [4, 5].

Amazon dieback would remove a large **carbon sink** from the Earth's climate system, meaning that more of our greenhouse gases would stay in the atmosphere, heating the Earth further and faster. The point at which there are not enough trees in the Amazon, or there is not enough rain, is an example of a possible tipping point on the land.

AMAZON DIEBACK

The loss of biomass due to climate change, such as changing rainfall patterns and increased wildfires.

CARBON SINK

Something that absorbs more carbon than it releases, thus removing carbon from the atmosphere. Rainforests are an example of a carbon sink.

Figure 3

Changing rainfall patterns and deforestation could result in a tipping point for the Amazon rainforest. As the number of trees is reduced, rainfall over the Amazon is also reduced. Eventually, this could result in Amazon dieback, in which trees are replaced by grasslands. Since the Amazon is an important carbon sink, Amazon dieback could disturb the Earth's climate system.

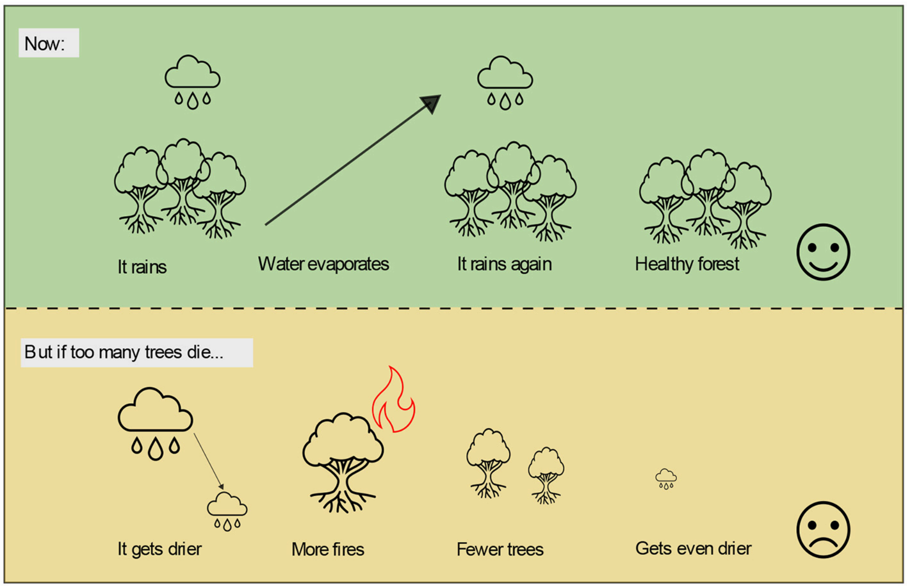

Figure 3

A TIPPING POINT FOR THE OCEAN

ATLANTIC MERIDIONAL OVERTURNING CIRCULATION (AMOC)

A system of currents in the Atlantic Ocean, circulating water from the tropics to the northern Atlantic.

In the ocean, there is a large set of water currents called the **Atlantic meridional overturning circulation (AMOC)**. These currents carry water from the tropics (near the equator) north toward the Arctic, where the water cools, sinks, and then travels back toward the tropics. This circulation drives itself—the more water that sinks in the north, the more water is brought up from the tropics to travel north and sink again, in turn. However, as the Greenland ice sheet melts and rainfall increases, a larger volume of cold, fresh water flows into the northern part of the Atlantic Ocean [6]. This freshwater mixes with the salt water, making it lighter and less likely to sink. This weakens the flow of water, causing the AMOC to slow down.

Climate scientists and oceanographers are trying to understand whether this slowing could ever become a complete shutdown, 'meaning that the overturning circulation would stop altogether. The AMOC is responsible for the mild climate in Western Europe—without it, the temperatures and rainfall there would be quite different. These enormous flows of water are also important for absorbing heat and carbon. Scientists are working to understand whether there is a critical point—a threshold—where the *slowing down* of the AMOC could tip into an irreversible *shutting down* [1]. This is an example of a potential tipping point in the ocean.

WHY SHOULD WE WORRY ABOUT TIPPING POINTS?

If tipping points exist in the Earth's climate system, could one tipping point set off the rest, like a line of dominoes? This is a very worrying possibility. Tipping elements can cause abrupt change or slow change but, in either case, passing the threshold causes the system to move inevitably toward a new state. Triggering a tipping point in one part of the Earth's climate system may make it more likely that we approach a threshold in another part. This effect of one tipping point causing another is called a **tipping point cascade** [7].

Will the Earth reach any tipping points soon? The Earth's climate system is very complex. Scientists use lots of different pieces of evidence to understand what will happen in the future; they build climate models and make observations of changes in particular places, like the ocean. At this point, we know that more greenhouse gases mean more warming, but we do not know *exactly how much* greenhouse gases would result in a tipping point for the ice sheets or dieback of the Amazon rainforest. This means there is still a lot of uncertainty about tipping points, when they could happen, and what they would mean [8].

However, just knowing that tipping points *might* happen could be enough to influence what we do today. Since the consequences of the tipping points we have described are so serious, even a small probability of reaching a tipping point may be a risk we are unwilling to take [9]. This is one of the main reasons why all the world's governments are making pledges to try to limit climate change so that we reduce the risks of these serious impacts.

TIPPING POINT CASCADES

Where the triggering of one tipping point causes changes in the climate which trigger another tipping point, and so on.

Scientists will continue working to understand whether tipping points exist in the Earth system, and if so, when they might be triggered and what might happen if they were. The more we learn about tipping points, the better we can plan ways to avoid them, or at least how to manage them if they do occur. The possibility of tipping points and **tipping point cascades** is a very good reason for us to take lots of positive action *today* to reduce our greenhouse gas emissions.

REFERENCES

1. Good, P, Bamber, J., Halladay, K., Harper, A. B., Jackson, L. C., Kay, G., et al. 2018. Recent progress in understanding climate thresholds: Ice sheets, the Atlantic meridional overturning circulation, tropical forests and responses to ocean acidification. *Progr Phys Geogr*. 42:24–60. doi: 10.1177/0309133317751843
2. Robinson, A., Calov, R., and Ganopolski, A. 2012. Multistability and critical thresholds of the Greenland ice sheet. *Nat Clim Change*. 2:429–32. doi: 10.1038/nclimate1449
3. van der Ent, R. J., Savenije, H. H. G., Schaefli, B., and Steele-Dunne, S. C. 2010. Origin and fate of atmospheric moisture over continents. *Water Resourc Res*. 46, W09525. doi: 10.1029/2010WR009127
4. Lovejoy, T. E., and Nobre, C. 2018. Amazon tipping point. *Sci Adv*. 4:eaat2340. doi: 10.1126/sciadv.aat2340

5. Staal, A., Fetzer, I., Wang-Erlandsson, L., Bosmans, J. H. C., Dekker, S. C., van Nes, E. H., et al. 2020. Hysteresis of tropical forests in the 21st century. *Nat Commun.* 11:4978. doi: 10.1038/s41467-020-18728-7
6. Lohmann, J., and Ditlevsen, P. D. 2021. Risk of tipping the overturning circulation due to increasing rates of ice melt. *Proc Natl Acad Sci USA.* 118:e2017989118. doi: 10.1073/pnas.2017989118
7. Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., et al. 2018. Trajectories of the earth system in the anthropocene. *Proc Natl Acad Sci USA*. 115:8252–9. doi: 10.1073/pnas.1810141115
8. Wang, S., and Hausfather, Z. 2020. ESD reviews: mechanisms, evidence, and impacts of climate tipping elements. *Earth Syst. Dynam. Disc*. 1–93. doi: 10.5194/esd-2020-16
9. Lenton, T. M., Rockstrom, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., et al. 2019. Climate tipping points - too risk to bet against. *Nature.* 575:592–5. doi: 10.1038/d41586-019-03595-0

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YOUNG REVIEWER

DAVID, AGE: 11
I like fishing and being outdoors. My favourite food is fried catfish with tarter sauce. My favourite colour is deep metallic green. My favourite movie is Harry Potter and the prisoner of Azkaban.

AUTHORS

SOFIA PALAZZO CORNER

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CHRIS D. JONES

Dr. Chris D. Jones is a climate researcher at the Met Office Hadley Centre in Exeter in the UK. He has over 25 years of experience of writing computer programmes to model how climate affects our natural ecosystems and how the carbon cycle helps reduce the amount of CO_2 pollution in the atmosphere. He leads a research programme with partners in Brazil and has visited research sites in the Amazon rainforest. The photo here is on top of the Mauna Loa volcano in Hawaii, where CO_2 is measured. †orcid.org/0000-0002-7141-9285

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THE IMPACTS OF CLIMATE CHANGE

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YOUNG REVIEWER:

ALMA
AGE: 13

Global warming has already caused our planet to heat up by around 1°C. This warming is causing a huge range of impacts. For example, heat waves are becoming more severe and affecting humans and animals; in some places, rivers are flooding more frequently due to heavy rainfall; droughts in other parts of the world are affecting crops. These changes can have a huge effect on people, making it difficult to grow food, find shelter, and avoid dangerous weather such as storms and heat waves. Many people have needed to leave their homes to search for safer places to live because the climate has changed so much. While all countries are affected by climate change, different countries face different impacts. By understanding these impacts and how vulnerable people are to climate changes, it is much easier to prepare for future changes and protect against them.

WHAT ARE THE IMPACTS OF CLIMATE CHANGE?

Our planet is a very complex place, made up of lots of different systems that all link together. These interrelationships mean that a

CLIMATE SYSTEM

The inter-linked system that affects our climate. This includes the atmosphere, water cycle, ice, rocks, and all living things.

small change in one part of the **climate system** can cause effects across the entire planet. When we burn fossil fuels, such as coal, oil, or gas, or when we cut down forests, we put more **greenhouse gases** (such as carbon dioxide, nitrous oxide, and methane) into the atmosphere. Adding these gases to the atmosphere has already caused the average temperature of the planet to increase by around 1°C. This might not sound like very much when you think about the temperature outside today, but scientists have found that it can have big effects on the weather and climate system, which can then affect things that we depend on, like food, water, and energy (for example, see the outer ring in Figure 1).

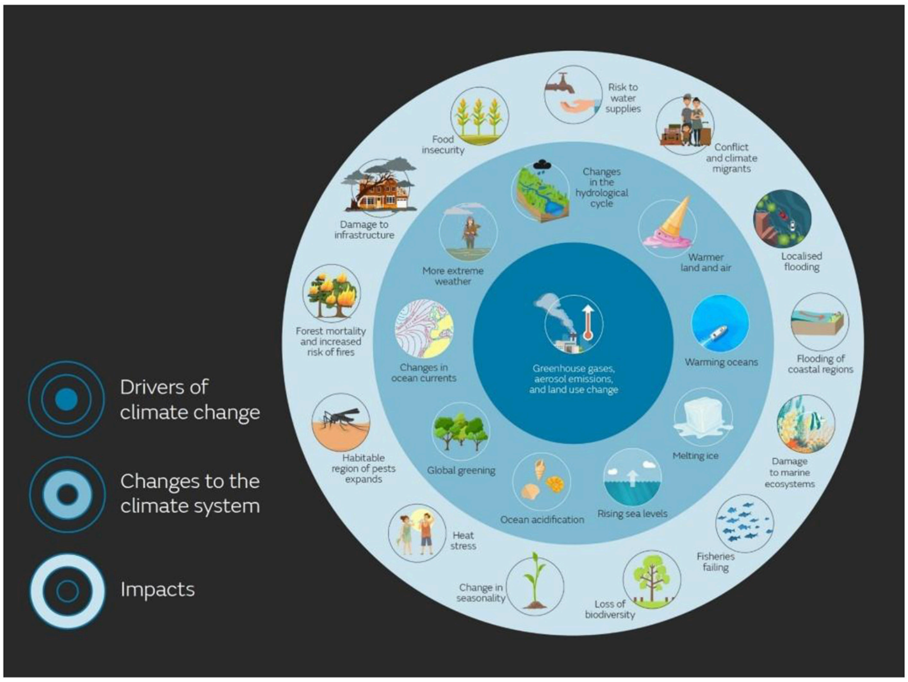

Figure 1

Figure 1

The center of the circle shows the drivers (causes) of climate change. The middle ring illustrates the changes that climate change can have on Earth's climate system. The outer ring shows examples of the impacts these climate changes can cause.

When we talk about the impacts of climate change, we are talking about how people's lives and the ecosystems they depend on are affected as the world gets warmer. For example, farmers growing crops depend on the right amount of rain, sunlight, and warm temperatures to produce food. People and animals need clean, fresh drinking water at all times of the year, even during dry spells. Many people must also live through extreme weather events such as heat waves, droughts, **Hydrological cycle** fires, and flooding each year. In the last 30 years, we have seen that climate change has already affected many of these aspects of our lives, sometimes in good ways, but more often in bad ways.

GREENHOUSE GASES

Gases in the atmosphere that trap heat from the sun at the earth's surface. These include carbon dioxide, methane, and nitrous oxide.

HYDROLOGICAL CYCLE

Water evaporates from rivers, lakes, soil and plants into the atmosphere, where it forms clouds, and falls to earth going back into rivers, lakes, and the sea.

HOTTER TEMPERATURES

GLOBAL AVERAGE TEMPERATURE

Thermometers around the world are used, on land and sea, to observe the average temperature on a particular day. We even estimate the temperature in places where there are not thermometers.

Although our planet has warmed by about 1°C over the past 100 years [1], this does not tell the full story. Some parts of the world have warmed by much more than this, while others have warmed less. For example, the North and South Poles are the coldest places on Earth, and they are heating much more quickly than the rest of the planet. Since 2000, observations have shown that the Arctic has warmed at double the rate of the **global average temperature**.

Higher temperatures have a range of impacts at the poles. For example, snow and ice normally melt in the summer and then refreeze in the winter. Warmer temperatures are causing ice to melt more quickly and to freeze more slowly, meaning that the total amount of ice in the Arctic is shrinking. Ice shrinkage is leading to even more warming, because darker land and seawater absorb more heat from the sun than the white snow cover does—snow and ice usually reflect sunlight back into space. Water from the melting ice is also flowing into the ocean, adding to sea-level rise.

