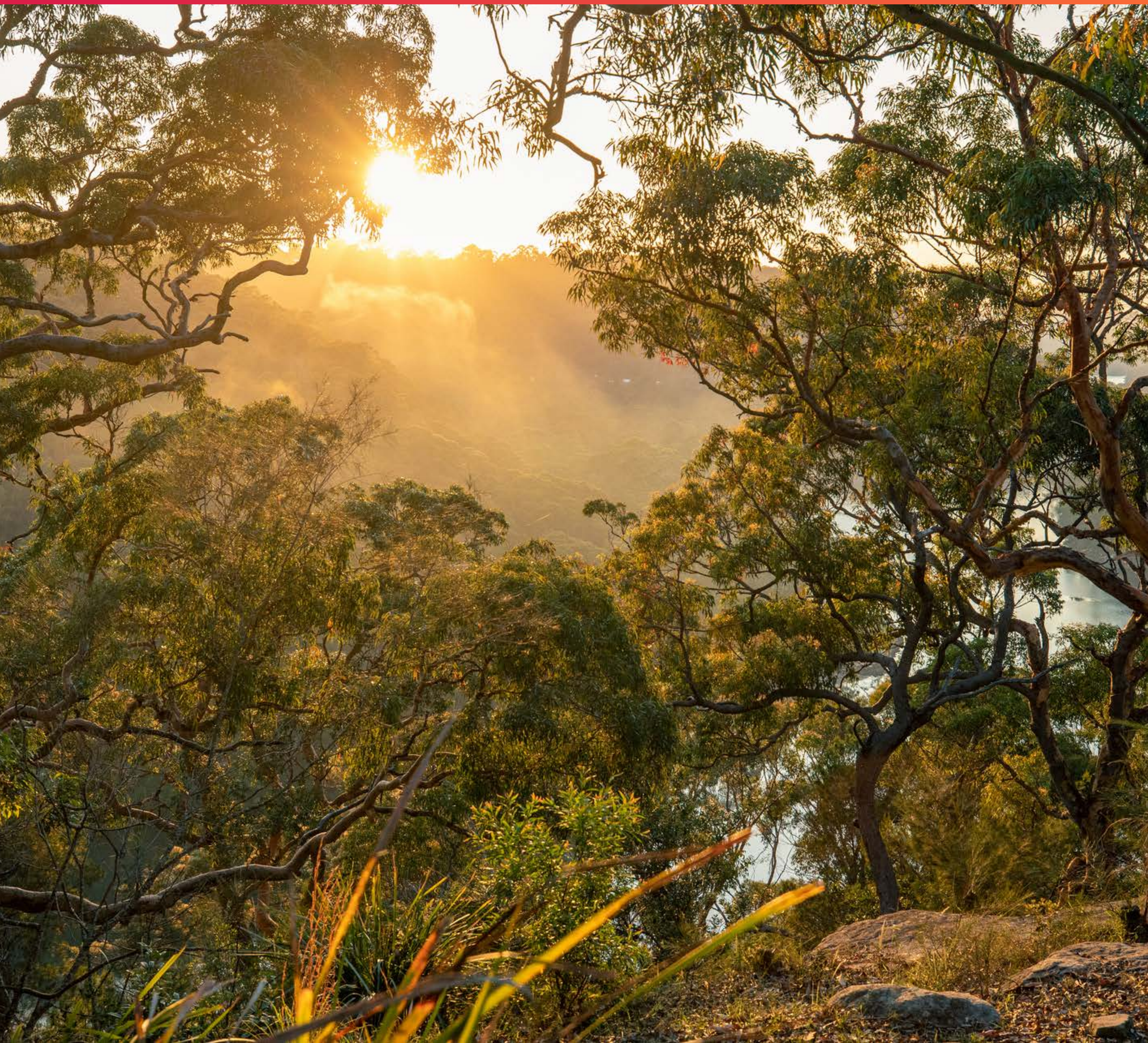
Australian Government
Australian Research Council

climate extremes
ARC centre of excellence

21st Century Weather
ARC Centre of Excellence

Understanding Net Zero



Net zero is achieved when human induced greenhouse gas emissions are balanced by their removal from the atmosphere by humans.

Limiting the impacts of climate change requires reaching net zero emissions as soon as possible.

Net negative emissions will achieve greater cooling of the planet and further reduce the impacts of climate change.

