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# Is the Climate Changing Faster than Expected?

Trends in global surface temperatures are close to longstanding predictions, despite the unusually high global temperatures of 2023/2024.

A more reliable indicator of lasting change is the rate at which energy is accumulating in the global system, which has accelerated over the last two decades.

There are aspects of the climate system where changes seem to be accelerating, including short duration rainfall intensification, sea ice loss around Antarctica and increasing heatwaves on land and in our oceans.

The impacts of global warming are increasing; to reduce them we require a deep and rapid cut in greenhouse gas emissions.

The media coverage of weather-related disasters around the world over the last few years has been confronting and has led to commentary suggesting that our climate is either changing more than expected or changing faster than expected. In particular, a remarkable spike in global surface temperature and a prevalence of concerning heat events are leading to a suite of questions such as "is this a tipping point" or "is climate change much worse than the scientists predicted". We explore these questions here.

## Causes of global climate change

Human-caused climate change is driven primarily by increases in greenhouse gases in the atmosphere (Figure 1) that cause additional heat to be trapped in the Earth's climate system. This additional heat in our atmosphere and ocean is rapidly growing as there has been a marked acceleration in the Earth's energy imbalance. It has doubled during the first twenty years of this century[1,2]. While some acceleration in net heating is expected due to rising greenhouse gas levels (Figure 1), the observed acceleration is much greater than expected, although we don't know whether it will continue or is a temporary surge.

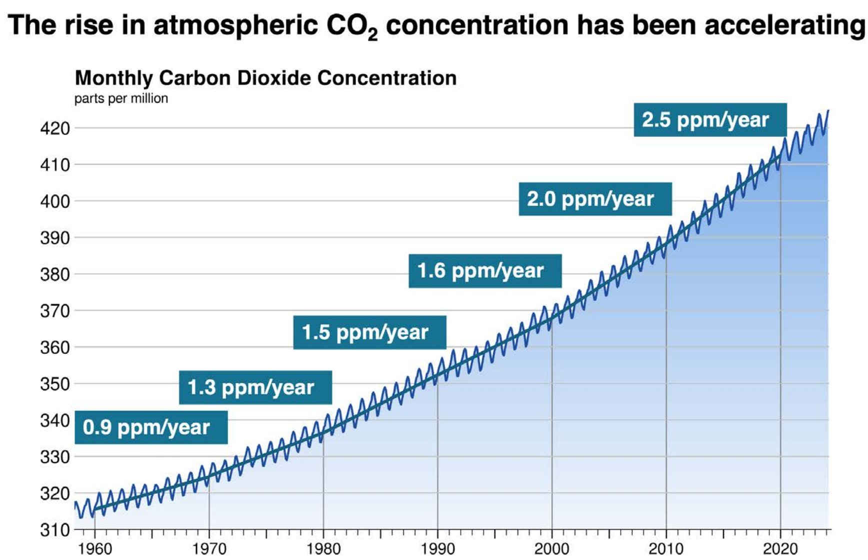



Figure 1: Atmospheric carbon dioxide concentration measured at Mauna Loa, showing the accelerating rate of rise for each decade since 1960. Source: Figure adapted by Nerilie Abram from Scripps $CO_2$ program: https://scrippsco2.ucsd.edu/graphics_gallery/mauna_loa_record/mauna_loa_record_color.html

There are implications for surface warming, which is likely to show signs of acceleration, although an acceleration is hard to see due to large year-to-year variability. In particular, the recent spike in surface air temperature in 2023-24 may partly reflect a "catching up" after being suppressed by a La-Niña-like ocean state during the previous years.

## Are global temperatures increasing beyond what is expected?

Global surface air temperatures (Figure 2) have been extraordinarily high since June 2023. However, the fact that the Earth is hot is not unexpected. Given the ongoing increases in atmospheric greenhouse gases and increases in the amount of energy trapped in the atmosphere and ocean, this is as anticipated. A full 12 months with temperatures in excess of 1.5°C above pre-industrial averages was not expected[3] and has shocked many in the science and broader community.

