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Out of the ordinary

Understanding future climate change by studying natural climate cycles

Eelco Rohling

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Out of the ordinary

Understanding future climate change by studying natural climate cycles

Eelco Rohling
Professor of Ocean and Climate change

Inaugural address as Professor at the Faculty of Geosciences
of Utrecht University, February 20, 2025

Mijnheer de Rector Magnificus

Welcome everybody and thanks for being here today.

The topic today is climate change. Allow me to present the problem (Figure 1). In the animation, you see temperature changes from 1880 to 2024. You can clearly see that in the past, places of cooling existed alongside places of warming, whereas the pattern in recent decades shows remarkable warming almost everywhere. In B and C we see the global mean changes over the last 2000 years, and 11,000 years. The exceptional rapidity of modern changes is evident.

Past, natural, climate cycles over even longer timescales (Figure 2) give direct evidence from past (natural) warm periods with high greenhouse gas

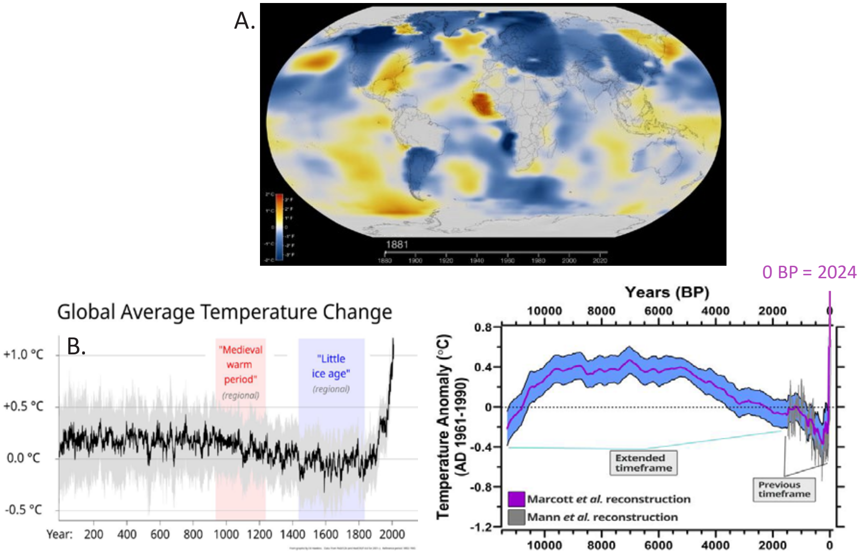


Figure 1. Our problem: Global Temperature Change.
A. NASA Goddard Institute of Space Sciences (https://svs.gsfc.nasa.gov /5450/). B. Ed Hawkins, UK National Centre for Atmospheric Science. C. Shaun Marcott, Oregon State.

levels. This helps us to better understand the long-term future of human-caused climate change. In the upper panel, we see that it has often been much warmer than today. And in the bottom panel, we see that CO_2 levels were up to 4 times higher than today. The yellow arrows indicate that we have to go back more than 3 million years to get to times when CO_2 and temperature levels exceeded those of today. Clearly, high greenhouse gas levels and globally warm conditions are nothing new to the planet. That is not what worries climate scientists.

What we worry about is the exceptional rapidity of change, and its impact on society (with its massive infrastructure and resource dependence) and on biodiversity (given that complex flora and fauna cannot evolve fast enough to adjust). Humanity is driving changes in a few centuries that naturally took many thousands to millions of years. Here, you can see this exceptional rapidity again, this time by comparison with CO_2 data of the past 800,000 years from fossil air bubbles in ice cores (Figure 3). The rapid modern rise overwhelms all natural mechanisms to remove CO_2, which take

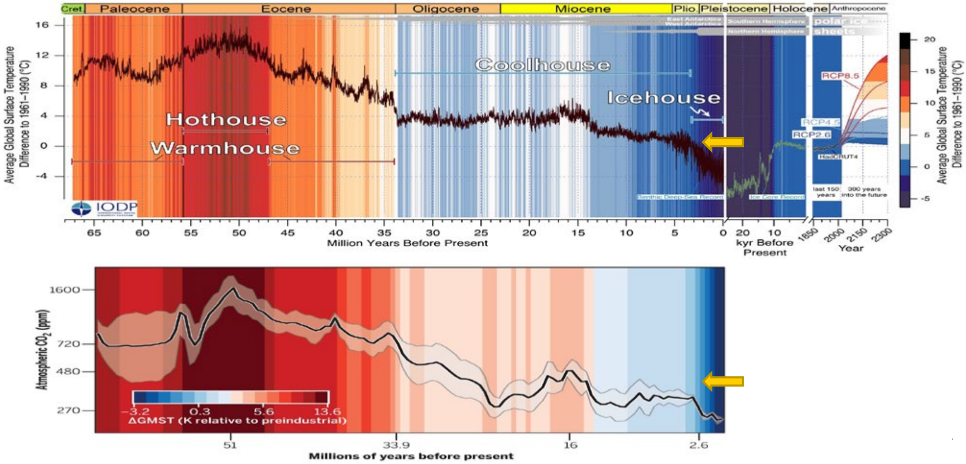


Figure 2. A 66 million-year perspective since the dinosaur extinction.
Upper: Thomas Westerhold, CENOGRID project. Lower: Hönish et al., 2023 Science.

