Chapter 1:
The science of climate change

Contents

Climate change is already happening, and past emissions have locked in further change. By signing up to the Paris Agreement, the world has committed to take action on climate change. Nations are responsible for determining how they will contribute to global efforts to limit warming to well below 2˚C and pursue efforts to limit it to 1.5˚C above pre-industrial levels and reduce the risks and impacts of climate change. Aotearoa has set itself the goal in the Climate Change Response Act 2002 (CCRA) of contributing to efforts to limit temperature increases to 1.5˚C above pre-industrial levels.

This chapter explores the science on climate change and sets out why urgent action is needed, looking at what effect our current behaviour has and what is at stake. It examines the forces affecting the global temperature, the role of different greenhouse gases and the possible emissions reduction pathways to meeting the 1.5˚C limit.

1.1 Introduction

Scientists have understood the role of greenhouse gases in global climate systems for more than 160 years.[1] The sun's energy warms the earth's surface, oceans, and atmosphere, and it is the ability of greenhouse gases to trap this warmth that makes life on earth possible. Without them, the average temperature of the earth would be around -18°C.[2]

Forty years after the greenhouse effect was discovered, scientists recognised the role that human activities could have in changing the global climate. In 1896, Swedish chemist Svante Arrhenius surmised burning coal to power the Industrial Revolution would heat the earth, although he thought it would take hundreds or thousands of years for this to happen.[3]

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[1] Eunice Foote discovered the absorption of thermal radiation by carbon dioxide and water vapour in 1856. In 1859, John Tyndall discovered that carbon dioxide and methane were strong absorbers of infrared radiation, and thus were able to trap heat radiating from the earth's surface. (Jackson, 2020)

[2] (Lang, 2010)

[3] (Arrhenius, 1896)

Box 1.1: Identifying the human fingerprint in global warming

Research combining observations of the factors that can affect global temperature has identified how much of the observed warming is due to natural variation, and how much is driven by human emissions of greenhouse gases. Natural factors include changes in solar activity, volcanic eruptions, and natural changes in aerosols like dust and fog.[4] Human activities include burning of fossil fuels, methane and nitrous oxide emissions from agriculture, production of aerosols and ozone depleting substances and carbon dioxide released from burning forests and land-use change.

If natural drivers of climate change were the only forces at play, the world's climate should be stable or cooling. Instead, human activities are driving significant increases in global air and ocean temperatures and related changes to the planet (Figure 1.1).

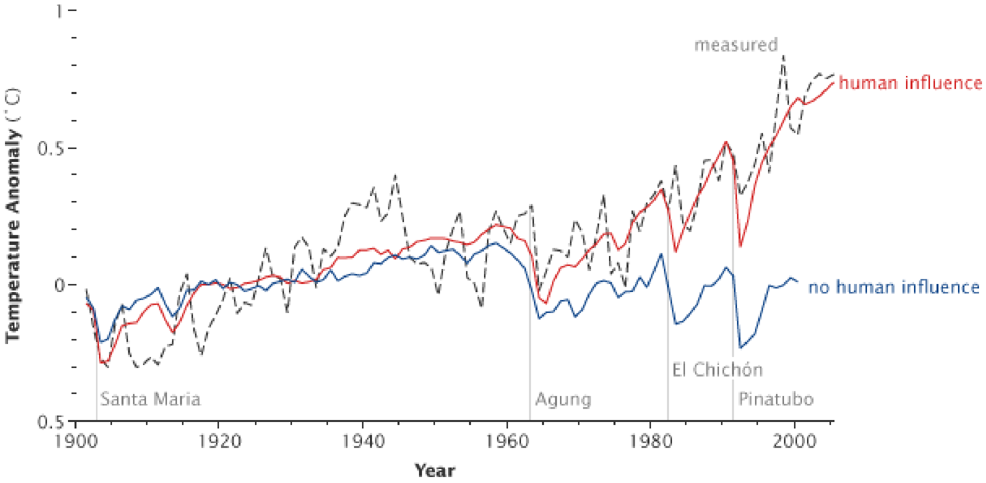

Figure 1.1: Human forces affecting global temperature[5]

1.1.1 We are seeing the effects of climate change now

Those early predictions of human-driven climate change have since been borne out. Human activities are estimated to have warmed the planet by approximately 1°C since the start of the Industrial Revolution.[6] More than half this warming has occurred since 1980. If the observed rate of warming were to continue, the world would reach 1.5°C of warming around 2040.[7]

This human-driven warming is already affecting the planet. The Intergovernmental Panel on Climate Change's (IPCC) *Fifth Assessment Report* concluded that:

'Recent climate changes have had widespread impacts on human and natural systems on all continents and across the oceans. Attributable impacts included an impact of climate change on crop

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[4] An aerosol is a particle that is small enough to be suspended in the air. For example, dust, smoke, fog and mist. They can be natural, like water droplets in fog or dust, or human-caused, like smoke from household fires or sulphur dioxide from burning oil. Around 90% of all aerosols come from natural sources. (Voiland, 2010)

[5] (NASA Earth Observatory, 2010)

[6] (IPCC, 2018b)

[7] (IPCC, 2018b)

yields, shrinking glaciers and changing rainfall patterns affecting water availability and changing geographic ranges of species on land and ocean.'[8]

Closer to home, we are already seeing the impacts of warming in Aotearoa. Average temperatures, and temperature extremes, are increasing significantly in many parts of the country, while winters are getting warmer and drier. Average sea level has increased by nearly 30cm since records began over 100 years ago and the rate of sea-level rise is accelerating. At the same time, we are observing a range of physical and environmental impacts from these changes - coastal erosion rates are increasing, coastal flood frequency is increasing, growing seasons are changing and environments are becoming uninhabitable for some of our native species.[9]

These changes are also having impacts on people and the economy. A recent study conservatively estimated that the contribution of climate change to floods and droughts cost Aotearoa $840 million in insurance claims and economic losses over the 10 years to 2017.[10] Local Government New Zealand has estimated that approximately $5 billion of roading, water infrastructure, buildings and other assets would be exposed under 1 metre of sea level rise.[11]

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[8] (Committee on Climate Change, 2019, p. 57)
[9] (Ministry for the Environment & Statistics NZ, 2020)
[10] (Frame et al., 2018)
[11] (Simonson & Hall, 2019)

Box 1.2: Iwi/Māori are also observing many changes in the environment that affect customary practices and values.

The numbers and distributions of taonga species are changing. Species are turning up at times and in places where they have not before. For example, mullet in Northland can now be caught year-round, something that never happened in the past.[12] Kingfish – a species unknown to early Ngāi Tahu – are being caught in increasing numbers along the east coast of the South Island, Te Waipounamu.

Traditional tohu (environmental indicators) are also changing. The flowering of pōhutukawa has traditionally been a sign that kina were ready for harvest. However, changes in sea temperatures have altered the reproductive period of kina,[13] meaning that kina are no longer ready for harvesting when pōhutukawa traditionally bloom in summer (Figure 1.2).

The physical impacts of climate change are also affecting special places such as marae and urupā (burial grounds). In particular, coastal sites are at increased risk of flooding from sea-level rise, and erosion.[14] For example, rising seas led to a 700-year-old urupā at Ōkūrei Point in Maketū collapsing onto the beach below.[15] In other areas, urupā at risk from flooding have already had to be relocated.

All in all, climate change is having and will have significant and wide-ranging impacts on Iwi/Māori. As the latest state of the environment report on atmosphere and climate notes:

"Climate change can contribute to degradation in the mauri (life force) of ecosystems and taonga species, and jeopardise the mātauranga associated with them. When a taonga species is lost, the whakapapa (lineage or ties) between iwi, hapū, whenua (land), and taonga is severed. The ability of tangata whenua to act as kaitiaki (guardians) over the taonga, and to engage in mahinga kai practices within their rohe (region) can also be degraded." [16]

"[…]Climate change is likely to affect marae and customary harvesting grounds, and cause major shifts in how whānau practice manaakitanga. Coastal marae may become inaccessible due to increased flooding. A loss of taonga species would mean whānau were no longer able to provide local delicacies to manuhiri. A combination of these situations could see some whānau unable to manaaki on their marae as they have for generations. The inability to gather kaimoana also has economic consequences because this practice has always supplemented low incomes and diet."[17]

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[12] (Te Hiku o te Ika Development Trust, 2018) cited in (Ministry for the Environment & Statistics NZ, 2020, p. 53)

