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TAKING EARTH'S TEMPERATURE: WILL ZERO CARBON MEAN ZERO CHANGE?

Sofia Palazzo Corner [1,2*] ***and Joeri Rogelj*** [1,2,3]

[1] *Centre for Environmental Policy, Imperial College London, London, United Kingdom*

[2] *Grantham Institute - Climate Change and the Environment, Imperial College London, London, United Kingdom*

[3] *Energy, Climate and Environment Program, International Institute for Applied Systems Analysis, Laxenburg, Austria*

YOUNG REVIEWERS:


ADDY
AGE: 14


TEDDY
AGE: 12


YOUNG SCIENTIST ACADEMY
AGES: 8–15

How do we stop global warming? We know that excess carbon dioxide (CO_2) in the atmosphere causes global warming, but when we stop emitting CO_2—a goal known as net zero—will warming stop at the same time? Our best understanding is that no more CO_2 emissions means no more warming, but we are not completely sure about this. The extra change in temperature after we reach net zero emissions is called the zero emissions commitment. In this article, we explain how understanding the way heat and carbon move around the Earth is key to working out whether we will get more global warming after net zero, see some cooling, or perhaps experience no change in Earth's temperature at all.

HOW DO WE STOP GLOBAL WARMING?

Today, humans are still adding more carbon dioxide (CO_2) to the atmosphere each year than the year before. CO_2 is a **greenhouse gas**,

GREENHOUSE GASES

Gases that trap heat in Earth's atmosphere, instead of allowing it to escape into space.

GLOBAL WARMING

The heating of the Earth due to an excess of greenhouse gases trapped in the atmosphere.

NET ZERO

The point at which no more CO_2 is added to the atmosphere from human activities.

ZERO EMISSIONS COMMITMENT

The temperature change that will still happen after net zero emissions is reached.

so its presence in the atmosphere causes the planet to heat up—this is called **global warming**. To keep humans and the natural world as safe as possible, global warming must be slowed and then stopped completely. To achieve this, we must reverse the current trend of increasing CO_2 emissions, so that eventually we are no longer adding *any* CO_2 to the atmosphere at all. At that point, we will have achieved **net zero** emissions. "Zero" is the most important word in this phrase, because it means that *no* CO_2 is being added to the atmosphere. "Net" means that if we *do* emit any CO_2, then we must *remove* the exact same amount so that, overall, the amount of extra CO_2 left in the atmosphere is zero (if you would like to know more about net zero and the chances of reaching it, see this article).

Scientists have calculated that when we reach net zero the Earth will probably not warm any further [1]. This means that global warming will stay the same, or stabilize—but we are not sure if it will stay *exactly* the same! The Earth is complicated and there are lots of interacting systems that make it difficult to predict what will *actually* happen when we reach net zero. Understanding whether net zero will be followed by some warming, some cooling, or no change at all is key to understanding how much CO_2 we can still emit while keeping the Earth below dangerous levels of global warming (for more information on dangerous levels of warming, see this Frontiers for Young Minds article). The change in global temperature that might still happen once we reach net zero emissions is called the **Zero Emissions Commitment** (ZEC), and scientists are doing a lot of work to figure out what this number is!

So, how do we figure out ZEC? We know that adding CO_2 to the atmosphere causes more heat from the sun to be trapped on Earth. We also know that, over time, some of this heat and carbon gets spread out across the planet. Carbon is taken up by trees, plants, and the ocean, while heat is mostly absorbed by the ocean. The interactions between these two main Earth processes that move carbon and heat around, and how much and how quickly they change after we reach net zero, hold the key to understanding what will happen to global warming. But as you will see, things are a bit more complicated than they look at first glance!

THE MOVEMENT OF HEAT: THE ROLE OF THE OCEANS

While we usually use the term "global warming" to describe the warming we experience on Earth's surface, the surface is not the only thing that is heating up—in fact, the oceans have absorbed over 90% of the heat caused by excess greenhouse gases in the atmosphere. The heat absorbed by the oceans warms the ocean waters, which are then pushed around the planet by ocean currents, spreading the heat all over the Earth (Figure 1A). That does not mean the ocean feels like a bath though! The ocean is huge, and even a tiny amount of ocean warming means that enormous amounts of heat have been absorbed. When we reach net zero and greenhouse gases in the atmosphere stabilize, the heat trapped by the atmosphere will stop increasing. As a result, the amount of heat absorbed by the ocean each year should also decrease (Figure 1B). On its own, this would mean more heat left in the atmosphere, which means more global warming after net zero (Figure 1C). But we are not sure exactly how much more warming, or how fast this change would happen.