Achieving net zero emissions is essential to limit the impacts of climate change. The goals of the Paris Agreement to keep global warming below 2°C and pursue efforts to limit warming to 1.5°C require reaching net zero as soon as possible. Once net zero is reached, global mean surface temperature will likely stabilise. However, more substantial cooling of the planet can be accomplished by striving for net negative emissions, which will reduce climate risks further.

The imperative of reducing emissions

The link between greenhouse gas emissions and climate change is unequivocal. The impacts of climate change are already being felt, causing significant impacts on communities across the world. Global temperatures have risen by around 1.2°C since the pre-industrial period[1]. In Australia, the frequency and intensity of heatwaves has increased across the country since the 1950s[2]. The risks of droughts and bushfires are showing emerging links to climate change, and these are expected to worsen[3,4]. In our oceans we have seen a doubling of marine heatwave days over the last century, threatening ocean ecosystems[5].

Every additional fraction of a degree of warming increases climate risks, therefore reaching net zero as soon as possible is critical.

What is net zero?

Net zero is the state where human induced greenhouse gas emissions are balanced by their removal from the atmosphere by humans (Figure 1). At net zero, the concentration of greenhouse gases in the atmosphere starts to decrease and the pace of climate change begins to slow down.

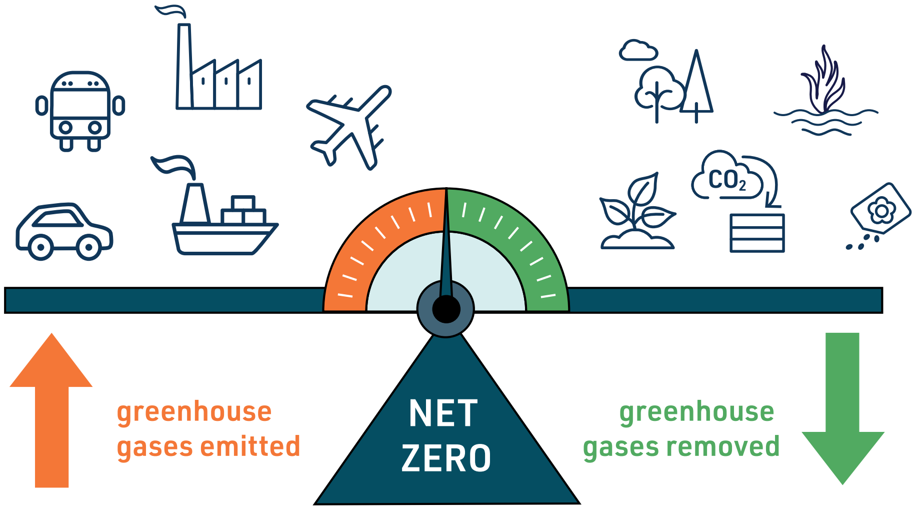


Figure 1: What is net zero? Greenhouse gases from sources like transport and industry need to be balanced by greenhouse gases removed by humans through methods such as nature-based solutions or engineered technologies.

By definition, net zero does not refer to a fixed level of emissions or warming, but the balance of greenhouse gas emissions and removal. Theoretically, net zero can range anywhere from:

- emitting high amounts of greenhouse gases and removing equally high amounts, to
- emitting no greenhouse gases at all, requiring no removal to achieve balance.

While the greatest reduction in climate impacts will be achieved by significant and rapid emissions reduction, there are strategies to remove greenhouse gases from the atmosphere.

The removal of greenhouse gases involves using methods like nature-based solutions[6] and engineered technologies that capture carbon from the air. Achieving net zero doesn't account for natural processes that already sequester carbon, such as the uptake by forests and oceans. Instead, it involves the extra efforts humans make to actively remove greenhouse gases from the atmosphere.

It is important not to overstate the potential of carbon removal methods as their capacity is uncertain. Some strategies remain in early-stage development or pilot stages. Some methods, such as nature-based solutions, may not provide a removal method that lasts long enough, particularly as fire risk increases. Significantly reducing greenhouse gas emissions is the most reliable way to achieve net zero.

Global greenhouse gas emissions

Carbon dioxide (CO_2) is the most prevalent greenhouse gas (Figure 2) and the largest contributor to climate change resulting from human activity. Limiting warming requires reaching net zero CO_2 and strongly reducing other greenhouse gas emissions. There may be limits to the reductions we can achieve in some greenhouse gases, such as methane (CH_4) emitted from agricultural processes such as livestock and rice production. Reducing CO_2 emissions to net negative, where CO_2 removal exceeds CO_2 production, may be necessary to compensate for this and allow overall net zero emissions.