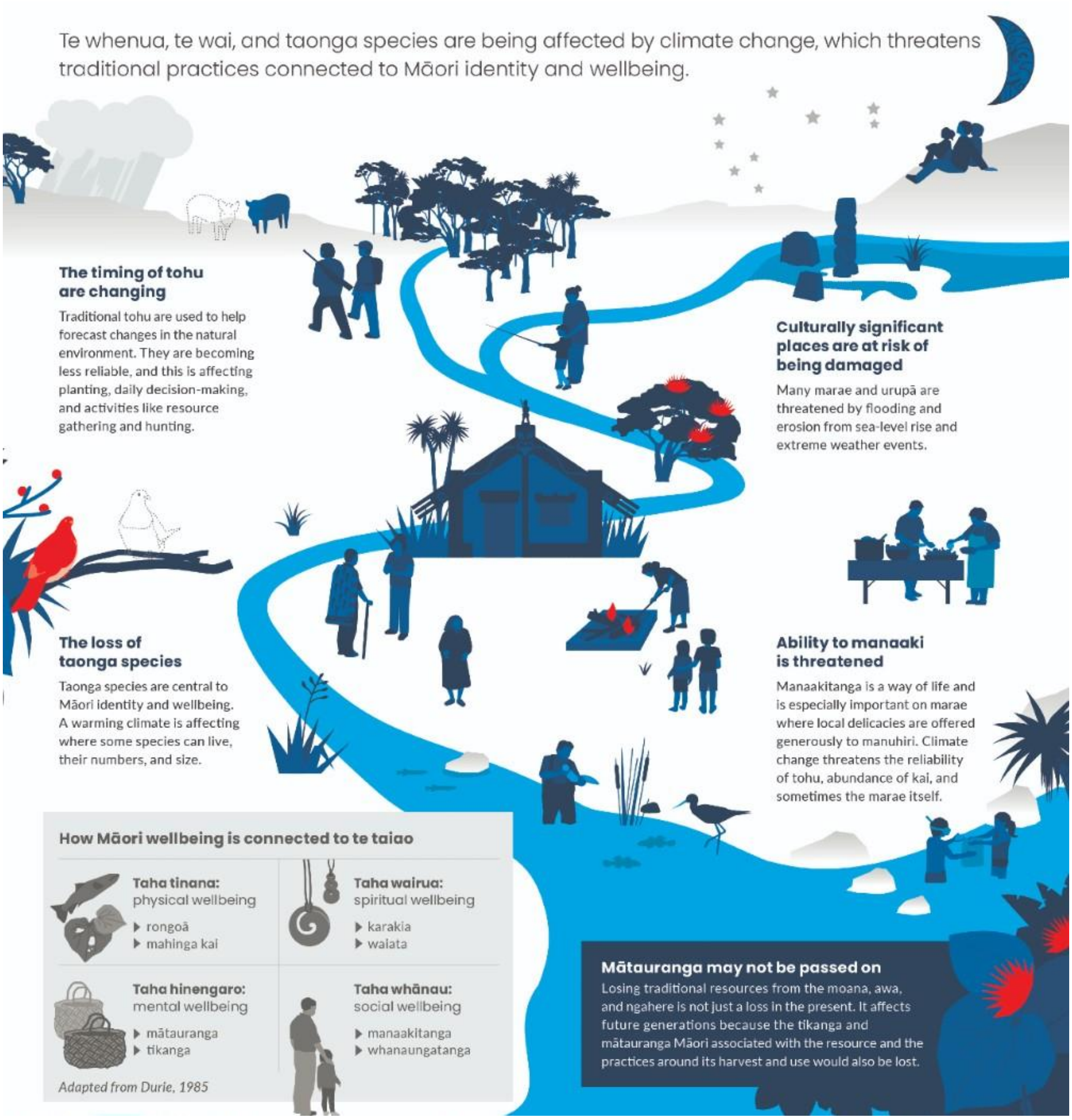
[13] (Ministry for the Environment & Stats NZ, 2019)

[14] (Colliar & Blackett, 2018)

[15] (Neilson, 2019)

[16] (Ministry for the Environment & Statsistics NZ, 2020, p. 54)

[17] (Patuharakeke Te Iwi Trust Board Inc., 2014) cited in (Ministry for the Environment & Statistics NZ, 2020, p. 55)


Te whenua, te wai, and taonga species are being affected by climate change, which threatens traditional practices connected to Māori identity and wellbeing.

The timing of tohu are changing

Traditional tohu are used to help forecast changes in the natural environment. They are becoming less reliable, and this is affecting planting, daily decision-making, and activities like resource gathering and hunting.

Culturally significant places are at risk of being damaged

Many marae and urupā are threatened by flooding and erosion from sea-level rise and extreme weather events.

The loss of taonga species

Taonga species are central to Māori identity and wellbeing. A warming climate is affecting where some species can live, their numbers, and size.

Ability to manaaki is threatened

Manaakitanga is a way of life and is especially important on marae where local delicacies are offered generously to manuhiri. Climate change threatens the reliability of tohu, abundance of kai, and sometimes the marae itself.

How Māori wellbeing is connected to te taiao

Taha tinana: physical wellbeing
- rongoā
- mahinga kai

Taha wairua: spiritual wellbeing
- karakia
- waiata

Taha hinengaro: mental wellbeing
- mātauranga
- tikanga

Taha whānau: social wellbeing
- manaakitanga
- whanaungatanga

Adapted from Durie, 1985

Mātauranga may not be passed on

Losing traditional resources from the moana, awa, and ngahere is not just a loss in the present. It affects future generations because the tikanga and mātauranga Māori associated with the resource and the practices around its harvest and use would also be lost.

Figure 1.2: Climate change and Māori-collective wellbeing[18]

1.1.2 Looking ahead

Climate risks will be significantly lower in years to come if warming is limited to 1.5°C rather than 2°C. In a 2°C world, sea levels are projected to rise further, there would be more species' loss and almost all the world's coral reefs would be destroyed. Hundreds of millions more people would be exposed to climate-related risks, including risks to health, water supply, food security and economic growth.[19]

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[18] (Ministry for the Environment & Stats NZ, 2020, p. 56)

[19] (IPCC, 2018a)

1.1.3 The world has committed to limit climate change

Under the Paris Agreement, most of the world has agreed to take action to limit climate change. Recognising the risks of uncontrolled warming, nations have signed up to efforts to:

"Hold 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 above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change."

"Increase the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production."[20]

Under the Paris Agreement, individual nations have the right to determine what specific actions they will take as part of their contribution to global efforts. They can undertake both domestic and international actions that reflect where there are opportunities to reduce emissions, and that also recognise their own specific culture, society, economy and environment. However, the Agreement also requires *'highest possible ambition'* contributions from all parties,[21] with developed countries taking the lead.[22]

Aotearoa has recently set out how it will act to reduce its own emissions. Under the CCRA, the government is required to contribute to efforts to limit warming to 1.5°C above pre-industrial levels. The CCRA establishes a domestic emissions reduction target for greenhouse gases for 2050. This target is to reduce biogenic methane emissions to 10% below 2017 levels by 2030 and 24-47% below 2017 levels by 2050 and reduce all other greenhouse gas emissions to net zero by 2050.

The CCRA also established the Climate Change Commission (the Commission). Our role is to provide advice to the government on the reductions in emissions over time that would ensure Aotearoa meets those targets, in the form of five-yearly emissions budgets. Critical for the Commission in providing this advice is an understanding of the size and rate of reductions in different greenhouse gases, and any other actionsthat may be required to limit warming to 1.5°C above pre-industrial levels.

In providing our advice, we need to consider what other countries are doing to tackle their emissions and to scope the opportunities and potential impacts for Aotearoa in reducing our emissions. We are required to understand potential impacts for Iwi/Māori. There is also an opportunity to learn from tangata whenua and how indigenous kaitiaki models can inform emissions reductions.

Through an additional request from the Minister of Climate Change, we have also been tasked with considering the long-term reductions in our biogenic methane emissions that would be compatible with limiting warming to 1.5°C. We are also required to consider whether our international

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[20] Paris Agreement, Article 2 (United Nations, 2015).

[21] Paris Agreement, Article 4.3 (United Nations, 2015).

[22] Paris Agreement, Article 4.4, 9.3 (United Nations, 2015).

commitments, in the form of our Nationally Determined Contribution, are compatible with this goal. Our response to these two questions is provided in our advice, *Ināia Tonu Nei*.

The remainder of this chapter sets out the scientific basis of the challenge we face to limit warming to 1.5°C. It sets out the properties of the main greenhouse gases – carbon dioxide, methane and nitrous oxide. It then sets out the effects they have individually and collectively on the climate and the implications for strategies to reduce emissions and warming.

1.2 The main greenhouse gases and global 1.5°C pathways

The following section outlines the scientific understanding of emissions pathways compatible with limiting warming to 1.5°C above pre-industrial levels. The section draws primarily on the *IPCC Special Report on Global Warming of 1.5°C* as well as other more recent papers and reviews.[23]

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[23] (Forster et al., 2021; IPCC, 2018a)

Box 1.3: The Intergovernmental Panel on Climate Change

The IPCC was established by the United Nations as its body for assessing the science related to climate change. It was established in 1988 with the purpose of providing *"policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options."*[24]

The IPCC draws on the peer-reviewed research and expertise of the world's climate scientists and identifies the state of knowledge about climate change and its impacts, as well as identifying where more research is needed. Its reports are extensively reviewed throughout their production to ensure objectivity and transparency.

The main reports the IPCC produces are Assessment Reports, which provide extensive assesments of the state of knowledge. The IPCC's *Fifth Assessment Report* was produced in 2014, with the sixth due in 2022.

The IPCC also produces special reports that go into more detail on specific issues. In 2018, it produced a report on the advantages, opportunities and challenges of limiting warming to 1.5°C above pre-industrial levels.[25] The conclusions of this report have been instrumental in many nations setting goals of limiting warming to 1.5°C, including here in Aotearoa.