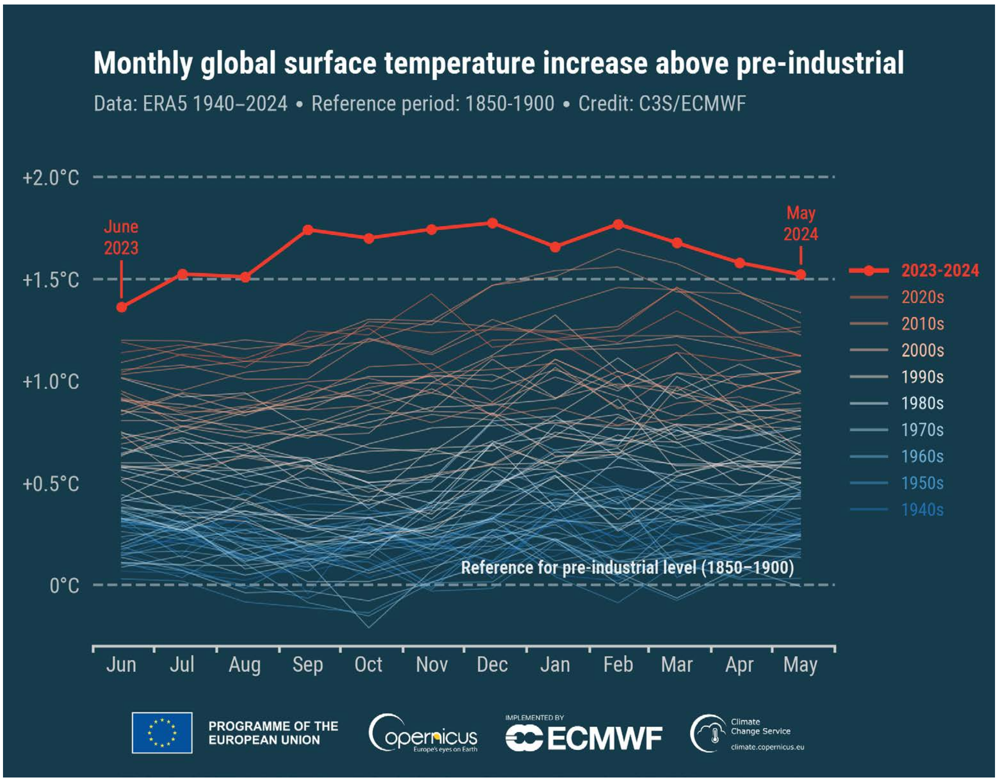



Figure 2: Reanalysis based monthly global surface air temperature anomalies (°C) relative to 1850–1900 from January 1940 to May 2024, plotted for all 12-month periods spanning June to May of the following year. Source: https://climate.copernicus.eu/surface-air-temperature-may-2024

While it is clear that the increasingly high temperatures and ongoing warming are caused primarily by the increase in greenhouse gases, there are no agreed explanations for the extremely large magnitude of increased surface temperatures of 2023/2024. However, possibilities include:

- Additional warming was caused by the 2023-2024 El Niño event, and reflected a "catching up" of global warming after being suppressed by three consecutive La Niña events in the preceding years. Very recent evidence suggests this is likely the most plausible explanation[4].
- Impacts of the Hunga Tonga-Hunga Ha'apai volcanic eruption which added a large amount of water vapour to the stratosphere (rather than the usual sulphur-rich emissions from volcanic eruptions that typically cause climate cooling). Research to date has not converged on whether the Tongan eruption caused warming or cooling[5].
- Changes in marine shipping emissions[6] which have reduced atmospheric sulphate levels and most likely caused a small warming (around a tenth of a degree).
- Impacts of other aerosols, particularly a reduction in Chinese aerosols, may have contributed to a small amount of warming.
- Increased radiation from the Sun as it reaches a maximum of the 11-year solar cycle, predicted to be between late 2024 and early 2026[7].