Rising temperatures can also affect wildlife. Global warming means that habitats for species such as polar bears, reindeer, and caribou are changing—often making it harder for them to find food [2]. As the world gets warmer, many species may have to move to find food, or otherwise adapt to changes in the seasons. For some species, adapting to climate changes might not be a problem, but other species are expected to struggle to find new places to live. Hotter temperatures also affect people around the world—through heat waves, for example. Hot days are getting hotter and more frequent, and cold days are becoming less common. Heat waves can cause some people, particularly those who have other health issues, to suffer from **heat stress**, which means their bodies overheat and they feel ill [3]. High humidity, high night-time temperatures, and poor air quality can also cause health problems during heat waves. Heat waves do not affect everybody in the same way though. For example, people who work outdoors, those who have breathing problems, and the elderly may suffer the worst impacts of heat stress.

HEAT STRESS

When it is so hot and humid outside that it causes your body to over-heat. When this happens we need to sit down in the shade and drink water.

FIRE AND DROUGHT

Many parts of the world naturally experience dry seasons when little to no rain falls for many months or even years. During these periods, grass, shrubs, and trees can become very dry. When this happens, it may take just a small spark to cause a big fire that stretches for many kilometers. Hotter temperatures mean that water evaporates faster, causing vegetation to dry out more quickly and making dry seasons even drier. On top of this, higher levels of carbon dioxide in the air help plants to grow, which creates more vegetation to burn when there is a fire.

Higher temperatures and changing rainfall patterns mean that dry seasons in some parts of the world, like North America, Europe, West and Southern Africa, and Australia, are expected to become longer and even hotter. This means that, in these areas, there is a greater chance of damaging wildfires like the ones seen in Australia in 2019–20, and California in 2020.

FOOD AND WATER

As climate change causes the air temperature to increase, the air can hold more water. This means that when it rains, the rainfall is much heavier! However, in some places, it also means that rainfall is happening less often, making dry spells longer. Lack of rain puts dry places at risk of not having enough freshwater available for drinking. In these situations, the ground can dry out, crops may not get enough water to grow well, and people may need to limit their water use. When it finally does rain, the dry ground is often too hard to soak up the water easily, which can cause flooding. Flooding also damages crops.

All people depend on growing or buying enough food to survive. This is called **food security** [4]. Climate change can affect food security in lots of ways. For example, warmer temperatures, more rainfall, and more carbon dioxide in the atmosphere are generally better conditions for plants to grow in. In areas where these changes happens, crops may produce *more* food which can either be eaten by the people living in those regions, or can be sent to places where it is needed. While the entire Earth will see increases in temperatures and carbon dioxide, it is more difficult to say which areas will see an increase in rainfall.

FOOD SECURITY

A way of describing how certain you are that there will always be food available to eat.

Livestock, such as cows, pigs, and chickens, can also be affected by hotter heat waves the same way that humans are. Crops can die during heat waves, leaving some people without any food. Some farmers might be able to plant more heat-resistant types of crops or build shelters to protect their animals. However, farmers need money to do these things, and so those in poorer areas may find it more difficult to protect their crops and animals.

CONCLUSION

In summary, climate change can affect people either directly, through more intense heat waves, more frequent and intense fires or long periods of drought, but also indirectly by affecting the ecosystems that provide us with food and water. This is important because as the climate continues to change in the future, many people, especially those in poor countries, are likely to experience the worst effects of climate change. In order to help these countries reduce poverty and reduce the impacts of climate change, all the countries in the United Nations' have agreed to follow Sustainable Development Goals which aim to make sure that everybody will have access to clean water, zero hunger and sustainable use of land in the future. By following these goals, and by taking action on climate change, countries hope to be able to end global poverty, become more sustainable, and limit the impacts of climate change.

REFERENCES

1. Morice, C. P., Kennady, J. J., Rayner, N. A., Winn, J. P., Hogan, E., Killick, R. E., et al. 2021. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 data set. *J. Geophys. Res. Atmos.* 126:e2019JD032361. doi: 10.1029/2019JD032361
2. Pagano, A. M., and Williams, T. M. 2021. Physiological consequences of Arctic sea ice loss on large marine carnivores: unique responses by polar bears and narwhals. *J. Exp. Biol.* 224:jeb.228049. doi: 10.1242/jeb.228049
3. Matthews, T. K. R., Wilby, R. L., and Murphy, C. 2017. Communicating the deadly consequences of global warming for human heat stress. *Proc. Natl. Acad. Sci. U. S. A.* 114:3861–6. doi: 10.1073/pnas.1617526114
4. Richardson, K. J., Lewis, K. H., Krishnamurthy, P. K., Kent, C., Wiltshire, A. J., and Hanlon, H. M. 2018. Food security outcomes under a changing climate: impacts of mitigation and adaptation on vulnerability to food insecurity. *Clim. Change* 147:327–41. doi: 10.1007/s10584-018-2137-y

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YOUNG REVIEWER

ALMA, AGE: 13

My name is Alma. I am 13 years old and I have three sisters and a brother. We also have six hens and one cat. In my sparetime I spend a lot of time playing handball. My favorite subject in school is mathematics.

AUTHORS

ANDREW J. HARTLEY

I am a weather and climate scientist currently working on improving our understanding of the impacts of climate change on people and ecosystems. I am especially interested in using satellite observations to evaluate and improve our models, particularly in developing countries. *andrew.hartley@metoffice.gov.uk

AYESHA TANDON

I am the climate science journalist at a company called "Carbon Brief." Most days, I read scientific papers and talk to climate experts, so I can write interesting articles about climate change. This is a great job for me, because I love learning about exciting new science and sharing important information with other people! I also spent 2 years working at the UK Met Office as a "climate science communicator." In my free time, I like dancing, yoga, and reading.

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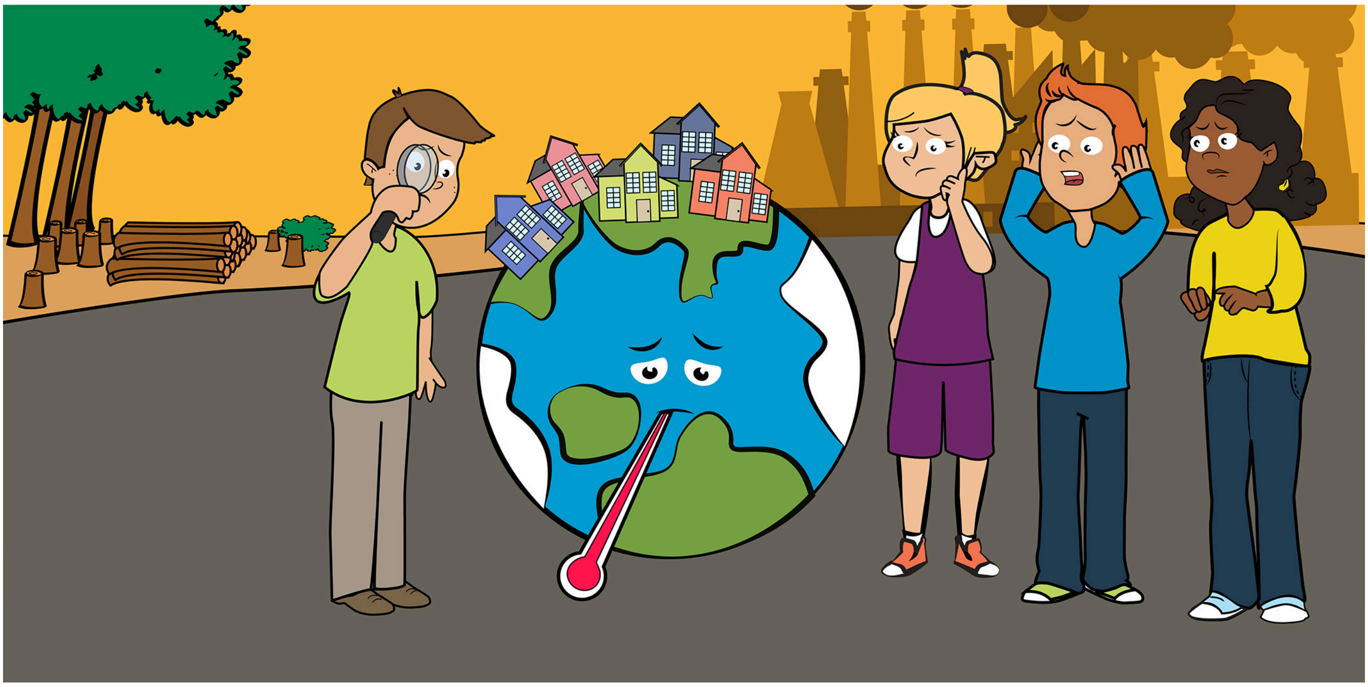

HOW WILL CLIMATE CHANGE AFFECT WHERE YOU LIVE?

Carolina Viceto[1*], *Pat Wongpan*[2] *and Alexander D. Fraser*[2]

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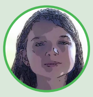
YOUNG REVIEWER:

ASPEN
AGE: 9



In recent times, scientists have seen large changes in our planet's climate. Although climate change is a global issue, the effects of climate change are not the same around the world. Each continent, country, and area will experience different effects. These effects include different speeds of warming or, in some places, cooling, and changes to rain- and snowfall. Since the climate is global, what happens in other places can also impact the place where you live. In this article, you will learn how various places on Earth have been affected by climate change up to now. We will also show you what kind of climate changes can be expected in the future.

GREENHOUSE GAS

Gases from human activities that end up in the Earth's atmosphere and trap heat from the sun, leading to global warming. Examples are carbon dioxide (CO_2), methane, and water vapor.

WHAT HAS CHANGED IN EARTH'S CLIMATE?

In recent decades, there has been an increase in Earth's air temperature. What caused this increase? The warming temperatures are related to **greenhouse gas emissions**, including the release of

EMISSIONS

The amount of **greenhouse gases** released into the atmosphere.

carbon dioxide (CO_2), into the atmosphere. Greenhouse gas emissions are mainly caused by human activities, such as the burning of fossil fuels to power our cars and to make electricity. Greenhouse gases in the atmosphere are also increasing because of the decrease in Earth's forested areas. We experience this human-made climate change as changes in things like the average air temperature and average rainfall during a certain period.

The average global temperature has increased by 1.2°C since the late 1800s. Figures 1A,B show the global average air temperature for 2018 and 2020, compared with the past period from 1981 to 2010. Despite a separation of only 1 year, there were big differences in the pattern of temperature change. In 2018, the Arctic was warmer, except for a part of Siberia. At the same time, Northern America was colder than before (Figure 1A). However, in 2020, the Arctic was much warmer, mainly over Siberia (Figure 1B). At the same time, some regions of Antarctica were colder than they have been. What does this mean? These data show that the climate naturally changes a little from year to year, and that it is normal for some years to be colder or warmer than others. But when we average the temperature for the whole globe, we see that it has gotten much warmer during the last 40 years (Figure 1C). Although 2018 was colder than the previous years, its annual average temperatures were much warmer compared with temperatures seen in the 1980s. The highest temperatures ever recorded have been seen in the last few years (2016 and 2020).

What are the consequences of global warming? Well, for example, since the late 1970s, the area of Arctic sea ice has decreased around 4% every 10 years [1]. Glaciers are getting thinner and shorter, not only

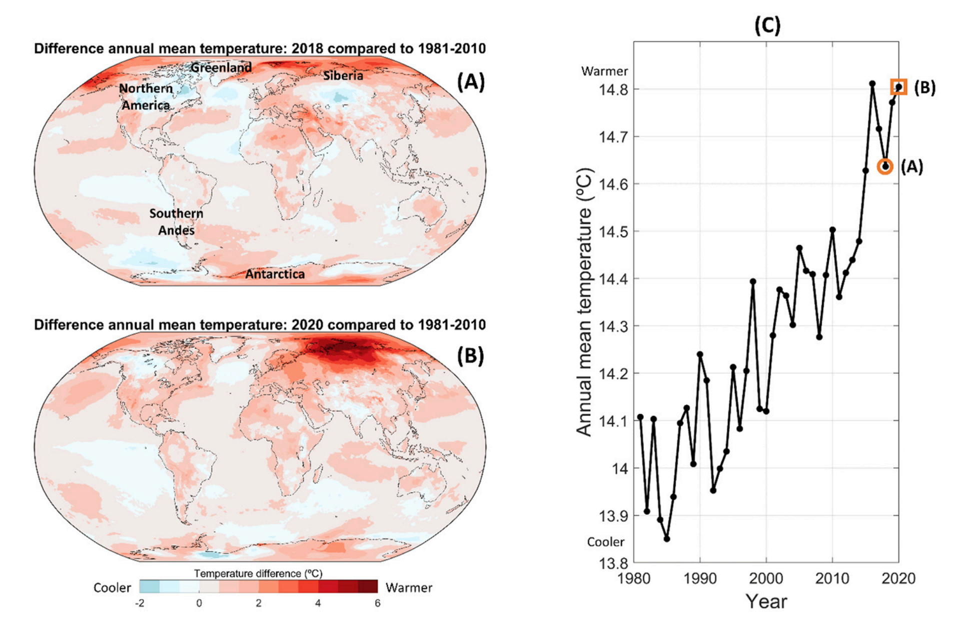


Figure 1

Figure 1

(A) Difference in average air temperature between 2018 and the years 1981–2010. **(B)** Difference in average air temperature between 2020 and the years 1981–2010. Red shows warmer and blue cooler temperatures than in the past years. **(C)** Global average air temperatures from 1981 until 2020. Note that the orange circle and square mark the years 2018 and 2020 that are shown in **(A,B)**.

in polar regions like Antarctica, Greenland, and North America, but also in high mountain regions, such as those in the Southern Andes and in Asia [1]. The ocean is also getting warmer: in recent years, the surface of the ocean has warmed by 0.11°C each decade [1]. This has caused **coral bleaching**, which means that the coral turned white. From 2014 to 2017, coral bleaching affected more than 70% of the world's coral reefs. Severe weather events, such as flooding and storms, have been occurring more often across the planet. The sea level has risen because of the warming ocean and melting glaciers, and this affects coastal areas. Global average sea levels have risen from 1 to 2 mm each year over the twentieth century, and now more than 3 mm each year, and the speed of this sea level rise is increasing [1]. Due to human activity, the amount of CO_2 in the air has increased more than 40% since 1750 [1].