In 2019, the IPCC also produced a special report on climate change and land. This report addressed greenhouse gas emissions and removals in land-based ecosystems, land use and management in relation to climate change mitigation and adaptation, as well as desertification, land degradation and food security.[26]

We have drawn heavily on these and other IPCC reports in producing our advice. Over time we will update and reassess any relevant conclusions as new IPCC reports are produced.

This section and the rest of the report are focused on the gases that are emitted as a result of human activities and are responsible for driving changes in the earth's climate system. They are the gases that are driving increases in temperature, sea levels, rainfall patterns and extreme weather, and also the gases that we are able to do something about.

The section first outlines the fundamental properties and impacts of the different greenhouse gases humans emit, before presenting the high-level results on global pathways compatible with the 1.5°C goal. The section then specifically examines the different effects of cuts to short- and long-lived greenhouse gases and the potential role of carbon dioxide removals from the atmosphere.

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[24] (IPCC, 2020)
[25] (IPCC, 2018a)
[26] (IPCC, 2019)

1.2.1 The three main greenhouse gases – carbon dioxide, methane and nitrous oxide

The impact that a greenhouse gas has on the climate depends on the combination of 1) its ability to absorb heat energy on a molecule-by-molecule basis and 2) its concentration in the atmosphere.

Some gases can absorb a wide range of the energy radiating off the earth's surface, while others have a much narrower range of energy that they can absorb. The ability of a gas to absorb energy is affected by the presence of other gases in the atmosphere with similar absorption bands. For example, there is overlap between methane and nitrous oxide in the energy they absorb, meaning the amount of energy absorbed by a given amont of methane will be less if there is also nitrous oxide present, and vice versa.

The impact of the gas is also affected by its concentration. The more gas there is in the atmosphere, the more total heat can be absorbed. However, there is also an interaction that modulates this effect. As the concentration of a gas rises, the atmosphere starts to 'fill up' with the gas – a term known as saturation. The more saturated the atmosphere is, the less of the heat energy each new molecule absorbs.

The overall impact of a greenhouse gas can be expressed as the 'radiative forcing' of that gas – a measure of how much that gas is driving the changes in temperature and climate (Figure 1.3).

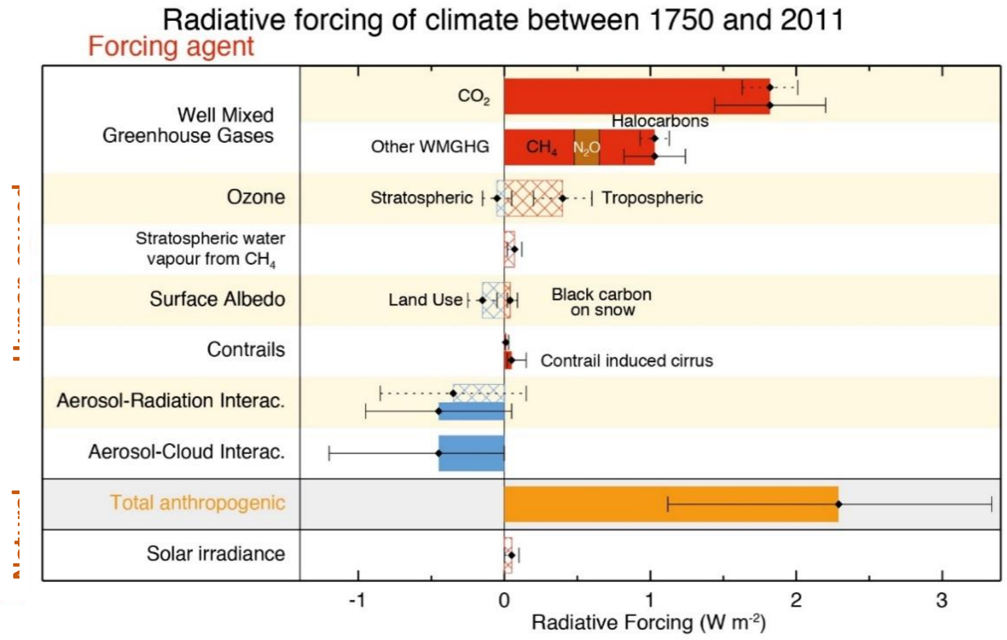

Figure 1.3: Estimates of radiative forcing of different greenhouse gases and other agents between 1750 and 2011[27]

Carbon dioxide is the most important greenhouse gas produced by human activities. It has the ability to absorb a wide range of radiated energy. It is also very long-lived, meaning that carbon dioxide

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[27] (IPCC, 2014a, p. 697, Figure 8.15)

released today can still be causing warming centuries or millennia into the future. It is the greenhouse gas the world is emitting the most of – more than 40 billion tonnes in 2018,[28] and emissions have been increasing at around 1% per year over the last decade.[29]

Carbon dioxide is also the greenhouse gas other than water vapour that has the highest concentration in the atmosphere (Figure 1.4).[30] The rates of addition of carbon dioxide to the atmosphere from human activities are 100 times faster than from natural sources like volcanoes.[31] Of the human sources of carbon dioxide, burning coal is the most significant globally, followed by burning gas and then oil.[32]

Large-scale deforestation was a particularly important source of carbon dioxide emissions in the past, although this contribution has been far surpassed in the last 60 years as fossil fuel use has increased. Around 90% of annual carbon dioxide emissions now come from fossil fuel use (Figure 1.5). Overall, carbon dioxide is responsible for the majority of human-driven warming to date.[33]

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[28] A Gigatonne is a billion tonnes, or 1,000,000,000. To give an idea of scale, a Gigatonne is equivalent to the weight of 3 million Boeing 747's, or 20,000 Titanics.

[29] (Ministry for the Environment & Statistics NZ, 2020)

[30] Water vapour is a greenhouse gas. Indeed, it is the gas with the highest concentration in the atmosphere (making up 95% of all greenhouse gases by concentration) and has been estimated to contribute up to 60% of the planet's total greenhouse effect.

But water vapour does not control the earth's temperature, rather it is controlled by the temperature. The warmer the surrounding atmosphere, the more water evaporates and the more water vapour it can hold – which will lead to more heat being trapped and more warming. This is known as a 'positive feedback loop'. However, a given volume of air becomes saturated as water vapour concentrations rise, meaning there is only so much water vapour it can hold. If the temperature decreases, some of this vapour condenses and will fall as rain or snow if the air gets cold enough.

In comparison, greenhouse gases like carbon dioxide, methane and nitrous oxide are non-condensable, meaning they do not drop out of the atmosphere if it cools. Instead they stay in the atmosphere and cause warming whatever the temperature, until they are broken down by chemical reactions – or taken up by photosynthesis in the case of carbon dioxide. As a result, the non-condensable greenhouse gases are known as 'drivers' of climate change.

[31] (Parliamentary Commissioner for the Environment, 2019, p. 48)

[32] Based on 2018 figures, coal makes up 40% of total human carbon dioxide emissions, oil makes up 34% and gas makes up 20%. The bulk of the remainder comes from cement production and flaring of natural gas. (Ritchie & Roser, 2020)

[33] (IPCC, 2014a, p. 678, Table 8.2)

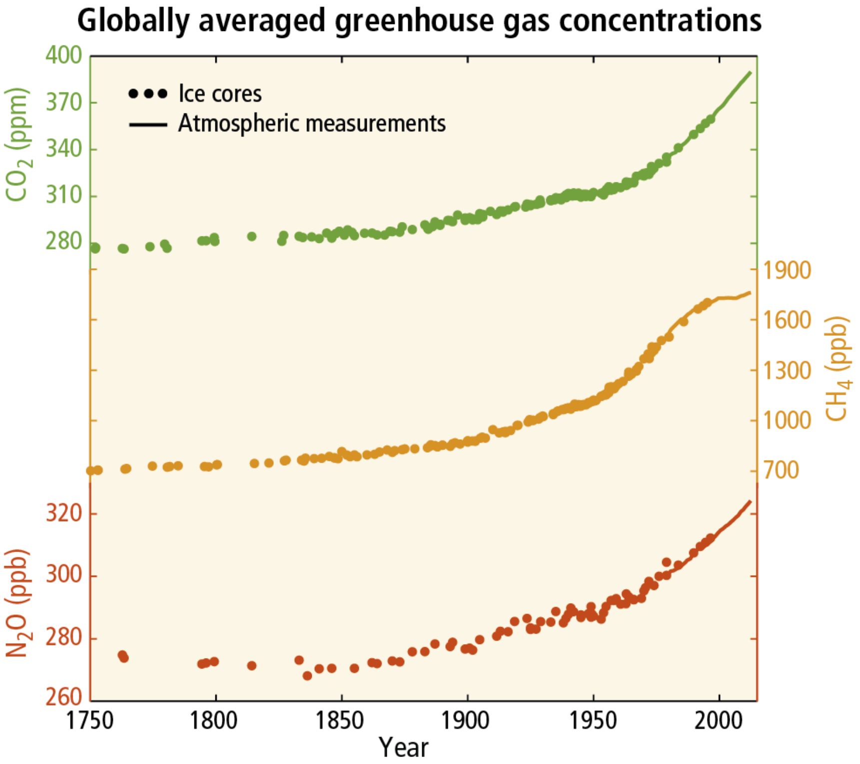

Figure 1.4: Observed changes in atmospheric greenhouse gas concentrations. Atmospheric concentrations of carbon dioxide (CO_2, green), methane (CH_4, orange) and nitrous oxide (N_2O, red). Data from ice cores (symbols) and direct atmospheric measurements (lines) are overlaid.[34]