The temperature spike is most likely a result of a combination of factors, in addition to the warming caused by greenhouse gases. It remains to be determined how these, or other factors combined to explain why 2023-2024 was so hot. However, it would not be possible to explain the unprecedented heat without first looking at the largest contributor, the highest atmospheric $CO_2$ concentrations observed in the historical record.

## Is anthropogenic warming accelerating?

This can be examined by considering the average surface temperature or the total heat content of the climate system.

To determine whether there is an acceleration in warming requires the removal of the impacts of variability linked with El Niño and other short-term factors. To date, research continues, and it remains unclear[8] whether the substantial surface warming signal is accelerating as distinct from increasing.

What is clear is that further warming will continue until the world achieves net-zero $CO_2$ emissions. Avoiding future warming of global mean surface temperature will depend on achieving dramatic reductions in emissions. Global emissions of carbon dioxide are not currently falling and Figure 3 highlights that 2023 likely showed a further increase in global $CO_2$ emissions from fossil fuel sources.

The world may be approaching peak emissions; while this means that human contributions to climate change each year are still the highest that they have ever been, there is hope that annual emissions may soon start to decrease.

There is a near linear relationship between cumulative carbon dioxide emissions and global temperature[9], meaning that all future emissions of $CO_2$ will add to worsening global warming. It is no longer realistically possible to limit warming to 1.5°C – the remaining carbon budget for that will be exhausted in just a few years. Stabilising the climate at well below 2°C of global warming will require dramatic year-on-year cuts in emissions that allow net zero emissions to be achieved within an increasingly small remaining carbon budget.