CORAL BLEACHING

When corals lose their source of food, causing them to turn white and more vulnerable to diseases. This can happen due to changes in temperature, light, or nutrients.

HOW DO WE KNOW WHAT WILL HAPPEN IN THE FUTURE?

Scientists use **climate models** to understand what happened to Earth's climate in the past and what is likely to happen in the future. These models are run on computers and use complex formulas that describe the links between the air, ocean, land, and ice-covered regions. Around the world, research centers create models using different scenarios of greenhouse gas emissions (such as the amount of CO_2 that is released into the atmosphere). These models help to explain how human activities may need to change in the future, to reduce greenhouse gas emissions. Climate models also take into account future increases in the world's population and changes in the world's economy (more sustainable development or larger use of fossil fuels, investment in health and education, changes in climate strategies). In the best-case scenario, people will take urgent action to reduce their greenhouse gas emissions and as a result, climate change will slow down. In the worst-case scenario, nothing is done to reduce CO_2 and global warming will continue to get worse.

CLIMATE MODELS

Models run in computers and based in complex formulas to simulate the factors that can affect Earth's climate, such as the links between the air, ocean, land, and ice-covered regions.

HOW WILL FUTURE CLIMATE CHANGE AFFECT VARIOUS LOCATIONS?

In the future, the average temperature across the world is expected to increase. However, some regions might warm more quickly than others. As shown in Figures 2A,B, land regions are likely to warm faster than the oceans. At the same time, the Arctic will warm faster than the tropics. This unequal warming is caused by differences in the type of surface. The land is quicker to warm than the water, which leads to slower warming of the oceans. The Arctic changes faster than the tropical regions due to a process called **Arctic amplification**. Arctic amplification happens because the whiter sea ice reflects more sunlight than the darker ocean, which absorbs most of the sunlight

ARCTIC AMPLIFICATION

Phenomenon known as the faster warming of the Arctic when compared to other regions of the world, during the last decades.

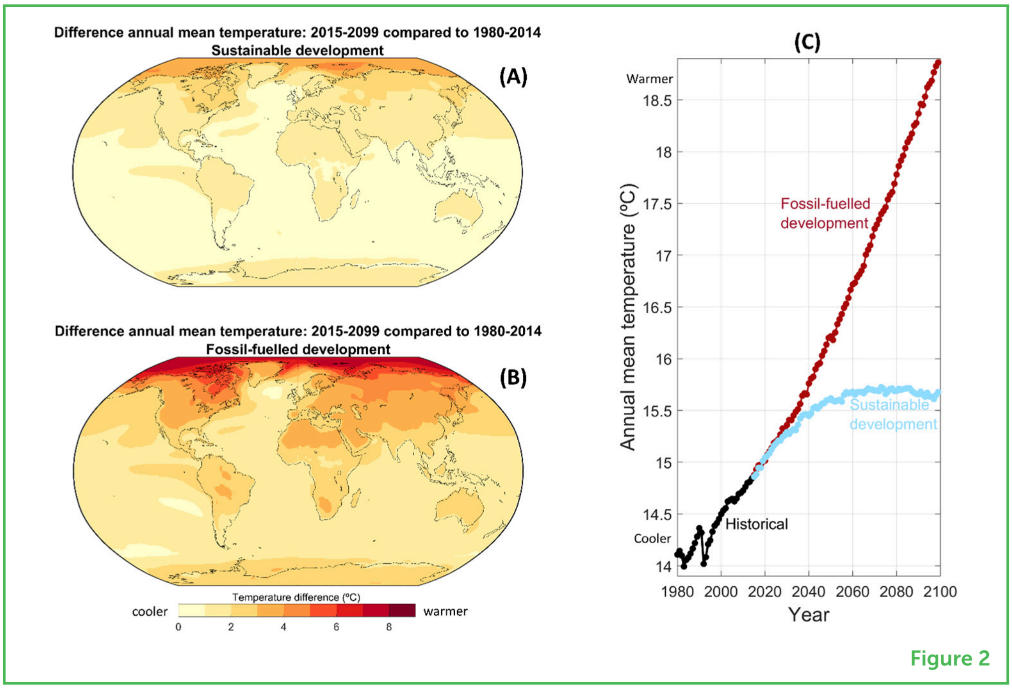


Figure 2

Difference in air temperature between future (2015–2099) and past years (1980–2014). **(A)** In the best-case scenario (sustainable development) where we act to decrease CO_2 emissions, air temperature increase stays below 4°C. **(B)** In the worst-case scenario (fossil-fuelled development), where CO_2 emissions increase, an 8°C warming is expected. Red colors show more warming. **(C)** Temperature record from 1980 until 2099. You can see that in the best-case scenario (blue line) the increase in annual mean temperature stays under 2°C by 2099, while in the worst-case scenario (red line) it can go up to 5°C.

that hits it. Sunlight absorption causes ocean warming and leads to sea ice melting. Melting of sea ice increases the area of the darker ocean, which then absorbs even more sunlight and gets even warmer, melting more sea ice. This process keeps going on.

If nothing is done, it is expected that the global air temperature will increase by 2°C by the year 2050. By the year 2100, a rise of 5°C is expected. However, if we act now to reduce CO_2 emissions, global warming could be <2°C by 2100 (Figure 2C) [2].

Since climate change is not equal around the world, people will experience different impacts depending on where they live [3]. Figure 3 shows how future climate change will affect specific areas. If you live in a coastal region, you might expect more flooding, due to sea level rise. On the other hand, the inland regions are expected to have less rainfall, on average, which will increase drought and bushfires in many regions. In the case of big cities, cars and factories cause pollution, which affects human health. In rural regions, climate change is expected to affect agriculture, which may impact the food supply. Also, we cannot forget the ocean and the **cryosphere**—the frozen part of Earth. These areas play important roles in many of the Earth's systems, since the oceans and cryosphere are responsible for the absorption and distribution of CO_2 and heat. This means that they can also accelerate temperature increase by changing how heat is absorbed and distributed. Global warming will continue to reduce the sea ice, glaciers, and ice sheets in areas including Antarctica. These changes affect not only humans, but also the ecosystems of the animals that live in these cold areas.

CRYOSPHERE

The part of Earth's surface with frozen water (snow and ice, over land, or ocean).

Figure 3

How climate change may affect specific regions in the future.

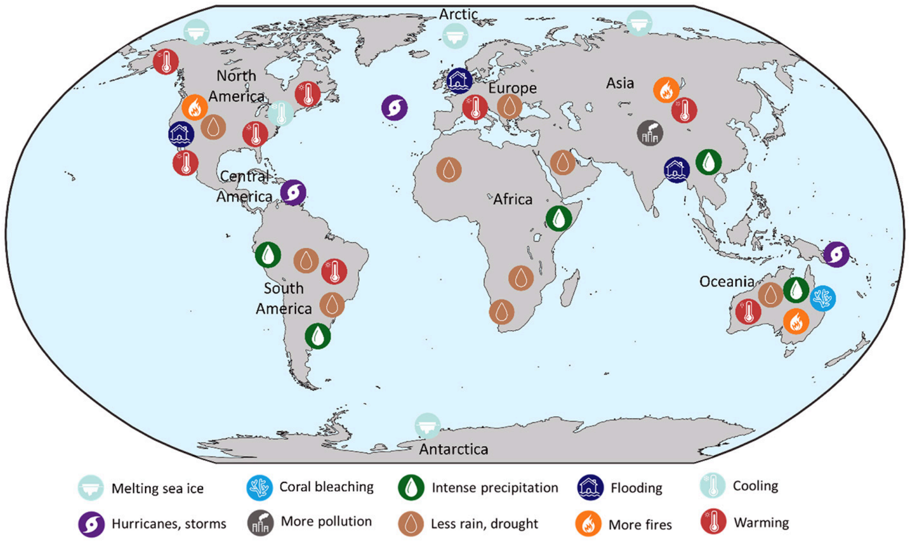


Figure 3

Focusing on specific regions, more wildfires are expected in North America, mainly over the West Coast (for example, in California). At the same time, more flooding is expected in coastal regions. In Central America, hurricanes are likely to happen more often. In South America, Amazonia might receive less rain, causing drought. This might affect the plant and animal life in this region. Similar changes are expected in Africa, where drought can affect the health of the human population due to effects on food and water supplies. In Oceania, less rainfall is likely, which may cause more forest fires and extremely hot temperatures. In this area, the increased ocean temperature is causing coral bleaching. Coral bleaching is associated with a loss of plant and animal species, some of which only exist in regions like the Great Barrier Reef. In Europe, higher air temperature and less rain are likely, which may cause more frequent extreme hot temperatures and droughts. These changes may affect farming and energy production. In Asia, expected changes vary depending on the region: extremely hot temperatures, droughts, heavy rain events, melting of glaciers, wildfires, and more pollution may happen across this area. Due to the population growth across Asia, a lot of people will be affected. Figure 3 shows how climate change is predicted to affect various regions in the future.

SUMMARY

During the last 40 years global air temperatures have increased by over 1°C, with important impacts being already observed, although they depend on the region where you live. In the future, global warming is expected to continue, with some regions warming faster than others. If we reduce CO_2 emissions, global air temperature increase can be <2°C by 2100, if not, a warming of 5°C is expected by 2100.

How can you help reduce climate change? First, it is important that you keep learning more about how our planet works to understand the climate, and what is causing climate change and its impacts. You can start from changing simple things in your daily routine to minimize global warming, such as walk or bike to school or recycle. With this information you can explain your parents and friends about this subject and try to convince them to change some of their habits that can help to reduce climate change.

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REFERENCES

1. IPCC. 2013. *Climate change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge; New York, NY: University Press). p. 1535.
2. Semmler, T., Danilov, S., Gierz, P., Goessling, H., Hegewald, J., Hinrichs, C., et al. 2020. Simulations for CMIP6 with the AWI Climate Model AWI-CM-1-1. *J. Adv. Model. Earth Syst.* 12:e2019MS002009. doi: 10.1029/2019MS002009
3. Arnell, N. W., Lowe, J. A., Challinor, A. J., and Osborn, T. J. 2019. Global and regional impacts of climate change at different levels of global temperature increase. *Clim. Change*. 155:377–91. doi: 10.1007/s10584-019-02464-z

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YOUNG REVIEWER

ASPEN, AGE: 9

Hi, my name is Aspen, I live in the U.S. and I like the outdoors and hiking. I am in 4th grade, and my favorite subjects are art, music, math, and Spanish. I love to read, particularly fantasy novels and series. I am very excited to be working with Frontiers for Young Minds!

AUTHORS

CAROLINA VICETO

I am currently a Ph.D., student at the Department of Physics at the University of Aveiro, Portugal. In my Ph.D., work I study atmospheric rivers (known as rivers in the sky) in the Arctic, and their influence on precipitation in Arctic's present and future climate. Before starting my Ph.D., I completed a master's degree in meteorology and physical oceanography. I am also a member of the Association of Polar Early Career Scientists (APECS) Portugal. *carolinaviceto@ua.pt

PAT WONGPAN

I am a quantitative sea ice biogeochemist/ecologist at the Australian Antarctic Program Partnership Institute for Marine and Antarctic Studies, University of Tasmania. I obtained my Ph.D. from the University of Otago in New Zealand, was a David Crighton fellow at the University of Cambridge, and a JSPS post-doctoral fellow at the Institute of Low Temperature Science, Hokkaido University, Japan. I am interested in sea ice-ice shelf-ocean interactions and their consequences on the ecosystem.

ALEXANDER D. FRASER

I am a glaciologist focusing on remote sensing of Antarctic sea ice. I work alongside Dr. Wongpan at the Australian Antarctic Program Partnership, a part of the Institute for Marine and Antarctic Studies at the University of Tasmania, Australia. I completed my Ph.D. at the University of Tasmania in 2011 and have since undertaken post-doctoral research fellowships both in Tasmania and at Hokkaido University's Institute of Low Temperature Science, Japan. Climate change continues to surprise me: last time I was in Antarctica, I was unexpectedly rained on (in June)!

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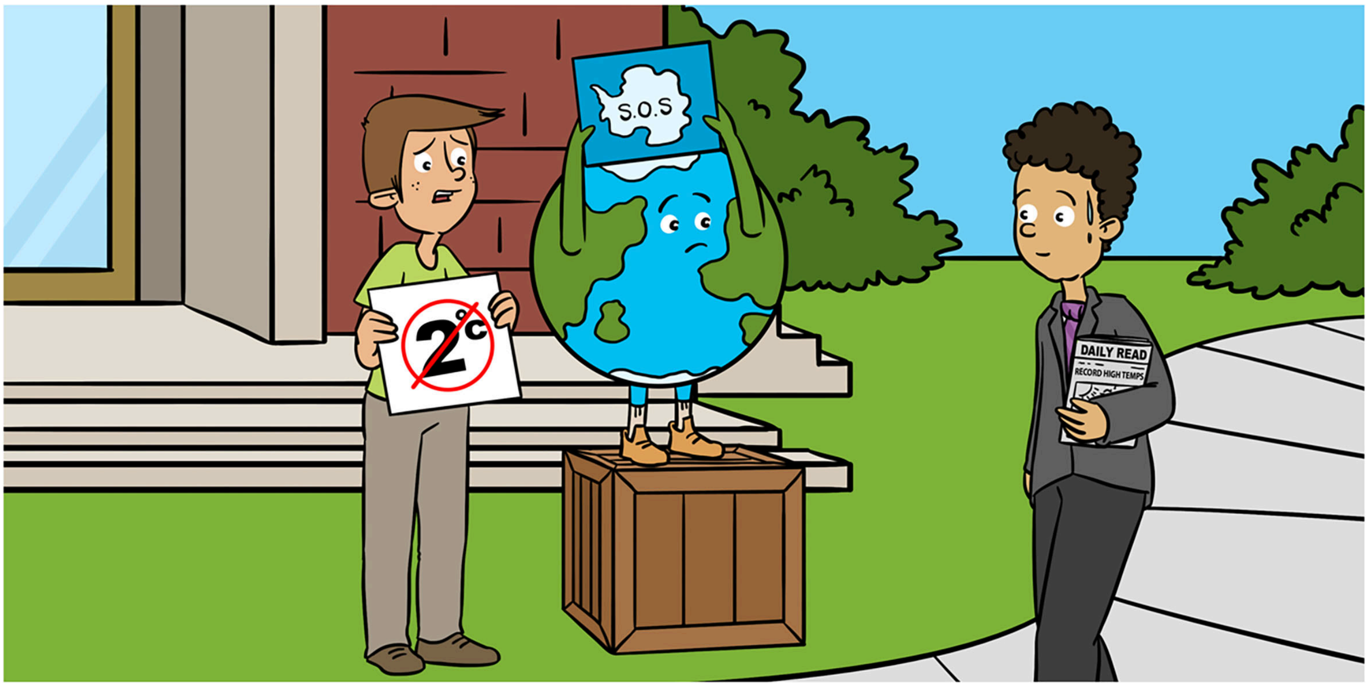

THE ANTARCTIC ICE SHEET—A SLEEPING GIANT?