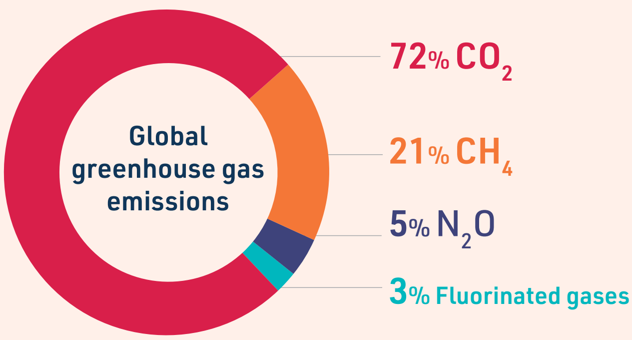


Figure 2. Global greenhouse gas emissions in 2022 (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases). Note the percentages don't add up to 100 due to rounding. Source: ARC Centre of Excellence for Climate Extremes, using data from Crippa et al. 2023[7].

Australia's commitment to net zero

Australia is a signatory of the Paris Agreement and has therefore committed to limit "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C"[8]. Many countries, including Australia have signalled their intention to reach net zero by 2050[9]. However, current global efforts put the world on track to reach around 2.9°C of warming this century, which would have catastrophic impacts[10]. Reaching net zero by 2050 is inadequate to meet the Paris Agreement goals.

Current global emission trajectories make exceeding 1.5°C inevitable. While the extent of warming is likely to be subject to uncertainties in how the climate system will react or is reacting, every fraction of a degree matters. The Intergovernmental Panel on Climate Change (IPCC) estimates that achieving net zero emissions by 2027 gives an approximate 83% chance of limiting warming to 1.5°C[11].

What happens to the climate after net zero?

Our understanding of what would happen beyond net-zero is based on modelling a very different climate from one observed over the last few centuries, where warming has occurred due to humanity's greenhouse gas emissions. Confidence in these projections will increase as modelling efforts expand and develop.

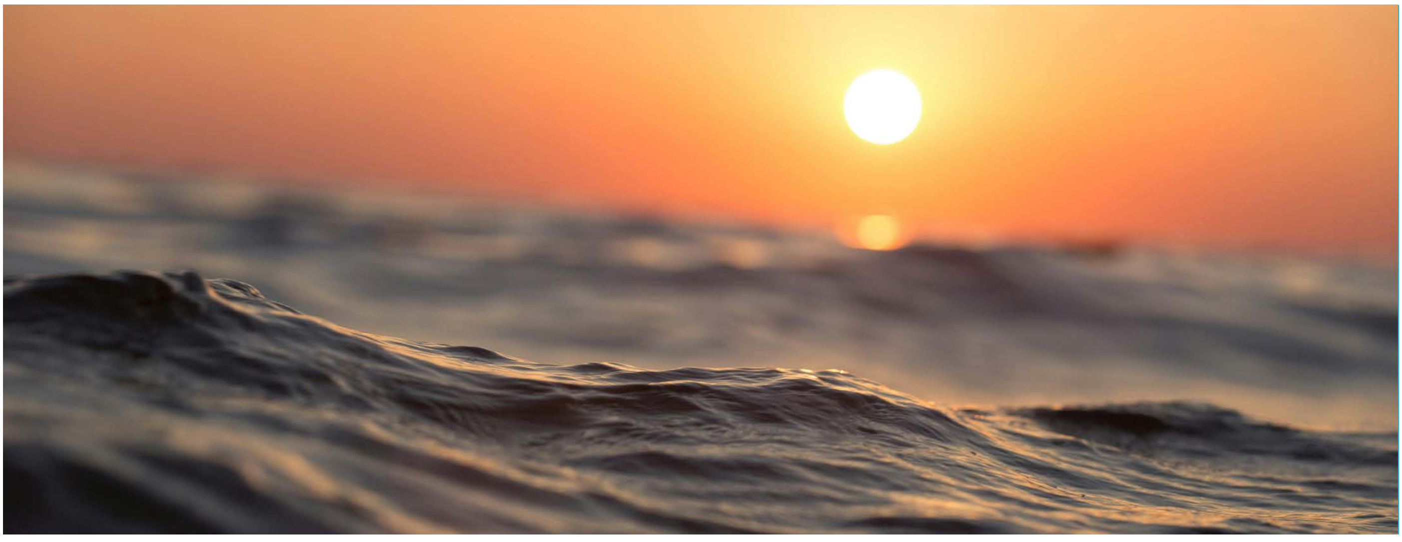
After net zero, the global average temperature is expected to roughly stabilise. Temperatures over land would begin to cool, while parts of the ocean continue to warm. Understanding the likely changes to the climate after net zero provides useful information on the implications of reducing greenhouse gas emissions and the possible futures to prepare for.