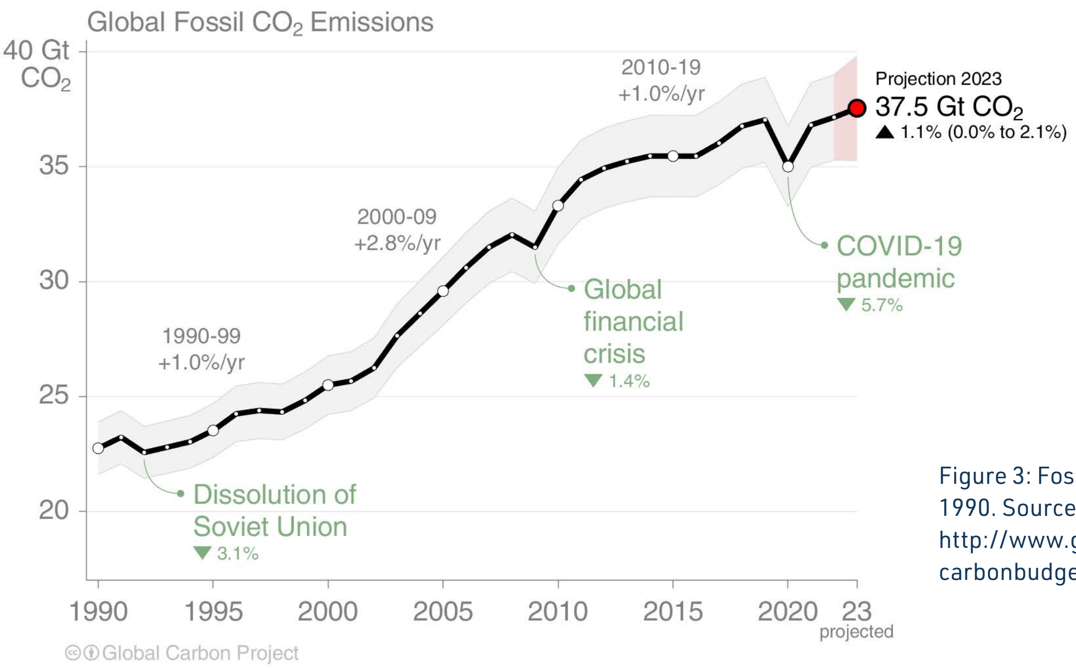
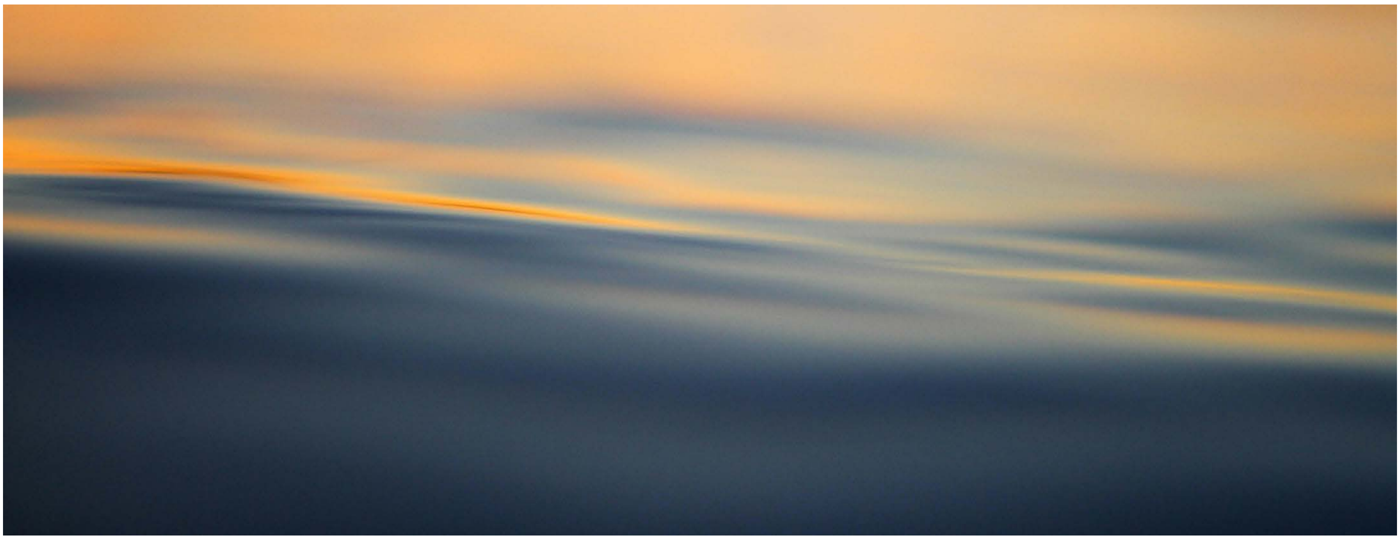



Figure 3: Fossil $CO_2$ emissions since 1990. Source: The Global Carbon Project, http://www.globalcarbonproject.org/carbonbudget



# Regional climate changes (Australia and its domains)

## Antarctic sea ice

Rapid changes are beginning to emerge in Antarctica. 2023 was particularly notable for the exceptionally low sea ice conditions. In winter of 2023 (Figure 4) an area greater than the size of Western Australia was missing from the normal Antarctic sea ice, which was well beyond anything expected by natural variability. These exceptionally low sea ice conditions have continued to be sustained throughout 2024, as outlined in various Australia-led studies[10,11] which indicates that a regime shift may have occurred in Antarctica's sea ice state[12].

Antarctic sea ice variability in a warming world is influenced by a range of competing factors including:

- changing surface winds,
- meltwater inputs from Antarctic land-ice loss[13] that tends to promote more extensive sea ice, and
- a warming surface ocean that makes it less favourable for sea ice formation.

Over most of the observational sea ice record (since 1979) it appears that the former factors dominated the gradual increase in sea ice around Antarctica. However, the recent precipitous decline in Antarctic sea ice seems to have been driven by ocean heat beginning to dominate the response in Antarctic sea ice. Antarctic sea ice loss over the last decade has brought observations into closer agreement with the expected response to human-caused climate warming seen in climate simulations[14].

However, historical and paleoclimate evidence also point to sustained declines in Antarctic sea ice throughout the 20th Century[15], suggesting that the observational record of Antarctic sea ice has not been long enough to understand Antarctic sea ice trends.