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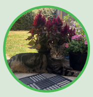
YOUNG REVIEWERS:


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!

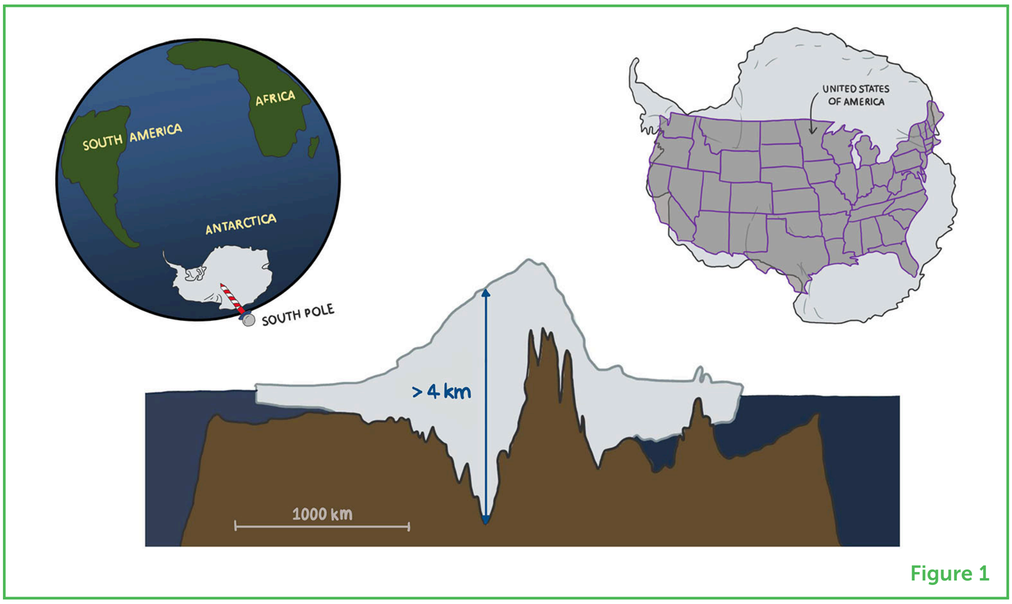


Figure 1

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.

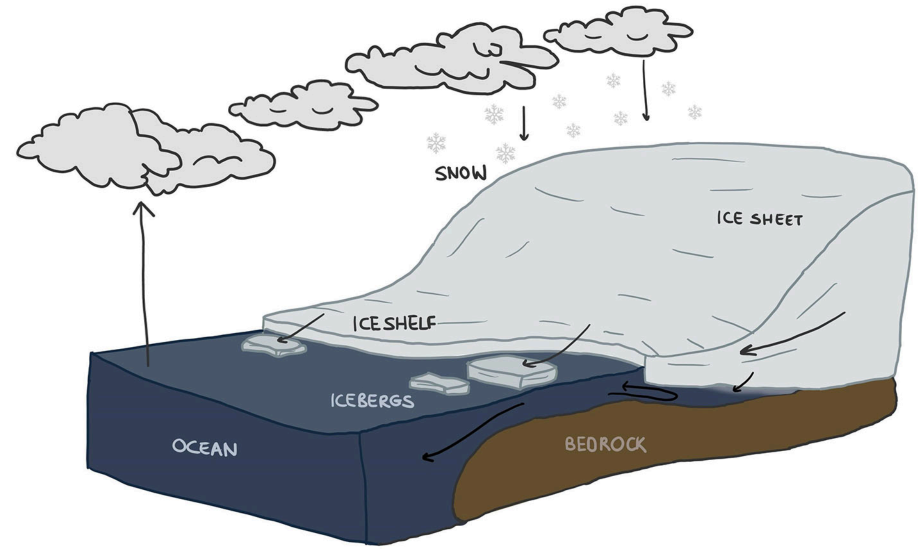


Figure 2

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

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.

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.

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.

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.

HOW IS ICE LOSS CHANGING TODAY?

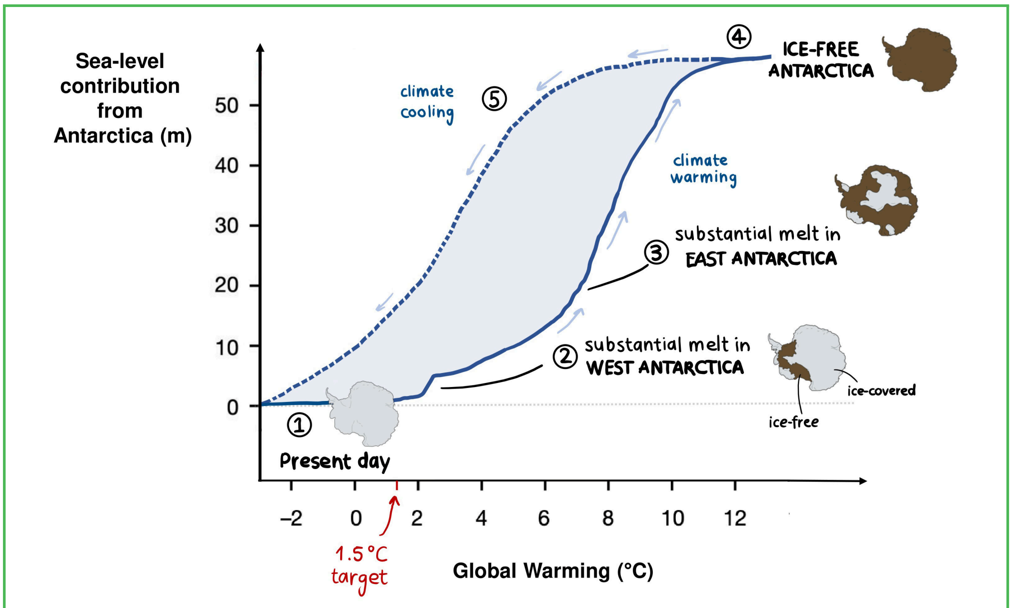
For thousands of years, the ice loss in Antarctica was largely equal to the amount of ice gained through snowfall, so the size of the ice sheet remained relatively constant—but this is changing now. Global warming, caused by greenhouse gas emissions from the burning of **fossil fuels** such as coal and 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.

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.

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

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.

REFERENCES

1. Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., et al. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 399:429–36.
2. The IMBIE Team. 2018. Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature* 558:219–22. doi: 10.1038/s41586-018-0179-y
3. Slater, T., Lawrence, I. R., Otosaka, I. N., Shepherd, A., Gourmelen, N., Jakob, L., et al. 2021. Review article: earth's ice imbalance. *Cryosphere* 15:233–46. doi: 10.5194/tc-15-233-2021
4. Garbe, J., Albrecht, T., Levermann, A., Donges, J. F., and Winkelmann, R. 2020. The hysteresis of the Antarctic Ice Sheet. *Nature* 585:538–44. doi: 10.1038/s41586-020-2727-5

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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.

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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.

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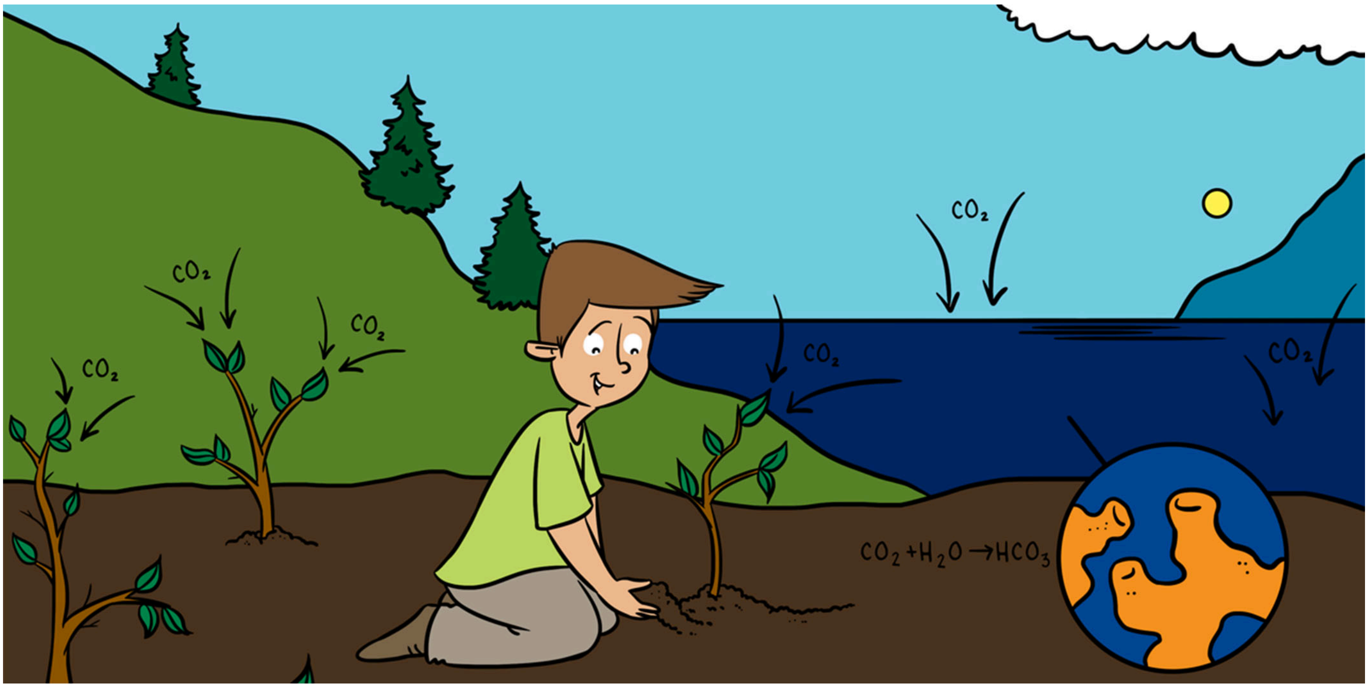

HOW DO ORGANISMS AFFECT AND RESPOND TO CLIMATE CHANGE?

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YOUNG REVIEWER:

DEREK
AGE: 14

Life on Earth is diverse at many levels, meaning there is a lot of variety within species and there are many different kinds of species. This biodiversity provides many of the resources that humans need and enhances our quality of life. All of Earth's organisms are affected by Earth's climate, but they also *influence* Earth's climate. In this article, we show how research on plants, animals, and microbes helps us

better understand how living things can both impact and respond to climate change. This research also gives us insight into what the future might be like for life on Earth. Such knowledge will help us to protect our planet—and the living things on it—from the harmful effects of future climate change.

WHAT IS BIODIVERSITY?

Many different kinds of microbes, plants, and animals (including people) live on Earth. Collectively, all these different organisms make up Earth's **biodiversity**. Biodiversity includes genetic diversity among individuals and among populations within species. Biodiversity also includes diversity of species, and communities of species within ecosystems. Biodiversity provides humans with many important resources, such as a variety of nutritious foods, and recreational activities. In addition, biodiversity can be important for cultural reasons, including national identity and religious ceremonies. Biodiversity also holds the potential for undiscovered benefits, like potential new medicines and protection of agriculture and livestock from disease outbreaks. For all these reasons, we must try to understand and protect Earth's biodiversity.

BIODIVERSITY

The variety of life (plants, animals, and microorganisms) measured at within a certain species, ecosystem or on Earth.

HOW CAN LIVING THINGS CONTRIBUTE TO CLIMATE?

Living things are clearly dependent on their environment, but they also *affect* their environment—even on a global scale. Organisms can affect the global climate because of their huge numbers. For example, the majority of carbon dioxide (CO_2) in the air is eventually consumed through rock weathering into dissolved river nutrients (Figure 1). However, the enormous numbers of plants and microbes on Earth collectively control the amount of CO_2 that remains in the air because they take it up to build their bodies. This is important for climate because CO_2 traps heat in the Earth's atmosphere, which, through the greenhouse effect, contributes to global warming.

According to the International Union for Conservation of Nature (IUCN)[1], the world's forests absorb about one-third of the CO_2 that is released from burning fossil fuels (like gas, oil, and coal). In addition, the Global Carbon Project[2] reported that a quarter of the CO_2 released from burning fossil fuels is quickly absorbed by the oceans. There, ocean microorganisms take up CO_2 and use it to build their cells.

The vast majority of carbon captured by organisms is released again to the air in a few years when organisms die. However, a small fraction of their carbon is deposited in the soil or ocean sediments. This removal of carbon from the environment is largely balanced out by volcanic processes. After hundreds of millions of years, the carbon returns to

[1] The International Union for Conservation of Nature (IUCN; https://www.iucn.org) is like the Intergovernmental Panel on Climate Change (IPCC), but with a specific focus on conservation of diversity. Like IPCC, it is funded by ~200 governments and civil society organizations, policy is built through intergovernmental studies and is government approved.