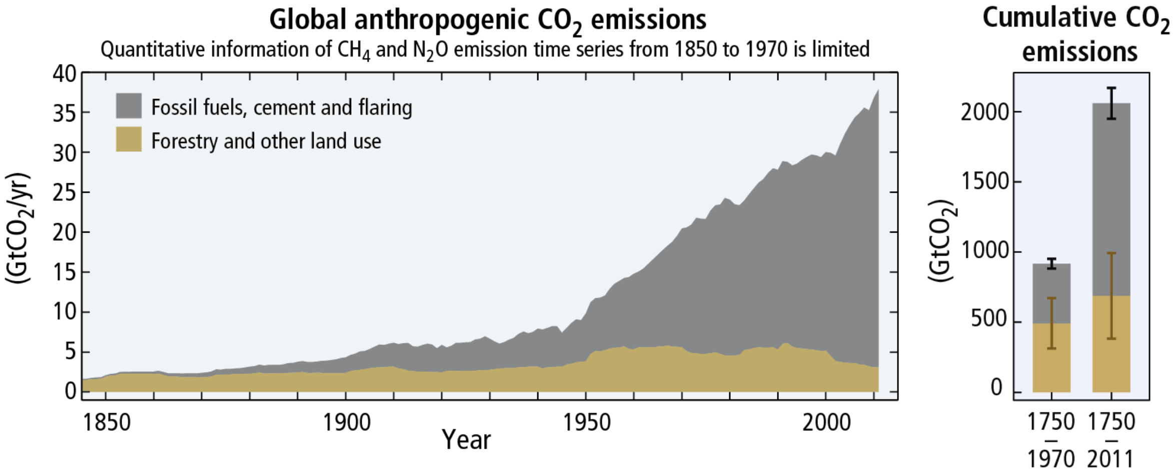

Figure 1.5: Historic carbon dioxide emissions from fossil fuels and land use[35]

Methane is the second most important greenhouse gas and is responsible for around a sixth of human-driven warming that has occurred to date. Molecule for molecule, methane emissions have a

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[34] (IPCC, 2014b, p. 44, Figure 1.3)
[35] (IPCC, 2014b, p. 45)

much greater warming effect than carbon dioxide. This is because methane is at much lower concentrations in the atmosphere than carbon dioxide, so each additional methane molecule can absorb relatively more energy than an additional molecule of carbon dioxide and therefore cause more warming.[36]

Methane is a short-lived greenhouse gas. It has an intense warming effect for the first few decades after it is emitted, but this effect dissipates as the methane breaks down in the atmosphere (Figure 1.6). However, a small proportion of methane-induced warming will linger much longer due to the inertia of the climate system and indirect feedback effects.[37,38] Methane also breaks down into carbon dioxide, which continues to have an ongoing radiative forcing effect.

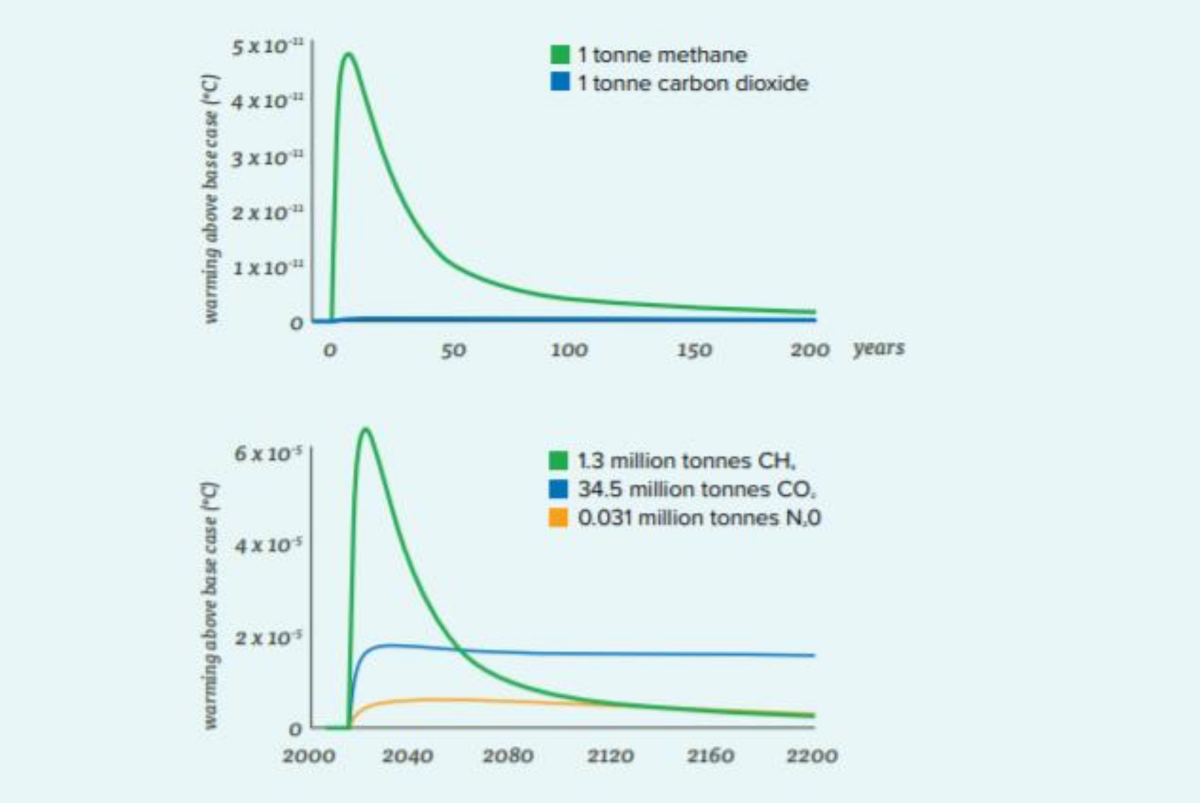

Figure 1.6: Top: Tonne for tonne, methane causes more warming than carbon dioxide over at least 200 years. Bottom: Aotearoa emits different quantities of different greenhouse gases, which affects the warming they cause and how quickly the warming dissipates from the atmosphere.[39]

Due to the heat trapping ability of the different gases and the time they stay in the atmosphere, emitting the same amount of each gas would have very different impacts on the climate over time.

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[36] (IPCC, 2014a, pp. 731–738, Appendix 8.A)

[37] While each emission of methane has a relatively short-lived impact on air temperatures, most of the warming it causes is taken up by the oceans. Indeed, Ocean warming accounted for more than 90% of the energy accumulated in the climate system between 1971 and 2010. (IPCC, 2014b)

[38] (Reisinger, 2018)

[39] Figure is based on 2016 emissions in Aotearoa. (Interim Climate Change Committee, 2019, p. 25, Figure 3.4)

Over approximately 200 years, one tonne of methane would cause more warming than one tonne of carbon dioxide.

Nitrous oxide is the third most important of the human-driven greenhouse gases in the atmosphere. Because nitrous oxide concentrations in the atmosphere are low, its energy absorption bands are much less saturated than those of carbon dioxide. As a result, it is a much more powerful greenhouse gas in the atmosphere than carbon dioxide on a molecule-by-molecule basis[40] and is relatively long-lived in the atmosphere. However, concentrations of nitrous oxide are much lower than carbon dioxide or methane – around a thousand times lower than carbon dioxide – and the overall effect means it has contributed less to human-driven warming (at around 6%).

1.2.2 Effects of long-lived and short-lived greenhouse gas emissions on climate

Long-lived greenhouse gases accumulate in the atmosphere – they are effectively being added faster than they are being removed.[41] Therefore, a constant rate of emissions leads to increasing concentrations and more warming.

Short-lived gases do not last as long in the atmosphere, so a constant rate of emissions would eventually lead to a constant concentration. This eventually leads to a zero additional warming, although this effect takes time to stabilise. For example, a constant rate of methane emissions would take more than a century to stabilise the concentration of methane and increase the warming effect by about a third.[42]

The different lifetimes and effects of long- and short-lived gases means different actions are required to reduce their effect on the climate.

Emissions of long-lived greenhouse gases need to drop to zero to stop warming. In comparison, any reduction in the rate of emissions of short-lived gases will lead to less warming. The more that they are reduced, the greater the reduction in the warming.

Reducing emissions of short-lived gases can have immediate impacts on the amount of warming that occurs, but to ultimately stop warming, it is the emissions of long-lived greenhouse gases – and of carbon dioxide in particular – that need to reduce to zero.

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[40] (IPCC, 2014a, pp. 731–738, Appendix 8.A).