Global mean surface temperature stabilises

Reaching net zero CO_2 will roughly stabilise global mean surface air temperature (the temperature of the land surface and ocean averaged across the globe). The temperature at which the earth stabilises depends on the cumulative emissions at net zero. As of 2024, cumulative emissions have resulted in 1.2°C of global warming above the pre-industrial average. If net zero is reached now, global warming will most likely be held close to this level.

While climate models indicate that the changes in global mean surface air temperature after net zero will be close to zero, a range of outcomes is possible. Models show the strongest cooling after net zero could be 0.36°C and the largest warming could be 0.29°C. Most models however, show that the change in globally averaged temperature across land and ocean could be close to zero[12,13].

It is expected that air temperatures on land will cool while parts of the ocean continue to warm (Figure 3). These opposing cooling and warming responses are likely to produce a stable global temperature on average, with year to year variability maintained.



The land surface cools

The air temperatures on land are expected to show a cooling response after net zero. This occurs through the uptake of atmospheric CO_2 by the land and the ocean, reducing the amount of CO_2 in the atmosphere that is causing warming. It is expected that the air temperatures on land will cool by 0.23°C on average within 50 years[13]. These temperature changes are regionally dependent, with the greatest cooling likely to occur in the Northern Hemisphere. This is because there is a greater proportion of land in the Northern Hemisphere compared to the Southern Hemisphere. Tropical regions and the Southern Hemisphere are likely to experience less change (Figure 3)[14].

Parts of the ocean continue to warm

It is expected that the ocean will take many millennia to reach a stable state, with regions of the ocean continuing to warm after net zero. This delayed response of the ocean compared to the land occurs because ocean and ice processes operate over very long timescales. The ocean has already absorbed more than 93% of the heat trapped by greenhouse gas emissions which can take thousands of years to be mixed throughout the deep ocean. Ice melt in the Antarctic may continue for thousands of years, causing ongoing impacts to ocean temperatures. Climate models indicate that the oceans response to net zero is regionally dependent, with the Southern Ocean likely warming while some other areas show cooling (Figure 3)[14].

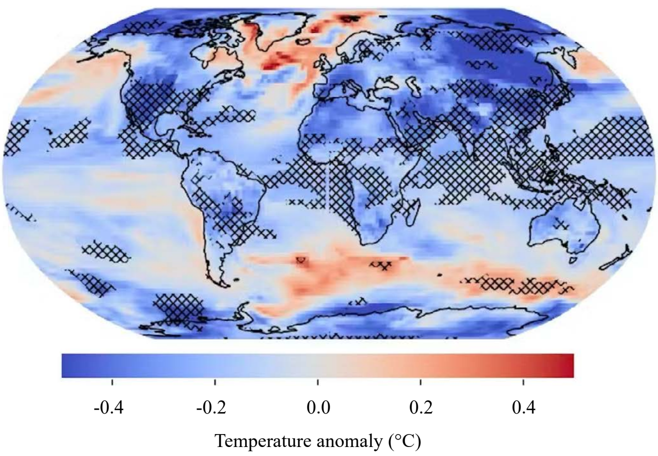


Figure 3. Regional temperature change over the century after net zero CO_2 emissions (°C). Cross-hatching indicates areas where we are most confident that regional temperatures increase (red hues) or decrease (blue hues) after net zero CO_2. Source: Cassidy et al. 2024.

Climate extremes after net zero

It is likely that the intensity and frequency of many climate extremes will change after net zero. This is a new area of research and there is a lack of model experiments to explore climate extremes under net zero, increasing the uncertainty in projected changes. However, there are some areas where science provides an indication about the future.