[2] Global Carbon Budget Summary Highlights.

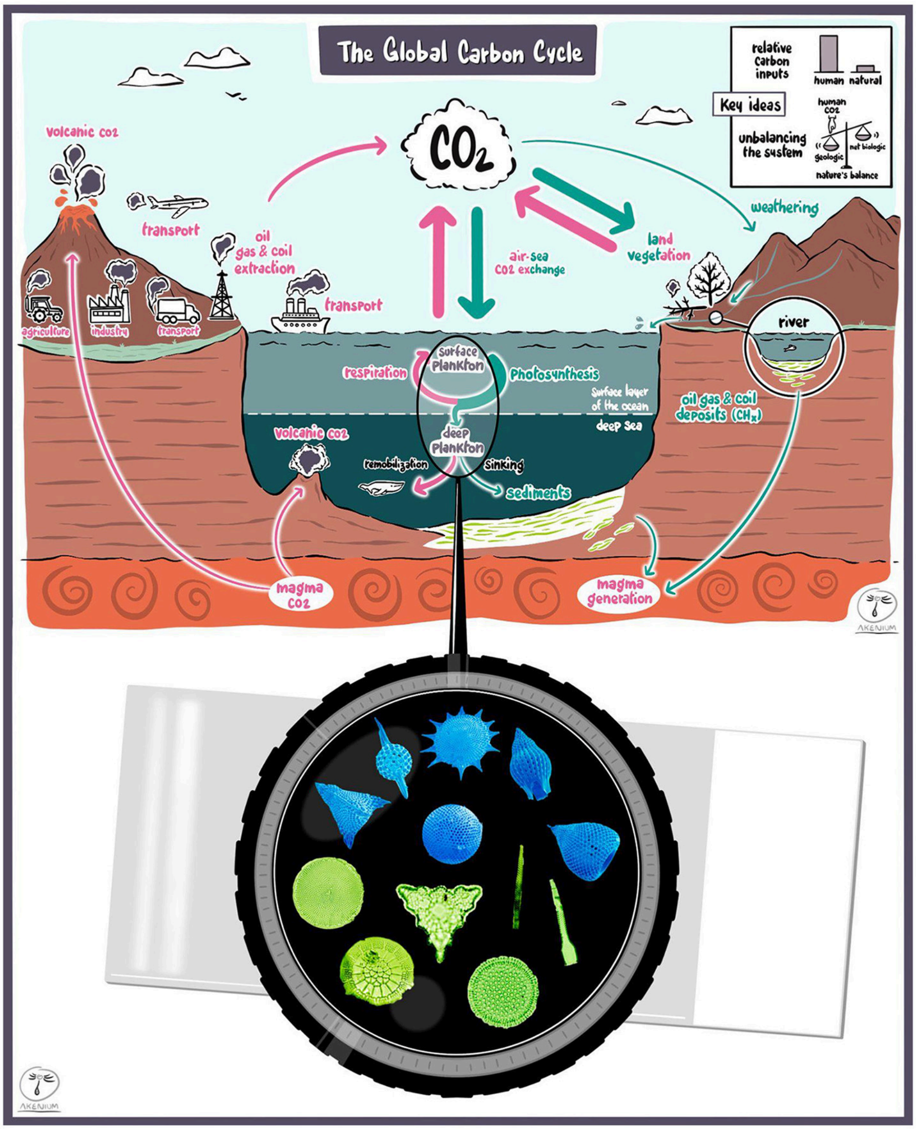

Figure 1

Figure 1

In the natural carbon cycle, the earth emits CO_2 from volcanoes. This is largely converted by the chemistry of rock weathering into dissolved river nutrients, which are taken up by plants and marine organisms along with atmospheric CO_2. The growth and death of organisms are in near perfect balance, with just enough carbon deposited into the soil and ocean sediments to balance the amount released by volcanoes. Human activities release nearly 100 times more carbon than is released by the natural cycle, causing rising atmospheric CO_2 levels and global warming [1]. Inset: Electron microsco5pe images of some of the ocean organisms that use carbon: marine zooplankton (radiolarians: blue) and phytoplankton (diatoms: green).

the air as CO_2 when volcanoes erupt, completing the natural carbon cycle (Figure 1). Atmospheric CO_2 has increased dramatically because many human activities rely on burning fossil fuels. Burning releases the carbon back into the atmosphere as CO_2 [1][3]. Currently, human activities release nearly 100 times more CO_2 into the atmosphere than volcanoes do [1].

Humans must therefore be part of the solution to climate change. We can stop burning fossil fuels and cutting down forests. Actively replanting forests and restoring or preserving other natural systems that store a lot of carbon (like peatlands) are also important to combat climate change. Scientists think that if oceans become warmer, there will be fewer carbon-removing microorganisms (Figure 1 insert). This would leave more CO_2 in the atmosphere. Preventing global warming will help protect the ocean's microorganisms, and thus help to stop climate change.

[3] In addition to the articles in this collection, for more information on climate change and global warming, check out these pages: NASA Climate Kids: Home and Climate Change and Global Warming.

HOW DOES CLIMATE AFFECT BIODIVERSITY?

Not only does life affect the climate, but climate also affects life [2]. As Earth's climate changes, some individuals that can tolerate the new conditions might survive and reproduce, passing on their tolerant traits, while others will die. This process is called **evolution**. Some organisms migrate to follow the conditions that are right for them. Animals might move because temperatures get too high, or because food sources become scarce. But not all species can move. For example, organisms in polar regions or at the tops of mountains are already living in the coldest places on Earth. When climate changes quickly, many species cannot adjust quickly enough, and become extinct [3]. The interactions of organisms with their environments can thus affect the Earth's biodiversity in many ways.

EVOLUTION

The changes in traits passed down through generations of organisms. Some traits, or adaptations, help individuals survive and succeed in their unique environments.

Changes in one species affects other species within the same community. Long-term studies of the interactions between species are important for predicting the future of life on Earth. For example, scientists have studied Edith's checkerspot butterfly for over 70 years (Figure 2). At one site, the success of the butterfly was dependent on one plant species (blue-eyed Mary). Then cattle ranchers brought in a new plant (plantain). Edith's checkerspot completely switched to using plantain. When cattle were taken off the land, the plant community changed again, and this time the butterfly population died off completely. Sometimes humans change things in the environment too fast for populations to adjust[4]. This can happen if there are not enough individuals in the population that can tolerate the new conditions.

[4] See the story of Edith's checkerspot on Youtube: The tale of the Edith's checkerspot: Butterflies caught in an evolutionary trap.

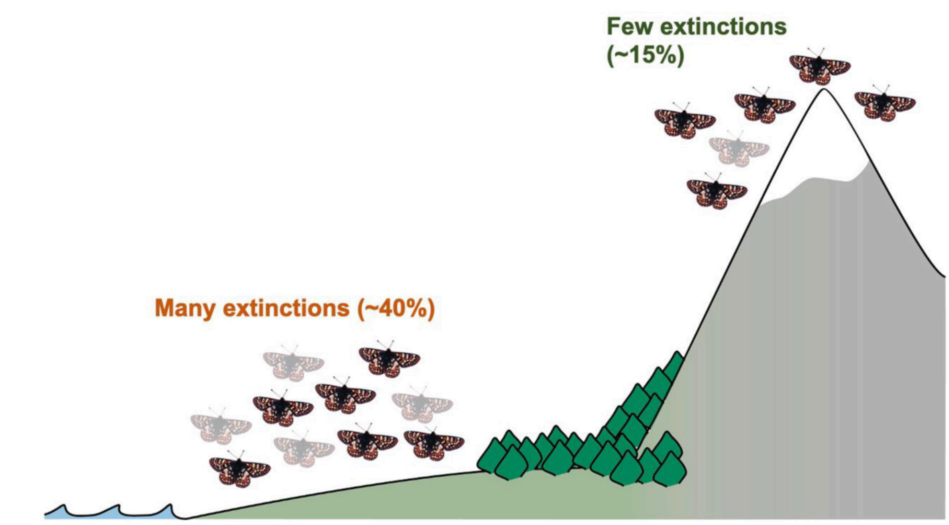

Figure 2

Figure 2

Edith's checkerspot butterfly lives in many habitats, from the seashore to the highest peaks of the Sierra Nevada mountains of California. This butterfly is sensitive to the climate. Whole populations can die off completely during extreme climate events. As western North America warmed by 0.7°C, many populations suffered at lower elevations—about 40% of the populations below 8,000 feet died off during our study. At the same time, only 15% of the populations above 8,000 feet were lost. The center of the species' range shifted 300 feet higher than it was previously [4].

Corals are another important example. These animals build their skeletons with a substance called calcium carbonate ($CaCO_3$), forming reefs like the Great Barrier Reef of Australia. Reef formation depends

CORAL

1: A tiny soft-bodied animal. Corals live in colonies and build a stony skeleton. 2: A piece of stony material which is the skeleton of corals.

[5] To learn more about the effects of ocean acidification, see the short animation about the potential impact on sea life in the Gulf of Maine A Climate Calamity in the Gulf of Maine Part 2: Acid in the Gulf.

INVASIVE SPECIES

Organisms that are transported to a new location where they had previously not existed but then begin to change or threaten the local communities.

[6] To learn more about the invasive knotweed, see the recent article in Attempto! magazine: `https://tinyurl.com/AttemptoKnotweed`.

on the amount of CO_2 in the atmosphere because that influences how much CO_2 is taken up by the ocean. CO_2 reacts with ocean water to form carbonic acid, which makes the ocean more acidic[5]. When ocean water is acidic, it reduces the growth and survival of corals. Coral reefs are important ecosystems—they provide breeding grounds for fish and hiding spots for other marine life. Without reefs, marine communities become less stable and collapse [5].

Marine habitats are also experiencing rapid changes in salt content. Rainfall patterns are changing around the world, and polar ice is melting rapidly. Oceans near the poles are becoming less salty, while the oceans closer to the equator are getting saltier. These rapid changes put enormous stress on marine organisms because salt levels must be maintained for proper function. Some populations can evolve in the saltier conditions, but others will die off. Species that do not live very long can evolve faster. For example, some copepods (small crustaceans) live only a few weeks and the average salt tolerance of the population can increase in just a few years. However, longer-lived plants and animals take much longer to evolve. This is true for many populations of fish which may decline in numbers or die off completely due to changes in salinity.

Changing climate conditions may also allow non-native species to thrive and become invasive. This is partly because native species may become stressed by the changing climate conditions. **Invasive species** may be more tolerant of the new conditions and may even grow more aggressively in the invaded areas than in their native areas! One example is Japanese knotweed. This plant tolerates many disturbed and stressful habitats, and has taken over in many areas around the world[6].

HOW DO WE PREDICT HOW ORGANISMS WILL RESPOND TO CLIMATE CHANGE?

Scientists study how organisms are changing in natural conditions and under experimental conditions. For over 100 years, studies of organisms in their natural conditions have shown changes in the life cycles and distributions of many plants, animals, and microbes in oceans, lakes, rivers, and on land as a result of climate change [2]. Warmer winters and springs have caused plants to flower earlier, trees to grow leaves earlier, and birds and butterflies to migrate earlier. Many plants and animals have moved closer to the poles and higher into the mountains as they try to keep pace with the changing climate (Figure 2).

It is hard to predict what will happen to living things when the Earth gets even hotter. One way is to take a closer look at corals because they provide an important window into the climate of the past (Figure 3). Corals grow slowly, and they incorporate the chemistry of the surrounding ocean into their skeletons. Scientists can "read" this information and use it to reconstruct the past living conditions of the corals. Some corals are 500 years old, giving us the chemical history of the last 500 years almost month by month!

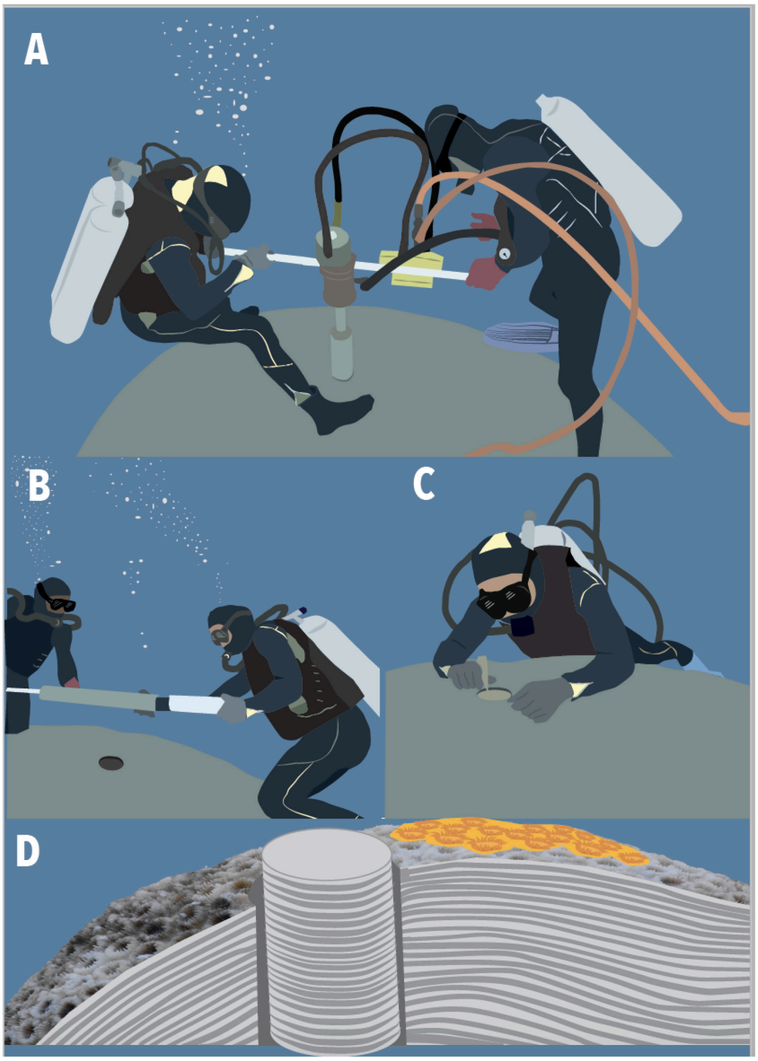

Figure 3

Figure 3

(A) Scientists dive down to an old massive coral, to take a sample. **(B)** The sample is removed and analyzed to reconstruct Earth's past climate. **(C)** The hole is filled with a cement that has similar properties to the coral skeleton, so no burrowing animals can enter and harm the coral. **(D)** The coral is not harmed by this process. From the sample, we can see the coral's density banding like tree-rings. One dark and one light band represent 1 year.