[41] Scientists talk about the 'lifetime' of a greenhouse gas in the atmosphere. The lifetime estimate is made up of how long an individual molecule stays in the atmosphere, which is known as the *turnover* time, and the time it takes for the atmospheric concentration to return to around 37% of its initial value following a one-off emission – known as the *perturbation* time. For carbon dioxide, the turnover time for an individual molecule can be as short as days or weeks. For example, carbon dioxide that is stored in a leaf may be quickly released back into the atmosphere once it decays, whereas another molecule may be stored in the wood of a tree for decades before it is released. However, carbon is only permanently removed from the atmosphere very slowly – through processes like burial in marine sediments when sea creatures die. As a result, the *perturbation* lifetime of carbon dioxide in the atmosphere is centuries to millennia.

[42] (Reisinger, 2018)

1.2.3 What reductions are required to limit warming to 1.5°C?

The *IPCC Special Report on Global Warming of 1.5°C* outlines the science on what global pathways are consistent with limiting warming to 1.5°C. In considering the pathways that are consistent with limiting warming to 1.5°C, the report draws on peer-reviewed modelling studies that are not based solely on atmospheric science, but also consider the feasibility and costs of reducing emissions across sectors and gases, using a range of socio-economic scenarios.

The IPCC report shows that limiting warming to 1.5°C will require rapid emissions cuts of greenhouse gases between now and 2030, then slower reductions until the end of the century. The 1.5°C compatible pathways show different pathways and reduction levels for the main greenhouse gases, which reflect their different warming properties and impacts. However, the compatible pathways have several features in common:

- Emissions of carbon dioxide and other greenhouse gases need to peak in the 2020s then rapidly reduce through the 2030s and 2040s.
- Gross emissions of long-lived greenhouse gases need to be near-zero by 2050. Most of the pathways have some remaining gross emissions in 2050 from hard-to-abate sectors: for example, carbon dioxide produced from cement manufacturing and nitrous oxide from agriculture. As a result, emissions removals are required in the pathways to ensure net emissions reach zero.
- Emissions of short-lived gases such as methane need to reduce significantly through the next 20 years, but not necessarily to zero by 2050 or 2100.

Box 1.4: IPCC pathways, Representative Concentration Pathways and other key assumptions

The IPCC pathways for future warming contain a range of assumptions about economic growth, technology developments and lifestyles. The IPCC modelling found 1.5°C compatible pathways that covered a broad range of possible future developments across economic and demographic changes.[43]

The IPCC developed four archetype scenarios to illustrate the breadth of possible 1.5°C trajectories the world could take. The four scenarios are:

S1 – A pathway based on sustainable development and a global focus on technology and behaviour change

S2 – A pathway with moderate assumptions about technology and population growth

S5 – A fossil-fuel intensive scenario, with a high reliance on carbon capture and storage and significant overshoot of the 1.5°C threshold

LED – Low energy demand. A scenario with a stronger focus on energy efficiency.

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[43] The IPCC also found that some features of global pathways are strong impediments to reaching the 1.5°C goal (IPCC, 2018a, p. 95). Keeping to 1.5°C was particularly difficult in global development pathways that included:

- a lack of global cooperation
- high global inequality
- high population growth, or rapidly growing resource-intensive consumption (section 2.3.1.1 (IPCC, 2018a, pp. 109–110))

Figure 1.7 illustrates the range of assumptions in these scenarios in population growth, world gross domestic product, global energy demand and global food demand. All 1.5°C scenarios are included in light blue; all other scenarios are included in grey; the four illustrative scenarios are highlighted in dark blue.

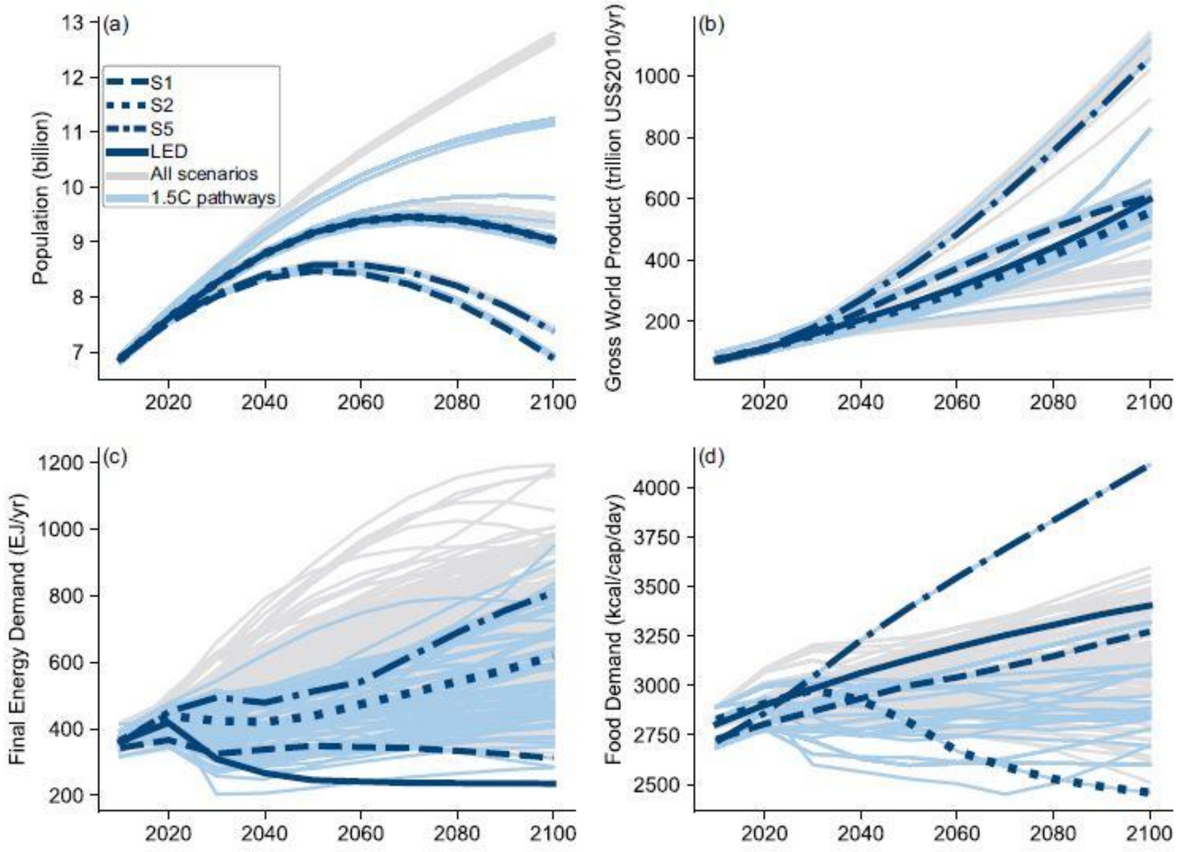

Figure 1.7: Range of assumptions and drivers in scenarios modelled by the IPCC[44]

Figure 1.8 illustrates that keeping warming to 1.5°C is not dependent on a particular technology, or any single future pathway for global development. There is a range of possible futures where the 1.5°C goal is achieved.

The modelled pathways that were the most difficult to keep warming to 1.5°C were those with significant fossil fuel development (SSP5), low global cooperation (SSP3) or high global inequality (SSP4). The middle-of-the-road assumptions (SSP2) with limited global cooperation, some technological progress and medium population growth, were still compatible with keeping to 1.5°C.[45]

A key conclusion from the scenarios that are compatible with limiting warming to 1.5°C is that they all assume global population and food demand will increase over the course of the century, although

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[44] (IPCC, 2018a, p. 111, Figure 2.4)

[45] Four out of six models found 1.5°C compatible pathways in the SSP2 scenario.

some of the scenarios expect both population and food demand to drop by 2100.