The magnitude of Antarctic sea ice loss over the past decade rivals the losses in the Arctic over the last 45 years. The radiative forcing effect (via albedo change) of Antarctic sea ice loss is now of a comparable magnitude to that of the Arctic, where sea ice changes are implicated in regional climate warming that is occurring at 3-4 times the global average[16]. Polar amplification of climate warming is possible in the Antarctic but has not yet been demonstrated, although recent years have witnessed exceptional heatwave events over Antarctica, including an event in 2022 where temperature anomalies 30-40°C above average were experienced across large parts of the Antarctic continent[17].

## Impact metrics

Even though global warming has developed largely as expected, there is some evidence that impact-related phenomena are appearing faster and becoming more severe than previous evidence suggested[18]. There is increasing confidence that some impacts are attributable to climate change, including the impacts of extreme events. Regional increases in temperature, aridity and drought have increased the frequency and intensity of large fires. The interaction between fire, land use change, particularly deforestation, and climate change, is directly impacting human health, ecosystem functioning, forest structure, food security and the livelihoods of resource-dependent communities. We next briefly comment on how some impact-related metrics are changing and whether there is evidence that the change is faster than expected or is accelerating.

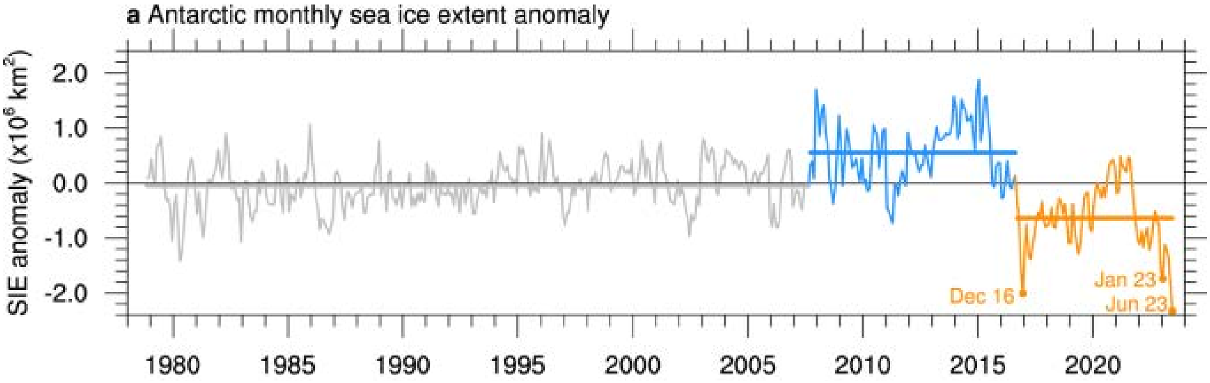



Figure 4: Antarctic monthly sea ice extent (SIE) anomaly time series from the National Snow and Ice Data Center over the satellite period, November 1978 to June 2023, in millions of square kilometres. SIE anomalies are calculated relative to the 1979–2022 climatology. Two change points are detected, separating the time series into three periods: November 1978 to August 2007 (grey), September 2007 to August 2016 (blue), and September 2016 to June 2023 (orange). The means of each period are shown by the horizontal lines and are statistically distinguishable. Source: Purich and Dodderidge 2023[12].

## Heatwaves

There is substantial evidence that the intensity, duration, and frequency of heatwaves have increased since at least the 1950s over much of Australia, with the strongest trends over the eastern half of the continent and central Western Australia[19]. These regions are also experiencing a lengthening of the heatwave season, with the first annual event occurring earlier each decade. Multiple studies have found that historical Australian heat extremes now occur more often and are more intense due to human influence on the climate[20], however, the precise role of climate change is unique to each event[21]. This aligns with the global body of evidence that climate change has overwhelmingly increased the intensity and frequency of high-impact and record-breaking heat extremes over the last two decades.