Heat extremes

It is expected that there will be a decrease in the frequency of heat extremes over most land areas after net zero, emerging within 25 years[14]. These changes are regionally dependent, with some regions projected to experience up to a 40% reduction while others may see minimal changes. Changes appear to favour regions of higher socioeconomic development such as North America and Western Europe compared to developing areas such as West Africa and Southeast Asia (Figure 4). Local cold extremes may become more frequent in many extratropical regions.

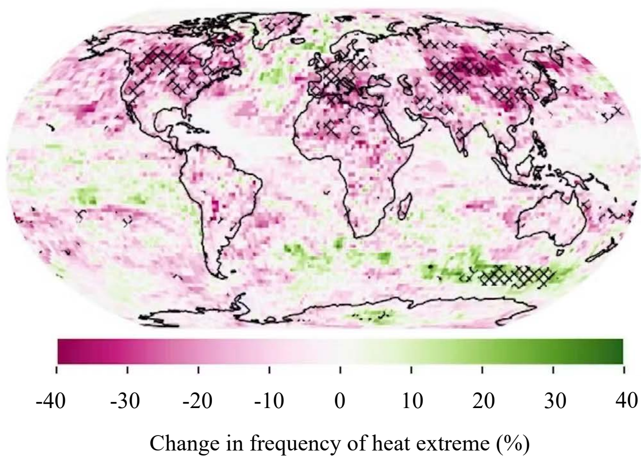


Figure 4: Changes in the frequency of heat extremes during the local hottest month over the century after net zero CO_2 emissions. Cross hatching indicates areas where we have highest confidence in the increasing (green hues) or decreasing (pink hues) frequency of heat extremes after net zero CO_2 emissions. Source: Cassidy et al. 2024.

Extreme rainfall

Changes in rainfall are more uncertain than temperature changes, as rainfall results from complex, local scale weather processes that are difficult to capture in climate models. There have been very few studies examining rainfall changes under net zero emissions. The changes will most likely be more subtle than those we are seeing in our rapidly warming world[12], but various outcomes are possible. There is some limited evidence that regions of the world that are drying in a warming world may experience some increase in rainfall after greenhouse gas emissions are reduced[15].

Monsoons

The change in land and ocean temperatures after net zero may impact monsoon season rainfall. Recent work indicates monsoon patterns may recover to their pre-industrial state[16], with some regions showing fast recovery while others show continuous expansion in the monsoon area even after net negative CO_2 emissions. Some regions may experience long-term delayed onset of monsoon rainfall, particularly in the Indian summer monsoon system which could have serious implications for billions of people due to impacts on rain-fed agriculture and water management[17].

Marine heatwaves

Increasing ocean temperatures are a risk factor for marine heatwaves; periods of warmer than usual ocean temperatures which cause negative impacts on ocean ecosystems and communities that depend on these resources. Marine heatwaves are expected to be four times as frequent by the end of the century even in a very low emission scenario[18]. The Arctic and tropical oceans are expected to be most affected by increased frequency of marine heatwaves.

Sea level rise

Global mean sea level has risen by over 0.20m, predominantly due to the melting of glaciers and thermal expansion - increased ocean temperatures cause the water to expand, rising sea levels[18]. Sea level will continue to rise for centuries after net zero from continued thermal expansion and ice sheet melt from Greenland and Antarctic ice sheets. It is expected that sea level will increase by another 10-25cm by 2050 and 40-80cm by 2100, but 1.5m by 2100 may also be possible[18].

Net negative emissions reduces climate risks

Net negative emissions refers to the removal of greenhouse gases from the atmosphere exceeding the production of greenhouse gases. Striving beyond net zero and achieving net negative emissions will further reduce the greenhouse gases in the atmosphere, allowing more substantial cooling of the climate. Ultimately, the aim is for global temperatures to stabilise at close to pre-industrial levels to minimise climate risks[19].

Our current understanding of our climate under net negative emissions is limited, as climate scientists are yet to develop appropriate model simulations to analyse these changes. Emerging climate model experiments will focus more on net-negative emissions pathways to support research around the implications of future cooling climates.

Written by

Alexander Borowiak
is a PhD student at the ARC Centre of Excellence of Climate Extremes, based at the University of Melbourne. In their PhD Alexander is using climate models to understand how the climate may look after net zero and how the temperature in different regions will respond over the next century. Previously Alexander explored the Madden-Julian Oscillation (MJO) and its relationship with the increasing rainfall trend in northwest Australia for their Masters degree at the University of Melbourne.