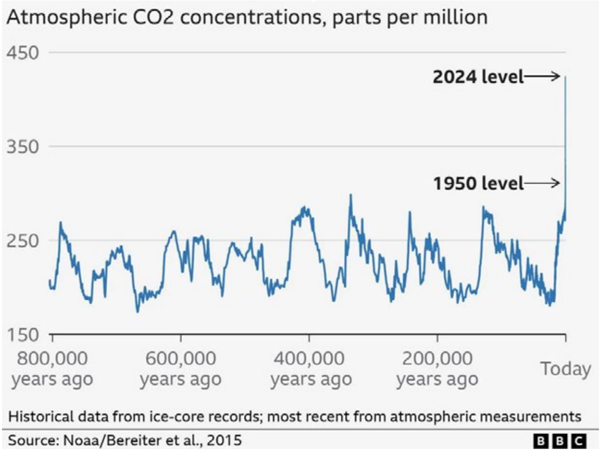


Figure 3. Carbon dioxide levels are higher than any time in the last 800,000 years.

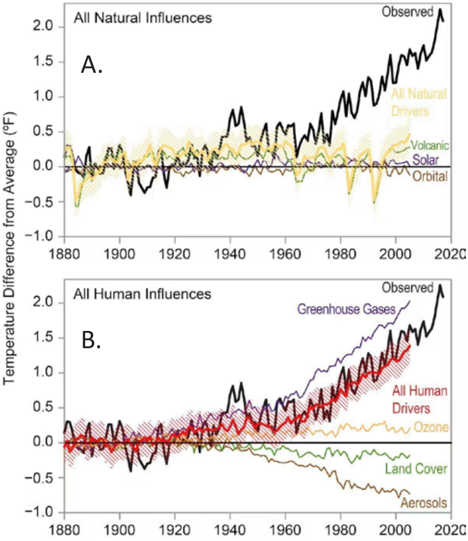
tens of thousands to millions of years. Therefore, if we let climate change happen, then we're stuck with it for a very, very long time.

Today, I will take you through some lessons we have learned from studying past natural climate changes, and what these mean for the future. And because I don't want to leave you feeling all depressed this evening, I conclude with an overview of possible solutions.

What is driving the change?

It is well understood that modern climate change is predominantly caused by human actions, and especially by greenhouse gas emissions (Figure 4). In black, we see the observed temperature changes in both panels. In the top panel I compare these with natural climate drivers, and in the bottom panel with human-caused climate drivers. Clearly, greenhouse gases are the dominant influence, and then especially CO_2. Incidentally, the greenhouse effect of CO_2 and other gases is not 'just a theory.' It was experimentally demonstrated already in the 1850s, by Eunice Foote and by John Tyndall.

Human and natural influences on global temperature



1°F change = 0.55°C change

Figure 4. What drives modern climate change?
A. Observed temperature change (black) and contributions by natural processes.
B. Observed temperature change (black) and contributions by human-driven processes.
Source: 4th US National Climate Assessment, 2018.

Let's start with some fundamentals. (Figure 5). Temperature in the climate system responds to the net balance between energy inflow and outflow. A net inflow raises temperature, and a net outflow reduces it. The main factors in this energy balance are:

a. The amount of solar radiation toward Earth, the Incoming Short-Wave Radiation.
b. The proportion of direct reflection of incoming solar radiation back into space.
c. The amount of Outgoing Long Wave Radiation (heat) that is retained by the atmosphere as Earth tries to cool.

Heat flux from the inside of Earth, for example from volcanoes, is negligible in comparison.

Incoming Short Wave Radiation
(ISWR, sunlight),

and

Outgoing Long Wave Radiation
(OLWR, thermal infrared 'cooling')

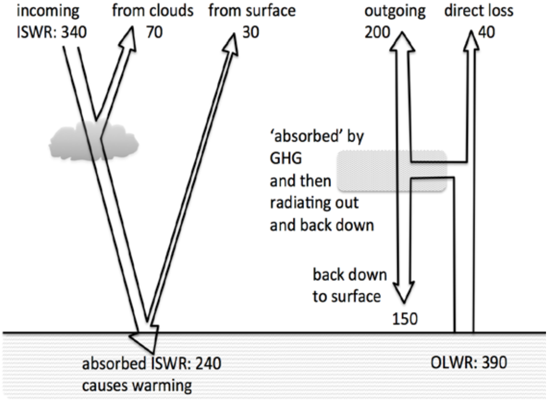


Figure 5. Energy balance of climate.
Source: Rohling, General public book "The Climate Question",
Oxford University Press, 2019.

A global average of 340 Watts per square metre of solar radiation reaches the top of the atmosphere each year. Earth's orbital variations cause fluctuations of less than half Watt per square metre over timescales of 100,000 years. And solar intensity itself fluctuates by +/- half a Watt per square metre over centuries to thousands of years.

About 30% of the incoming radiation is reflected straight back into space. This proportion fluctuates by a few percent because of variations in cloud cover and in Earth surface cover (such as ice and snow, or vegetation changes). These cause variations of about 3 Watts per square metre through time.

The net incoming solar radiation would keep Earth's surface temperature at about negative 18°C, if there was no atmosphere. But the actual value is close to positive 15°C. To understand this, we need to look at what the atmosphere does with outgoing radiation, the cooling of Earth to space. Some 40% of the surface heat loss does not make it out through the atmosphere. Instead, it is absorbed by water vapour and greenhouse gases, and re-radiated. This concentrates heat in the lower atmosphere; an effect known as the greenhouse effect. It has caused variations of typically 3 to 5 Watts per square metre through time.

Earth's climate responds to any energy imbalance through a complex of feedback processes that affect both reflection and the greenhouse effect (Figure 6). Some are very rapid, while others take millions of years. To get a full view of these, we need to consider both the modern case, and climate cycles in the geological past – before humans became important. Before humans, past natural climate cycles resulted from small and slow changes in radiative forcing, and large but slow subsequent feedback responses.

The temperature response to ***net*** radiative changes is known as climate sensitivity. When comparing climate sensitivity between modern and geological climate changes, it is important to realise that estimates from geological studies include slow feedbacks, which are less relevant to climate projections for the next century or two. So, we need to correct for these slow feedbacks.

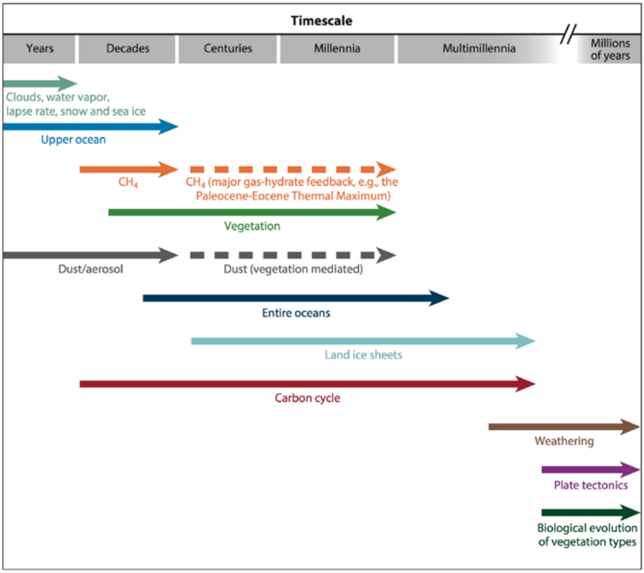


Figure 6. Schematic of the main feedbacks and their timescales. Source: Rohling et al., 2018 Annual Reviews of Marine Science.

It turns out that, at a minimum, we need information about:

1. global temperature changes;
2. greenhouse gas changes; and
3. global ice-volume changes.

Let’s look at some findings

Global temperature changes are tracked by means of deep-sea temperature studies that use deep-sea sediment cores, global surface temperature studies that use marine and land-based records, and polar temperature reconstructions based on ice cores.

Greenhouse gas variations are tracked using measurements on fossil air bubbles in polar ice cores, and using indirect geochemical measurements on samples from sediment cores. Natural greenhouse gas variations happen because of biological and chemical feedbacks to relatively small initial climate changes. In addition, anomalous warmings happen due to exceptional greenhouse gas emission events such as major volcanic episodes and methane releases, or – indeed – the modern human-driven changes.

Continental ice-volume variations completely dominate sea level on timescales of more than a century. We have methods to directly resolve global ice volume, and to do it indirectly using sea-level changes. Over the last 60 million years (Figure 7), sea level approximately fluctuated as shown in the upper panel. A first indication of deep-sea temperature variations is shown in the lower panel. During the last one million years, sea level varied between 130 m below present during peak ice age conditions, and up to 10 m higher than today during the intervening warm periods. And, as we saw before, temperatures further back in time have been much higher than today. As we also saw before, records of greenhouse gas concentrations are not yet as finely resolved in time, with exception of the last one million years.

When we combine such data, we get some really intriguing and useful information. Here, I plot sea-level probability for different CO_2 levels (Figure 8). CO_2 levels are given in the horizontal, and sea level relative to

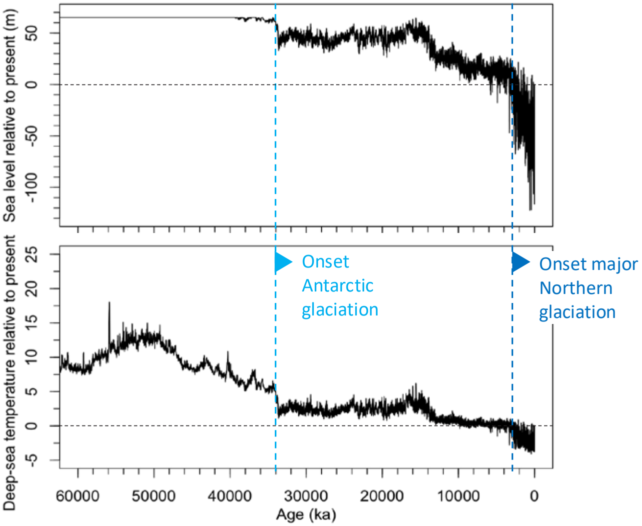
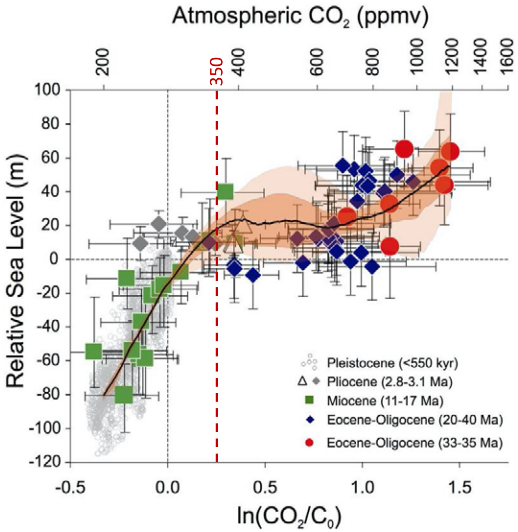


Figure 7. 60 million years of sea-level and deep-sea temperature changes. Source: Rohling et al., 2022 Reviews of Geophysics.

the present is given in the vertical. The dark and light orange indicate the zones containing past sea level at 68% and 95% probability. The different coloured dots are reconstructions for different intervals of time. The dashed lines indicate pre-industrial conditions with CO_2 at 275 parts per million and relative sea level at 0 m.

Today, the atmospheric CO_2 level is close to 425 parts per million. Equilibrium (natural) sea level for such a CO_2 level stood a massive 9 to 31 m higher than today at 68% probability. Note that all this is based on real-world observations, not 'just models' as we sometimes hear from climate denialists. We are constantly refining the relationship using new CO_2 and sea-level records. The new picture is more subtle, but the main message remains the same:

> *"If we keep atmospheric CO_2 at modern levels (or higher) long enough to allow the slow climate feedbacks to play out, then we may expect sea level to rise by tens of metres above the present.*



Dark orange: 68% probability interval
Light orange: 95% probability interval
Coloured symbols: different periods of time

Figure 8. Equilibrium sea-level change for past CO_2 levels.
Source: Foster and Rohling, 2013 PNAS. Rohling et al., 2013 Scientific Reports.

> *Admittedly, this would take many centuries, but similar studies that focus on rates of change indicate that there will be jumps of 1 to 2 metres per century. Even one such jump could wipe out entire nations – including most of the Netherlands – and destroy the global economy."*

Sea-level jumps relate to partial collapses in the continental ice sheets[1]. Ice sheets have a lot of inertia. This means that they respond slowly to a forcing increase, and also to a forcing reduction. As a result, we can only avoid major sea-level rise if we take immediate action. Today, our fossil fuel addiction keeps CO_2 rising rapidly; in 2023 the annual increase was even greater than ever before, at 3.6 part per million! Our action needs

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[1] We don't know when to expect such a collapse. But alarmingly, ice loss has been accelerating rapidly, as seen with satellites since the late 1970s, especially in West Antarctica and Greenland (https://climate.copernicus.eu/climate-indicators/ice-sheets).

to both stop this increase, and remove vast amounts of CO_2, reducing atmospheric levels to less than 350 parts per million.

Now to the issue of climate sensitivity.

How much warming occurs for a given increase in greenhouse gas concentrations? In 2012 we undertook a major international review to evaluate existing evidence (Figure 9). We considered the radiative effects of greenhouse gases, land ice, aerosols, and vegetation (left panel). We found that only greenhouse gases and land ice were sufficiently resolved in geological records, and that ignoring the other effects causes underestimation of climate sensitivity by up to 15% (Rohling et al., 2018 Ann. Rev. Mar. Sci.). This exercise found an average global temperature

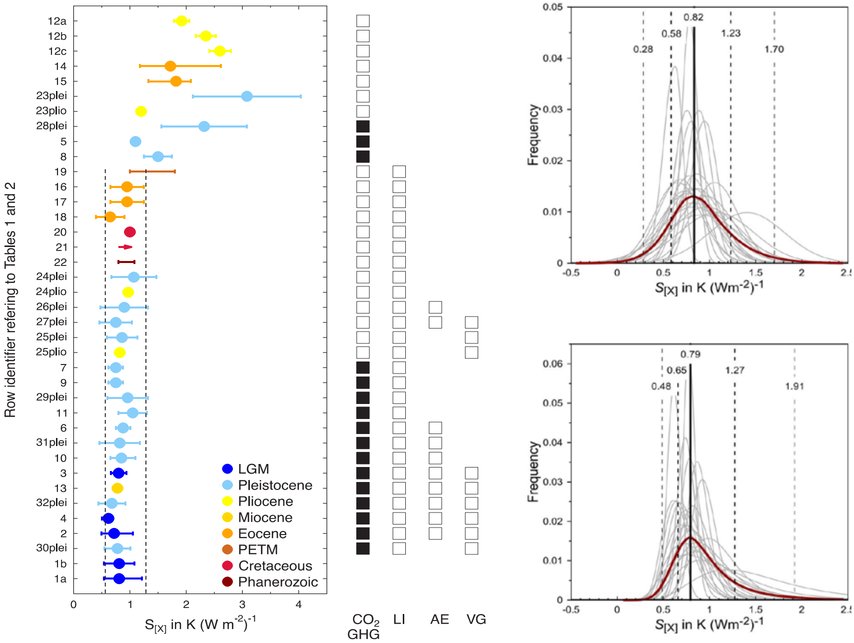


Figure 9. Climate sensitivity analysis through geological time.
Source: PALAEOSENS, 2012. Nature.

Analysis includes:
- modern data,
- geological data,
- climate model results,
- physical first principles.

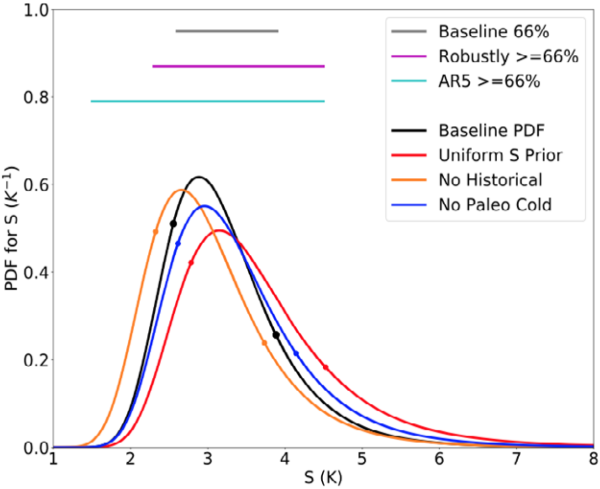


Figure 10. Climate sensitivity synthesis across multiple lines of evidence.
Source: Sherwood et al., 2020 Reviews of Geophysics.

sensitivity of 2.4 to 5.2°C for each doubling of CO_2 levels, over the last 50 million years or so.

Each CO_2 doubling is equivalent to about 4 Watts per square metre of net gain in the Earth's energy balance.

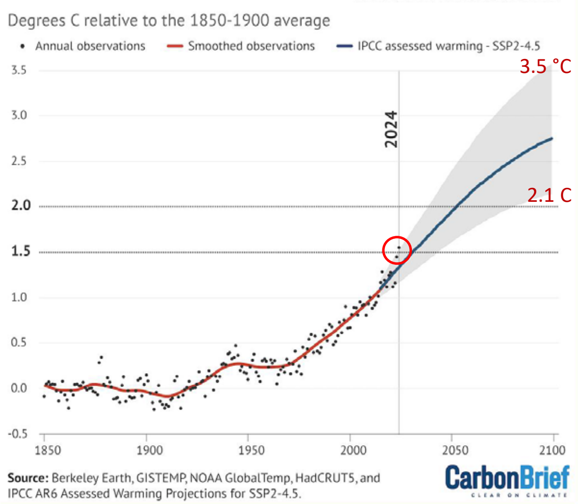
Then, in 2020, we performed a major review across all lines of evidence, including geological estimates, modern estimates, climate model estimates, and physical first principles (Figure 10). We found 2.3 to 4.5°C for each doubling of CO_2 levels. This range, therefore, is very similar across different methods. Other studies have found largely similar values again.

So, 2.3 to 4.5°C for each CO_2 doubling ... Let's think about what that means. Humanity's net impacts on climate in 2022 already added up to 3 Watts per square metre of extra radiative forcing (https://essd.copernicus.org/articles/15/2295/2023/#&gid=1&pid=1). That's equivalent to every person on Earth running 130 big patio heaters (1500W) running full blast every day and night of the year.

And reasonably optimistic scenarios until 2100 that assume major climate intervention still see us reach a level of heating of more than 4 Watts per square metre by 2100. That's equivalent to every person on Earth running 170 big patio heaters. But no serious climate interventions have even started yet. Based on current behaviour, we're actually heading closer to a radiative increase of 8 Watts per square metre in 2100 ...

If we do manage to limit it to 4 Watts per square metre, then our climate sensitivity estimates from geological data indicate an equilibrium warming between 2.3 and 4.5°C. Examples of the trajectory to that equilibrium value can be obtained from climate models (Figure 11). What we see here in grey is an uncertainty envelope for intermediate emission scenarios, which reaches 2.1 to 3.5°C in 2100. The red circle shows how our actual impacts are tracking at or above the upper end of the grey band, and that on an annual basis, warming already exceeded 1.5°C in 2024.

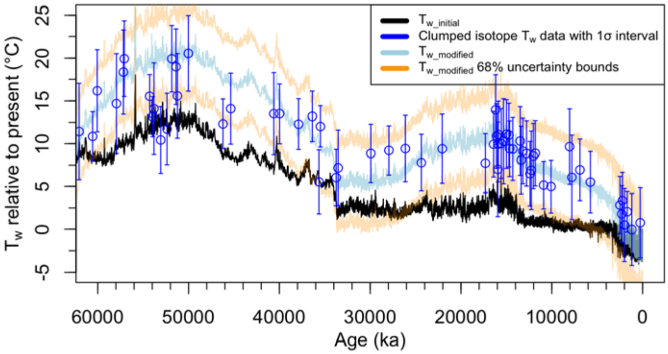
It gets worse when we consider the longer-term future. I here summarise new geological evidence from global research efforts, which indicates that



Source: Berkeley Earth, GISTEMP, NOAA GlobalTemp, HadCRUT5, and IPCC AR6 Assessed Warming Projections for SSP2-4.5.

Grey:	Range of intermediate emissions scenario projections
Dots:	Observed annual warming
Red line:	Smoothed observations
Circle:	2023 and 2024

Figure 11. Forward projection based on climate models.



Black: traditional view

Blue dots: new data

Light blue: modified record according to blue dots

Figure 12. Revised understanding of deep-sea temperature variations. Source: Rohlinget al., 2024 Paleoceanography and Paleoclimatology.

we have systematically underestimated past temperature changes (Figure 12). Long-term temperature changes over millennia appear to have been double what we had thought.

It seems that, once all slow feedbacks have equilibrated over many centuries to millennia, we are likely to experience double the temperature response that we just discussed for the next century or two. So, where we should expect 2.3 to 4.5°C rise on a centennial timescale, this increases to 4.5 to 9°C on a millennial scale. If anything, this is a major indication that our actions today will lock us in to ever increasing warming over many centuries into the future. We are today causing climate forcing that increases extremely rapidly, and the Earth system is slow to respond (which is why natural – feedback dominated – climate changes were so much slower). But what we now see is that, once the Earth system does respond, it will be almost unstoppable because it is for a large part responding to something that we have done already until today.

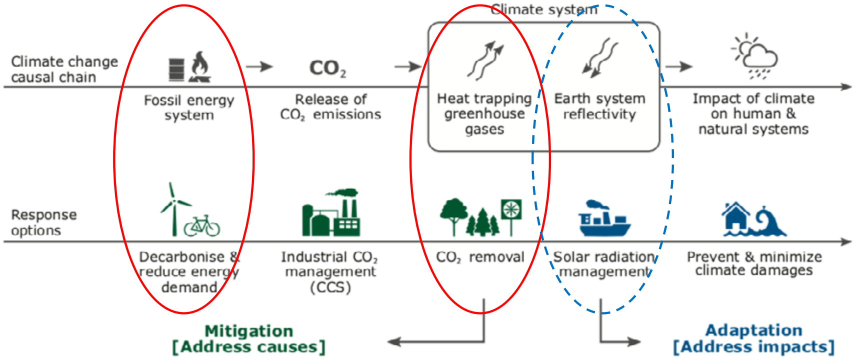
To make matters worse, the Earth system will similarly respond very slowly to any CO_2 reductions we might make in the future. As a consequence, it is essential that we stop the CO_2 rise right now and bring the levels back down. Only that can minimise the abrupt ‘shock’ to which the Earth system will slowly respond.

What can we do?

There are two ways of reducing, and reversing, the net energy gain of the planet (Figure 13). First, to reduce the man-made greenhouse gas levels in the atmosphere. Here, we find the Net Zero emissions and CO_2 or Carbon Removal concepts. Second, we can try to reduce the amount of sunlight that is absorbed at the Earth surface. Here we see, for example, marine cloud brightening, stratospheric aerosol injection, and polar refreezing concepts, but also ideas of mirrors in space.

How do these approaches fit together? (Figure 14).

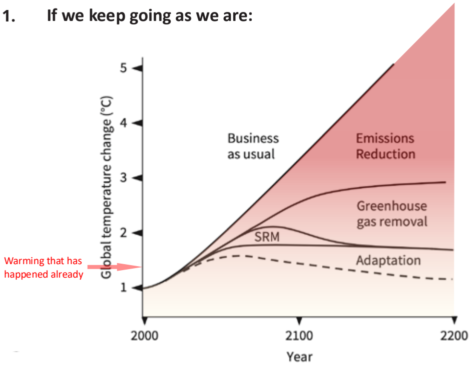
- If we keep going as we are, dangerous levels of warming will soon be reached.
- Emissions reduction is like patching up the hole in a leaking boat. Massive emissions reduction will stop matters from rapidly getting worse and worse.
- Greenhouse gas removal is like bailing water from a leaking boat. It is needed to ensure that we reach our target climate level.



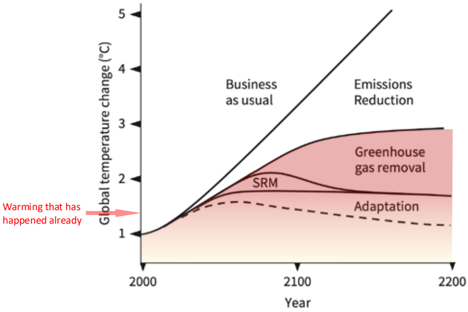
Red: greenhouse gas influences, Blue dashed: reflection influences

Figure 13. Climate change causes and response options.
Source: Minx et al., 2018 Environmental Research Letters.

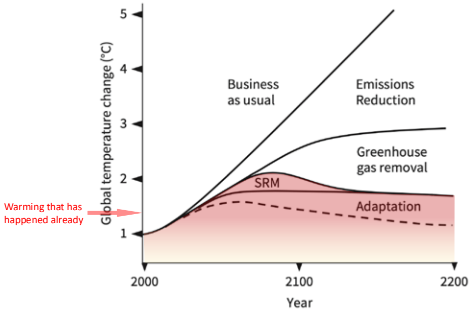
1. If we keep going as we are:



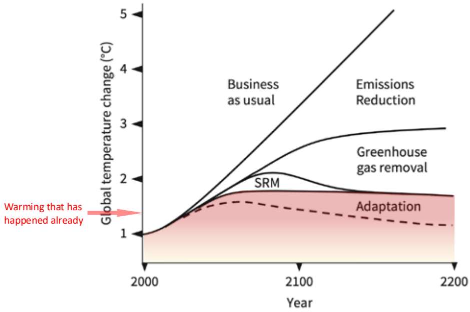
2. With massive global emissions reduction:



3. With massive global emissions reduction + Greenhouse gas removal



4. Adding some Solar Radiation Management (SRM) to avoid a temperature overshoot



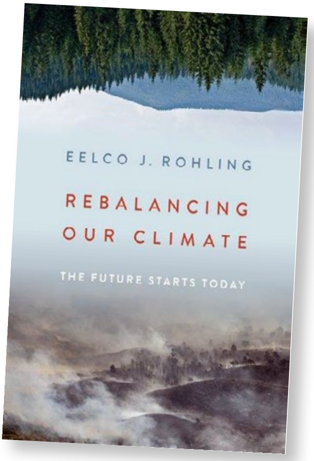
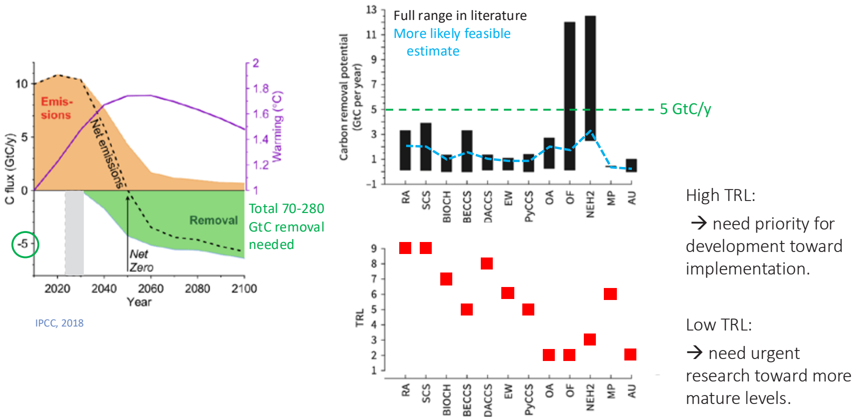


Figure 14. Different approaches.

Source: Rohling, 2021. General public book at Oxford University Press.

What is needed for Net Zero.

Many options, but Technological Readiness Levels (TRLs) are low, and capacities seem overly optimistic.



Total 70-280 GtC removal needed

IPCC, 2018

High TRL:
→ need priority for development toward implementation.

Low TRL:
→ need urgent research toward more mature levels.

Figure 15. What is needed for Net Zero.

Source: IPCC, 2018 (left). Rohling, 2021. Rebalancing our climate. Oxford University Press (right).

- Solar Radiation Management may be needed for a while to avoid a temperature overshoot before we settle to the target value[2].
- Any warming that is not addressed will need to be adapted to.

With respect to greenhouse gases, it is clear that reaching Global Net Zero Emissions is needed before 2050 (Figure 15). For this, we need two things:

1. Realistic emissions *de*crease of the order of 2 to 4% every year.
2. Major removal of carbon from the climate system, which across emissions scenarios amounts to 70 to 280 billion tons by 2100.

As we speak, however, emissions are not *de*creasing at all, but instead continue to *in*crease by some 3% every year. As a result, the amount of CO_2 in the climate system continues to rise faster than ever, so that carbon removal requirements become greater by the day.

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[2] Ironically, sulphate reduction in heavy marine fuels is driving the opposite: a reflectivity *decrease*. While good for health, this is bad for the climate.

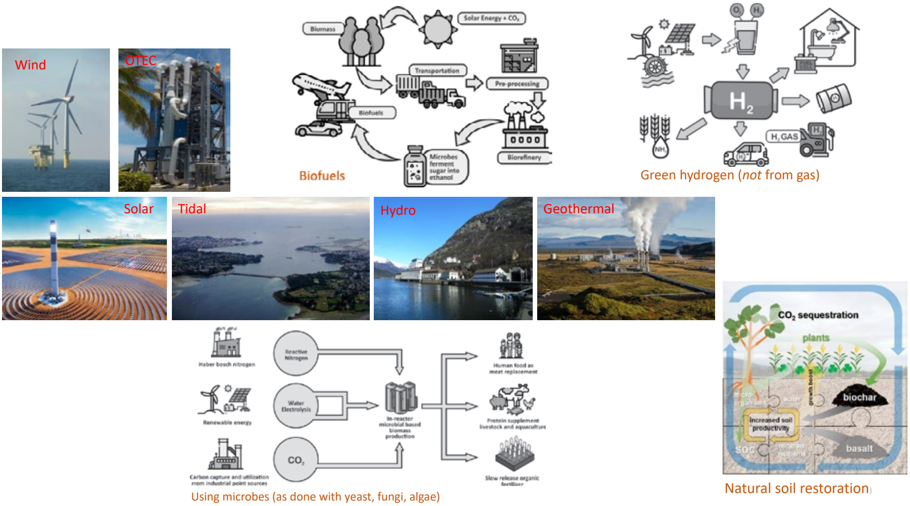

Figure 16. Emissions reduction.

Source: Rohling, 2021. Rebalancing our climate. Oxford University Press.

Many politicians are counting on some 'superhero technology' for carbon removal to come and save the day. But in reality, the removal methods are only in their infancy. In fact, most remain poorly understood in terms of their potential, drawbacks, and financial and social costs[3]. Despite optimistic capacity estimates, absolutely none of the methods is anywhere near implementation at the sort of carbon removal scales needed[4].
But we have some obvious ways to start.

Large-scale reforestation and forest protection could capture up to 70 *billion* tons of carbon (Mo et al., 2023 Nature). Early adoption of such a

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[3] The level of development is expressed with the Technological Readiness Level or TRL. TRL=1 means that the method has only been suggested, and TRL=9 means that it's ready for large-scale implementation tests.

[4] The largest technological application planned for 2025 is expected to reach just 150 thousand tons of carbon per year (4 to 5 times more than the currently biggest installation) … We need some 35 THOUSAND times that annual capacity!

Landscape regeneration

Before

After

Biochar and PyCCS

Marine solutions

Figure 17. Greenhouse gas removal.
Source: Rohling, 2021. Rebalancing our climate. Oxford University Press.

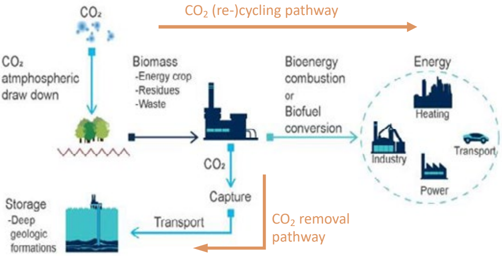
major-capacity approach is essential to reaching the overall target. Of course, we would first need to stop global deforestation, which in 2023 alone caused emissions of just under 1 billion tons of carbon (https://research.wri.org/gfr/latest-analysis-deforestation-trends).

Let's briefly look at some examples of technologies to help address the climate problem.

In Emissions reduction (Figure 16), we see the more familiar ones. They include:

- a transition to renewable energy, and
- biofuel and hydrogen developments, but also
- the use of microbe protein in food production, and
- soil health improvement.

Greenhouse gas removal (Figure 17) can exploit natural pathways that are artificially intensified and accelerated.