Scientists also study fossils from the distant past. Over great spans of time, plants, animals, and microorganisms have been forced to respond to very large climate changes. Sometimes, the changes were similar in size to changes we will see in future climates. In the fossil record, we can see what happened to life when the climate changed dramatically [3]. During major changes in Earth's past climate, many species migrated to more comfortable locations, some species became extinct, and a very few managed to stay in place and adapt to the new climate.

HOW CAN BIODIVERSITY HELP US UNDERSTAND THE FUTURE?

As far as we know, the diversity of life seen on Earth is unique in the universe. This diversity has provided humans with many of the things we need to survive. Plants and microbes on land and in the oceans, produce the oxygen that all animals (including humans) need to breathe. Ocean fisheries provide food and jobs for many people. Reefs, marshes, and mangroves protect our coasts. Forests provide us with wood to build things, and our croplands give us food. In addition, living things remove CO_2 from the atmosphere and the oceans. Without them, temperatures would be much hotter. Living things are also affected by the changing environment. Climate affects the availability of resources and the chemistry of the oceans. By studying many different types of life and many different environments, we hope to understand how life will respond to—and affect—future climate change.

AUTHOR'S NOTE

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REFERENCES

1. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., editors, et al. *IPCC, 2021: Summary for Policymakers. Climate Change 2021: The Physical Science Basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press. Available online at: https://www.ipcc.ch/report/ar6/wg1/
2. Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Evol. Syst.* 37:637–69. doi: 10.1146/annurev.ecolsys.37.091305.110100
3. Trubovitz, S., Lazarus, D., Renaudie, J., and Noble, P. J. 2020. Marine plankton show threshold extinction response to Neogene climate change. *Nat. Commun*. 11:5069. doi: 10.1038/s41467-020-18879-7
4. Parmesan, C. 1996. Climate and species' range. *Nature*. 382:765–6. doi: 10.1038/382765a0
5. Pandolfi, J. M., Connolly, S. R., Marshall, D. J., and Cohen, A. L. 2011. Projecting coral reef futures under global warming and ocean acidification. *Science*. 333:418–22. doi: 10.1126/science.1204794

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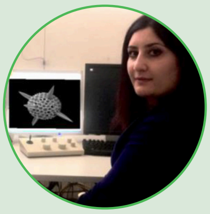
YOUNG REVIEWER

DEREK, AGE: 14
My name is Derek. I enjoy playing soccer and I also enjoy reading.

AUTHORS



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Marie is currently working on her Ph.D. at the Leibniz Center for Tropical Marine Research (ZMT) in Bremen. Although situated in the north of Germany, she is investigating corals as climate archives and is trying to reconstruct environmental changes in the Caribbean Sea and Gulf of Mexico with a special focus on ocean acidification as part of the MOPGA team "OASIS."

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Jed grew up in Silicon Valley, California where he hiked in the nearby mountains and played computer games. He combined his passion for nature and computers into university degrees in earth sciences and geography and later a Ph.D. in plant ecology. As a climate change researcher, Jed has lived in Sweden, Germany, Canada, Italy, Switzerland, and China. He is now a MOPGA research fellow at Augsburg University, Germany and professor of earth sciences at The University of Hong Kong. Jed is passionate about nature and the outdoors, and loves working with students and young people.

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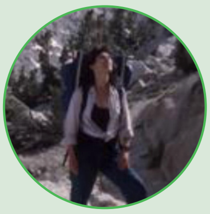

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Camille is a professor at the Experimental and Theoretical Ecology Station in France and a MOPGA laureate. She studies the impacts of climate change on wild plants and animals with field-based work on butterflies in North America and in Europe, and global analyses across a range of terrestrial and marine species. She has worked with the Intergovernmental Panel on Climate Change for more than 20 years, and is an official contributor to IPCC's Nobel Peace Prize in 2007. She is also affiliated with the University of Plymouth (UK) and the University of Texas at Austin (USA). She lives on a farm in the foothills of the Pyrenees, where she can watch butterflies all year.

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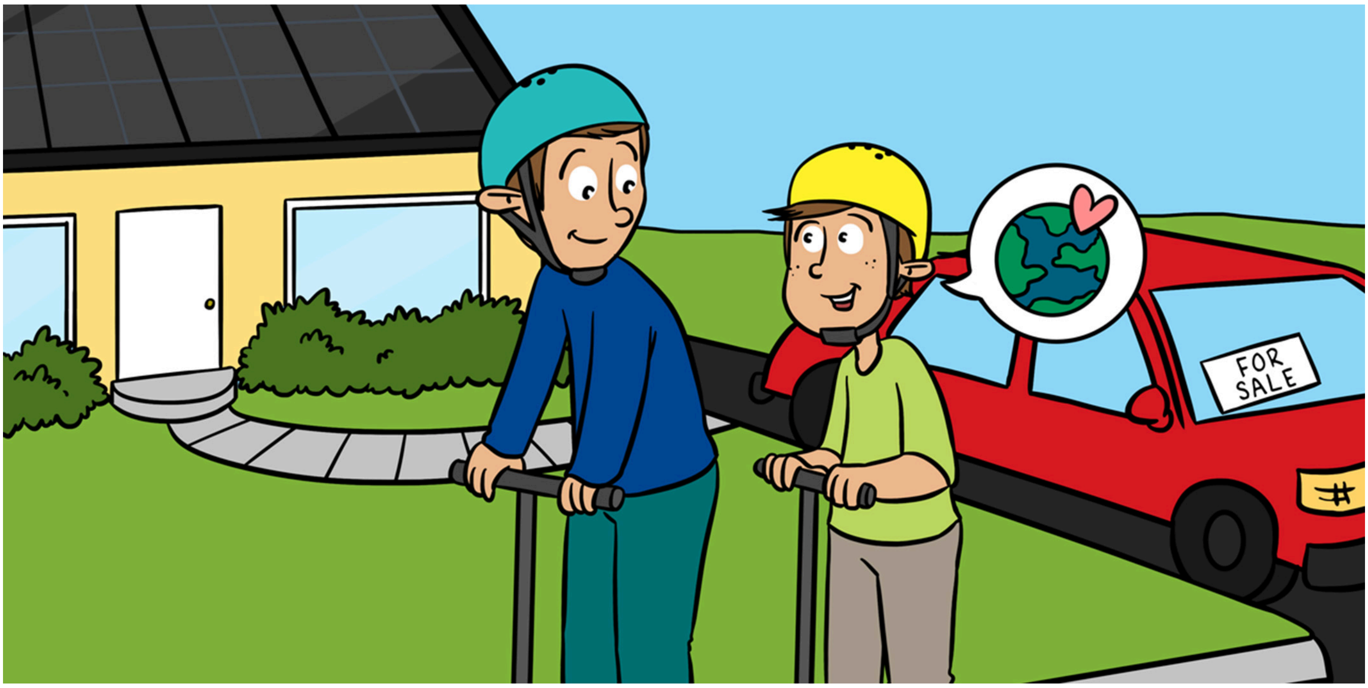

WHAT CAN WE DO TO ADDRESS CLIMATE CHANGE?

Paloma Trascasa-Castro[1*] *and Christopher J. Smith*[1,2]

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YOUNG REVIEWER:

EVA
AGE: 12

Climate change is one of the most serious problems that humans face today, but until now progress in stopping it has been slow. Climate simulations show that Earth will only stop warming when we reach "net zero" emissions. This means that carbon dioxide (CO_2) emissions are cancelled out by an equal amount of greenhouse gas removal from the atmosphere. Worldwide efforts to achieve net zero emissions by 2050 are necessary to avoid some of the worst effects of climate change. Achieving net zero will require huge changes to our society. While there are some things we can all do to fight climate change, the biggest changes need to come from the way our businesses and countries are run, where we get our energy from, how we travel, and how much "stuff" we consume and waste. By taking urgent action, we can ensure the future well-being of billions of people worldwide.

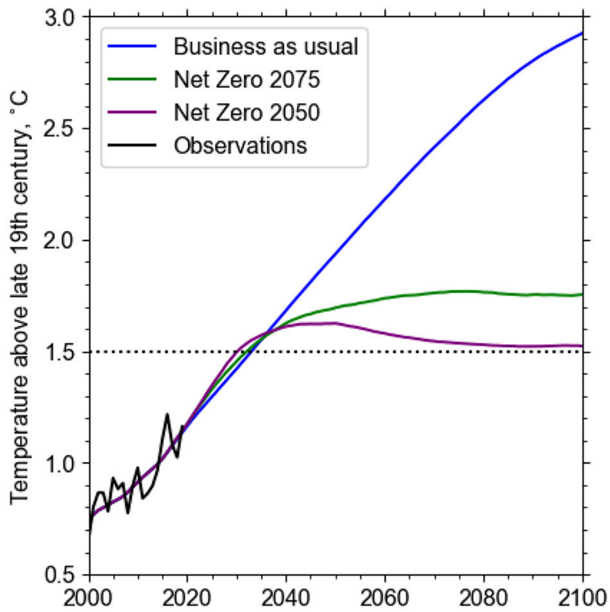

Figure 1

Figure 1

Expected global temperatures if we reach net zero by 2050 (purple) or by 2075 (green). Our current trend is shown in blue. The pledges made by countries in the Paris Agreement are not currently enough to meet the 2050 target and will result in around 3°C of warming by the end of the century.

OUR FUTURE CLIMATE

In 2015, almost every country in the world signed up for the Paris Agreement. The aim of this agreement is to limit global warming by keeping the world's average temperature increase to below 2°C (and hopefully only 1.5°C) above the average temperature of the late Nineteenth century. This level of warming sounds small, but it could cause big problems. Scientists know that climate extremes like floods, heatwaves, and droughts become more likely and worse with more warming. These weather events can lead to crop shortages and increased food prices, which could cause more people to go hungry. Sea levels will rise because of melting land ice and the expansion of warmer ocean water. This will put millions of people in coastal cities and small islands at risk. The more warming that occurs, the greater these impacts will be. *Every tenth of a degree matters.*

The planet has already warmed by 1.2°C since the late Nineteenth century and the effects have already been felt. To have a good chance of keeping global warming below 1.5°C, we need to reduce our emissions of carbon dioxide (CO_2) by half by 2030, and then reduce emissions to zero by 2050 (Figure 1). These are ambitious targets that require urgent and wide-ranging changes in our society and economy. The pledges made by countries in the Paris Agreement are not currently enough to meet these targets and will result in around 3°C of warming by the end of the century (blue line in Figure 1).

The good news is that the future climate change we see is mostly based on the choices we make today. However, these choices are not easy, and the speed at which we must change our world to limit climate change is unlike anything we have seen before.

NEGATIVE EMISSIONS

CO_2 removal from the atmosphere.

Most human activities involve burning fossil fuels for energy, which releases CO_2. In 2019, we emitted 42 billion tonnes of CO_2. Despite the coronavirus crisis, emissions only dropped by 7% in 2020 [1]. Moving to renewable energy sources (such as wind turbines and solar power) and switching road vehicles from petrol and diesel to electric power will help us reduce CO_2 emissions. In addition, we may need to *remove* CO_2 from the atmosphere, a process that is called **negative emissions**. Reaching **net zero emissions** globally—which means that we remove from the atmosphere the same amount of CO_2 that we emit–will take individual and collective action.

NET ZERO EMISSIONS

The amount of CO_2 emitted equals the amount of CO_2 removed from the atmosphere through natural or artificial methods.

WHAT CAN WE DO?

There are several things you can do as an individual to reduce your impact on the climate. The amount of CO_2 that each one of us emits to the atmosphere every year is known as a **carbon footprint**. On average, each person in the world emits 6.7 tonnes of CO_2 per year, but this varies widely within and between countries. Generally, richer people in richer countries are responsible for most of the CO_2 emitted. Research has shown that the amount of energy required to live comfortably is in fact quite low [2]. If everybody in the world had this same comfortable standard of living, it would result in an improvement in quality of life for billions of people in the developing world, but would require rich people and rich countries to consume and waste less.

CARBON FOOTPRINT

Amount of greenhouse gases released to the atmosphere as a result of our daily activities. It is measured in equivalent tonnes of CO_2 per person and year.

Towns and cities should be designed to be more friendly to walking, cycling, and public transport. Changing the way we travel is the most powerful action we can take to reduce our carbon footprints. For example, living car-free can save up to 5 tonnes of CO_2 emitted per person every year [3], and it is also good for your health and the local air quality. A long-distance flight adds a lot of CO_2 to the atmosphere. This can be reduced by taking a train whenever possible or by going on holidays closer to home. Towns should have good transport links and be built or modified to be more energy efficient, so that they are easier to keep cool in the summer and warm in the winter.

We can also reduce our impact on the climate by being careful where we spend our money. Try to buy only from companies that are sustainable and do not compromise the environment. For example, try to buy electricity from a provider that uses 100% renewable energy. Renewable energy companies get their energy from solar panels and wind turbines. Switching on the lights and heat at home only when necessary also helps reduce our emissions—and our bills! Eating less meat (especially beef) and dairy and avoiding food waste are also powerful individual actions that can save up to two additional tonnes of CO_2 emissions per person per year.

Individual actions will only go so far, and we should not feel badly if our lifestyles do not allow some of them. For example, not everyone can afford an electric car or to put solar panels on the roof. However, remember that your actions can inspire others. Use your voice! Talking about climate change with your friends, family, and classmates really helps to raise awareness and drive further action.