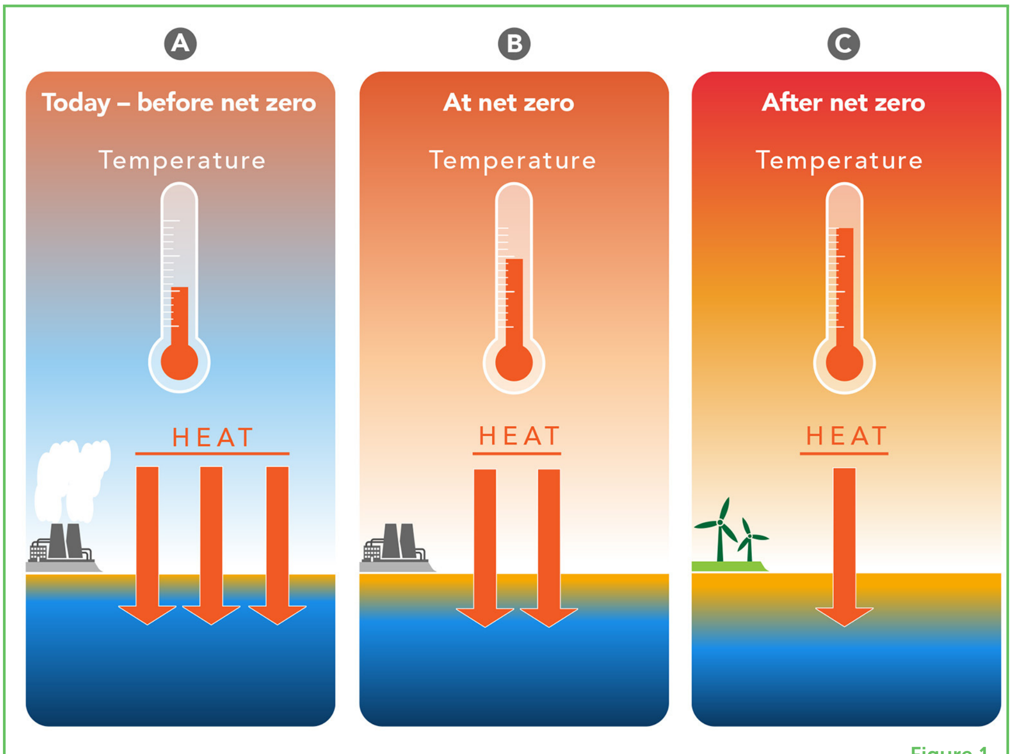

Figure 1

(A) Today, humans are still emitting greenhouse gases, so more and more heat is being trapped in the atmosphere. The ocean absorbs much of this heat. **(B)** When we reach net zero, no more CO_2 will be added to the atmosphere. This means the amount of heat trapped by the atmosphere will stop *increasing*, and the amount of heat absorbed by the ocean will start to *slow down*. After a very long time, the ocean will eventually reach a new balance (equilibrium) with the atmosphere. **(C)** On its own, this decreasing ocean heat uptake will cause more heat to stay in the atmosphere, resulting in more global warming.

OVERTURNING

The circulation of ocean water from the surface to the deep ocean. This process can help to remove heat from the atmosphere.

For example, the heat that is absorbed at the ocean surface in the Atlantic is eventually transported to the deep ocean through various types of mixing, including large movements of water called **overturning**. Like a huge ocean conveyor belt, this water moves heat from the southern hemisphere to the northern hemisphere, cools, sinks, and returns cold, deep water southwards again. As the planet warms, scientists believe overturning will weaken, but they are not sure exactly how much, or how fast [2, 3]. Changes to overturning and other types of mixing are expected to mean less heat would be absorbed by the ocean and stored in deep waters—which in turn would mean more heat stuck in the atmosphere, leading to more global warming.

THE MOVEMENT OF CARBON: THE CARBON CYCLE

When we burn fossil fuels, we transform carbon from stable, solid stores under the ground (for example, coal) into the gas CO_2, which spreads around the atmosphere and stops heat from escaping back into space. To understand how carbon is moved around the Earth, we need to understand the balance between carbon sinks and sources: **carbon sinks**, like trees, absorb and store carbon, taking it *out of* the atmosphere; **carbon sources**, like burning coal, transfer carbon *into* the atmosphere (Figure 2A). When we reach net zero and stop emitting CO_2, the carbon in the atmosphere will slowly be redistributed to the land and the ocean via plants (Figure 2B), soils, and ocean carbon uptake. For example, seagrass, which uses CO_2 for photosynthesis, transforms CO_2 in the ocean to carbon in its stems, leaves, and roots. As carbon is redistributed to carbon stores like these, the amount of CO_2 in the atmosphere should decrease, which on its own would mean the Earth would start cooling after net zero (Figure 2C).