While heatwave temperatures, and the length of heatwaves, have been rising in step with the global average, their impact is likely accelerating, although this is hard to measure. Acceleration is expected because impact increases dramatically as heat approaches human coping limits. Recent physiological studies have shown that healthy young people cannot thermoregulate if the "wet-bulb" temperature (a combined measure of temperature and humidity) reaches around 31°C or sometimes lower, which is very close to the highest that now occur in most regions[22]. Vulnerable populations (e.g., aged or pregnant) are less resilient. As peak wet-bulb temperatures climb toward or past these thresholds, health impacts will accelerate and heat events will be a factor in fatalities, such as the hundreds of deaths during the Hajj pilgrimage to Mecca (2024)[23]. Events such as these are likely to become much more common.

## Extreme rainfall

Observational studies have found that short-duration (~hourly or less) extreme rainfall is increasing faster than expected based only on thermodynamic considerations (increased water vapour in the air)[24,25]. While increased water vapour is a straightforward result of anthropogenic warming, changes in various types of circulation change could also occur. Although extreme rainfall changes have not formally been attributed to climate change, model projections of future climate change do indicate that these short duration rainfall extremes will continue to increase at rates faster than expected from water vapour increases alone[26]. There is no indication in data or models as to whether rainfall totals are increasing at an accelerating rate.

## Marine heatwaves

There is substantial evidence that the intensity, duration, and frequency of marine heatwaves have mostly increased across the globe[27,28] and that these increases are mainly due to long-term warming trends in sea surface temperatures[29]. A study of marine heatwaves across the globe found that the occurrence probabilities of the intensity, duration and cumulative intensity of the large and high-impact marine heatwaves have increased more than 20-fold attributed to human-induced climate change[30]. These trends are projected to increase further through the 21st century, including higher intensity marine heatwaves[31,32]. Further, studies have projected a factor of 16 increase in marine heatwave days for a global warming of 1.5°C and a factor of 23 increase for a 2.0°C global warming, relative to pre-industrial levels[33]. Moderate and strong category marine heatwave days per year have increased around much of Australia, while severe category marine heatwaves became evident in the latter period off Australia's southeast relative to a 1983-2012 baseline[34].

## Droughts

There are multiple types of droughts, including meteorological, hydrological and ecological drought; what is common to all kinds is that they are complex phenomena and respond to a wide range of drivers including the modes of variability. A drought lasting several years may have multiple different mechanisms causing the low rainfall[35] that in turn leads to drought.

There is limited evidence in Australia that meteorological or ecological droughts are increasing, or increasing faster than expected, except in southwest Australia which has been undergoing a long-term and rapid decline in rainfall. However, hydrological droughts are more complex. There are clear downward trends on streamflow in many parts of eastern and southeastern Australia[36] which are not fully explained by changes in rainfall. These trends in streamflow may reflect increased evaporation associated with increased demand by the atmosphere[37], or the widespread greening trend leading to more vegetation able to transpire[38], or changes in rainfall variability[39].

## Why does the rate of warming matter?

The current rates of global warming are unprecedented in recent millennia and have reached about 0.2°C over the recent decade[40]. This is much faster than can be explained by natural rates of climate change. The magnitude of climate change is important, and efforts to keep warming closer to 1.5°C than 2.0°C are important, and so the rate by which climate changes is also very important.

If the magnitude of warming is limited, and the rate of warming is slowed, some important natural systems might be able to adapt, at least to some degree. Human systems, including agriculture, infrastructure and emergency services are already beginning to adapt to climate change. The more time these have to adapt the easier and cheaper those adaptation strategies will be.

## Looking to the future

One of the most critical elements of how climate change will be expressed on human systems is how the weather will change in a warming climate. Understanding how the weather will change in a warming climate is crucial for agriculture, renewable energy, and disaster management. This is an enormous scientific challenge which the research community has only just started to explore. This urgent research is led in Australia by the ARC Centre of Excellence for the Weather of the 21st Century (https://www.21centuryweather.org.au).

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