Large businesses, city/state leaders, and national governments are the organisations that can make the big changes we need. How do we influence them? There are multiple ways to make elected governments hear your voice. Educate yourself on the climate commitments for each candidate or political party in your town, city, or country. Discuss climate issues with the adults in your life, because this may help influence the way they vote. And use your vote when you are old enough! Even if you are not old enough to vote, you can have a huge influence. The #Fridays4Future school strike movement, started by then 16-year-old Greta Thunberg, helped communicate some of the anger that young people are feeling about inaction on climate change.

Mass protests around the world have raised awareness of the climate crisis in the political arena. Many local and state governments have now acknowledged the issue and declared a "climate emergency" that requires urgent action. Collective action has been shown to be very useful. It is only at the society level that we will be able to make changes for a better future.

At the national level, countries are making transitions toward clean energy sources and pledging to become net zero (Figure 2). These countries must quickly reduce their emissions of greenhouse gases, and unavoidable emissions (like those from aeroplanes) should be balanced by negative emissions. Whether the world is ultimately successful at reaching net zero by 2050 depends on making sure more countries commit to their own targets and work hard to achieve them.

CAN NEGATIVE EMISSIONS REVERSE CLIMATE CHANGE?

There are two reasons why we might try to remove CO_2 from the atmosphere. First, the total warming the Earth has experienced is closely related to the total amount of CO_2 that has ever been emitted [5], so there is a possibility we might be able to reverse warming in the future, with net-negative emissions. The second reason relates to net zero emissions: it is hard to avoid CO_2 emissions caused by some activities, like flying. While we need to reduce the amount we fly, it is unlikely that we will stop flying completely in the future, so we need a way to "cancel out" the positive emissions from flying.

Figure 2

Target dates to become net zero. Suriname and Bhutan (pink) are currently carbon negative. Countries in green have made legally binding pledges to become net zero by 2045 or 2050. Small island states have proposed legislation to achieve net zero by 2050 (Data from [4], last updated in December 2020).

CARBON CAPTURE AND STORAGE

Nature-based process by which CO_2 is taken from the atmosphere and stored in a safe location (like geological formations) where it is not harmful for the climate system or the ecosystems.

BIO-ENERGY WITH CARBON CAPTURE AND STORAGE

Nature-based alternative to fossil fuels consisting of planting trees to later burn them, generating a lot of energy. The CO_2 released in the process is captured and kept away from the atmosphere

DIRECT AIR CARBON CAPTURE AND STORAGE

Human-created solution to remove CO_2 from the atmosphere via "hoovering" large amounts of air and storing CO_2 underground.

CARBON SEQUESTRATION

Process through which plants capture CO_2 from the atmosphere and store it in the soil.

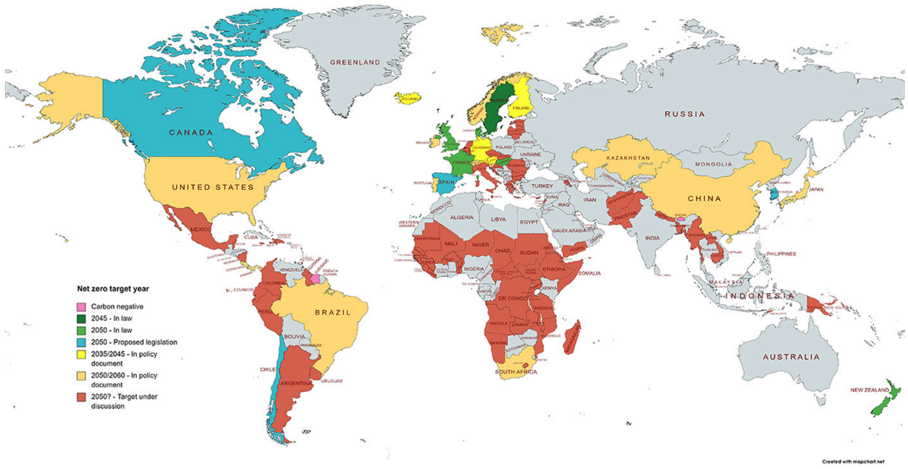

Figure 2

There are several nature-based and human-created ways to remove CO_2 from the atmosphere where it affects climate. Some examples are shown in Figure 3. One idea is to capture and bury CO_2 underground in unused oil wells and geological formations, storing it away from the atmosphere. This is known as **carbon capture and storage** (CCS). Planting trees is a good idea too, because trees suck up CO_2 and release oxygen when they perform photosynthesis. We could even grow trees to burn for fuel (instead of using fossil fuels), and then capture the CO_2 that is released. This is known as **bio-energy with carbon capture and storage** (BECCS). BECCS is a negative-emissions method because the carbon in the tree material was already in the atmosphere, and then we capture and remove it. BECCS has the potential to remove about a quarter of our current total emissions by 2050. CO_2 can also be "vacuumed" directly from the atmosphere and stored underground, a process known as **direct air carbon capture and storage** (DACCS).

Trees naturally remove CO_2 from the atmosphere, so planting more trees and could cancel out another 5.5 billion tonnes of CO_2. Through **carbon sequestration**, plants naturally capture carbon from the atmosphere and store it in the soil. Burning trees and plants in the absence oxygen also helps to store CO_2 in a solid form for thousands of years, keeping it away from the atmosphere. The resulting product is called **biochar**. Although a large amount of CO_2 is released in the biochar process, it still might be a powerful source of negative emissions in the medium-to-long term. Biochar can also be used as a fertiliser to help crops grow.

There are several drawbacks to these methods of removing CO_2 from the atmosphere. DACCS technology is currently very expensive and uses a lot of energy. Solutions based on trees and plants require lots of land, which is limited and could reduce the amount of land available to grow food. Food shortages could increase food prices

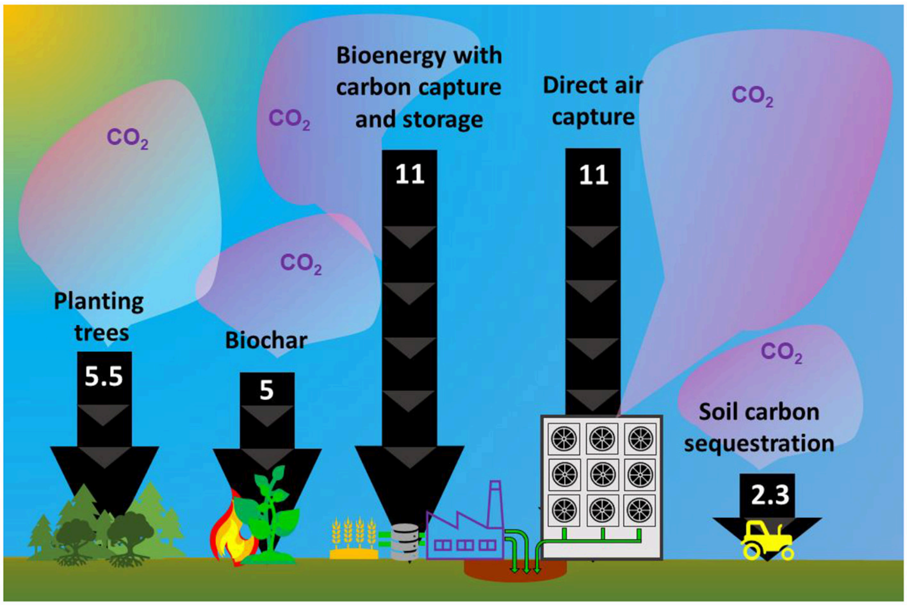

Figure 3

Figure 3

Potential of various solutions to remove atmospheric CO_2 by 2050. Units are billions of tonnes of CO_2 per year (Adapted from Minx et al. [6]).

BIOCHAR

Waste product obtained by burning trees and plants in the absence of oxygen.

and more people could go hungry. Successfully removing carbon from the atmosphere will require cooperation between countries and people, and the willingness of governments to make big, expensive investments in carbon-capture technologies.

Even if *all* the potential negative emissions methods were used, they still would not be enough to reach net zero CO_2 with our current emissions of 42 billion tonnes per year. Therefore, negative emissions are not a miracle cure—we still need to reduce our emissions in other ways, too.

It is up to us whether we avoid the worst consequences of global warming. Talking about climate change is the most effective way to get everyone on board. We all need to work hard to achieve net-zero by 2050 at the individual and collective level. Remember: every tenth of a degree matters!

REFERENCES

1. Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., et al. 2020. Global Carbon Budget 2020. *Earth Syst Sci Data*. 12:3269–340. doi: 10.5194/essd-12-3269-2020
2. Millward-Hopkins, J., Steinberger, J. K., Rao, N. D., and Oswald, Y. 2020. Providing decent living with minimum energy: a global scenario. *Glob Environ Change*. 65:102168. doi: 10.1016/j.gloenvcha.2020.102168
3. Wynes, S., and Nicholas, K. A. 2017. The climate mitigation gap: education and government recommendations miss the most effective individual actions.

Environ Res Lett. 12:074024. Available online at: https://iopscience.iop.org/article/10.1088/1748-9326/aa7541?TB_iframe=true&width=921.6&height=921.6
4. Energy & Climate Intelligence Unit. 2020. *Countdown to Zero Plotting Progress Towards Delivering Net Zero Emissions by 2050*. Available online at: https://ca1-eci.edcdn.com/reports/ECIU_Countdown_to_Net_Zero.pdf (accessed January 4, 2021).
5. Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., et al. 2009. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*. 458:1163–6. doi: 10.1038/nature08019
6. Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. 2018. Negative emissions—Part 1: research landscape and synthesis. *Environ Res Lett.* 13:063001. Available online at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9b

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YOUNG REVIEWER

EVA, AGE: 15
I am Eva I still go to school and I enjoy subjects like science and I also really like art. I love to draw, play video games and to meet my friends.

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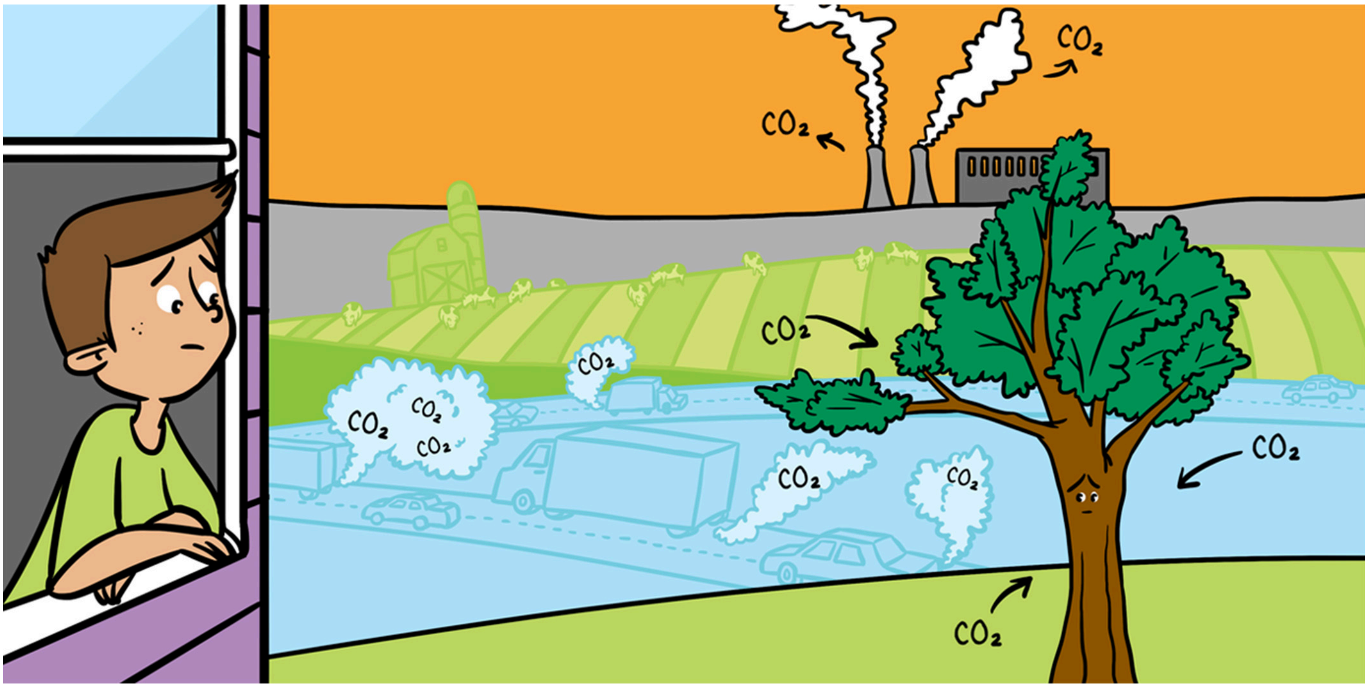

HOW QUICKLY WOULD WE SEE THE EFFECTS OF CHANGING GREENHOUSE GAS EMISSIONS?

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National Institute of Environmental Studies, Tsukuba, Japan

YOUNG REVIEWERS

KING'S SCHOOL CANTERBURY

AGES: 14–15

Greenhouse gases (GHGs) help to maintain the Earth's temperature by trapping heat. Without GHGs, our planet would be so cold that no life could exist. In the present era, human activities such as the burning of fossil fuels emit huge amounts of GHGs into the atmosphere each year. Consequently, the Earth's temperature is increasing to an uncomfortably high level. To halt the rise in Earth's temperature, we must reduce and ultimately eliminate GHG emissions. However, reducing emissions may not instantly result in lower GHG levels in the atmosphere, as the GHGs we emit now can remain in the atmosphere for decades to centuries. This article explains the rate at which two essential GHGs (carbon dioxide and methane) might accumulate in the atmosphere and how their concentrations could change in the future because of emissions reductions.