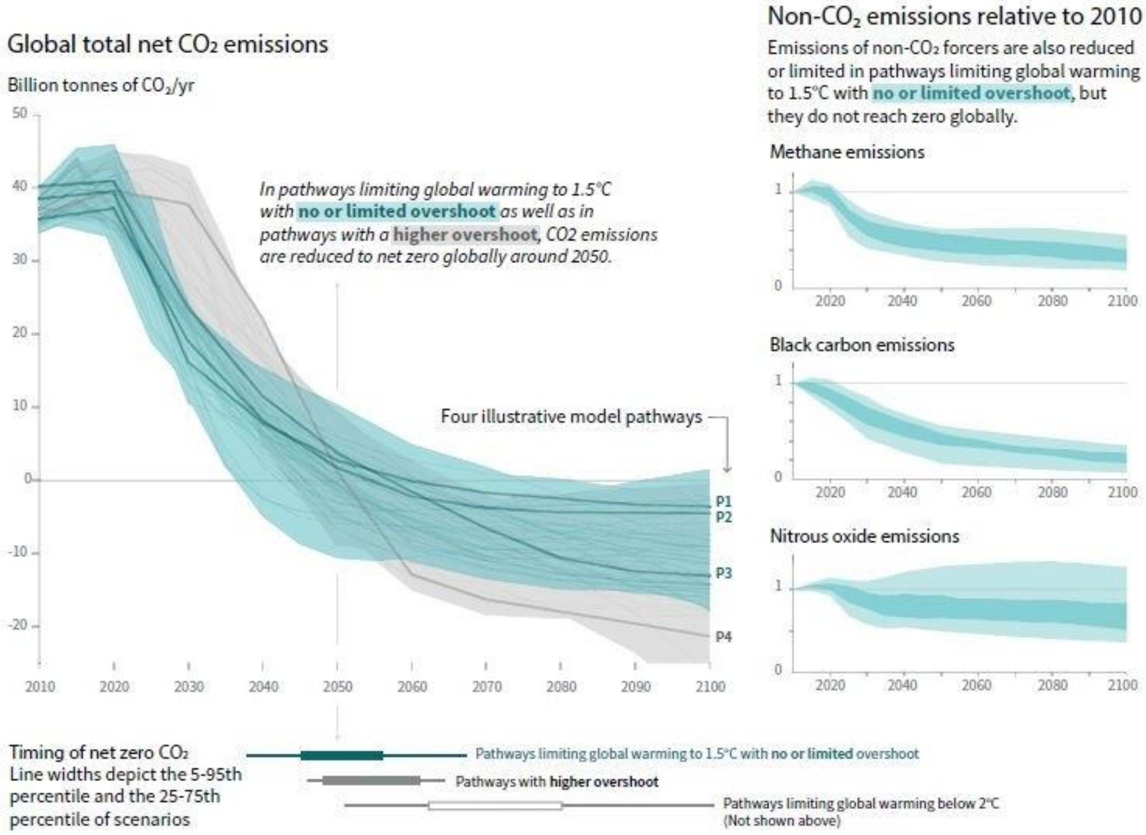

Figure 1.8: Global 1.5°C emissions pathways used by the IPCC[46]

1.2.4 What is 'overshoot' in the IPCC models?

Most of the scenarios that the IPCC modelled overshoot 1.5°C warming to some extent before returning back to 1.5°C in the second half of the 21st century. To bring warming back down, they require removing carbon dioxide from the atmosphere – for example, by sequestering carbon dioxide in permanent forests or using carbon capture and storage – or deeper reductions in methane and other short-lived gases.

The IPCC classified different modelled pathways based on how much they would overshoot 1.5°C (Table 1.1) and concluded that pathways with little or no overshoot were the most likely to limit warming to 1.5°C. These pathways were also assessed as the ones most likely to lead to the best overall social, economic and environmental outcomes.[47]

Pathways with higher overshoot allow more gradual reductions in gross emissions, however they rely on deploying large scale emissions removal technologies after 2050. For example, the pathways

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[46] (IPCC, 2018b, p. 13, Figure SPM.3a)
[47] (IPCC, 2018a)

that assume slower reductions in fossil fuel use require carbon dioxide sequestration to scale up to around a third of current global carbon dioxide emissions levels by 2050.

Table 1.1: The IPCC classified the 1.5°C pathways based on how much they would overshoot 1.5°C[48]

Level of overshoot	Description
No overshoot	Pathways limiting peak warming to below 1.5°C during the entire 21st century with at least 50% likelihood.
Limited overshoot	Pathways limiting median warming to below 1.5°C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier, generally implying peak warming of less than 1.6°C.
Higher overshoot	Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying peak warming of 1.6-1.9°C.

There are significant risks that the scale of emissions removal technologies required in these high overshoot pathways may not be feasible. To date, none of these technologies have been trialled or used at scale. In many of the pathways the required levels of deployment exceed recent literature assessments of the potential for their deployment by the middle of the century.[49]

Afforestation and reforestation are also unlikely to provide the scale of emissions reductions required to bring temperatures back down in high-overshoot pathways. This is because reforesting removes carbon that was originally emitted from deforesting in earlier decades (or centuries). While afforestation can be thought of as capturing the emissions associated with the deforestation, it does not undo the emissions associated with fossil fuel combustion and cannot alone be relied upon to ensure net zero targets are met.

The higher overshoot pathways are also associated with higher levels of climate change impacts due to the higher warming experienced throughout the 21st century. Higher overshoot pathways would mean that future generations would have to deal with more severe climate impacts and adaptation challenges at the same time as needing to deliver large scale emissions reduction technologies to compensate for delayed action from the present generation.

Based on the above analysis, we have excluded pathways with higher overshoot from our analysis of 1.5°C compatible pathways – both for the globe and for Aotearoa.

1.2.5 1.5°C compatible pathways: the reductions in greenhouse gases needed to limit warming

From here on, we refer to pathways that are compatible with limiting warming to 1.5°C with no or limited overshoot as '1.5°C compatible pathways.'

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[48] Table 2.1, (IPCC, 2018a, p. 100)
[49] (IPCC, 2018b, p. 17)

Within the IPCC 1.5°C compatible pathways there are a wide range of assumptions that feed into the models. Some of these are less likely than others. For example, some of the pathways assume slower reductions in gross emissions which are then offset by removals in the order of 7-13 $GtCO_2$ each year.

Removals of emissions on this scale rely on technologies like carbon capture and storage (CCS) that are very expensive or are not yet widely in use. For example, CCS has been deployed at only a small scale globally. In 2020 there were 59 facilities operational with a capacity of 127 $MtCO_2$ per year.[50] Bioenergy with carbon capture and storage (BECCS) is only a small subset of wider CCS deployment. According to the global CCS institute, as of 2019, five facilities globally were using BECCS, capturing a total of 1.5 $MtCO_2$ per year.[51] Other pathways assume unrealistically optimistic emissions reductions in the near term – reaching net zero carbon dioxide globally as early as 2036.

Excluding the most unrealistic pathways gives the following reductions in net carbon dioxide, and methane and nitrous oxide from agriculture in 2030 and 2050 (Table 1.2).[52]

Table 1.2: Reductions in greenhouse gas emissions in IPCC model pathways with no or limited overshoot (interquartile range)

Greenhouse gas emissions	**Percentage change relative to 2010**	
	2030	2050
Net carbon dioxide emissions	-40 to -58%	-94 to -107%
Agricultural methane emissions	-11 to -30%	-24 to -47%[53]
Agricultural nitrous oxide emissions	+3% to -21%	+1% to -26%

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[50] (Global CCS Institute, 2020)

[51] (Consoli, 2019)

[52] To exclude the most unrealistic pathways in our analysis, we have used the interquartile range of the IPCC pathways scenarios.

[53] This range provided the basis for the 2050 methane target in the CCRA of 24-47% below 2017 levels. Methane emissions in Aotearoa changed by less than 0.5% between 2010 and 2017, so a later base year was used for easier comparison.

Box 1.5: New analysis since the IPCC 1.5°C report was released

Since the *Fifth Assessment Report* and the *IPCC Special Report on Global Warming of 1.5°C,* there have been several comparisons and assessments of the range of available climate models.[54] One factor that has improved in the models over time is how they model the sensitivity of the climate to the greenhouse gases. The updated evidence on the sensitivity of the climate has narrowed the range of possible response to future greenhouse gas emissions.[55] As this revised uncertainty in the earth's climate sensitivity largely affects the tails of the distribution, the central estimates of projected warming remain similar to those shown in the *Fifth Assessment Report* and the *IPCC Special Report on Global Warming of 1.5°C*.[56] This gives us greater confidence that the emissions pathways presented in the *IPCC Special Report on Global Warming of 1.5°C* provide a sound basis for describing the actions needed at a global level to limit warming to 1.5°C.

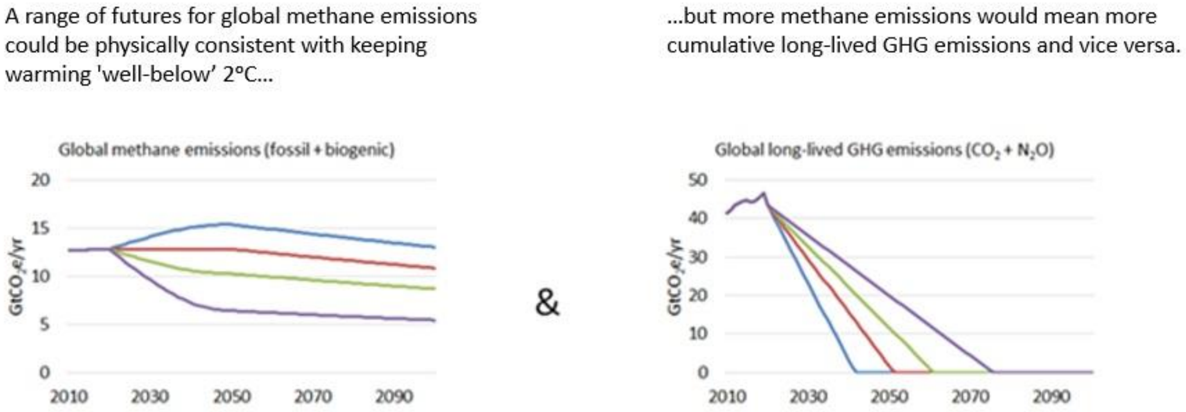
1.2.6 Trading off reductions and removals within the 1.5°C compatible pathways

These pathways give the ranges of reductions for each gas that have been modelled to limit warming to 1.5°C. They all require significant and rapid reductions in carbon dioxide and methane. Within them, there are different combinations of reductions of the gases and emissions removals that can potentially lead to the same warming outcomes. However, different combinations of actions can have different implications on longer-term temperatures and impacts, and on the costs people face.

In the IPCC pathways, the level of cuts to methane emissions modelled in the long-term to be compatible with the 1.5°C goal depends on two inter-related relationships:

1. the speed of reaching net zero for long-lived greenhouse gases, and
2. the extent to which we can rely on removal technologies.

First, there is a relationship between the rate of methane emissions globally in the period before peak warming and the modelled cumulative long-lived greenhouse gas emissions from now (2021) until the peak temperature is reached. The more long-lived greenhouse gases are reduced, the relatively smaller reductions in methane are needed (Figure 1.9).



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[54] Including the sixth climate model intercomparison exercise.

[55] (Sherwood et al., 2020)

[56] (Forster et al., 2021)

Figure 1.9: Stylised trajectories that illustrate the trade-off between global trajectories for methane emissions caused by humans (fossil and biogenic sources) and long-lived GHG (LLGHG) emissions using the framework of Cain et al. (2019). Trajectories are constructed to keep expected peak warming to approximately 1.75°C above pre-industrial levels.[57]

Second, reductions in the rate of methane emissions have an equivalent effect on warming to net removals of carbon dioxide, by immediately reducing the warming contribution of methane. In the long-term, greater reductions in the rate of methane emissions reduce the world's dependence on carbon dioxide removal.[58] Conversely, the more carbon dioxide removal that can be deployed, the fewer methane reductions are required for the same temperature outcome. However, there are also consequences for the climate from the temperature pathway up to and after the peak temperature, which is affected by the relative trade-offs between methane reductions and net removals of carbon dioxide. This is discussed in the next section.

Therefore, for a given temperature goal in the medium-long-term – out to 2050 and beyond – the three factors can be balanced between each other with more emissions of one kind requiring greater reductions of another (Figure 1.10):

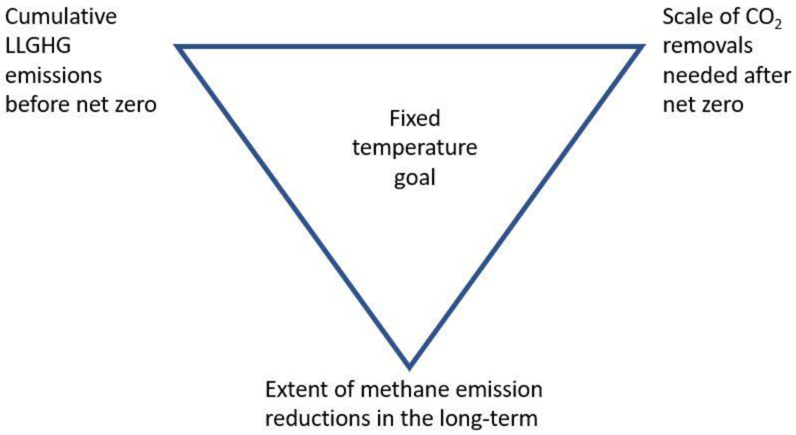

Figure 1.10: Interaction between the fixed temperature goal and various options

Box 1.6: What are metrics and how are they useful?

Greenhouse gas emissions metrics are used to assess the contributions to climate change of different gases. They can be thought of as exchange rates that allow different gases, which have different heat trapping properties and lifetimes in the atmosphere, to be compared using a common scale.

Metrics commonly relate the climate effects of emissions to those of carbon dioxide, with carbon dioxide taking a value of 1. A formula or weighting factor is used to convert mass units (e.g. tonnes) of non-carbon dioxide gas emissions into carbon dioxide equivalent emissions (CO_2e). This aims to equate the non- gas emissions to an amount of carbon dioxide that would generate the same amount of warming.

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[57] (Forster et al., 2021)

[58] (Forster et al., 2021; Parliamentary Commissioner for the Environment, 2018)

Metrics are used in a range of contexts where there is a need to aggregate, compare or evaluate emissions of multiple greenhouse gases. For example, they are used in:

1. **Reporting**, to express aggregate emissions of various gases, such as in national greenhouse gas inventories or in 'carbon footprints' of products (lifecycle assessment).
2. **Mitigation policy**, to make decisions about the effort and cost warranted to reduce or avoid the emissions of a quantity of one gas as compared to another gas at a given time.
3. **Evaluating pathways**, to consider trajectories across different gases to reach climate policy objectives, such as emissions reduction targets or the 1.5°C temperature goal.

To date, the most well-known metrics used in climate policy and related literature are the Global Warming Potential (GWP) and the Global Temperature change Potential (GTP). Recently, a new metric called GWP* has been developed.

GWP compares gases based on the amount of carbon dioxide that would have produced the same warming effect ('radiative forcing') over the same period as the gas being emitted. GTP compares gases based on the actual warming they cause at a specific single future point in time. Both GWP and GTP values depend on specific time horizons (i.e. how far into the future the climate effects of each gas are considered). GWP* is a new variation on GWP. It compares a sustained change in the rate of emissions of a short-lived gas with a one-off emissions of carbon dioxide, rather than GWP's and GTP's comparison of the climatic effects of one-off emissions of both types of gases.

Different metrics are suited to different purposes

There is wide agreement across scientists that the appropriate choice of metric cannot be determined by science alone but depends on broader policy contexts and goals and underlying value judgements.[59] Different metrics have different strengths and weaknesses and there is no one 'correct' metric that is useful for all purposes.

This can be illustrated by considering the GWP with a time horizon of 100 years (GWP_{100}, the metric adopted for reporting aggregate emissions under international agreements) with GWP*.

When GWP_{100} is used to look at mitigation scenarios over long timeframes (several decades or longer) it does not provide robust estimates of actual temperature outcomes.[60] It does not give good information for making decisions about trade-offs between reducing methane emissions vis-à-vis carbon dioxide emissions when considering trajectories for, or compliance with, temperature targets such as the 1.5°C goal in the CCRA.

GWP* was developed to provide a better representation of the warming impacts of methane relative to those of carbon dioxide.[61] In particular it better reflects the fact that a gas like methane has a short lifetime in the atmosphere and captures the effects of increases or decreases to the rate of methane emissions on temperature outcomes relative to that of carbon dioxide . Although understanding of GWP* is still developing, it appears to be more suitable than GWP_{100} for analysing global emissions reduction pathways to limit temperature increases.

However, GWP* is less useful in other accounting, reporting and domestic policy applications because it relies on more complex interactions over time. It cannot be applied consistently to a pulse of emissions in a given year as the warming effect depends on the level of warming over previous decades. As a warming metric it is also more uncertain than a forcing metric such as

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[59] (Hollis et al., 2016; IPCC, 2009; Levasseur et al., 2016; Tanaka et al., 2013)

[60] (Allen et al., 2016)

[61] (Ibid.)

GWP_{100} as it incorporates uncertainty in the global temperature response to a given level of forcing.

Changes to methane emissions that are relatively small under GWP_{100} are much larger under GWP*. For example, if a dairy farmer added one cow to their herd in a given year and that cow emitted 100 kg of methane, this would be the equivalent of emitting 250 tCO_2 in that year under GWP*, rather than 2.5 tCO_2 under GWP_{100}. If these emissions were priced, this would incur a one-off liability of $8,750, assuming an emissions price of $35/tonne.

GWP_{100} provides a more stable way of accounting and reporting greenhouse gases and is the metric required for emissions budgets under the CCRA. Its use for this purpose is not inaccurate as this does not involve assessing warming impacts. In Aotearoa, the split-gas 2050 target already reflects the different warming effects of biogenic methane and there is no need to make a choice of metric to attempt to better reflect the warming impact of different gases.

While the CCRA and the international emissions reporting and accounting framework require that targets be reported against and accounted for using GWP_{100}, there may be merit in further exploration of how GWP* could be useful domestically.

Finally, use of metrics is not always necessary. In our mitigation pathway analysis, we have applied a split-gas framework that avoids the use of metrics to compare methane with other gases or trade off emissions reduction efforts across the different gases.

1.2.7 When are the reductions in methane needed and why?

The above section shows there are trade-offs that can be made between reductions in methane and removals of emissions that can lead to the same temperature goal. However, it is also important to consider whether methane is acted on sooner or later.

Emissions of methane in the short-term are important because they affect the temperature trajectory in reaching the long-term goal. Whether a given level of reductions in methane emissions occurs sooner (2020-2040) or later (2040-2060) will affect the level of warming the world experiences and the chance of significant overshoot.

Reducing methane emissions earlier rather than later in the century leads to a higher likelihood that temperatures will not overshoot the 1.5°C threshold. Figure 1.11 illustrates two generalised scenarios for a given level of cuts to methane in the long-term. The trajectory of cuts to long-lived greenhouse gases are the same in both scenarios, as are the long-term cuts to methane emissions. Consequently, the final temperature is also the same in both scenarios. However, in one scenario the cuts to methane emissions happen earlier, which leads to temperatures remaining below the final temperature threshold rather than overshooting and then returning to it.