CARBON SINK

A storage place in nature that absorbs and holds onto carbon from the atmosphere.

CARBON SOURCE

Something that releases carbon into the atmosphere, like burning fossil fuels or wildfires.

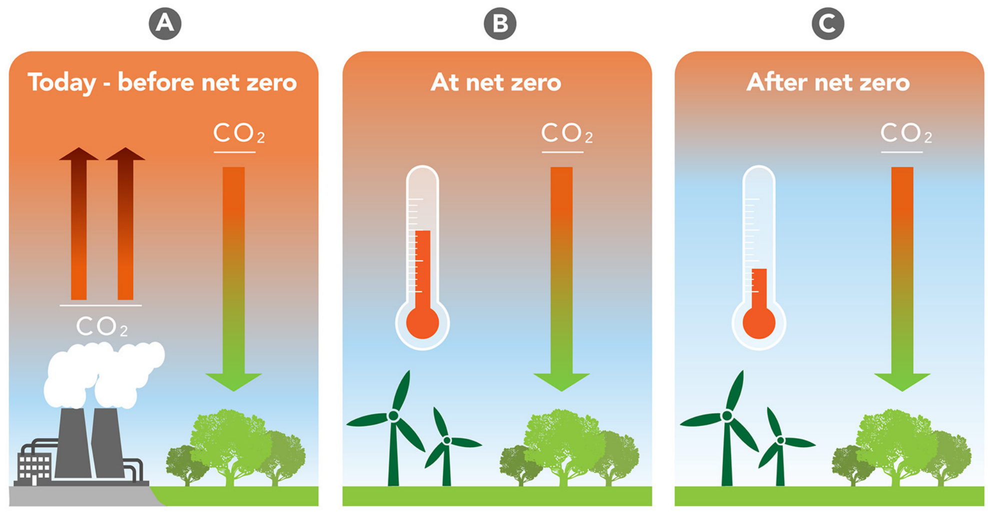

Figure 2

Figure 2

(A) Today, humans are still releasing increasing amounts of CO_2 into the atmosphere. Carbon sinks like forests are absorbing some of this CO_2, but there is still much more CO_2 going into the atmosphere than being taken out. **(B)** At net zero, the CO_2 concentration in the atmosphere will stop increasing as carbon sources from human activities are reduced to zero. **(C)** Over time, the CO_2 in the atmosphere will be absorbed by forests and other carbon sinks. This will decrease the amount of CO_2 in the atmosphere which, on its own, would cause cooling.

Restoring ecosystems and protecting forests and peatlands will help the land to continue absorbing carbon, removing more CO_2 from the atmosphere. But more frequent wildfires, and carbon lost from other parts of the land like thawing permafrost, could do the opposite [3]. Wildfires can turn a carbon sink into a carbon source—*adding* to the CO_2 in the atmosphere instead of removing it. Uncertainty about how the land will respond to a world with higher temperatures and changing rainfall patterns contributes to the uncertainty about how the Earth's overall temperature will change after net zero.

HEATING OR COOLING: WHICH WILL BE STRONGER?

So, overall, the slowdown of ocean heat uptake causes more heating, and the reduction of CO_2 in the atmosphere causes cooling! Which will win out (Figure 3)? To understand what happens to global warming after net zero, we need to know how strong and how fast each of these changes are.

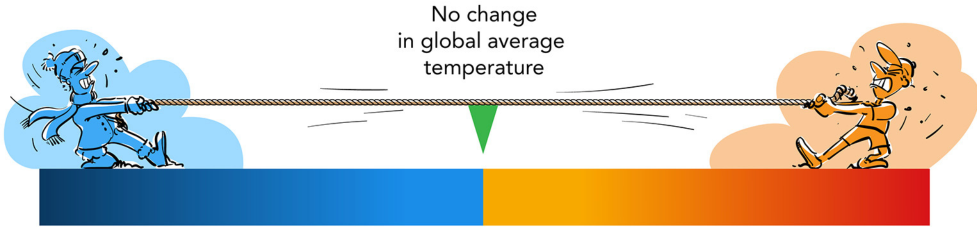

Figure 3

To determine the change in Earth's global temperature that will happen after net zero (the ZEC), we must understand whether cooling or warming will eventually "win out". The balance between decreasing ocean heat uptake, which could lead to more global warming, and decreasing concentrations of CO_2 in the atmosphere, which could lead to global cooling, will determine whether there will ultimately be more warming, some cooling, or no change in average global temperature.

At the moment, our best understanding is that these two processes happen at the same rate, pulling equally hard in opposite directions. The amount of warming from the slowdown of ocean heat uptake looks to be the same as the amount of cooling from decreasing amounts of CO_2 in the atmosphere. If the warming and cooling processes *do* end up canceling each other out after net zero, there will be no further temperature change once we stop emitting CO_2... but as you have probably gathered, all the processes involved make this prediction quite difficult, and scientists are still working to understand it fully.

Furthermore, the outcome of this tug-of-war between heat and carbon can change over time. The value of ZEC therefore also depends on *how long after net zero* we measure the change. We think some processes have an effect very soon after net zero, like the land response to a change in CO_2, whilst others, like melting ice sheets, will take a long time to adjust to the new balance in heat and carbon. This means that the change in global temperature 50 years after net zero could be quite different from the change in temperature 1,000 years after net zero. Fortunately, we know more about what would happen in the first 50 years compared to the first 1,000 years.

WHAT DOES ZEC MEAN FOR OUR FUTURE?

The most important message is that we should try to reach net zero CO_2 emissions as soon as possible. This will give us the best chance to stop global warming. If we can confidently predict that global warming will stop once we reach net zero, then a big piece of the climate change problem will be solved once net zero is achieved. However, if warming continues after we have reached net zero, we might have to figure out how to counteract it. For instance, scientists are working on ways to remove additional CO_2 from the atmosphere and store it forever in the ground, but it will take some time before this can be done safely and on a large scale. Carbon-removal solutions can have an impact in any warming scenario, but they may be needed sooner if we expect that warming will continue after net zero. If we succeed in this carbon removal, we could even gradually reverse global warming in the very far future.

It is also important to know that, even when global warming stops, parts of the planet will continue to change. For example, the ice near the North and the South Poles will continue to melt for many hundreds or even thousands of years. This melting ice adds water to the oceans, and this means that sea levels will continue to rise, even when global warming does not increase further. We will still need to address these problems, regardless of ZEC.

In summary, many scientists are trying to understand what will happen to global temperatures after net zero, so that we can make the best possible decisions about emissions today. These processes are complicated, but understanding how heat and carbon are moved around the Earth, and how these processes affect temperature, is key to effectively preparing for the future. Regardless of whether Earth's temperature will decrease, increase, or stay the same after we stop emitting CO_2, the most critical step is *reaching* net zero as soon as possible—so that we have the most time to prepare for future challenges and the best chance of protecting the Earth and all its inhabitants.

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ORIGINAL SOURCE ARTICLE

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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

ADDY, AGE: 14

I am in 8th grade and really enjoy volunteering at my local museum. I really like helping animals and I hope to become an environmental lawyer when I get older. My favorite class in school is my dance class (I am very flexible) and I love to travel.

TEDDY, AGE: 12

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.

YOUNG SCIENTIST ACADEMY, AGES: 8–15

The young reviewers are Arturo (13 years old), Juliet (13), Ava (11), Anastasiia (10), Zlata (11), William (11), Rokia (15), Haya (15), Fathieh (9), Abdulhadi (12), Glenda (10), Yaya (10), Angel (11), and Naomy (13). Young Scientist Academy (YSA) is a youth science NGO headquartered in North Carolina that empowers all youth to become community ambassadors in science and technology. We strive to help elementary to middle school aged youth address real world scientific issues that are relevant to their local and global communities. This in turn supports advancement of scientific knowledge among their peers, families, and larger networks. Our mission engages students' innate interest in the natural world, allowing them to explore and research science, technology, engineering, and math (STEM) topics. YSA uniquely uses science and technology as an avenue to break down social and economic barriers in order to create a bridge for youth around the world to become future leaders to serve their communities.

AUTHORS

SOFIA PALAZZO CORNER

Sofia Palazzo Corner is a Ph.D. student at Imperial College London, researching low probability, high-impact processes in the Earth's climate system—some of which could be relevant for ZEC. She is co-supervised by Professor Joeri Rogelj. Sofia has an undergraduate degree in physics and a master's degree in applied mathematics.
*s.palazzo-corner19@imperial.ac.uk

JOERI ROGELJ

Joeri Rogelj is a professor of climate science and policy at Imperial College London. He explores how societies can become more sustainable and can tackle climate change. He has written articles on 1.5°C pathways, carbon budgets, net zero targets, and climate agreements such as the Paris Agreement. He regularly serves as an author on reports of the United Nations and advises the European Union on climate science issues.