GREENHOUSE GASES

Greenhouse gases (GHGs) are a vital component of the atmosphere and they control the state of Earth's climate. Without GHGs, Earth would be a frozen, uninhabitable world. Due to GHGs, Earth's average surface temperature is about 15°C, but it would be −18°C without GHGs—approximately a 33°C increase above the GHG-free atmosphere. GHGs give us a livable planet. Water vapor (water in the form of gas), carbon dioxide (CO_2), and methane (CH_4) are the most abundant GHGs in Earth's atmosphere. For millennia, these GHGs have been part of Earth's atmosphere, because they are produced by natural processes. However, humans have altered the levels of GHGs in the atmosphere. We cut down trees to clear land for growing crops or to use as wood for construction. We burn wood and fossil fuels like coal, oil, and gas, and burning emits a large amount of CO_2 into the atmosphere. We have increased CH_4 **concentrations** through coal mining, by pumping gas *via* leaky pipes to warm our homes, by dumping our waste in open areas, and by raising large numbers of cows and sheep for milk and meat production.

CONCENTRATION

The amount of a particular gas in the atmosphere. CO_2 concentrations are measured in parts-per-million (ppm) and CH_4 in parts-per-billion (ppb). One ppm is equivalent to one drop of water diluted into roughly 13 gallons of liquid.

HOW LONG DO GHGS STAY IN THE ATMOSPHERE?

After emission, each of the GHGs stays in the atmosphere for a different length of time. Think about it like a bathtub—the amount of water in the bathtub depends on the input from the tap and the output *via* the drain. A wide drain hole allows for quick removal of water from the bathtub, while water will be retained in the tub for longer if the drain hole is narrow. The same principle also explains how long GHGs stay in the atmosphere (Figure 1). The atmosphere (bathtub) fills up with billions of tons of GHG emissions from human activities and drains due to natural activities. For example, CH_4 is removed from the atmosphere by natural chemical reactions with hydroxyl radicals, chlorine, and oxygen (Figure 1B). CO_2 is removed from the atmosphere by photosynthesis and is absorbed by the oceans (Figure 1A). For both CO_2 and CH_4, the amounts produced (**inflows**) and removed (**outflows**) are out of balance; inflows outweigh outflows. Excess emissions cause GHGs to accumulate in the atmosphere. As a result, the GHGs we emit now exist in the atmosphere for a long time, ranging from a few years to centuries. The lifetime of a given GHG in the atmosphere is measured by the time that required to remove half of the released amount from the atmosphere.

INFLOW

The process/measure of incoming mass. The emissions entering into the atmosphere from different sources at surface can be consider as inflow here.

OUTFLOW

The process/measure of outgoing mass. The emissions removed from atmosphere by different natural processes can be consider as outflow here.

CH_4 is removed from the atmosphere faster than CO_2 is removed, because there are no chemical reactions that remove CO_2 from the atmosphere. As a result, the lifetime of CH_4 (about 10 years) is shorter than that of CO_2 [2]. Unlike CH_4, CO_2 is not destroyed—it just moves from the atmosphere into storage locations on land and in the ocean, through processes including photosynthesis. CO_2 is stored in

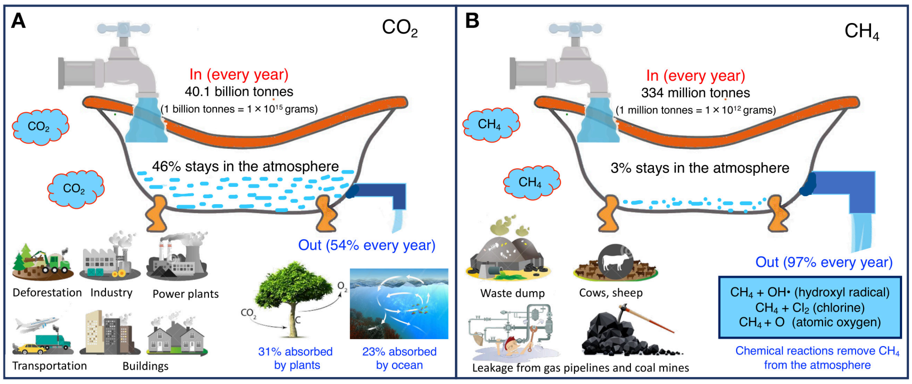

Figure 1

Figure 1

CO_2 and CH_4 cycles, using a bathtub analogy. Inflows indicate total yearly emissions from human activities. The water left in the bathtub reflects the accumulation of CO_2 and CH_4 in the atmosphere every year. The wider drain hole in the CH_4 bathtub illustrates that CH_4 is removed from the atmosphere more quickly than CO_2 is removed. The latest Intergovernmental Panel on Climate Change (IPCC) report gives more details on GHG emissions and removals [1]. The idea for this figure came from `https://www.climateinteractive.org/tools/climate-bathtub-simulation/`. **(A)** CO_2. **(B)** CH_4.

ecosystems in the form of carbon, which is eventually emitted back to the atmosphere [1]. For example, when a plant dies, the carbon stored in the plant is released back to the atmosphere. The flows of carbon throughout the atmosphere, plants, and the ocean are complex and challenging to understand. Calculating the exact lifetime of CO_2 in the atmosphere is difficult because of all these complex processes. Rather than a single value, scientists provide a range: for every kilogram of CO_2 emitted, 40% remains in the atmosphere after 100 years, 20% after 1,000 years, and 10% after 10,000 years [3, 4].

HOW WILL GHG CONCENTRATIONS CHANGE IN THE FUTURE?

The natural removal of CO_2 and CH_4 from the atmosphere is not enough to cancel out man-made emissions, so their concentrations are quickly increasing [1]. Every ton of CO_2 and CH_4 remaining in the atmosphere causes heating, so Earth's temperature is rising to an uncomfortably high level. To stop or limit future global temperature increases, we must stop adding CO_2 to the atmosphere.

Since it is impossible to predict how emissions will change in the future, experts look at a range of different outcomes, called scenarios, in which they account for population growth and economic growth. We will look at three different emission scenarios, called SSP1, SSP2, and SSP3; SSP stands for "shared socio-economic pathways" (Figure 2). SSP1 is an ideal scenario, in which there is a rapid decrease in GHG emissions, while SSP3 is an extreme scenario, in which emissions continue to rise. SSP2 is an intermediate scenario, in which emissions gradually decrease until the end of the century. How will GHG concentrations change under the three scenarios? Scientist use computer models of the climate system, called **climate models** to predict future GHG concentrations. In these models, various processes occurring in the atmosphere, on land, and in the ocean interact with each other.

CLIMATE MODELS

A set of computers programs, like a laboratory in a computer, that helps scientists understand how various factors influence Earth's climate.

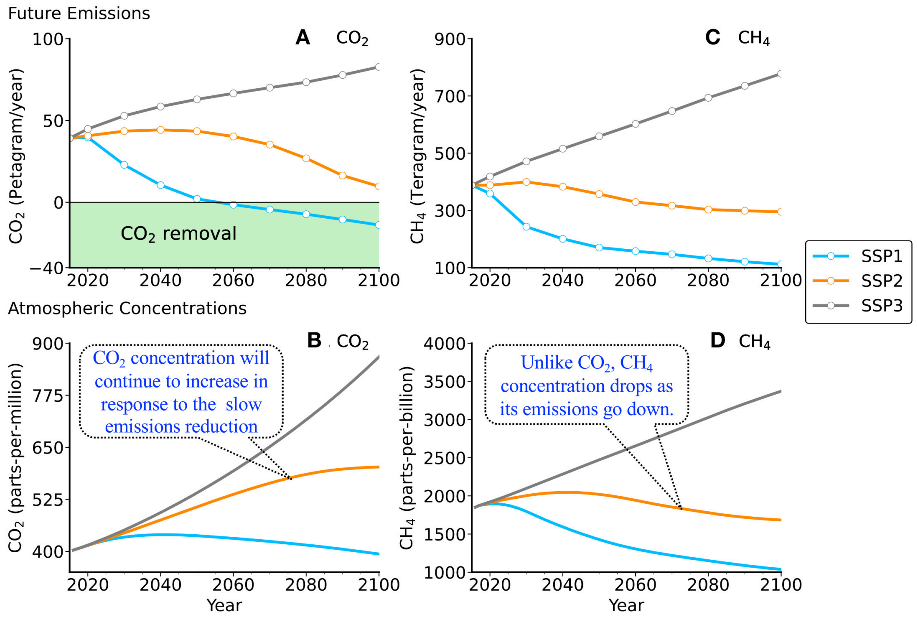

Figure 2

Figure 2

Three scenarios for GHG emissions **(A,B)** and their effects on atmospheric concentrations **(C,D)**. SSP1 is an ideal scenario, with a rapid decrease in GHG emissions. SSP2 is an intermediate scenario. SSP3 is an extreme scenario in which emissions continue to rise.[1] A petagram (1 billion tons or 1×10^{15} grams) is equivalent to the weight of 100,000,000 elephants or the water in 400,000 Olympic pools. One teragram is equivalent to 0.001 petagram. The concentrations are in parts-per-million (ppm) or parts-per-billion (ppb). One ppm is equivalent to 1 L of water in a swimming pool; 1 ppb as 1 ml of water.

Future concentrations of CO_2 and CH_4 in the air largely depend on decisions we make now (Figure 2). Without global action to rein in GHG emissions (SSP3), CO_2 and CH_4 concentrations will continue to increase through the twenty-first century and beyond. This would result in huge environmental effects. On the other hand, if countries gradually reduce their GHG emissions as in SSP2, although CH_4 concentrations would peak and decline, the CO_2 concentration would not. This is because CH_4 has a short half-life in the atmosphere, so levels will drop within about 10 years after emissions decrease, while CO_2 has a long half-life and responds more slowly. As long as we keep emitting CO_2, its concentration will continue to rise. The atmospheric CO_2 concentration can only stabilize and drop after CO_2 emissions are reduced to zero and we take steps to actively remove it from the atmosphere, as in SSP1. This would be very challenging to do.

WE MUST ACT NOW!

In summary, the different atmospheric lifetime of each GHG dictate how quickly they are removed from the atmosphere. CO_2 concentration stabilizes or decreases only after a few decades of reducing CO_2 emissions because it has a very long half-life in the atmosphere. Any short-term reductions in CO_2 emissions, like those we have seen during the COVID-19 pandemic, do not have a detectable effect on atmospheric CO_2 concentration or global temperature. Recent studies show that global temperature will take a long time to fall after CO_2 emissions reach zero. In fact, the CO_2 response time is so long that we may not notice the effect while we are still alive. On the other hand, atmospheric CH_4 levels respond swiftly

[1] Emissions scenarios are based on population and economic growth in the future. See: `https://tntcat.iiasa.ac.at/SspDb` and [5].

to reductions in emissions, so reducing CH_4 emissions is important for stopping global warming in the short term.

Eventually, the awareness about the impact of our habits on climate can help to control/reduce climate change. The more we learn about the GHGs emission sources and their sustaining footprints in our atmosphere and climate, the better we can plan to avoid them. This basic information can help to imagine how our present activities and decision will decide future GHGs levels in the atmosphere. Nevertheless, there is hope to defeat the climate change monster, but we all have to behave responsibly and start reducing GHG emissions from our daily activities.

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REFERENCES

1. Canadell, J. G., Monteiro, P. M. S., Costa, M. H., Cotrim da Cunha, L., Cox, P. M., Eliseev, A. V., et al. 2021. "Global carbon and other biogeochemical cycles and feedbacks," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Cambridge; New York, NY: Cambridge University Press), 673–816. doi: 10.1017/9781009157896.007
2. Patra, P. K., Houweling, S., Krol, M., Bousquet, P., Belikov, D., Bergmann, D., et al. 2011. TransCom model simulations of CH_4 and related species: linking transport, surface flux and chemical loss with CH_4 variability in the troposphere and lower stratosphere. *Atmos. Chem. Phys.* 11:12813–37. doi: 10.5194/acp-11-12813-2011
3. Archer, D., Eby, M., Brovkin, V., Ridgwell A., Cao, L., Mikolajewicz, U., et al. 2009. Atmospheric lifetime of fossil fuel carbon dioxide. *Ann. Rev. Earth Planet. Sci.* 37:117–34. doi: 10.1146/annurev.earth.031208.100206
4. Inman, M. 2008. Carbon is forever. *Nat. Clim. Change* 1:156–8. doi: 10.1038/climate.2008.122
5. Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., et al. 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev*. 13:3571–605. doi: 10.5194/gmd-13-3571-2020

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We are an energetic year 11 class who are curious about the latest science. Three members of the class took on leadership roles as we reviewed this manuscript. We are happy that we can support working scientists through this review during the pandemic.

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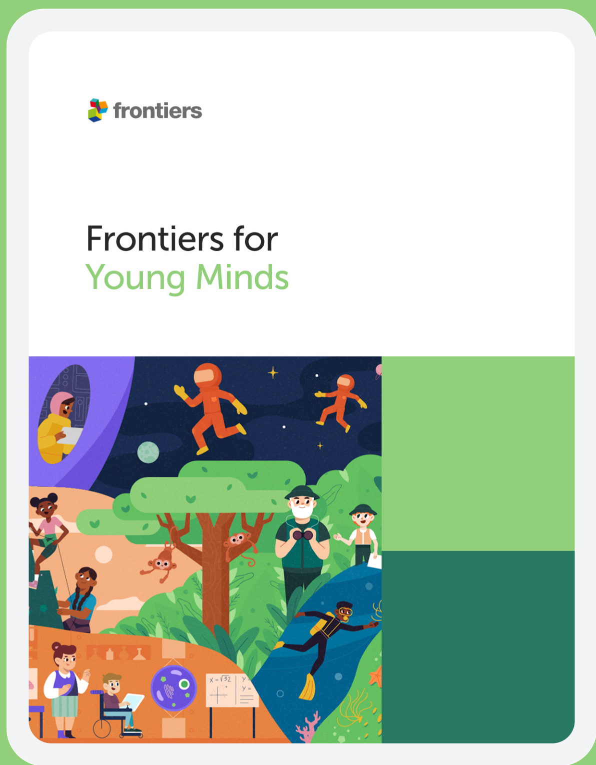

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