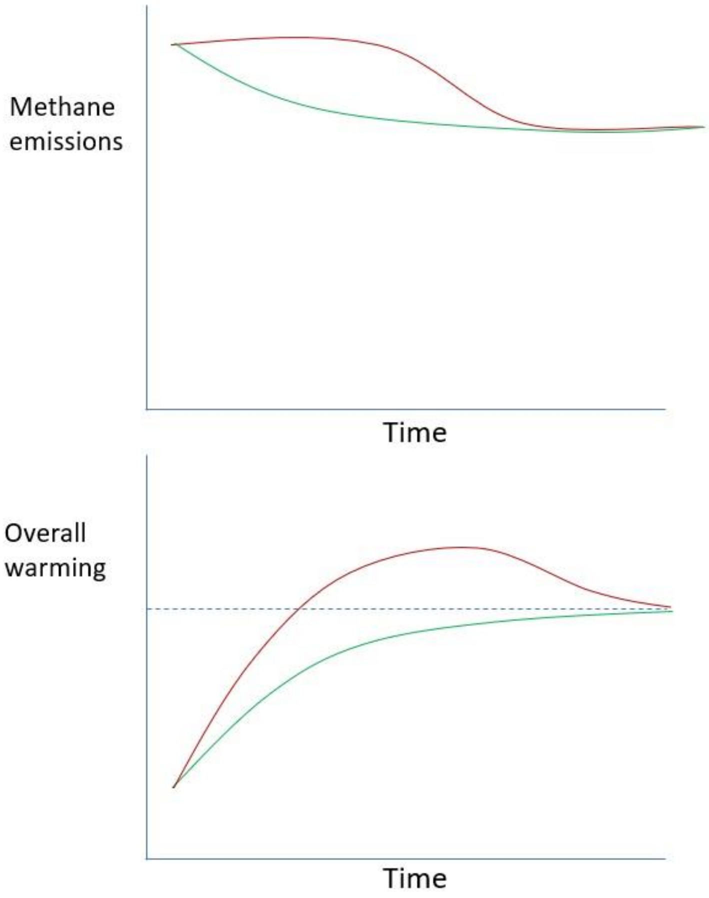

Figure 1.11: The impact of early action (green line) versus later action (red line) on reducing methane emissions. The same level of reduction in methane would ultimately lead to the same temperature outcome. However, earlier cuts lead to less cumulative warming and reduce the chance of overshooting the goal and experiencing the negative impacts associated with higher temperatures.

As a result, in modelled pathways compatible with limiting warming to 1.5°C, much of the cuts to biogenic methane occur between 2020 and 2030, with slower reductions between 2030 and 2050 and much more limited reductions after 2050 (as illustrated in Figure 1.11).

The timing of cuts to methane required to be compatible with the 1.5°C global goal depends on our view of overshoot and how much we value avoiding warming in the near-medium term in addition to reducing warming in the long-term. It also depends on how much we wish to rely on removals to meet our goals and for what purpose we want to use those removals.

Acting earlier on methane has advantages in that it:

- Leaves more time to reduce gross emissions of hard-to-abate long-lived greenhouse gases.
- Reduces risks of impacts from higher temperatures, including irreversible changes such as species' extinctions or catastrophic damage from more extreme weather events and faster and higher sea level rises.
- Leaves more of the emissions removal opportunities available to be used to get long-lived greenhouse gases to net zero.

These benefits were reiterated in the work by the UN Environment Programme and the Climate and Clean Air Coalition. Their report *Global Methane Assessment: Benefits and costs of mitigating methane emissions* (2021) emphasised that the short atmospheric lifetime of methane means that making emissions reductions early will more quickly result in reductions in concentrations and more rapidly slow temperature increase.

1.3 How different are the pathways that limit warming to 1.5°C to those that limit warming to well below 2°C?

Our domestic emissions reduction goal raises an important question about the level of effort that is required to reduce emissions. Aotearoa has set a different goal for its domestic actions compared to what may be required under the wording of the Paris Agreement – Aotearoa has set a domestic target of limiting warming to 1.5°C. The Paris Agreement sets the goal of limiting temperature increases to well below 2°C while pursuing efforts to limit the temperature increase to 1.5°C. How material is the difference of a few tenths of a degree between our domestic and international obligations?

Analysis of the 1.5°C compatible pathways compared to pathways that limit warming to well below 2°C shows some key similarities (Figure 1.12). Both sets of pathways require very similar reductions in gross emissions, particularly of carbon dioxide. The rates that global temperatures change out to the peak temperature are also broadly the same (Figure 1.13). Under both temperature goals, carbon dioxide needs to rapidly reduce over the next two decades and reach very low levels by 2050.

The main difference is in the amount of carbon dioxide removals required in the different pathways. More emissions removal is needed in the 1.5°C compatible pathways to limit warming to the temperature target, often by bringing the temperature back down to 1.5°C after it has overshot the target.

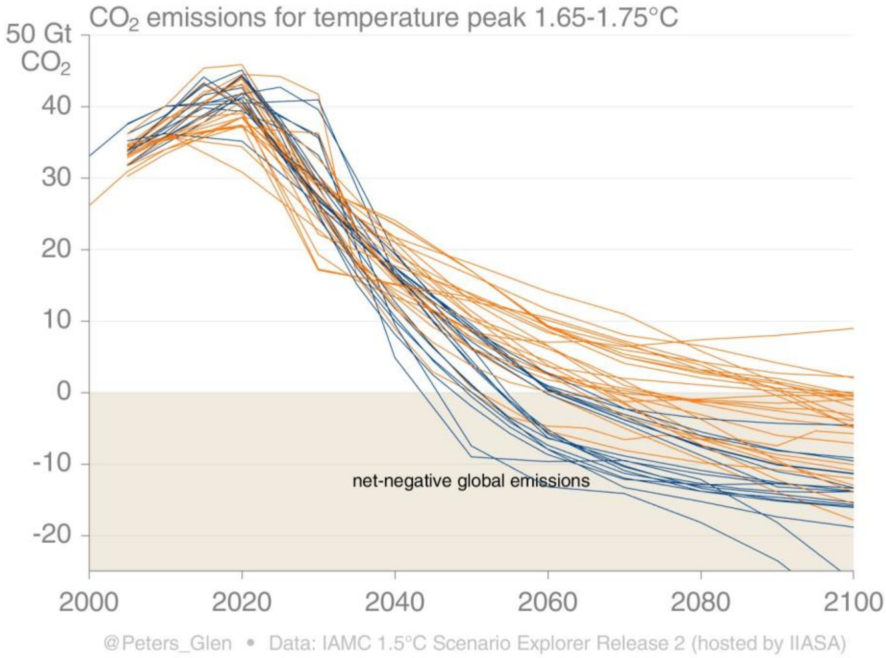

Figure 1.12: Reductions in CO_2 required in pathways compatible with less than 2°C (orange) and 1.5°C (blue)[62]

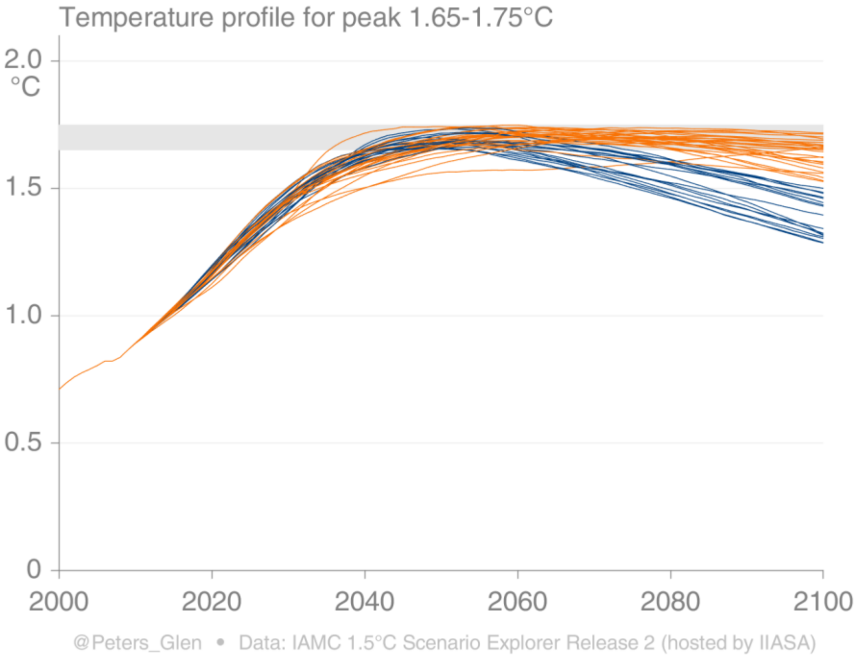

Figure 1.13: Peak temperatures in less than 2°C (orange) and 1.5°C compatible with limited overshoot (blue). 1.5°C compatible pathways reach the same temperatures before dropping back down.[63]

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[62] (Peters, 2020a) using data from (Huppmann et al., 2019)

[63] (Peters, 2020b) using data from (Huppmann et al., 2019)

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