BECCS

DACCS

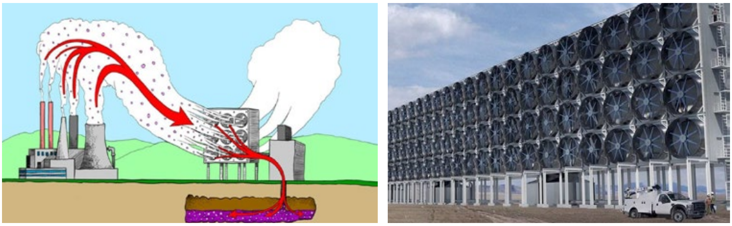


Figure 18. Greenhouse gas removal.
Source: Rohling, 2021. Rebalancing our climate. Oxford University Press.

Sulphate aerosols
(inspired by Pinatubo cooling effect)

Marine cloud brightening
(inspired by ship-exhaust effects)

Surface reflection (inspired by Mediterranean villages)

Figure 19. Solar radiation management.
Source: Rohling, 2021. Rebalancing our climate. Oxford University Press.

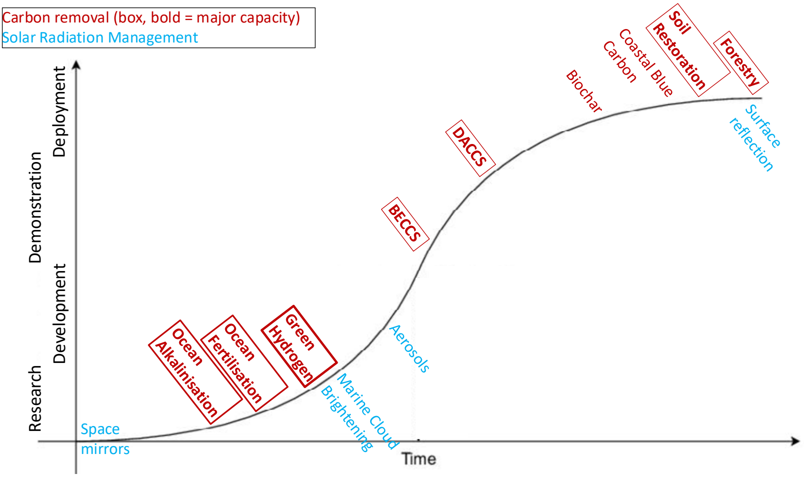


Figure 20. Carbon removal.

Or it can follow more technological routes (Figure 18).

Meanwhile, Solar Radiation Management also includes an array of concepts (Figure 19), all of which have problems and potentials that need to be carefully balanced.

The way forward

This is a personal summary of development of the various methods (Figure 20). The task ahead is so large that we need to develop all feasible approaches, including new inventions. We will need a broad portfolio.

Note that many of these approaches will reduce pollution and improve public health. And there is an economic upside. Given that the new technologies will be needed for a long time and at great capacities, they represent major business opportunities – just think back to about what happened once solar-voltaic and wind-energy technology reached maturity.

Figure 21. The alternative is …

Unfortunately, the current wave of anti-science and anti-education sentiments causes us to seriously fall behind in these global mega-business opportunities. Ironically, the anti-science sentiments are fuelled by the same politicians who continuously claim that innovation will solve all problems. Maybe they could specify which innovations they mean, and where these innovations are supposed to come from …? Some like to point at the commercial sector. Yet, universities and government institutes remain critical to the fundamental ad technical research and engineering at the low Technological Readiness Levels where most of these opportunities still sit (because of high costs and major risks of failure). And such institutes are almost the only route for environmental and social impact research. The commercial sector will be vital for getting developments through the higher Technological Readiness Levels.

Summary

It is unquestionable that we risk everything if we allow climate change to continue unchecked (Figure 21).

For the necessary level of innovation to combat climate change, and to sustain that over the next century, we need exactly the opposite of deep cutbacks in education and research. More broadly, it’s safe to say that – if we continue to flip back and forth every election cycle between opposing policies, regulations, and funding structures – we will never get there. We need a stable, action-oriented approach, and we need it immediately. If not, then we really will end up with the alternatives ...

Only real action on a global scale can limit these disasters. So: Let’s be modern, forward-looking, and civilised again and learn, invent, develop, and *solve* problems ... together ... across the world.

Thank you
Ik heb gezegd.

www.uu.nl/medewerkers/EJRohling

Eelco Rohling's research focuses on ocean and climate change over geological to modern timescales. He obtained his PhD in 1991 from Utrecht University, followed by a Postdoctoral Fellowship between Utrecht University and the Woods Hole Oceanographic Institution (USA). Next, he worked from July 1994 to January 2013 at the University of Southampton (UK), where he remains affiliated, and from February 2013 to October 2023 at the Australian National University in Canberra. On 15 April 2024, he started a professorship at Utrecht University.
Eelco was installed in 2008 as Correspondent of the Royal Netherlands Academy of Arts and Science, and in 2017 as Fellow of the American Geophysical Union. He is a Web of Knowledge Highly Cited Researcher (2019) and received a UK Royal Society Wolfson Research Merit Award in 2010, an Australian Laureate Fellowship in 2012, and the AGU & US Navy Maurice Ewing Medal in 2019.
Eelco has published more than 240 peer-reviewed journal articles and three public-oriented science books: *The oceans – a deep history* (2017 Princeton University Press), and *The climate question – natural cycles, human impacts, future outlook* (2019 Oxford University Press), and *Rebalancing our climate – the future starts today* (2021 Oxford University Press). He has served 4 years as joint Chief Editor of *Paleoceanography*, 10 years as Editor of *Reviews of Geophysics*, and since 2020 is the founding Chief Editor of *Oxford Open Climate Change*. In 2024, Eelco became a Board of Advisors member, Climate Protection and Restoration Initiative, Oregon, USA.