Liam Cassidy
is a PhD student at the ARC Centre of Excellence of Climate Extremes, based at the University of Melbourne. Liam is interested in using climate models to better understand global and regional climate change during net zero and net negative greenhouse gas emissions futures.

Dr Andrew King
is a Chief Investigator at the ARC Centre of Excellence for 21st Century Weather and an Associate Investigator at the ARC Centre of Excellence for Climate Extremes. He is a senior lecturer in climate science at the University of Melbourne. Andrew's research focuses on climate change and variability, climate extremes, and climate projections. Andrew has a PhD in Climate Science from UNSW and an undergraduate degree in Meteorology from the University of Reading.

Aditya Sengupta
is a PhD student at the ARC Centre of Excellence of Climate Extremes, based at the University of Melbourne. Aditya's PhD is studying the impacts of climate change on the El Niño Southern Oscillation (ENSO), particularly how ENSO will change after we reach net zero emissions. He completed his B.Sc. (Honors) in Physics from Amity University and M.Sc. in Atmospheric Sciences from the National Institute of Technology, Rourkela in India.

Alice Wilson
is a knowledge broker at the ARC Centre of Excellence for Climate Extremes. Alice holds a Master of Environment with a specialisation in Climate Change from the University of Melbourne. She has a passion for acting on climate change and believes in the importance of translating high quality climate science to stakeholders to inform climate action.

Produced by

Engagement and Impact Team - Knowledge brokers: Angela Kaplish, Alice Wilson
Communications: Laure Poncet **Graphic design:** Georgina Harmer

References

1. Forster et al. (2024). Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. https://doi.org/10.5194/essd-16-2625-2024
2. Jyoteeshkumar et al. (2021). Intensifying Australian heatwave trends and their sensitivity to observational data. https://doi.org/10.1029/2020EF001924
3. Devanand et al. (2024). Australia's Tinderbox Drought: An extreme natural event likely worsened by human-caused climate change. https://www.science.org/doi/10.1126/sciadv.adj3460
4. Abram et al. (2021). Connections of climate change and variability to large and extreme forest fires in southeast Australia. https://doi.org/10.1038/s43247- 020-00065-8
5. Oliver et al. (2018). Longer and more frequent marine heatwaves over the past century. https://doi. org/10.1038/s41467-018-03732-9
6. ARC Centre of excellence for Climate Extremes. (2024). Nature-based solutions. https://climateextremes.org.au/nature-based-solutions/#:~:text=Some%20nature%2Dbased%20solutions%20can,risks%2C%20soil%20erosion%20and%20landslides.
7. European Commission, Joint Research Centre, Crippa et al. (2023). GHG emissions of all world countries – 2023. https://data.europa.eu/doi/10.2760/953322
8. Untied Nations Framework Convention on Climate Change. (2015). The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement
9. Parliament of Australia. (2022). Climate Change Bill 2022.
10. United Nations Environment Programme. (2023). Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again). Nairobi. https://doi.org/10.59117/20.500.11822/43922.
11. ARC Centre of Excellence for Climate Extremes. (2021). What is left in the global carbon budget? https://climateextremes.org.au/what-is-left-in-the-global-carbon-budget/
12. Borowiak et al. (2024). Projected Global Temperature Changes After Net Zero Are Small But Significant. https://doi.org/10.1029/2024GL108654
13. MacDougall et al. (2022). Substantial regional climate change expected following cessation of CO2 emissions. https://iopscience.iop.org/article/10.1088/1748-9326/ac9f59
14. Cassidy et al. 2024. Regional temperature extremes and vulnerability under net zero CO2 emissions. DOI 10.1088/1748-9326/ad114a
15. Grose and King (2023). The circulation and rainfall response in the southern hemisphere extra-tropics to climate stabilisation. https://doi.org/10.1016/j.wace.2023.100577
16. Paik et al. (2023). Hysteretic behaviour of global to regional monsoon area under CO2 ramp-up and ramp-down. https://doi.org/10.1029/2022EF003434
17. Zhang et al. (2024). Delayed onset of Indian summer monsoon in response to CO2 removal. https://doi.org/10.1029/2023EF004039
18. Fox-Kemper et al. (2021). 2021: Ocean, Cryosphere and Sea Level Change. 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. https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-9/
19. King et al. (2022) Preparing for a post-net-zero world. https://doi.org/10.1038/s41558-022-01446-x

Contact
clex@unsw.edu.au

Follow Climate Extremes: