

METHANE SCIENCE AND TARGET REVIEW

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Executive Summary

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Introduction

The purpose of the Methane Review Panel, as described in the Terms of Reference (Appendix 1) is to deliver an independent review of methane science, and the 2050 target, for consistency with no additional warming from agricultural methane emissions. In this report, we review the science of methane and its warming impact and provide advice on what a biogenic methane target consistent with the principle of no additional warming would look like for New Zealand (NZ).

NZ's 2050 target was set as part of the Climate Change Response (Zero Carbon) Amendment Act 2019, which amended the Climate Change Response Act 2002 (CCRA). Further details on the legislation are provided in the next section. Under the CCRA, NZ adopted a split-gas approach to the 2050 target based on scientific evidence that biogenic methane, as a short-lived gas, has a different warming impact in comparison to other greenhouse gases so does not have to reduce to zero to limit global warming. The legislated 2050 target for biogenic methane requires that NZ's gross emissions of biogenic methane in a calendar year are 24 - 47% less than 2017 emissions by 2050 and for each subsequent calendar year.

New Zealand is unusual for a developed country in having a relatively high proportion of methane emissions in its inventory, and these arise largely from agriculture. Our portfolio of emissions is more typically found in developing countries ~~and is very unusual for a developed country~~: in most other developed countries, methane emissions are associated with fossil fuel production. In such instances, decreasing methane emissions from both fossil fuel production and waste have been identified as low cost solutions and have been included in policy directions. Reducing the emissions from agriculture, by contrast, is more problematic due to the challenges in meeting the Paris Agreement stipulation that it must be 'in a manner that does not threaten food production' **and the availability of technology** to do so for both rice paddies and farm animals within this constraint. Accordingly, NZ is striving to monitor and mitigate its own methane emissions situation consistent with meeting the legislative requirements, including no additional warming from agricultural emissions by 2050.

In the five years since NZ's emissions targets were devised, understanding of the science of methane's climate impact has evolved. In particular, how scientific understanding of methane is represented and how short and long-lived gases are compared. This report reviews that understanding, defines what no additional warming means and assesses what targets are consistent with no additional warming from biogenic methane.

Terms of Reference

The scope defined in the Terms of Reference (Appendix 1) is for the report to include:

- a) a background on New Zealand's climate change targets and legislation;

- b) an overview of the concept of no additional warming, including a clear definition of what no additional warming is in the context of a biogenic methane target;
- c) a review of previous studies that estimate a no additional warming target for biogenic methane (including any differences between them);
- d) an up-to-date explanation and summary of the warming impact of biogenic methane, specifically including biogenic methane from New Zealand's agricultural sector;
- e) a brief explanation of the global emissions scenarios relevant for determining target ranges for biogenic methane emissions;
- f) consideration of a range of no additional warming biogenic methane emission reductions targets that reflect different background global emissions scenarios, including a scenario that is consistent with limiting global warming to 1.5 degrees Celsius (e.g., Shared Socioeconomic Pathway 1-1.9 from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)); and
- g) estimates of biogenic methane emissions reductions needed in 2050 and 2100 to achieve and maintain a state of no additional warming from New Zealand's biogenic methane emissions relative to 2017 levels of warming.

Out of scope was making any conclusions or recommendations that go beyond performing the scientific review and providing the evidence-based advice required by these terms of reference, and reviewing any other aspects of the 2050 Target as set out in s5Q of the Climate Change Response Act 2002

The Panel Approach

The panel has endeavoured to capture the most up to date scientific evidence on methane and its impact to address the challenges raised in the terms of reference. The approach taken has been to first summarise the legislation, critical in the fact that it distinguishes between short and long term gases and gives them separate targets.

The science of methane is then presented to provide clarity for the reader and to inform the modelling assumptions used later in the report. This is followed by an explanation of NZ's methane profile and how it has evolved in recent years within the context of the global methane budget. As the topic of this report is methane, no attempt is made to present it as carbon dioxide equivalents or any other metric. Throughout the report we present methane emissions in megatonnes¹ of methane (Mt CH₄).

The next section explains the complex role of methane as a greenhouse gas and how this is the basis for the modelling of future possibilities. A definition of additional warming follows with examples given of previous studies that have determined targets that are consistent with no additional warming from agricultural methane emissions.

To simulate the temperature effects of a range of possible changes in future NZ methane emissions, it is necessary to apply these to possible, plausible global scenarios for future emissions from the rest of the world. This is due to the fact that global levels of methane will influence the warming impact of NZ's methane emissions. Because NZ's methane emissions are around ~~just~~ 0.35% of global anthropogenic methane emissions, a range of global scenarios provide essential context for the evaluation of New Zealand biogenic methane's contribution to warming. The scenarios chosen for this review to provide that context, the socio-economic pathways (SSPs) adopted by the IPCC, are outlined next along with an explanation of the dynamic relationship between them and methane lifetime, a critical variable in the analysis.

The impact of a range of methane emissions futures within each scenario were explored to assess conditions under which there may be no additional warming from New Zealand's biogenic methane. The range includes both per annum and straight line reductions as well as the two targets for 2050 currently in the legislation. The results of this modelling are presented and discussed with reference to how they deliver to the challenges raised in the terms of reference.

The Appendices include the full terms of reference, the methodology of the modelling, further legislative details and a 'frequently asked questions' section that provides answers on challenges not central to the report but received in the submissions.

¹ One megatonne (Mt) equals one million metric tonnes.

Legislation

The Paris Agreement & NZ's response

NZ signed the Paris Agreement in 2016. The aim of the agreement, as described in Article 2, is to have a stronger response to the danger of climate change; it seeks to enhance the implementation of the United Nations Framework Convention on Climate Change through:^[3]

(a) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

(b) Increasing 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;

(c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

Countries furthermore aim to reach "global peaking of greenhouse gas emissions as soon as possible."

NZ's Climate Change Response (Zero Carbon) Amendment Act 2019, which amended the Climate Change Response Act 2002, established the domestic climate change 2050 target, designed to contribute to the global effort to pursue efforts to limit warming to 1.5°C. It enables NZ to:

- meet international obligations under the United Nations Framework Convention on Climate Change (UNFCCC) Kyoto Protocol and the Paris Agreement;
- contribute to the global effort under the Paris Agreement to pursue efforts to limit the global average temperature increase to 1.5° Celsius above pre-industrial levels.
- allow NZ to prepare for and adapt to the effects of climate change.

The 2019 amended act resulted in four key actions:

1. Set the domestic climate change target (the 2050 target).
2. Establish the emissions budgets (EBs) system.
3. Develop a framework for policies for climate change adaptation and mitigation.

4. Establish the Climate Change Commission (CCC) to provide independent expert advice and monitoring.

International reporting

The Paris Agreement transparency framework requires that emissions data be reported according to the United Nations Framework Convention on Climate Change (UNFCCC) guidelines.

NZ's Greenhouse Gas Inventory (MfE, 2024) is published annually as part of international reporting obligations under the Paris Agreement and UNFCCC. The inventory is the official annual report of estimated human-induced emissions and removals of greenhouse gases in Aotearoa.

The inventory reports greenhouse gas emissions and removals from five sectors: agriculture; energy; industrial processes and product use (IPPU); land use, land use change and forestry (LULUCF), waste. Gross emissions are reported as the total emissions from agriculture; energy, IPPU and waste. Net emissions are reported for the LULUCF sector.

The latest Greenhouse Gas Inventory (MfE, 2024) reported on greenhouse gases that have direct warming effects: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride. Indirect gases are also reported but not included in Aotearoa's greenhouse gas total.

NZ's Greenhouse Gas Inventory presents all gases as CO₂ equivalents (CO₂-e). To obtain CO₂-e values, methane emissions (in kilotonnes, kt) are multiplied by their 100-year global warming potential of 28 (see Frequently Asked Questions). This is to enable international reporting and, as stated in the report, is consistent with decisions 1/CP.24, 18/CMA.1 and 5/CMA.3 (IPCC, 2013). In this report we consider methane emissions only by their mass and not as CO₂ equivalent to assess emissions consistent with no additional warming.

NZ's Greenhouse Gas emissions projections to 2050 are reviewed every 2 years as part of international reporting. In addition, NZ is required to submit national climate change action plans known as Nationally Determined Contributions (NDCs) to UNFCCC every five years to help achieve long-term goals. Further details on the NDC process are provided in Appendix 3.

Domestic targets

NZ's domestic climate change targets are established under the Climate Change Response (Zero Carbon) Amendment Act. The 2050 Targets are:

- Net zero emissions of all greenhouse gas (GHG) emissions other than biogenic methane by 2050.

- 24 to 47 per cent reduction below 2017 biogenic methane emissions by 2050, including 10 per cent reduction below 2017 biogenic methane emissions by 2030.

NZ’s domestic target is a split-gas approach, reflecting the different warming impact that methane has in comparison to other greenhouse gases, such as carbon dioxide. Under the Act, biogenic methane refers to all methane greenhouse gases produced from the agriculture and waste sectors (reported as CO₂ equivalents in the NZ Greenhouse Gas Inventory Report).

The NZ Greenhouse Gas Inventory states that in 2022, NZ’s methane emissions were 38339.3 kt CO₂-e or 1.369 Mt CH₄ (MfE, 2024). Unlike most developed countries, most of New Zealand’s methane emissions are produced by livestock through enteric fermentation 32617.2 kt CO₂-e (1.164 Mt CH₄) in the agriculture sector (Fig. 1). Methane is also the largest component of waste sector emissions, contributing 1803.7 kt CO₂-e (0.064 Mt CH₄) 0.116. Based on this information the biogenic methane, including manure CH₄, is calculated as 37679.6 kt CO₂-e, or 1.345 Mt CH₄.

Breakdown of NZ CH₄ emissions

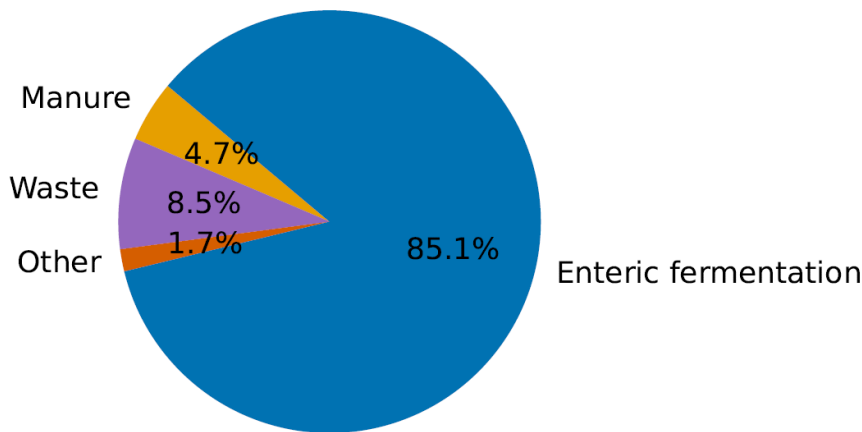


Figure 1: Breakdown of NZ CH₄ emissions in 2022. Data sourced from MfE (2024)

From 1990 to 2006, methane emissions increased, peaking in 2006. Since then, despite some fluctuations, methane emissions have mostly been on the decline, consistently decreasing each year since 2019 (Fig. 2).

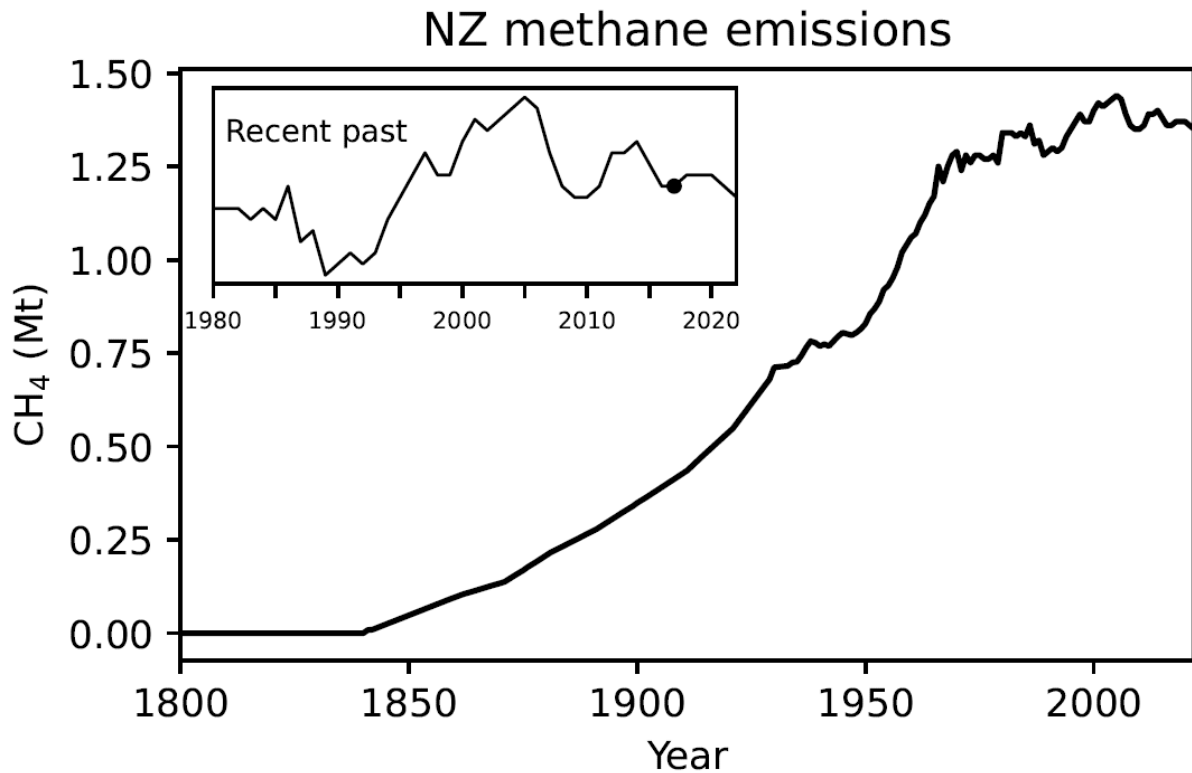


Figure 2: New Zealand’s biogenic (agricultural + waste) methane emissions. Emissions in 2017 were 1.36 megatonnes (Mt), indicated by the black circle in the inset. Data source: Reisinger & Leahy (2019).

The idea of “net zero” emissions has its origins in the relationship between cumulative emissions of long-lived greenhouse gases and temperature (Allen et al., 2009). Exactly how short-lived greenhouse gases like methane fit within this framework depends on how gases are aggregated (Fuglestedt et al., 2018). Most scientists working actively on the issue of comparing gases endorse the idea that policy should indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets (Allen et al., 2022b). New Zealand’s split gas target is consistent with this.

Unfortunately, despite NZ legislation calling out this difference, the Greenhouse Gas Inventory report presents methane emissions as CO₂ equivalents, as this is required for international reporting. The report provides CO₂-e by sector and by gas, the sector amount combines all gases and the gas amount includes all sectors. To determine biogenic methane emissions specifically it is necessary to back calculate the numbers from breakdowns provided in the body of the report. This review focuses on biogenic methane, so reported CO₂e values from the National Inventory Report have been converted to methane emissions throughout.

New Zealand’s 2050 target for biogenic methane was set by using values from a table in the Intergovernmental Panel on Climate Change’s (IPCC) Special Report on Global Warming of 1.5°C (SR1.5) published in 2018. The SR1.5 Report found that to limit warming to 1.5°C, the

world would need to reach net-zero emissions of carbon dioxide by about 2050, along with deep reductions in other GHGs.

The biogenic methane component of the 2050 target was set from ~~an experiment using~~ Integrated Assessment Models (IAMs), and evaluated the range of modelled pathways for biogenic methane from Agriculture, Forestry and Other Land Use (AFOLU) from global scenarios consistent with limiting warming to 1.5°C with no or limited overshoot (Table SPM3b). These pathways were illustrative, and only those models that managed to meet the 1.5°C target were included. The table presenting the results bore the following caveat: “these pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements.”

None of the IAMs in the SR1.5 ~~experiment~~ resolve New Zealand - in all of the IAMs the New Zealand economy is aggregated alongside Australia's, and in several of the IAMs both New Zealand and Australia are included in a larger OECD Asia-Pacific grouping which includes Japan and Korea. Therefore the table used to set New Zealand's biogenic methane target did not evaluate the feasibility of the target from a domestic perspective.

Additional sources of information were also considered as part of the decision-making process for setting the biogenic methane target, though no national economic impact report was sought from the Treasury. Evidence that was sought included evidence related to the achievability of the target as discussed in the Biological Emissions Reference Group (BERG) Report (2018), research commissioned by the Parliamentary Commissioner for the Environment (PCE) on the contribution of methane emissions from NZ livestock to global warming (produced by the New Zealand Agricultural Greenhouse Gas Research Centre), and consideration of technological advancements, scientific advice and New Zealand's national circumstances.

Methane (CH₄)

Methane (CH₄) gas is present in Earth's atmosphere. In 2023, the global average concentration of methane in Earth's atmosphere was 1922 ppb (parts per billion). This means that for every billion molecules in the atmosphere, 1922 of them are methane. Although it is present in small amounts, methane plays an important role in Earth's radiative balance – that is, the energy balance between solar radiation received by the Earth, and terrestrial (thermal infrared) radiation emitted by the Earth.

As with any atmospheric trace gas, there are two quantities that scientists draw on which are related, but distinct. One is the emissions, which correspond to the quantities (megatonnes CH₄) directly released into the atmosphere. The other is the abundance or concentration (parts per billion CH₄) that are found in a volume of air. This reflects the amount, net of emissions and depletion, which, for short lived gases, is very relevant. In simple terms, if there is no increase in emissions of a short-lived gas then there is no increase in concentration. By contrast, for long lived gases the concentration will increase and reflect the accumulation of those gases over time.

Methane is produced by bacteria in anaerobic environments, including wetlands, inland freshwaters, rice paddies, landfills, and the digestive tracts of animals; fossil fuel production and use; and fires. It is broken down by chemical reactions in the atmosphere and by bacteria in well oxygenated soils. The global sources and sinks are summarised in Figure 3, which is produced by the Global Carbon Project, an international consortium of experts that review the literature and provide a regularly updated global methane budget. Methane sources and sinks can be estimated in two different ways: 1) “bottom up” approaches that model the physical or chemical processes of methane emissions to estimate emissions by sector and 2) “top down” approaches that infer emissions from measurements of methane in the atmosphere from sites at the surface, satellites, or other platforms and atmospheric models.

Between 2010 and 2019, atmospheric methane grew by an average of 21 Mt/yr, with a range of 19-33 Mt/yr, called ‘change in atmospheric abundance’ in Figure 3. Anthropogenic activities are responsible for two thirds of this growth (Jackson et al., 2024.) Figure 3 provides both a top down measure of 21 Mt/yr based on observations and a bottom up calculation of 36 Mt/yr based on model estimates. A previous report by this consortium taken from 2008 to 2017 (Saunio et al., 2020) gave numbers of 13 (0-49) Mt/yr and >100 Mt/yr for the top down and bottom up methods respectively. The difference between reports demonstrates the evolution of scientific understanding and modelling of methane. In particular, the two reports accounted for freshwater sources differently.

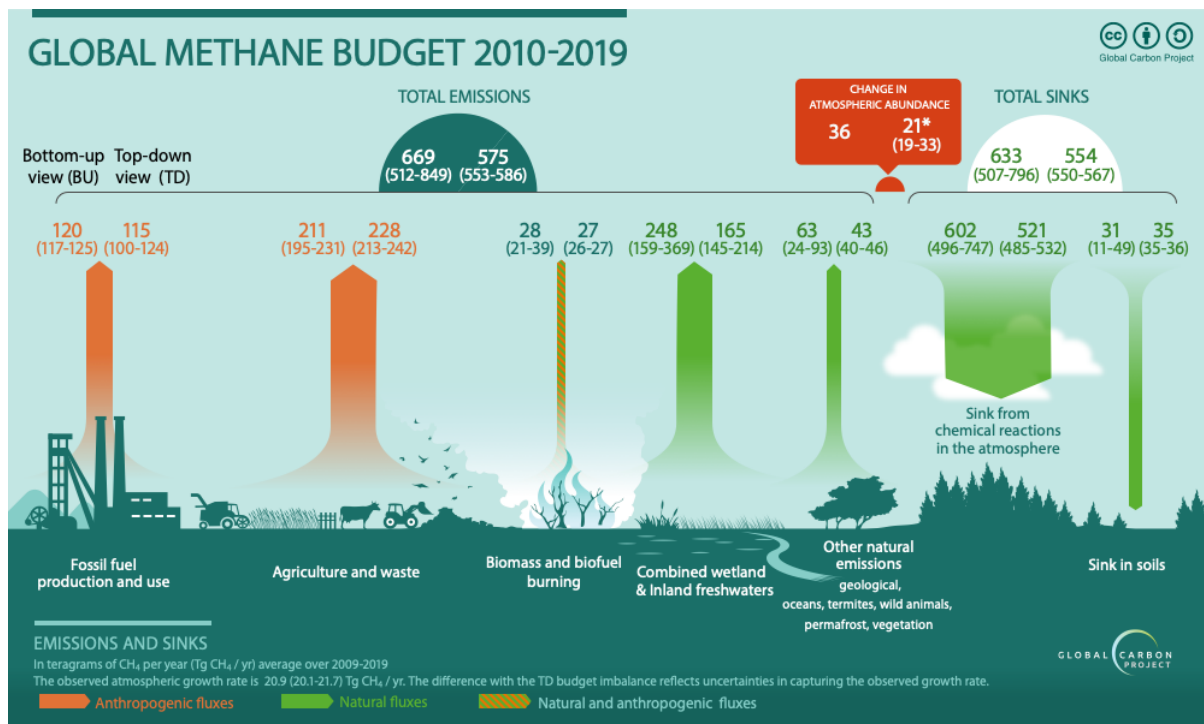


Figure 3: Summary of global methane sources and sinks between 2010-2019. (Saunio et al., 2024). Fluxes are given in teragrams (Tg) of methane per year. One teragram is equivalent to one megatonne (Mt), the unit used elsewhere throughout this report.

Methane Sources

Agriculture

Agriculture, food production, is the largest global source of methane from human activities, and contributes approximately two-thirds of anthropogenic emissions (Figure 3). Methane emissions from livestock primarily come from the digestive processes of ruminant animals, such as cows and sheep. These animals have a special stomach, the rumen, that ferments food and produces methane as a byproduct. In addition, manure from livestock can emit methane when it decomposes, especially in wet conditions.

Methane is also emitted from rice paddies primarily due to the flooded conditions in which rice is typically grown. When fields are flooded, water creates a low-oxygen environment in the soil. This environment allows bacteria that break down organic matter and produce methane to thrive. The methane then escapes to the atmosphere, especially when the water is drained or disturbed during harvesting.

Waste

Methane is emitted from the breakdown of organic matter in landfills and wastewater treatment facilities. Like flooded rice paddies, landfills and wastewater treatment plants are low-oxygen

environments that favour methane-producing bacteria. Thus, methane is generated from the decomposition of organic materials such as food scraps, yard waste, human waste and paper in these environments. Managing waste effectively, such as through composting or capturing methane for energy, can significantly reduce these emissions.

Fossil fuels

While carbon dioxide emissions are a byproduct of combustion, methane emission from fossil fuels are an inadvertent byproduct of extraction, transport, and incomplete combustion of fuel. Natural gas is primarily composed of methane. When extracted, it can escape into the atmosphere through leaks in pipelines, during transportation, and at drilling sites. Methane can also be released from coal seams, a phenomenon known as coalbed methane. This occurs when organic matter in the coal breaks down, producing methane that can escape during mining operations. When oil is extracted and refined, methane can be emitted during drilling, transport, and combustion. Incomplete combustion of oil products can also release methane into the atmosphere.

Fossil methane has become a focus in international climate policy in part because addressing methane leaks from fossil extraction and transport are more economically feasible than many other climate mitigation activities.

Biomass burning and biofuels

Methane is also emitted from the combustion of organic materials such as wood, crop residues, biofuels, and other plant materials. When biomass is burned for energy, incomplete combustion can release methane to the atmosphere along with carbon dioxide and other pollutants. This is particularly common in uncontrolled or open burning practices, such as slash-and-burn agriculture or forest clearing. Similarly, methane is emitted from human caused and natural wildfires.

In the case of biofuels, which are derived from organic materials, methane can also be emitted during the production process.

Wetlands, peatlands, and inland freshwaters

Natural methane emissions are dominated by wetlands, peatlands and inland freshwaters such as lakes, rivers and reservoirs. Methane emissions from these ecosystems arise primarily from the decomposition of organic matter in low-oxygen conditions in waterlogged environments. Wetland and peatland methane emissions are characterised by large year-on-year variability driven by temperature, water level, nutrients, and land use practices.

Termites

Termites are key decomposers in many ecosystems, particularly in tropical regions. They digest cellulose from plant material using symbiotic microorganisms in their guts, which include bacteria and protozoa. The digestive process occurs in a low-oxygen environment within the termite gut, leading to methane production.

While termite emissions are a smaller fraction of total methane emissions compared to sources like wetlands and agriculture, they are still significant. Estimates suggest that termites contribute about 1–3% of global methane emissions.

Wild animals

Wild animals such as deer, moose, elk, and other herbivores grazing produce methane through their digestive systems, similarly to livestock. In addition, the droppings of wild animals, especially in large concentrations such as herds, can contribute to methane emissions when decomposed in wet or low-oxygen environments.

Geological sources

Methane generated within the Earth's crust can be emitted to the atmosphere through tectonic faults and fractured rocks. Geologic methane can be emitted from gas-oil seeps where hydrocarbons rise to the surface naturally on land or beneath the ocean surface and volcanic activity.

Methane can also be emitted from methane hydrates, which are crystalline structures in which methane molecules are trapped within a lattice of water ice. Methane hydrates are stable under high pressures and low temperatures typically found in deep sediment regions and permafrost regions. Emissions from these sources are presently thought to be small, but it has been hypothesised that changes in these conditions driven by climate change can destabilise them leading to additional methane emissions.

Permafrost

Similarly, methane emissions from permafrost are currently thought to be small. However, as global temperatures rise, permafrost may begin to thaw, allowing the decomposition of organic material accumulated over thousands of years to be decomposed by microbes. Due to the low-oxygen environment, this decomposition would lead to significant methane emissions.

Methane Sinks

Chemical destruction by hydroxyl radical

Methane emitted to the atmosphere is broken down over time by chemical processes, unlike carbon dioxide which can remain in the atmosphere for hundreds of years once emitted. The

dominant methane sink is reaction with hydroxyl (OH) radicals² in the atmosphere. Hydroxyl reacts with methane, ultimately breaking it down into carbon dioxide and water. Hydroxyl is often referred to as the ‘detergent’ of the atmosphere, because it is the primary sink for not only methane but also a range of trace gases. This rate of methane loss by reaction with hydroxyl is faster at higher temperatures so methane is lost more rapidly in a warmer climate.

The amount of hydroxyl in the atmosphere can vary due to changes in solar radiation, water vapour, and the amount of methane and other atmospheric constituents. Hydroxyl is produced by sunlight-driven reactions, so variability in solar radiation from either solar activity or cloud cover can impact hydroxyl concentrations. Changes in water vapour from climate change and natural climate variability also influence hydroxyl production, because the reactions that produce hydroxyl involve water molecules.

The amount of hydroxyl in the atmosphere is affected by short-lived atmospheric constituents such as nitrogen oxides³ ($\text{NO}_x = \text{NO} + \text{NO}_2$) and volatile organic compounds (VOCs), which have natural and human-created sources. In general, increased NO_x emissions will increase hydroxyl production whereas increased VOC emissions will increase its loss. Finally, while hydroxyl breaks down methane, hydroxyl is also destroyed in the process. Thus increasing methane concentrations can decrease the methane sink from hydroxyl, leading to a feedback effect that accelerates warming (Staniaszek et al., 2022). This effect will be explored in our model simulations to assess methane targets consistent with no additional warming.

Minor methane sinks

Certain microbes in soils can consume methane, acting as a biological sink. These microorganisms metabolise methane and convert it into carbon dioxide. Methane that reaches the stratosphere (a layer of the atmosphere about 15 to 50 km above the Earth’s surface, Fig. 10) is destroyed by chemical reaction with chlorine produced from the breakdown of chlorofluorocarbons, and other trace gases. In the lowermost atmosphere, methane can also be destroyed by naturally occurring chlorine emitted from oceans.

Accumulation of methane in the atmosphere

Methane has an atmospheric lifetime⁴ of around 9 years, mainly due to its reaction with hydroxyl, which accounts for approximately 90% of methane loss (Saunios et al., 2024, Szopa et al., 2021). Methane loss via minor sinks is slow. For example, the methane lifetime with respect to loss via soils has been calculated as 135 ± 44 years (Szopa et al., 2021).

² A radical is a highly reactive chemical species containing an unpaired electron.

³ Not to be confused with nitrous oxide (N_2O), an important greenhouse gas.

⁴ Atmospheric lifetimes can generally be thought of as the ‘average’ time between the emission and removal of a species from the atmosphere. With the exception of CO_2 , all greenhouse gases can be characterised using a single atmospheric lifetime.

The historical imbalance between methane’s sources and sinks has caused it to accumulate in the atmosphere. The concentration of methane in the atmosphere has more than doubled since preindustrial times (Gulev et al. 2021), as has the world’s population and its need for food.

Atmospheric measurements taken at the Baring Head monitoring station in New Zealand show that methane concentrations increased by 12% between 1989 and 2022 (Figure 4). Baring Head is a ‘clean air’ station, situated such that it measures the background concentration of well-mixed trace gases from air flowing up from the Southern Ocean. Thus, the trends in methane measured at Baring Head are determined by global methane emissions and not just New Zealand’s emissions.

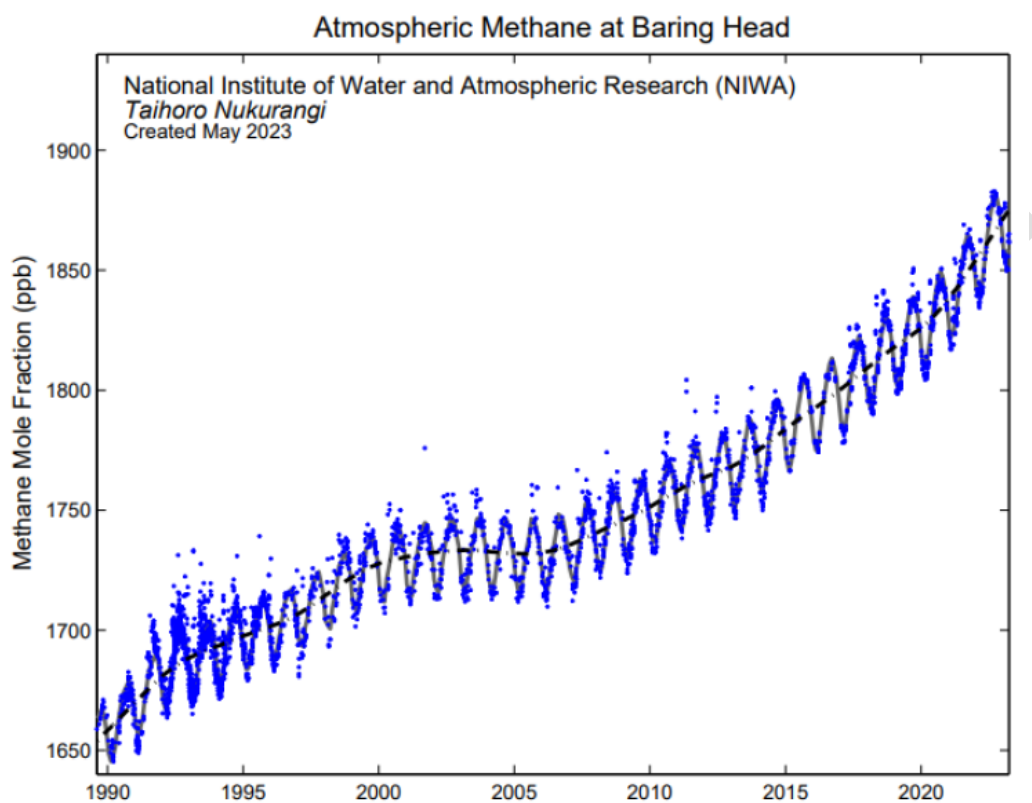


Figure 4: Methane concentrations measured at Baring Head, New Zealand between 1989-2023. Data source: NIWA (2024).

Methane in Context

In this section, the profile of methane is explained from a NZ perspective.

At the global level, as shown in Figure 3, the imbalance of methane sources and sinks is well illustrated, as is the relative impact of each. This has been well quantified from a network of atmospheric observing stations around the world (Lan et al., 2024). The methane sourced from fossil fuel production differs from other sources in that it is adding ‘**new**’ carbon to the atmosphere, or carbon that has been locked up for many years underground. In contrast the other sources are ‘**current**’ carbon, the result of bacteria in anaerobic environments (wetlands, inland freshwaters, rice paddies, landfills, and the digestive tracts of animals) breaking down plant matter recently formed through photosynthesis. While the source makes no difference to the warming impact of methane once it gets into the atmosphere (refer to Frequently Asked Questions), the additive nature of ‘new’ carbon in methane from fossil fuels does distinguish it from the recycled carbon in methane from biogenic and other sources in that the methane creates new carbon dioxide once it is broken down.

Each signatory to the Paris Agreement has its own methane profile and NZ is no exception. The NZ Greenhouse Gas Inventory shows that most of New Zealand’s gross annual emissions of methane come from food production, the agriculture sector, particularly from ruminant livestock, the remainder is from the waste sector. With limited fossil fuel production and use, the profile of NZ’s methane concentration therefore consists of biogenic emissions from ‘current’ carbon as well as the other natural phenomena of sources and sinks as illustrated in Figure 3.

Methane emissions reported as kt CO₂-e in New Zealand’s National Inventory Report and presented in Figure 2 as Mt CH₄ are calculated using data on animal populations, country-specific emission factors based on measurements made on animals in New Zealand, production, and other data (MfE, 2024). This approach follows IPCC guidelines established for all nations to follow in international reporting under the Paris Climate Agreement (IPCC, 2006). New Zealand has invested in research to provide country specific equations and emissions factors that provide a more accurate picture of our emissions than the default values provided by international studies would. New Zealand’s methane emissions from animals are known to within 16% (Kelliher et al., 2009), and our agricultural emissions from manure management and burning of agricultural residues are known to within 20% (MfE, 2024).

New Zealand’s methane emission estimates (bottom up) are in excellent agreement with independent estimates based on atmospheric measurements (top down) from a network of stations across New Zealand (Figure 5, Geddes et al., 2020; MfE 2024). As air travels across our landscape, methane concentrations are influenced by emissions or sinks in the landscape it passes over. Atmospheric measurements of methane at observing stations can be combined with models that describe the pathway the air took before arriving at the stations to infer

methane emissions (Manning et al., 2011, Geddes et al., 2020, Henne et al., 2016). Emissions estimates from inventories and atmospheric observations both have uncertainties, but these approaches are entirely independent. Thus, atmospheric measurements are recommended to support inventory estimates in the most recent refinement to the IPCC guidelines for national inventory reporting (IPCC, 2019). For New Zealand, these estimates agree to within percent on an annual basis, with atmospheric measurements finding slightly higher methane emissions in the summer compared to inventory data.

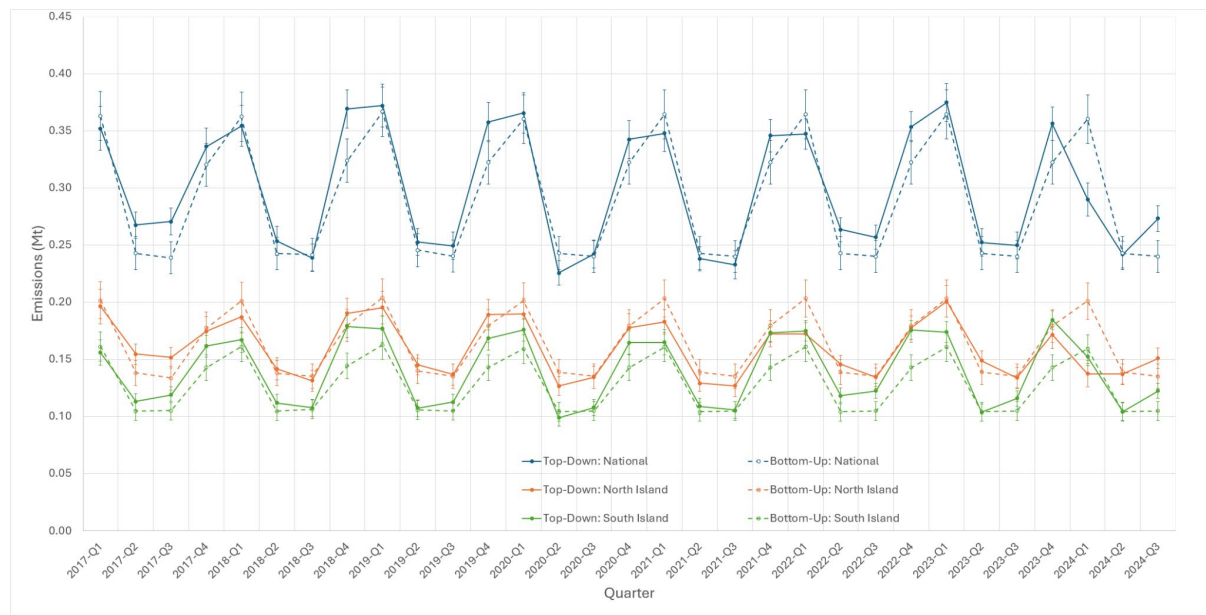


Figure 5. Top-down emissions of methane based on atmospheric observations (solid lines) and bottom up inventory methods (dashed lines) for the North Island (orange) the South Island (green) and nationally (blue). This figure demonstrates the agreement between these two different methods to infer New Zealand’s emissions. The South Island had a larger number of atmospheric methane observations for the study period and therefore we have higher confidence in the top down estimates for the South Island compared to the North Island. (Geddes, A. Personal comm)

The inventory analysis is continuously improving. The Ministry for Primary Industries (MPI) has a range of work underway to account for new low emissions technology both at farm and national level when they reach the evidential threshold for inclusion in the National GHG Inventory. This will require field trial data that robustly demonstrates the effectiveness of the mitigations in New Zealand farm conditions, as well as verifiable and auditable data on their use on farms. As farming practices change and new emission technologies come to market, the inventory will adapt to reflect these changes. Further information can be found on MPI’s web site: [Greenhouse gas reporting | NZ Government](#).

Figures 2 and 5 provide useful illustrations of NZ emissions and how there has been no increase in emissions in recent years, with a decrease since 2019. Given the short term nature of methane it is also useful to examine the estimates of the concentration of methane, the net amount

including both sources (emissions) and sinks (its depletion) that come from modelling; these have also indicated a levelling off of emissions for some time (Figure 6).

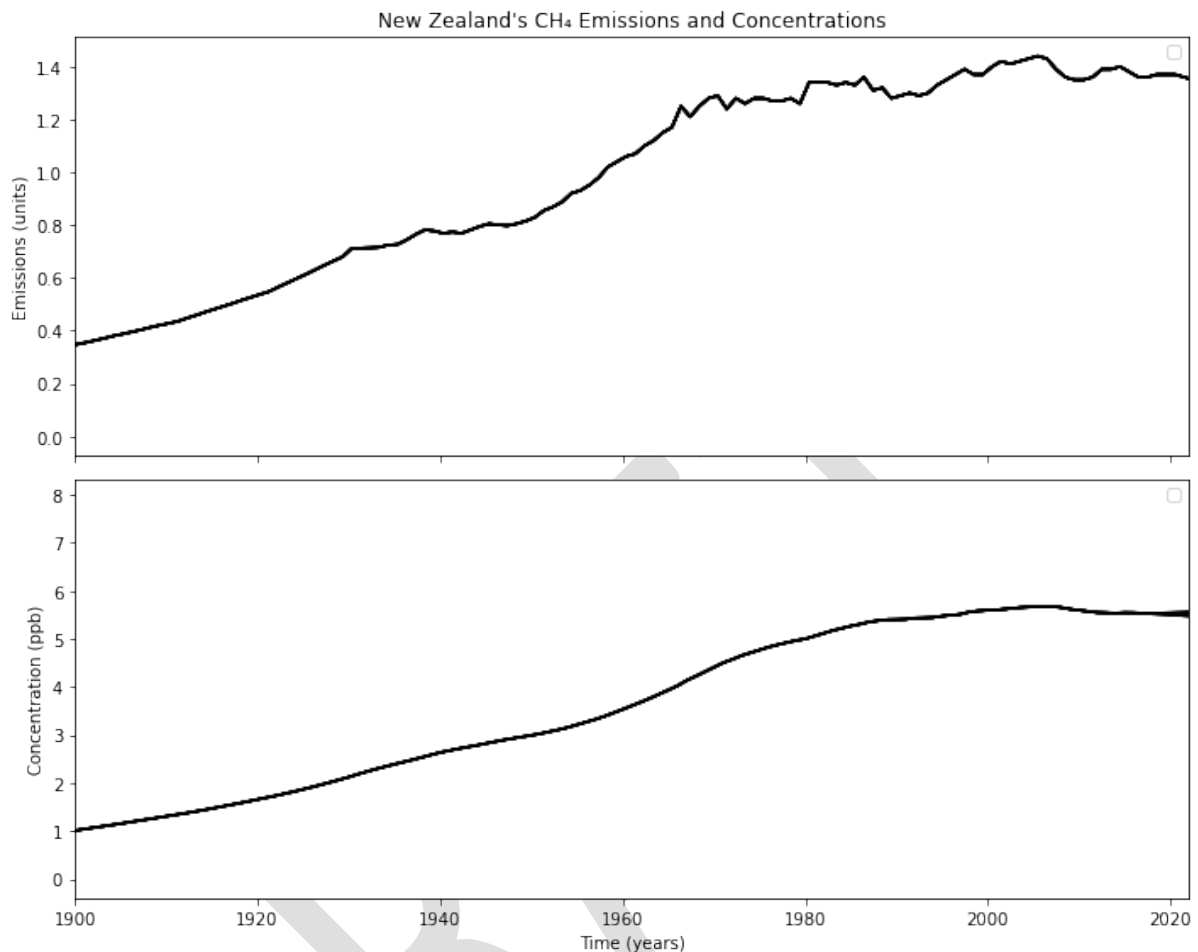


Figure 6: New Zealand's methane emissions (top) and contribution to concentrations (bottom) as assessed by the FAIR model.

In summary, the evidence to date shows New Zealand's methane emissions have been largely stable for some years ~~and gradually decreasing since 2017~~. The increase in methane concentrations related to NZ's emissions has slowed over the past decade, reflecting the ~~reduction~~ in emissions and NZ's contribution to 'holding the increase in the global average temperature'.

In contrast, global average methane concentrations in the atmosphere grew more quickly in 2020 and 2021 than at any time since records began in the 1980s (Lan et al., 2024). Three potential mechanisms have been proposed for this striking increase in atmospheric methane. A detailed analysis of both bottom up and top down estimates for 2020 show that at least half of the 2020 growth rate can be explained by vigorous emissions from wetlands due to

anomalously warm, wet conditions that year (Peng et al., 2022). Atmospheric chemistry may also play a role. COVID-19 lockdowns lowered emissions of atmospheric pollutants that contribute to the production of methane's primary chemical sink, which would lead to more rapid accumulation of methane in the atmosphere during 2020 and 2021 (Peng et al., 2022, Skeie et al., 2023, Stevenson et al., 2022). Increased emissions from fossil fuels may play a role (Shindell et al., 2024). However, measurements of isotopes in methane, which are influenced by source and sink processes, reveal that the striking growth in atmospheric methane after 2019 was primarily caused by biological processes such as wetlands, agriculture, or waste (Michel et al., 2024).

The role of methane as a greenhouse gas

Greenhouse gases and Earth's energy balance

The temperature of the Earth is maintained through an energy balance between the sunlight absorbed and the heat energy lost through terrestrial radiation (Fig. 7). Gases that readily absorb terrestrial radiation – greenhouse gases – affect climate by altering the balance between the amount of energy entering and leaving the Earth system (Fig. 8). Greenhouse gases trap terrestrial radiation in the lower atmosphere, and this causes the 'global warming' effect.

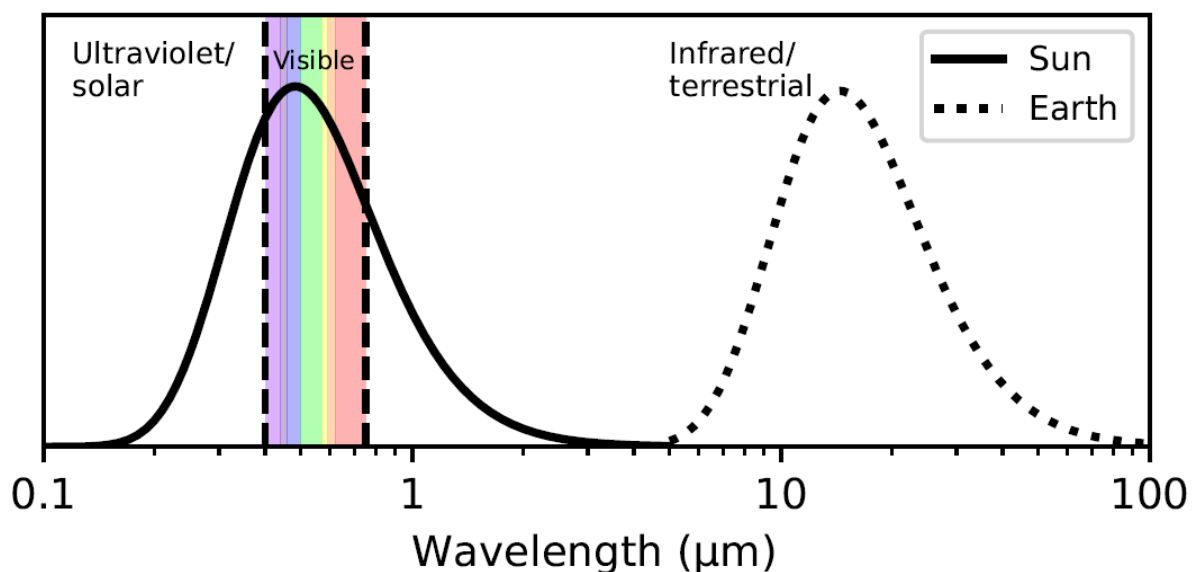


Figure 7: Normalised intensity of radiation emitted by the sun and the Earth.

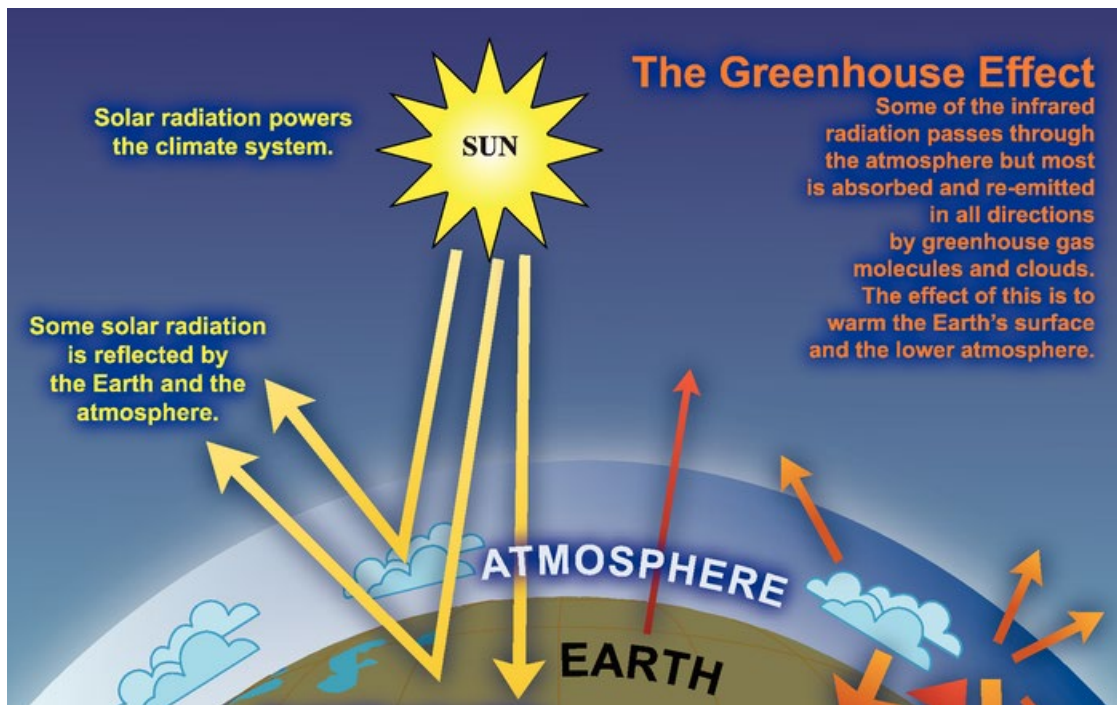


Figure 8: Schematic of the greenhouse effect. From IPCC (2007).

Greenhouse gases and other drivers of climate change alter the Earth's energy balance by changing radiative forcing. A positive radiative forcing means that more energy enters the climate system than leaves it, thus warming occurs. Similarly, a negative radiative forcing means that more energy leaves the Earth system than enters it, thus cooling occurs. Although the radiative forcing is not a climate impact that is experienced directly, the radiative forcing determines how much the Earth warms or cools (Forster et al., 2021).

Greenhouse gases absorb radiation at specific wavelengths with different efficiencies in detailed patterns known as their absorption spectra (Fig. 9). Radiative forcing values are determined by sophisticated calculations that account for the fine details of the absorption spectra, the spatial and seasonal variation of surface temperatures, the vertical pattern of temperatures in the atmosphere and the absorption of radiation by other gases in the atmosphere (principally water vapour, carbon dioxide and nitrous oxide).

Radiative forcing of methane

The strongest climate effect of methane is in absorbing terrestrial (thermal infrared) radiation from the Earth's surface and reradiating it out to space at a colder temperature (Collins et al.

2006). Methane also directly absorbs radiation from the sun (Etminan et al., 2016). Both of these effects warm the climate. Figure 9 shows that below around 7 μm most of the terrestrial radiation absorption is due to water vapour (H_2O), and between 7 and 8 μm the absorption is due mostly to methane and nitrous oxide (N_2O).

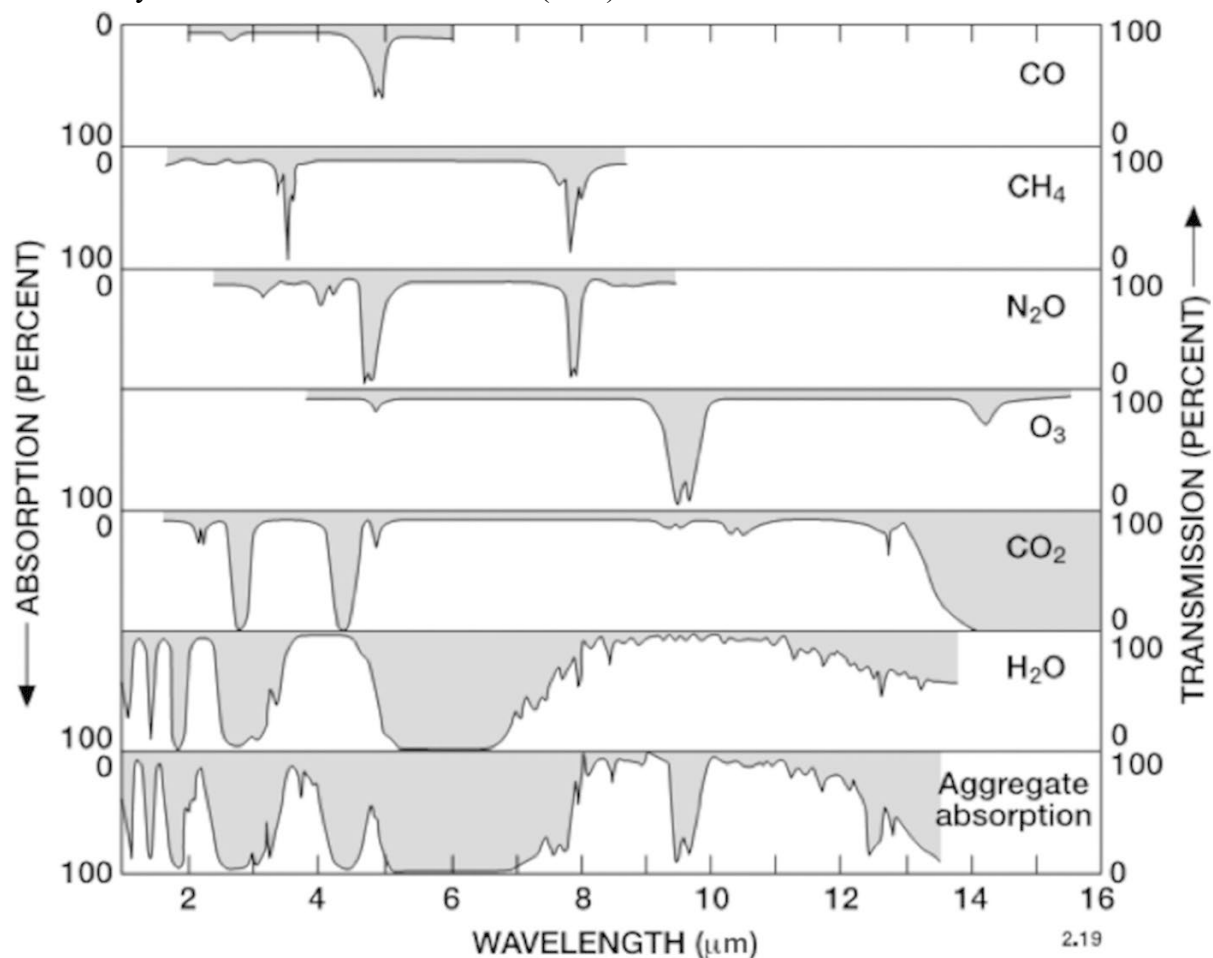


Figure 9: Vertical atmospheric absorption and transmission of infrared (terrestrial) radiation from the surface to the top of the atmosphere as a function of wavelength for greenhouse gases in Earth's atmosphere (Brasseur & Jacob, 2017).

Radiative forcing calculations show that the effectiveness of methane as a greenhouse gas decreases with increasing concentrations of methane as the absorption bands become saturated. Furthermore, because some of the methane absorption bands overlap not just with those of nitrous oxide but also carbon dioxide (Etminan et al., 2016). This is important because it means that methane's effectiveness as a greenhouse gas depends on the concentrations of other greenhouse gases in the atmosphere.

Methane affects atmospheric composition as it is chemically reactive. Chemical reactions involving methane lead to production of ozone, water vapour and carbon dioxide, all of which are also greenhouse gases and so add to the overall radiative forcing from methane. For ozone, it is the chemical production in the lowermost layer of the atmosphere - the troposphere (surface

to approximately 15 km; see Fig. 10) that is most important⁵, whereas for water vapour the production in the stratosphere (15 – 50 km) is most important because the water vapour concentration in the stratosphere is naturally very low. Ozone and water vapour are short-lived in the atmosphere, but contribute to positive radiative forcing, and hence warming, while they exist.

Because methane’s radiative efficiency is dependent on atmospheric composition, the climate impact of a specific methane source (e.g. NZ’s biogenic emissions) depends on how the overall composition of the atmosphere might evolve in different future scenarios. These will be examined in the next section.

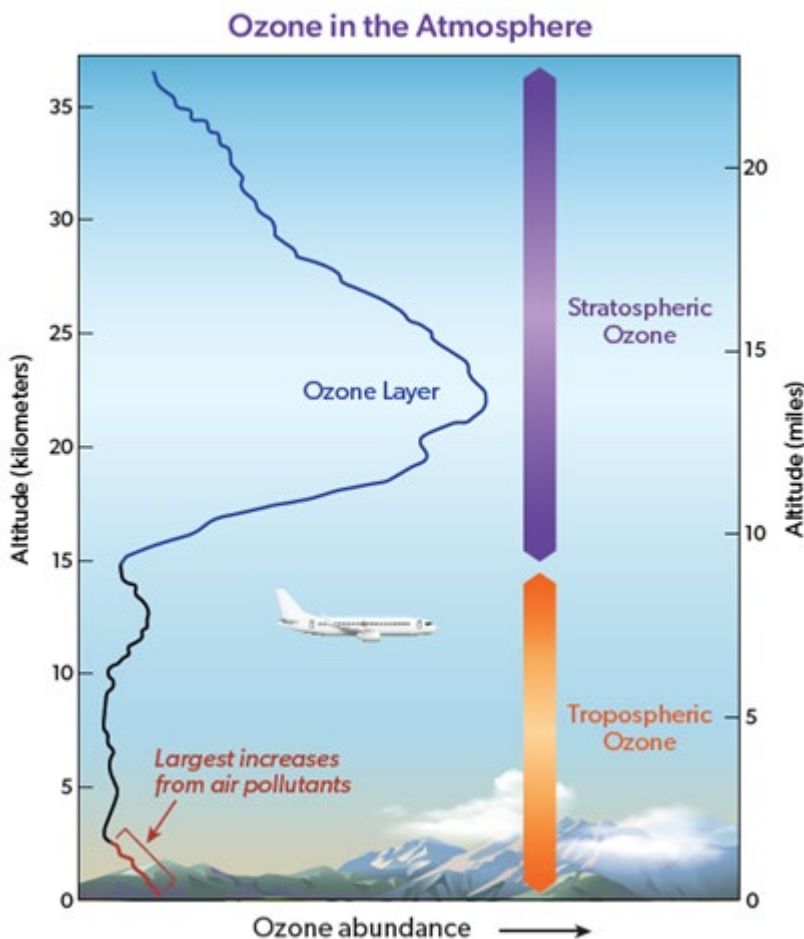


Figure 10: ozone in the different layers of the atmosphere (Salawitch et al., 2023).

In summary, the key points concerning methane’s role as a greenhouse gas are:

- Methane contributes to climate change because it is a greenhouse gas, and absorbs terrestrial radiation (heat) emitted by the Earth.

⁵ Ozone in the stratosphere is critical for shielding life on Earth against solar UV-B radiation. However, ozone is present in smaller amounts in the troposphere, where it is a respiratory agent and greenhouse gas.

- Methane also contributes to climate change because it is chemically reactive, leading to the production of other greenhouse gases such as ozone, water vapour and carbon dioxide.
- The effectiveness of methane as a greenhouse gas depends on the concentration of other greenhouse gases in the atmosphere such as nitrous oxide, and the amount of methane itself.

DRAFT

Methane Targets: achieving no additional warming

Additional warming refers to the change in warming relative to a reference year level. Additional warming has been used by the IPCC (e.g. Canadell et al., 2021) mainly in the context of CO₂ budgets. For CO₂ the additional warming compared to a reference year is approximately proportional to the cumulative amount emitted since then. Hence if global CO₂ emissions decline to net zero by a particular year (as in the “falling emissions” scenario sketched in Fig. 11) then from then on CO₂ will cause approximately no additional warming compared to that year. This does not apply to short-lived gases. From the “constant emissions” scenario sketched in Fig. 10 it can be seen that a relatively small decrease in emissions would be needed to achieve no additional warming.

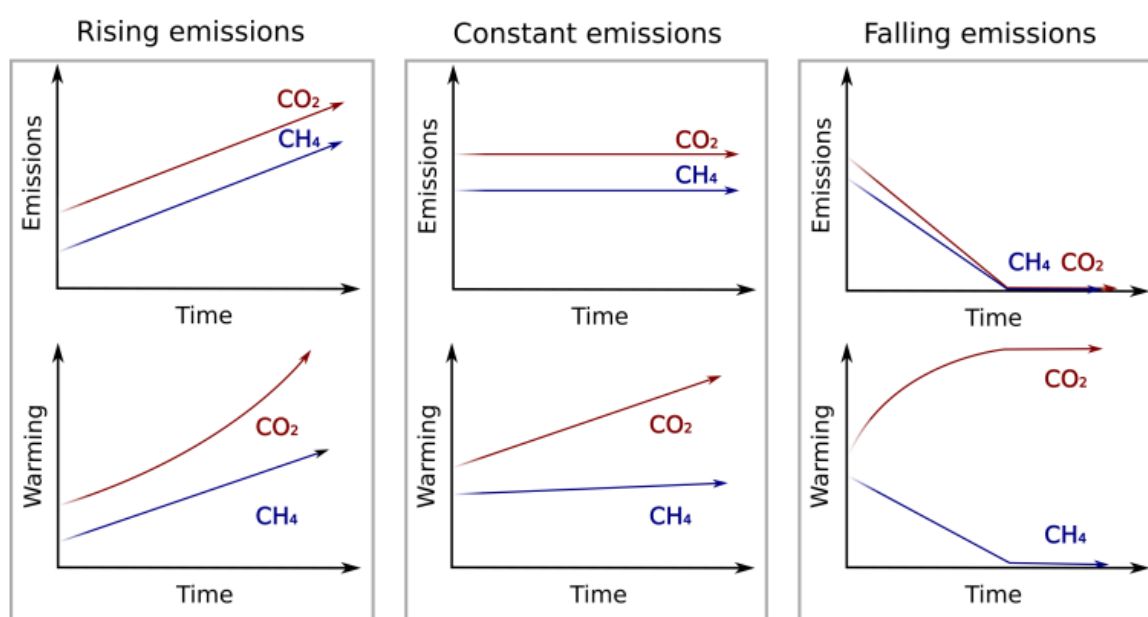


Figure 11: Relationship between emissions and warming for carbon dioxide and methane (Allen et al., 2022a).

The IPCC stated “*In general, achieving net zero CO₂ emissions and declining non-CO₂ radiative forcing would be sufficient to prevent additional human-caused warming*” (Forster et al., 2021). Since net zero CO₂ emissions are straightforward, we must ask what ‘declining non-CO₂ radiative forcing’ would look like in terms of methane emissions and studies have considered this. Reisinger et al. (2018) suggested that a useful benchmark could be to quantify the reduction in methane emissions needed to result in no additional warming relative to the warming caused by methane emissions already. The IPCC does not specify that any particular year should be used for the base year. The terms of reference for this panel state that this year should be 2017, which is embedded in NZ’s Climate Change Response Act (outlined in the Introduction). In 2017, NZ’s biogenic methane emissions were 1.36 Mt (Figure 2).

The IPCC report on Global Warming of 1.5 °C defined climate neutrality as the concept of a state in which human activities result in no net effect on the climate system (IPCC, 2018). If this were considered in terms of the effect on global surface temperature, then both net zero CO₂ and no additional warming from methane could be considered to be climate neutral. However in terms of other quantities such as sea-level rise or ice-sheet loss, neither net zero CO₂ nor no additional warming would be considered climate neutral (discussed below).

Although methane emissions only remain in the atmosphere for around a decade on average, the warming they cause lasts much longer as the heat penetrates into the ocean which can take decades to centuries to heat up or cool down. This means that the amount of warming caused by methane up until the year 2017 is not solely due to methane emitted in the last couple of decades, but has contributions from methane emitted over the 20th century. If the concentrations of methane could be fixed at a constant level, warming would continue due to the time lag in the response of the oceans. Hence for no additional warming the radiative forcing from methane has to decrease. The rate of that decrease depends on how quickly the forcing had increased up to that point, and the timescales for the oceans to respond. This can be calculated using simple climate models which emulate complex Earth system models.

The additional warming concept can also be applied to national and sectoral emissions of methane rather than the global total (Reisinger, 2018). Here the definition takes the difference comparing the global warming from total methane excluding New Zealand biogenic emissions with that including these emissions.

The concept of no additional warming from previous studies of targets for biogenic methane

The IPCC report on 1.5 °C (IPCC 2018) assessed a range of future greenhouse gas scenarios generated by economic models (IAMs). In those “illustrative pathways” that managed to limit warming to 1.5 °C (or with limited overshoot above this) the range of agricultural methane emissions in 2050 (i.e. not including biogenic methane from waste) was 24 to 47% (25th to 75th percentiles) below 2010 values. As discussed above (section ‘Domestic targets’), the IPCC did not intend these as “central estimates, [or] national strategies, and do not indicate requirements.” A study by Reisinger and Leahy (2019) found that if the rest of the world followed a low emission scenario then a 24% reduction of New Zealand’s methane emissions, below 2010 values by 2050 was sufficient to stabilise New Zealand’s contribution to warming from methane and a 47% reduction would reduce New Zealand’s contribution to methane’s warming below current levels.

The required methane emissions for no additional warming from New Zealand biogenic methane have been calculated in other studies. Reisinger (2018) found that historical New Zealand livestock emissions had contributed between 0.0011 and 0.0015 °C of warming by 2016. The reductions in New Zealand methane needed depended on the levels of methane emitted by the rest of the world. This is because if global methane concentrations are rising,

the radiative forcing caused by every tonne of methane emitted by New Zealand decreases (see section 2.1). Hence for a moderate global methane concentration (similar to SSP2-4.5) the necessary New Zealand reductions were smaller than if global methane concentrations followed a lower emissions scenario (similar to SSP1-2.6). The warming from methane was also found to reduce the amount of carbon dioxide taken up by the land and oceans which amplified the effect of methane. The reductions necessary for no additional warming after 2016 were 5% (moderate global methane) and 16% (lower global methane) by 2050, but increased to 10% and 22% when the reduced CO₂ uptake was accounted for. For approximately stable warming from 2016 to 2050, most of these reductions needed to occur before 2030.

The finding that higher emissions from the rest of the world means that New Zealand has to reduce less seems counterintuitive. However this is because the calculation is not for the total warming from methane (which would be rising with higher rest of the world emissions), but for the contribution of New Zealand's methane to this warming.

A study by Barth et al. (2023) found a similar dependence on greenhouse gas emissions scenario when using a newer set of shared socioeconomic pathways (see the next section). The range of reductions needed by 2050 (relative to 2020 values) to achieve no further warming since 2020 was 8% for the high emissions SSP3-7.0 scenario, 15% for the middle-of-the-road SSP2-4.5 scenario and 27% for the low emissions SSP1-1.9 scenario.

In summary the key points with respect to how additional warming is defined are:

- Additional warming calculations have been applied to CO₂ budgets. A similar concept of additional warming can be applied to methane, but different calculations are needed because of its short-lived presence in the atmosphere.
- A reference year is needed to define no additional warming. 2017 was specified as the base year for this submission consideration.
- The warming effect of New Zealand's methane is not solely dependent on New Zealand's actions. It is also affected by emissions of methane and other gases from the rest of the world.

Scenarios: projections of future climate change

Shared Socioeconomic Pathways (SSPs)

Calculating methane emission targets consistent with ‘no additional warming’ requires consideration of longer-term changes in atmospheric composition. Modelling greenhouse gas emissions to the end of the 21st century (and beyond) can inform decision-making. To carry out such modelling, climate models require greenhouse gas and aerosol⁶ scenarios. The scenarios developed for the sixth (and most recent) assessment report by the Intergovernmental Panel on Climate Change are called the Shared Socioeconomic Pathways (SSPs). The SSPs represent narratives for energy use, land use, air pollution control and greenhouse gas emissions based on evolving socio-economic and technological conditions. These narratives are documented by Riahi et al. (2017) and summarised briefly in Table 1.

Table 1: Summary of SSP narratives, adapted from Riahi et al. (2017).

SSP1	‘Sustainability’ (low challenges to mitigation and adaptation). The world shifts toward a more sustainable path, management of the global commons improves and perceived environmental boundaries are respected.
SSP2	‘Middle of the road’ (medium challenges to mitigation and adaptation). The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Challenges to reducing vulnerability to societal and environmental changes remain.
SSP3	‘Regional rivalry’ (high challenges to mitigation and adaptation). Resurgent nationalism and regional conflicts push countries to focus on domestic issues. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.
SSP4	‘Inequality’ (low challenges to mitigation, high challenges to adaptation). Inequalities increasingly occur across and within countries. Social cohesion degrades while technology development is high in the high-tech economy and sectors. Environmental policies focus on local issues around middle and high income areas.

⁶ Aerosols, also known as ‘particulate matter’ are tiny droplets or solid particles suspended in air, for example black carbon (soot).

SSP5	‘Fossil-fueled development’ (high challenges to mitigation, low challenges to adaptation). The push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. The global economy grows rapidly.
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On top of the SSP narratives there are different levels of climate mitigation. The only scenarios widely used which are consistent with the goals of the Paris Agreement are SSP1-1.9 and SSP1-2.6. The ‘1.9’ and ‘2.6’ refer to the increase in radiative forcing between the preindustrial period and the end of the 21st century (i.e. an increase of 1.9 W m^{-2} and 2.6 W m^{-2} , respectively). These radiative forcing changes span a range of potential values identified via literature and modelling (van Vuuren et al., 2011).

In contrast, SSP3-7.0 and SSP5-8.5 would require reversal of some current climate policies (Hausfather & Peters, 2020) and lead to $\sim 4\text{-}5 \text{ }^\circ\text{C}$ increases in global-mean temperature by the end of the 21st century (Tebaldi et al., 2021). SSP5-8.5 is considered highly unlikely due to developments in the energy sector (Hausfather & Peters, 2020).

Historical (up until 2014) and projected (following the SSPs) methane emissions and concentrations are shown in Fig. 12. Carbon dioxide is also shown, since it is the dominant greenhouse gas emitted from human activities and is long-lived – thus driving most of the global temperature change. Meeting the goals of the Paris Agreement via SSP1-1.9 (for example) would require global emissions of carbon dioxide and methane to follow the SSP1-1.9 pathway illustrated in Fig. 12. Emissions of other greenhouse gases (such as nitrous oxide) and aerosols would also have to follow their respective SSP1-1.9 pathways.

When the SSPs were developed, projected methane concentrations for 2022 ranged between 1884 ppb (for SSP1-2.6) and 1980 ppb (for SSP4-6.0; Meinshausen et al., 2020). The actual concentration in 2022 was measured to be 1911 ppb (Lan et al., 2024), i.e. mid-way between these two extremes.

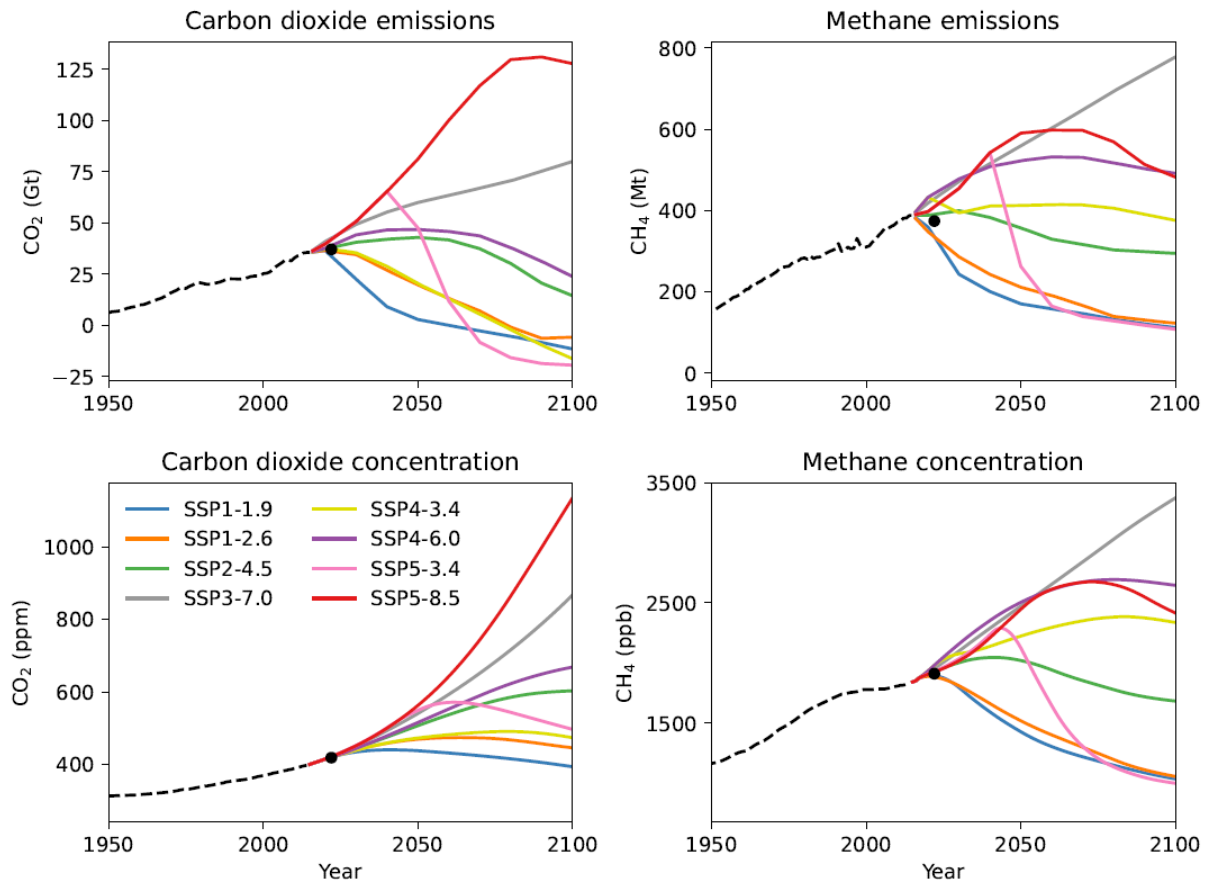


Figure 12. Top row: Global annual-mean carbon dioxide and methane emissions for the historical period (until 2014; dashed black line) and for future scenarios following the Shared Socioeconomic Pathways (SSPs). Black circles indicate global emissions in 2022. Bottom row: Global annual-mean carbon dioxide and methane concentrations following the SSPs. Data source: Meinshausen et al., (2020)

Key points:

- The Shared Socioeconomic Pathways (SSPs) represent a range of possible climate futures.
- The SSPs were developed for the most recent assessment by the Intergovernmental Panel on Climate Change and are widely used in climate change modelling.
- In the following sections, the SSPs are used to assess NZ methane emissions consistent with no additional warming.

Methane Lifetime

Methane's lifetime in the atmosphere has been around nine years in the recent decade (Szopa et al., 2021, Saunois et al., 2024), but can vary from this by more than a year (Stevenson et al. 2020) depending on the atmospheric concentrations of a range of species (CO_2 , CH_4 , NO_x and volatile organic compounds) which affect the prevalence of the hydroxyl radical, which helps break methane down into CO_2 , water vapour, and other trace gases. The SSP scenarios include a range of different possible futures for the composition of the atmosphere, and the FAIR model calculates how these affect methane's atmospheric lifetime as shown in Figure 13.

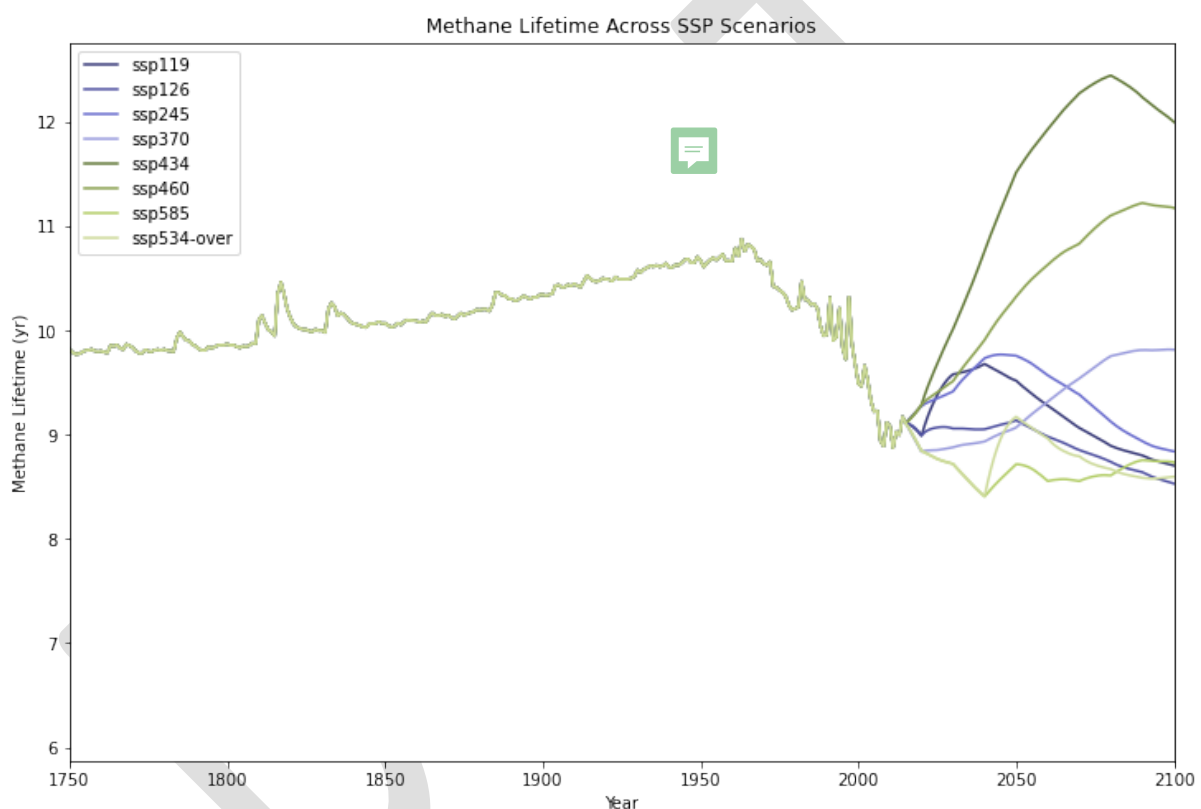


Figure 13. Methane lifetime as calculated by the FAIR model under historical conditions and the SSP scenarios used in this report.

If the chemical composition of the atmosphere is changed along the lines of the SSP4 'inequality' narrative (Table 1), involving the burning of large quantities of biomass, then the lifetime of methane could be extended by over three years. As methane lasts longer this means that methane concentrations increase, requiring steeper cuts to maintain a constant level of warming. Conversely, if the world follows a high emissions and warming scenario such as SSP5-8.5, then methane lifetimes would reduce (due to the enhanced production of the hydroxyl radical), lowering the level of CH_4 emissions reductions required to satisfy the no additional warming (NAW) condition.

Continued monitoring will inform scientists and policymakers of both composition and the level of overall warming, and hence of adjustments needed to near-term requirements for emissions reductions consistent with no additional warming.

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Results - methane emission futures

Twenty different methane emissions futures (MEFs) for New Zealand were explored to assess conditions under which there may be no additional warming from New Zealand's biogenic methane. The functional form of emissions reduction was varied to include both percent per annum emissions reductions and straight-line emissions reductions to 2050 or 2100.

The MEFs are shown in Figure 14. A number of percent per annum emissions reductions MEFs were generated, spanning a range in 0.1%pa increments from constant emissions through to 0.5%pa, and then in 0.25%pa increments from 0.5%pa to 2.0%pa, with a final MEF of 2.5%pa. Alongside these were a number of MEFs that involve linear reductions in methane emissions from 2022 levels to some specific level, -5%, -10%, -15%, -20%, on 2022 levels and -24%, -35%, -47% on 2017 levels, in 2050, and then constant emissions afterwards.

Temperature responses to these MEFs, as calculated by FAIR, for each of the SSPs considered are presented in [Time Series Plots](#) at the back of the review and Table 2 summarises the results. If the MEF satisfies the no additional warming on 2017 levels criterion in 2050 or 2100, the cell is clear, if the MEF fails the test, i.e. there is warming above 2017 levels under that MEF under the global scenario, by the date in the cell then the cell is shaded grey.

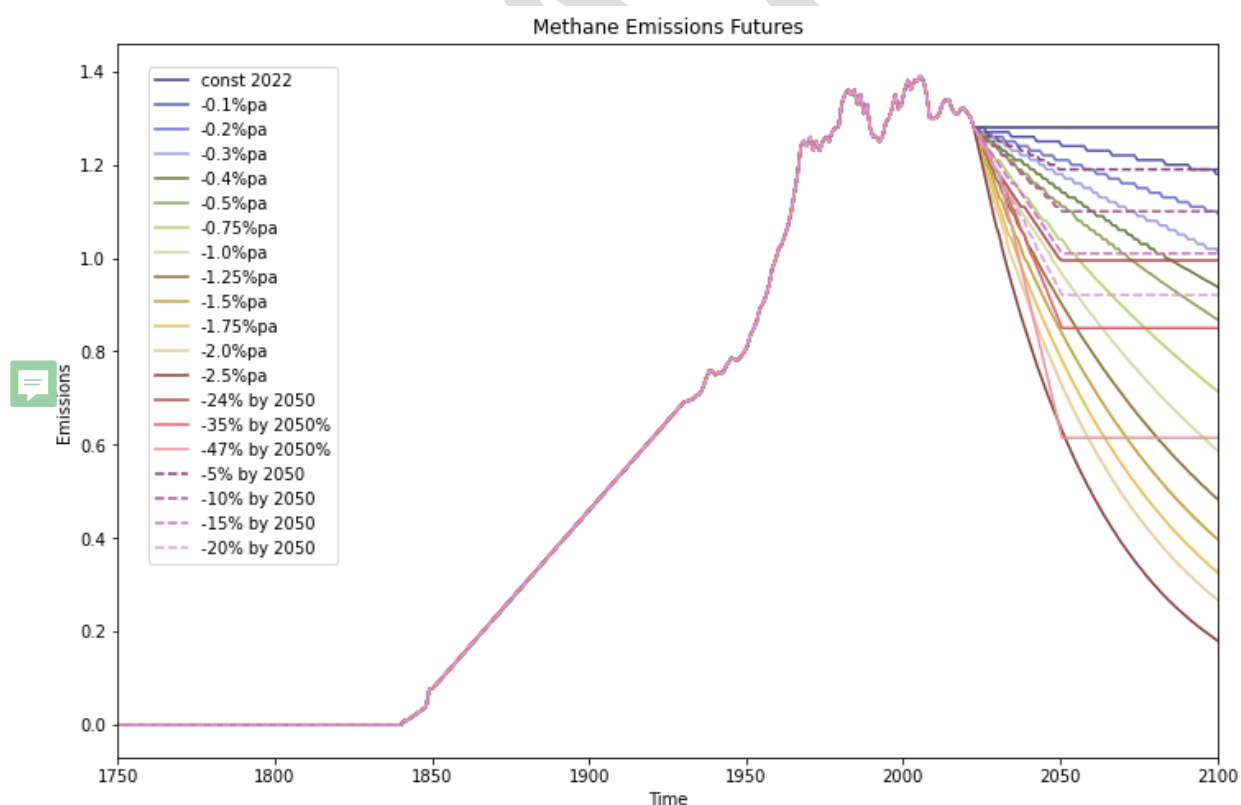


Figure 14: Methane emissions futures (MEFs) used in this study. Historical emissions until 2023 are from the Climate Change Commission website. Emissions futures begin in 2023 and either follow constant per annum percent reductions, or decline linearly until 2050, remaining constant thereafter.

Table 2: Tests for no additional warming (relative to 2017) under 8 SSPs and various future emissions. Grey means there is additional warming, white means no additional warming.

Methane emissions futures involving constant per annum percent emissions reductions																
	SSP1-1.9		SSP1-2.6		SSP2-4.5		SSP4-3.4		SSP4-6.0		SSP5-3.4		SSP3-7.0		SSP5-8.5	
Constant	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-0.1%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-0.2%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-0.3%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-0.4%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-0.5%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-0.75%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-1.0%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-1.25%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-1.5%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-1.75%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-2.0%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-2.5%pa	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Methane emissions futures involving linear emissions reductions																
	SSP1-1.9		SSP1-2.6		SSP2-4.5		SSP4-3.4		SSP4-6.0		SSP5-3.4		SSP3-7.0		SSP5-8.5	
-5% by 2050	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100

-10% by 2050	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-15% by 2050	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-20% by 2050	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-24% by 2050	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-35% by 2050	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
-47% by 2050	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100

The MEFs are either specified as a percent per annum decline or a straight line decline to a fixed amount by 2050. The reason for both is to enable the model to reflect the breadth of responses to policy targets over time. The reductions start in 2023, based on the last year of available 2022 inventory numbers. For comparison a 0.3% per annum reduction would lead to a 8% decrease by 2050, and a 1.0% per annum reduction would lead to a 24% decrease by 2050.

Whether or not the MEFs imply warming that stays below 2017 temperature levels depends in large part on whether and how much emissions of methane and other GHGs from the rest of the world decline in the coming decades. Global scenarios that are consistent with the aspirational target of limiting warming to less than 1.5 °C above pre-industrial levels are represented by the SSP1-1.9 scenario. This scenario involves rapid reductions in emissions of CO₂ and CH₄, beginning in 2015. Under this scenario, 2023 global emissions of CO₂ were modelled to be 32.3 Gt CO₂, and 324.1 Mt CH₄, respectively. Actual 2023 emissions of these gases were 36.8 Gt CO₂ and 374.2 Mt CH₄, respectively, illustrating that global emissions would need to drop rapidly to achieve that aspirational target.

The Panel was asked to pay attention to this scenario as it is in NZ’s legislation. For SSP1-1.9, MEFs exceed the no additional warming (NAW) condition in 2050 for MEFs with lower than 1.0% per annum reductions, or equivalently for linear reductions less than 24% reductions on 2017 levels by 2050. For this scenario, emissions reductions of 35% on 2022 methane emissions levels by 2050 are sufficient to meet the NAW condition. Emissions reductions of 35% compared to 2022 levels by 2050 would be needed to meet the NAW condition by 2050. Because most of the changes in methane’s radiative efficiency associated with this scenario occur before 2050, as CH₄ concentrations drop rapidly, and because efficiency remains more

constant in the second half of the century, a wider range of MEFs meet the NAW condition by 2100: emissions reductions of 10% by 2050 and 20% by 2100, or per annum emissions reductions of 0.2% or more across the century, are sufficient to satisfy the NAW condition in 2100, though the condition will not have been met in 2050.

At the other end of the global scenario range, scenarios which involve on-going growth in global emissions of GHGs see NZMEFs satisfy the NAW condition with low annual rates of reduction. For the highest GHG global scenario, SSP5-8.5, annual emissions reduction rates of 0.1% are sufficient to reduce warming to less than 2017 levels until 2050, and rates of 0.2% per annum see warming below 2017 levels until 2100. This scenario features prominently in the Ministry for the Environment's (MfE) Coastal hazards and climate change guidance.

Unless global emissions of GHGs reduce extremely rapidly in the next couple of decades, cuts averaging 0.3% per annum are sufficient to keep warming from New Zealand's biogenic methane to levels at or below 2017 levels. Similar results apply for the straight-line reduction MEFs. The current legislated targets are for cuts between 24% and 47% by 2050 from 2017 emission levels. Cuts amounting to 35% by 2050 are always consistent with the NAW condition, while those associated with 24% reductions by 2050 are also usually sufficient to keep or return warming to at or below 2017 levels, except where VOCs rapidly change (SSP4-3.4). For mid-range scenarios and those most like the International Energy Association's emissions scenarios, cuts of 25% by 2050 are consistent with meeting the NAW condition. For the scenario nearest current observations of global emissions since 2015, SSP2-4.5, linear reductions of 10% on 2022 levels or more targets satisfy the NAW condition for 2050, or equivalently cuts of 0.3% per annum. By 2100, any cuts beyond 5% on 2022 levels do not lead to additional warming beyond 2017 levels.

Sensitivity analyses

Sensitivity to uncertainty in the amplitude of Methane Emissions

There is some uncertainty regarding New Zealand's current CH₄ emissions. To test the sensitivity of results to the amplitude of emissions we increased and decreased the entire New Zealand CH₄ emissions data series by 16%. This made no material difference to which scenarios were consistent with the NAW condition.

Sensitivity to Historical Emissions

There is some uncertainty around emissions time-series and although this uncertainty is decreasing as measurement of emissions improves, it provides an important factor to which the detailed results presented in Table 2 are sensitive. Revisions to biogenic emissions during the early years of the inventory period, or revisions to estimates of 20th century methane emissions, could shift the emissions reduction rate required to meet the NAW condition. The more recent

the revision, the greater the effect. This is because warming associated with methane is very sensitive to recent emission rates. But it is also sensitive to emissions that occurred earlier.

This is not because methane is long lasting – it leaves ~~no~~ chemical signal behind after 100 years – but because while it is aloft it traps radiation which warms the planet, especially the ocean, and this warming persists. This is a well-understood phenomenon associated with how the earth’s climate deals with perturbations to its energy budget (Forster et al., 2021, Box 1, Gregory et al., 2004). The ocean dominates the heat capacity of the earth’s climate system, and perturbations to the earth’s energy budget act both to warm the atmosphere and slowly increase ocean heat storage. CH₄ is short-lived, and acts to warm the atmosphere and surface, and this in turn adds to the ocean’s heat storage; the same is true for any source of (positive) radiative forcing. If that source of radiative forcing is turned off, surface temperatures will drop from peak levels, but not return all the way to pre-industrial levels, because the ocean – with its vast heat capacity – has been warmed above pre-industrial levels, and this heat store maintains surface temperatures above pre-industrial levels.

Climate response parameters

There are uncertainties in the climate response associated with the strength of climate feedbacks, and with the response time of the climate system. [During the draft review process we are conducting an uncertainty analysis regarding these parameters.]

Discussion

NZ’s methane emissions are largely sourced from biogenic, i.e. agricultural and waste, activities. Evidence indicates that NZ’s methane emissions have been decreasing since 2019 and methane concentration in the atmosphere are levelling off. Article 2 of the Paris Agreement on climate change “aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty” by “Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels”. The subsequent NZ legislation established domestic climate change 2050 targets (24-47%) to contribute to the global pursuit of efforts to limit warming to 1.5 °C.

When assessing such targets the dynamics of global atmospheric GHG concentrations and delayed methane-induced warming resulting from oceanic thermal inertia must be taken into consideration, as do socioeconomic factors evolving over time. These variables can have a significant influence on resultant levels of warming, and the impact of NZ’s methane emissions.

Studies designed to predict these variables over a longer time period use sophisticated modelling tools, that combine historic and ongoing measures of methane with projected socio-economic developments to calculate what changes to methane profiles could result going forwards – not just to the established 2050 target date but beyond that to the end of the 21st century in order to plan how to meet the no additional warming goal.

Scenarios	% pa decrease to 2050 for no additional warming	2050 target % decrease for no additional warming
SSP1-1.9	-1.0	-24
SSP1-2.6	-0.4	-10
SSP2-4.5	-0.4	-10
SSP4-3.4	-1.0	-20
SSP4-6.0	-0.3	-10
SSP5-3.4	0	0
SSP3-7.0	-0.1	0
SSP5-8.5	0	-10

Table 3. A summary of the % per annum decreases and the straight line 2050 target in each scenario that met the requirement for no additional warming (relative to 2017) by 2050.

As summarised in Table 3 the cuts in New Zealand's biogenic methane that are necessary to meet the condition of no additional warming are strongly dependent on the path taken by the rest of the world. If the rest of the world were to rapidly increase its climate policies to meet the Paris goal of pursuing efforts towards limiting temperatures to 1.5 °C above pre-industrial levels then New Zealand's biogenic methane emissions would need to be reduced by more than 1% per annum from 2023 (24% by 2050) for no additional warming on 2017 levels by 2050. The SSP2-4.5 scenario is closest to observations as well as current NDCs, in which case a 0.3% per annum reduction (8.1% by 2050) would meet a target of no further warming from New Zealand's biogenic methane. If the world were to reverse some of its climate policies then the global increased methane would reduce the impact of New Zealand's emissions such that a 0.2% per annum reduction (5.5% by 2050) would be sufficient for no further warming for the rest of the century.

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Appendices

1. Terms of Reference

METHANE SCIENCE AND TARGET REVIEW – TERMS OF REFERENCE

Review Title	Review of the methane science and target
Duration	30 June – 29 November 2024
Date issued	24 June 2024

Purpose

1. The purpose of the Advisory Group (referred to as the Panel) is to deliver an independent review of methane science and the 2050 target for consistency with no additional warming from agricultural methane emissions.
2. This should include a scientific understanding of methane and its warming impact in order to provide advice on what a biogenic methane target consistent with the principle of no additional warming would look like for New Zealand.
3. The Panel’s review will be independent of the Climate Change Commission’s review of the 2050 target this year. It will provide the Government targeted advice to inform its response to the Commission’s advice in 2025.

Scope

4. The main output of the Panel will be a report that disseminates the findings of the review to the Government. The report will be made publicly available and should be written in plain language and be accessible to the public.

5. The report should provide the following:

- a) background on New Zealand's climate change targets and legislation;
- b) overview of the concept of no additional warming, including a clear definition of what no additional warming is in the context of a biogenic methane target¹;
- c) a review of previous studies that estimate a no additional warming target for biogenic methane (including any differences between them);
- d) an up-to-date explanation and summary of the warming impact of biogenic methane, specifically including biogenic methane from New Zealand's agricultural sector;
- e) a brief explanation of the global emissions scenarios relevant for determining target ranges for biogenic methane emissions;
- f) consideration of a range of no additional warming biogenic methane emission reductions targets that reflect different background global emissions scenarios, including a scenario that is consistent with limiting global warming to 1.5 degrees Celsius (e.g., Shared Socioeconomic

1 For the purposes of this review the biogenic methane target includes all methane greenhouse gases produced from the agriculture and waste sectors (as reported in the New Zealand Greenhouse Gas Inventory).

Pathway 1-1.9 from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)); and

- g) estimates of biogenic methane emissions reductions needed in 2050 and 2100 to achieve and maintain a state of no additional warming from New Zealand's biogenic methane emissions relative to 2017 levels of warming.

6. In doing so, the review should consider the following:
 - a) the limitations and constraints of any advice in relation to target setting;
 - b) providing a clear rationale and justification for any methodological choices and an explanation of any assumptions or limitations;
 - c) the advancements in methane science and its warming impact since the target was set in 2019;
 - d) any relevant science that was not considered during the setting of the methane target in 2019;
 - e) the latest published scientific literature, including the IPCC AR6 report;
 - f) global scenarios of future greenhouse concentrations and associated emissions;
and
 - g) what is included as biogenic methane in New Zealand.

7. The following issues are out of scope of the review:

- a) making any conclusions or recommendations that go beyond performing the scientific review and providing the evidence-based advice required by these terms of reference. For example, the advice will not cover implications of any new proposed target on the broader climate strategy. It will not try to make values-based judgements about the burden sharing responsibilities of different sectors or nations; and
- b) reviewing any other aspects of the 2050 Target as set out in s5Q of the Climate Change Response Act 2002.²

Approach

8. The review will take place from June to November. Within the four-month period, the Panel will:

- a) engage with relevant experts if they choose to, in the development of the report;
- b) ensure an effective quality assurance process is undertaken, for example, including through an independent external review process;
- c) where possible, provide a consensus view in its report. Where this is not possible, feedback from individual members will be captured, and considered as part of subsequent advice;

- d) provide a process where interested parties, including iwi/Māori, can submit relevant evidence, including mātauranga Māori;
- e) provide a draft report to the Minister of Agriculture and Minister of Climate Change by 1 November 2024; and
- f) provide a final report to the Ministers by Friday 29 November 2024.

2 Section 5Q of the CCRA sets out the domestic target for 2050. The 2050 target requires that net accounting emissions of greenhouse gases in a calendar year, other than biogenic methane, are zero by the calendar year beginning on 1 January 2050 and for each subsequent year.

- 9. The review process should adhere to the following principles:
 - a) rigorous - Uses the most up-to-date and comprehensive body of evidence; recognises and minimises bias; is independently reviewed as part of a quality assurance process;
 - b) inclusive - Considers many types and sources of evidence; uses a range of skills and people;
 - c) transparent - Clearly describes the research question, methods, sources of evidence and quality assurance process; communicates complexities and areas of contention; acknowledges assumptions, limitations and uncertainties, including any evidence gaps; declares personal, political and organisational interests and manages any conflicts; and
 - d) accessible - Is written in plain language; is available by 29 November 2024; is freely available online (this will be actioned by Ministers upon receipt of the report).

Context

10. Biogenic methane, a short-lived greenhouse gas (GHG), contributes to ~48% of New Zealand's gross aggregated annual greenhouse gas emissions. Most of New Zealand's gross annual emissions of biogenic methane come from the agriculture sector (~91%), particularly from ruminant livestock. The remainder is from the waste sector (~9%).

11. New Zealand's 2050 target was set as part of the Climate Change Response (Zero Carbon) Amendment Act 2019 which amended the Climate Change Response

Act 2002 (CCRA). At the same time the purposes of the CCRA were expanded to include the following purpose – “to provide a framework by which New Zealand can develop and implement clear and stable climate change policies that contribute to the global effort under the Paris Agreement to limit the global average temperature increase to 1.5° Celsius above pre-industrial levels” (see section 3(1)(aa)(i)).

12. Under the CCRA New Zealand adopted a split-gas approach to the 2050 target based on scientific evidence that biogenic methane, as a short-lived gas, does not have to reduce to zero to limit global warming.

13. The legislated 2050 target for biogenic methane requires that New Zealand’s gross emissions of biogenic methane in a calendar year are 24 - 47% less than 2017 by the calendar year beginning on 1 January 2050 and for each subsequent calendar year.

14. The Government has committed to “maintain a split-gas approach to methane and carbon dioxide through to 2050 and review the methane science and targets in 2024 for consistency with no additional warming from agricultural methane emissions”.

15. The Minister of Climate Change and the Minister of Agriculture are seeking advice on what New Zealand’s biogenic methane target should be to ensure no additional warming.

16. Determining an appropriate target for New Zealand is a judgement for the Government based on a range of considerations including equity, responsibility, cost, and economy wide opportunities for emissions reductions.

Skills and experience:

17. To ensure a robust and independent review process, the Panel will need to collectively hold sufficient expertise and capability across the following topics:

- a) climate science – including climate modelling and the warming impact of short and long-lived greenhouse gases;
- b) New Zealand’s greenhouse gas emissions, particularly biogenic methane from the agriculture sector; and

- c) understanding of New Zealand's climate change targets and budgets under the Climate Change Response Act.

Memberships

18. Four Panel members and a chair will be appointed by the Minister of Agriculture and Minister of Climate Change (Ministers) following approval from APH Committee and Cabinet.

19. A chair will be appointed by Ministers. The chair is expected to:

- a) lead the work programme and ensure effective delivery of the final report;
- b) meet with Ministers to discuss progress of the review;
- c) liaise with the Secretariat on support required for the Panel; and
- d) maintain an effective working relationship with Panel members.

20. A member may resign from the Panel by informing the Ministers in writing.

21. A replacement chair, or new members can be added to or removed from the Panel by Ministers, subject to Cabinet approval.

Fees

22. To be derived from the relevant Cabinet Fees Framework (Category 4).

23. Letters of appointment will detail the remuneration and reimbursement arrangements for the chair and Panel members.

Secretariat / Support:

24. The Panel will be supported by ministry officials (the Secretariat). Full Secretariat support and functions will be confirmed with the chair and Panel members.

Deliverables

25. The Panel is to provide a draft report by 1 November 2024 and a final report by 29 November 2024.
26. Additional interim deliverables may be determined in agreement between Panel members, the Secretariat and Ministers as required.

Conflict of interest

27. Group members are expected to disclose any perceived or real conflicts of interest to the chair and Secretariat. A conflict-of-interest register will be maintained by the Secretariat.
28. Where a conflict of interest is declared a management plan will be put in place and monitored by the Chair with the support of the Secretariat.

General confidentiality requirements

29. If the Panel receives an official information request, they must immediately provide it to MfE/MPI via the Secretariat and advise the requester that the request was referred to MfE/MPI.

2. Modelling methodology

Preparation of emissions data

We followed the methodological approach of the recent Barth et al., 2023 study from Oxford who used the PRIMAP emissions database estimate for New Zealand's biogenic methane emissions from 1750-1990, scaled to match the inventory data from 1990-2022, and then used inventory data from 1990-2021. The dataset matches the inventory data from 1990-2022. Prior to the commencement of the inventory data in 1990, the PRIMAP data largely fits an exponential growth curve from very low values in the early years of the record, rising to near-inventory levels later in the series. This is unlikely to be reflective of the true history of New Zealand's agricultural methane emissions, because New Zealand's ruminant numbers have not

followed the curve assumed in the PRIMAP data. Numbers of livestock reported in yearbooks and other statistical records during the 20th century suggest somewhat steadier growth, though of course, in the absence of measurements, it is impossible to know exactly how agricultural methane emissions evolved during the 20th century. In this study we used a series from Reisinger and Leahy (2019) as the basis for estimates of historical emissions, scaled in the manner of Barth et al. (2023) to match the inventory data 1990-2022. To help understand uncertainty arising from historical emissions we compared the effects of approximating prior emissions with straight line growth rather than exponential growth. The results of this sensitivity test are explained in the results section. We also scaled the entire historical NZ emissions timeseries to examine how uncertainty in current emissions would affect possible responses to future methane emissions. We chose the full range of SSP scenarios, from SSP119 to SSP585.

3. Further Legislative Information

How NZ achieves its targets

NZ has emissions budgets (EBs) as stepping stones to track towards the 2050 domestic target and there are always three in place. An emissions budget sets the maximum emissions in a 5-year period. The Government published the first three emissions budgets (EB1: 2022–2025, EB2: 2026–2030, EB3: 2031–2035) in May 2022. The Climate Change Commission is due to advise the government on the fourth emissions budget (EB4: 2036 – 2040) and review the first three by the end of 2024.

The emissions budgets include emissions of all the greenhouse gases specified in the Climate Change Response Act: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride.

NZ's emissions reduction plans (ERPs) set out strategies, actions, and policies for achieving the corresponding EB. The first emissions reduction plan (ERP1) was published in 2022, which sets out policies and strategies for delivering EB1. The second emissions reduction plan (ERP2) is due to be published by the end of 2024.

NDCs

Under the Paris Agreement^[1], every country must set its own nationally determined contribution (NDC). NDCs represent each country's commitment to delivering on the goals of the Paris Agreement, reducing greenhouse gas emissions, and addressing climate change. These contributions outline the specific targets and actions that nations plan to undertake to limit global warming, typically submitted every five years. NDCs are unique to each country, tailored to their specific circumstances, capabilities, and development priorities.

New Zealand's first Nationally Determined Contribution (NDC1) under the Paris Agreement is to reduce net GHG emissions to 50 per cent below gross 2005 levels by 2030. It was updated in October 2021.

The NDC1 differs from the domestic target established under the CCRA. It can be achieved through actions taken in Aotearoa to reduce domestic emissions, as well as through purchasing international mitigation.

The NDC1 target is economy-wide, encompassing all sectors and greenhouse gases. This contrasts with Aotearoa's domestic target, which employs a split-gas approach. As a result, any adjustments to the domestic methane target will necessitate modifications in other sectors to achieve the overall NDC1, or alterations in the use of offshore mitigation.

The Government is to advise the second Nationally Determined Contribution (NDC2) by February 2025.

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Frequently Asked Questions

What is the Global warming potential of methane?

This report does not use climate emission metrics for its calculations, but they are described here for completeness.

Climate metrics were first designed to compare the climate effects of emissions of different greenhouse gases. In the IPCC First Assessment Report (FAR) this was done by comparing the relative radiative effects of a single pulse emission of 1 kg of a gas compared to that of carbon dioxide. (Shine et al. 1990). The radiative effect chosen was the radiative forcing integrated over a number of years (referred to as the “time horizon”) following the pulse, and termed the Global Warming Potential (GWP). However the IPCC cautioned: *“It must be stressed that there is no universally accepted methodology for combining all the relevant factors into a single [metric] ... A simple approach [i.e. the GWP] has been adopted here to illustrate the difficulties inherent in the concept.”* (Shine, 2009). The FAR reported this quantity over three different time horizons, 20, 100 and 500 years. Again a caveat was provided *“These three different time horizons are presented as candidates for discussion and should not be considered as having any special significance”* (Shine 1990).

The GWPs for biogenic methane are 79.7 ± 25.8 , 27.0 ± 11 and 7.2 ± 3.8 for 20, 100 and 500 year time horizons. These metrics imply that a 1 kg emission of methane has a “climate effect” that is equivalent to a 79.7 kg emission of carbon dioxide if we are interested in effects over the next 20 years, or equivalent to a 7.2 kg emission of carbon dioxide if we are interested in the effects over the next 500 years⁷. The wide variation is because methane is removed from the atmosphere on a timescale of around a decade. This contrasts with carbon dioxide which accumulates over centuries (Canadell et al. 2021). After a couple of decades the pulse of methane will have mostly decayed and contribute little further radiative forcing whereas the pulse of carbon dioxide will still persist. Hence the climate effect of methane relative to that of carbon dioxide decreases as the time horizon increases.

The GWPs for methane include additions from the chemical production of ozone and stratospheric water vapour. For fossil methane (not considered further in this report) they also include the effect of the carbon dioxide produced.

FAQ What is the GWP* metric?

Since a methane pulse decays within a couple of decades, but a pulse of carbon dioxide persists for centuries the difference in behaviour makes comparisons between the two very sensitive to time horizon. In comparison a step change in methane emissions (i.e. an increase in the rate of

⁷ Under the “Paris Rulebook” (Decision 18/CMA.1, annex, paragraph 37), parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs. In addition, parties may use other metrics to report supplemental information on aggregate emissions and removals of GHGs.

emission) leads to a persistent increase in methane concentration that is more similar to the persistence of a pulse of carbon dioxide. A new climate emission metric GWP* was devised (Allen et al., 2018) to compare methane with carbon dioxide that combines 75% of a step with 25% of a pulse (Cain et al., 2019). Under this metric a methane emission that decreases by around 0.3% per year would lead to no additional warming, because the reduction in warming from the short-lived term cancels the extra warming from the long-lived term. Methane emissions that are positive but declining at this rate correspond to a GWP* of 0, i.e. would be equivalent to zero emissions of carbon dioxide.

The step-pulse (GWP*) metric and the pulse-pulse (GWP) metrics are both physically-based metrics, and GWP* uses GWP in its calculation, but the assessments of climate impacts are different because GWP* matches the temperature effects of a time-series of gases and GWP does not.

The IPCC 6th Assessment Report (AR6) explicitly does not recommend a metric *“this Report does not recommend an emissions metric because the appropriateness of the choice depends on the purposes for which gases or forcing agents are being compared”* (Forster et al. 2021). The causes of controversy with metrics are how they are applied. If the GWP is applied to a methane emission that is changing over time, the climate change resulting from the equivalent carbon dioxide emission can be very different to that resulting from the original methane emissions (Cain et al., 2019). It has been argued that the GWP* should be applied to a baseline of no emissions, rather than starting from the last 20 years (the 20-year timescale is embedded in the GWP* metric) (Reisinger et al., 2021).

It is not necessary to use climate metrics at all if short-lived gases are reported separately to long-lived gases, and if they are treated separately in policy (Allen et al., 2022). Since the question being addressed in this report is focussed entirely on biogenic methane, no metrics are needed to compare with other gases. Since New Zealand policy envisages separate schemes for methane and carbon dioxide, there is no need for metrics in policy, either.

FAQ Do fossil and biogenic methane have different climate effects?

Once aloft in the atmosphere, the climate effects of methane are independent of how it originated, i.e. whether from a recent biological process or from fossil stores. As discussed above, the products of methane chemistry are ozone, water vapour and carbon dioxide. The additional effects of ozone and water vapour have always been included in the climate metrics for methane, but the effect of carbon dioxide is often excluded to avoid double counting. For instance, a carbon budget calculation is often based on how much natural gas is used regardless of whether it is actually combusted or whether it is lost through leaks into the atmosphere. If the carbon has been counted once in the gas usage, it should not be counted again in the climate metric for fugitive methane emissions. Similarly although carbon dioxide is produced in the decomposition of biogenic methane, this carbon will have been removed from the atmosphere previously in growing the animal fodder or producing the organic material that was disposed

of in the landfill. Since the uptake of carbon is not included in carbon budgets, the production of carbon dioxide from biogenic methane should not be included either.

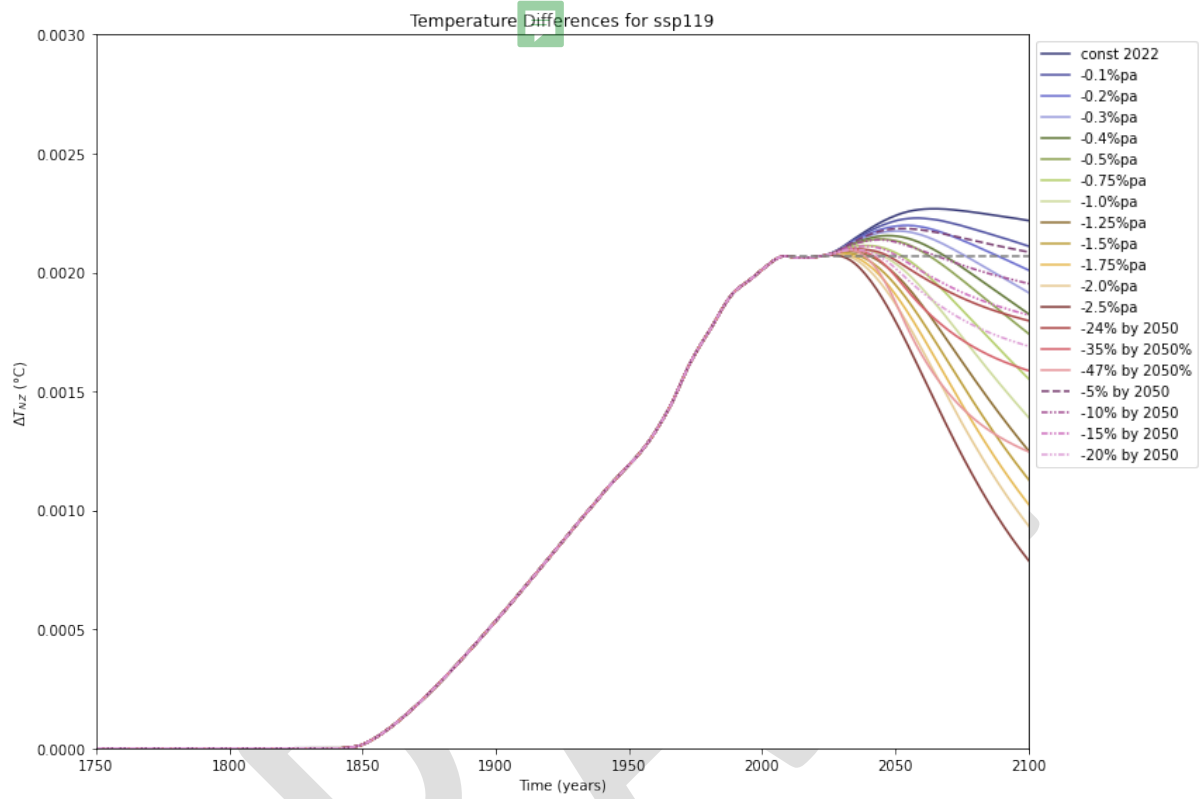
There is an allowance in the AR6 assessment (Forster et al. 2021) where some of the carbon is lost through removal of formaldehyde from the atmosphere, and also from delayed emission from the methane oxidation. This is very uncertain, it only contributes a small fraction of the climate metrics for methane and will not be considered in this report.

[\[2\]](#) Under the “Paris Rulebook” (Decision 18/CMA.1, annex, paragraph 37), parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs. In addition, parties may use other metrics to report supplemental information on aggregate emissions and removals of GHGs.

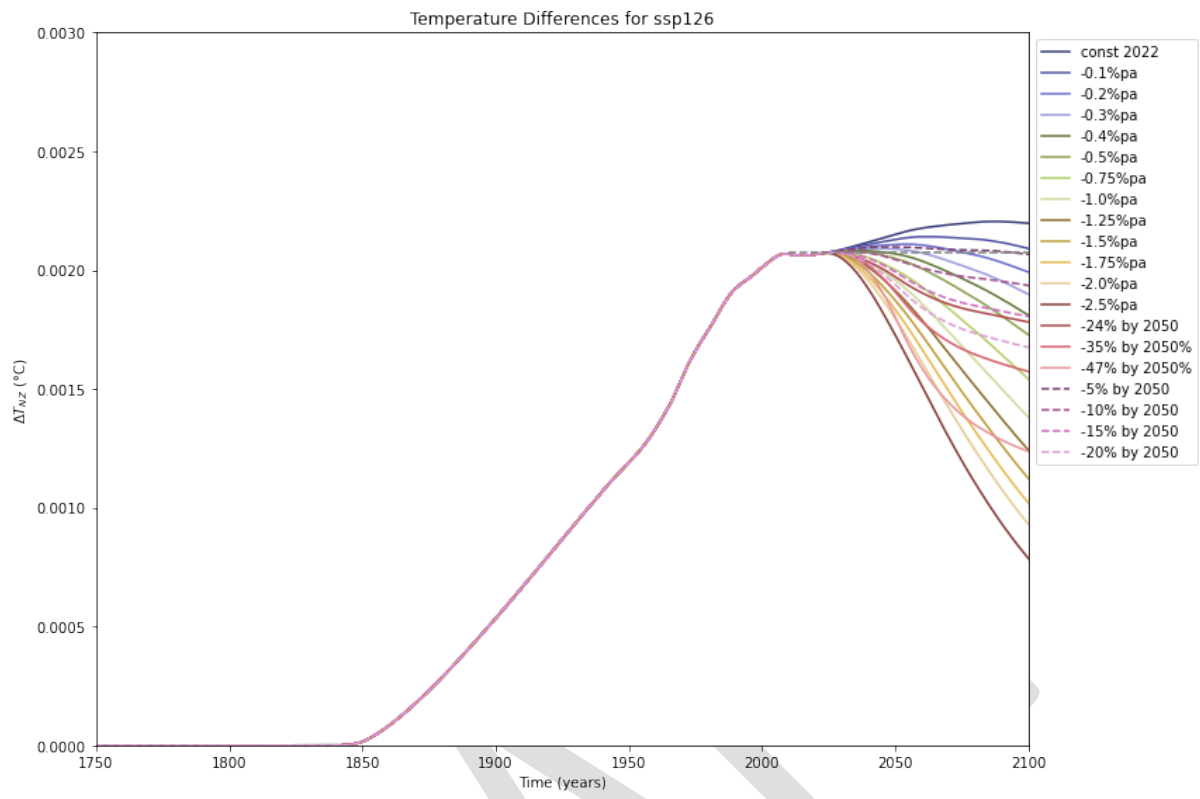
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Time Series Plots

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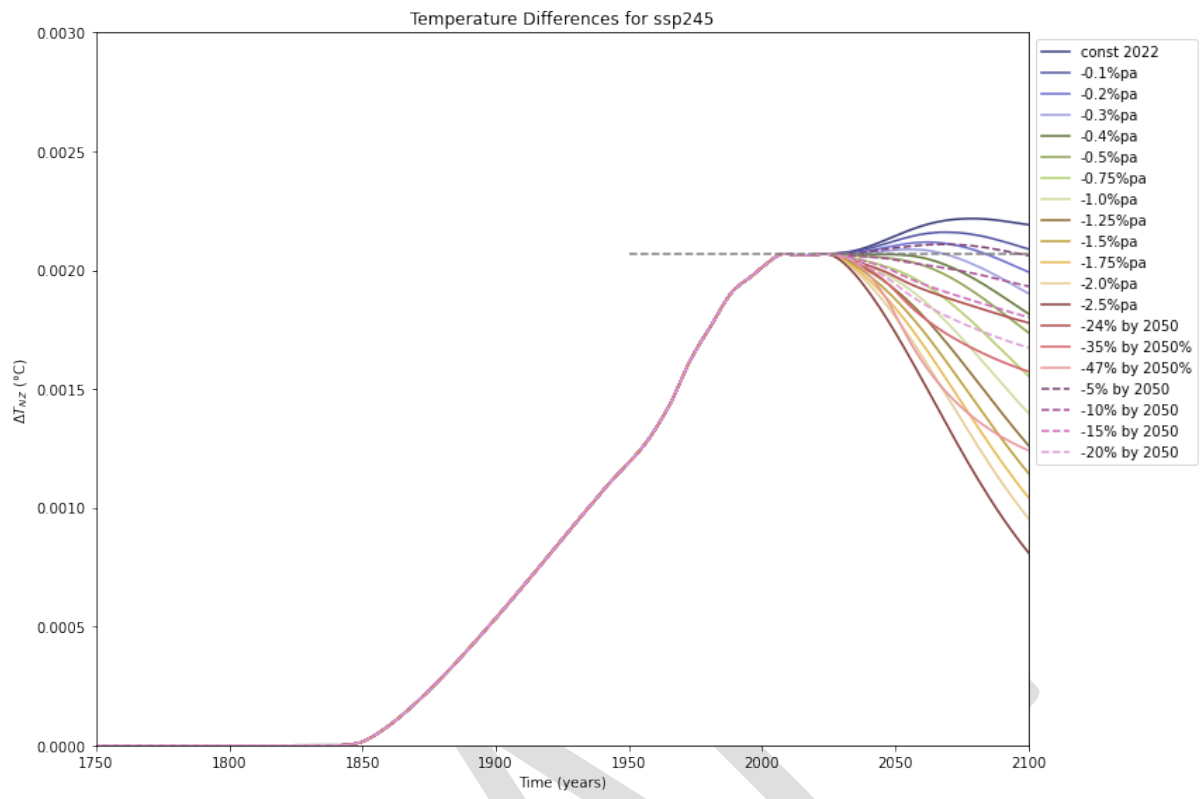


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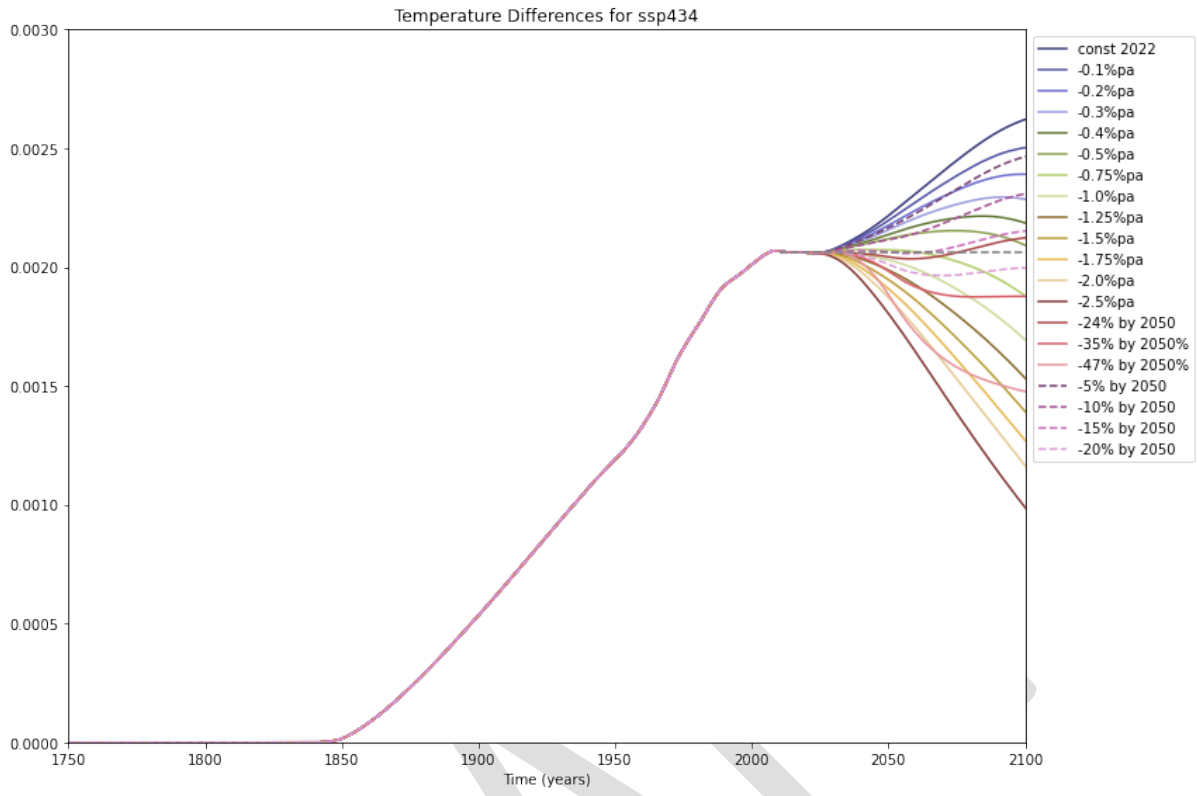
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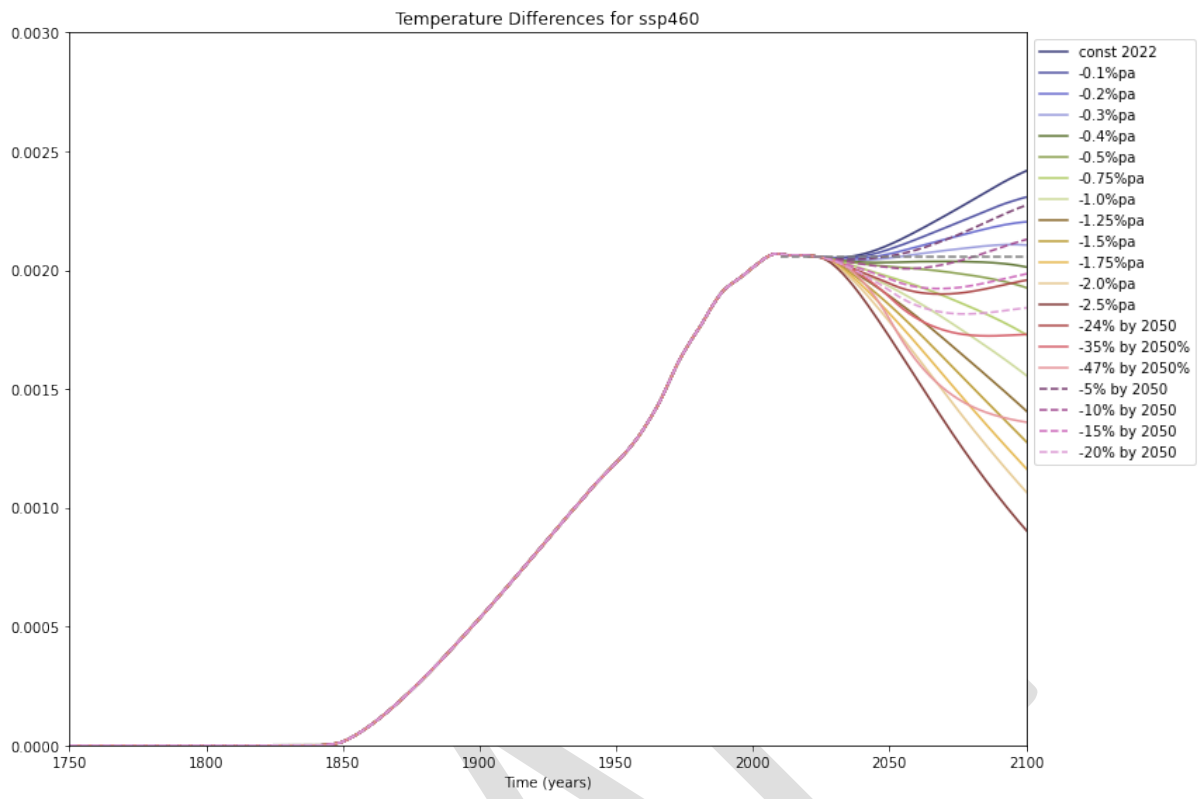
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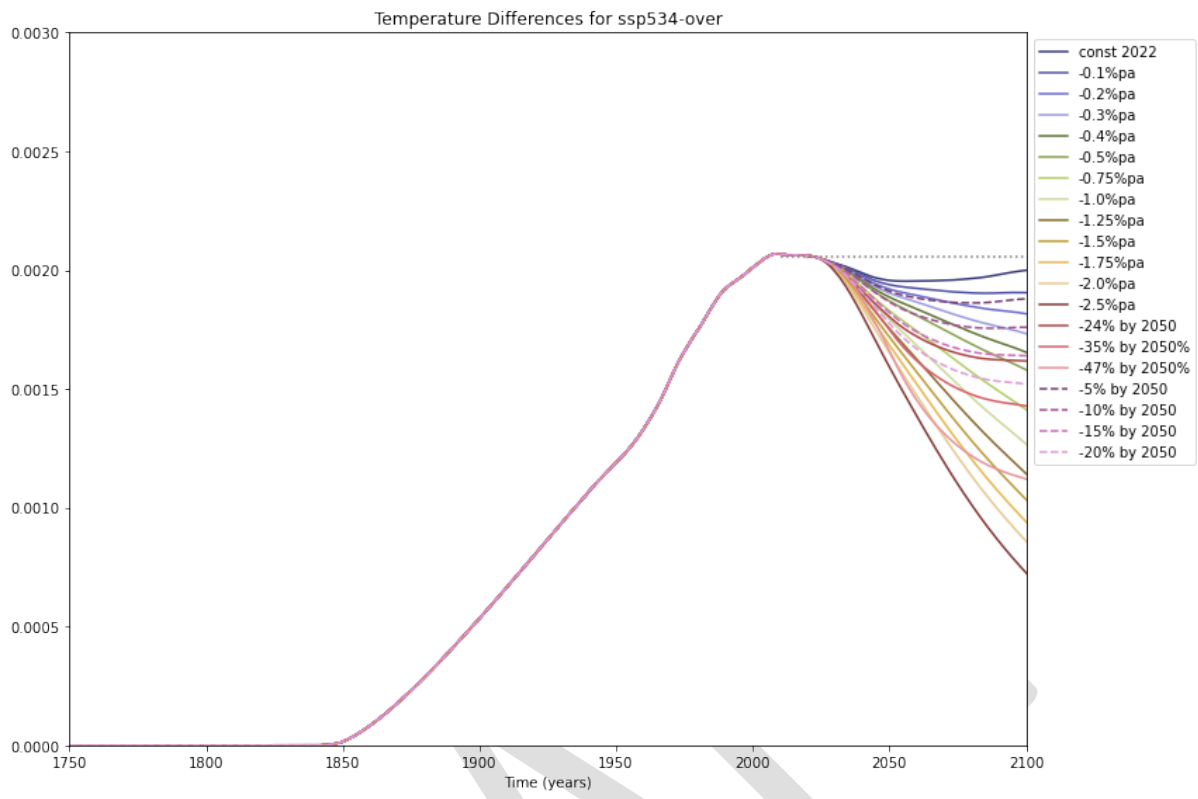
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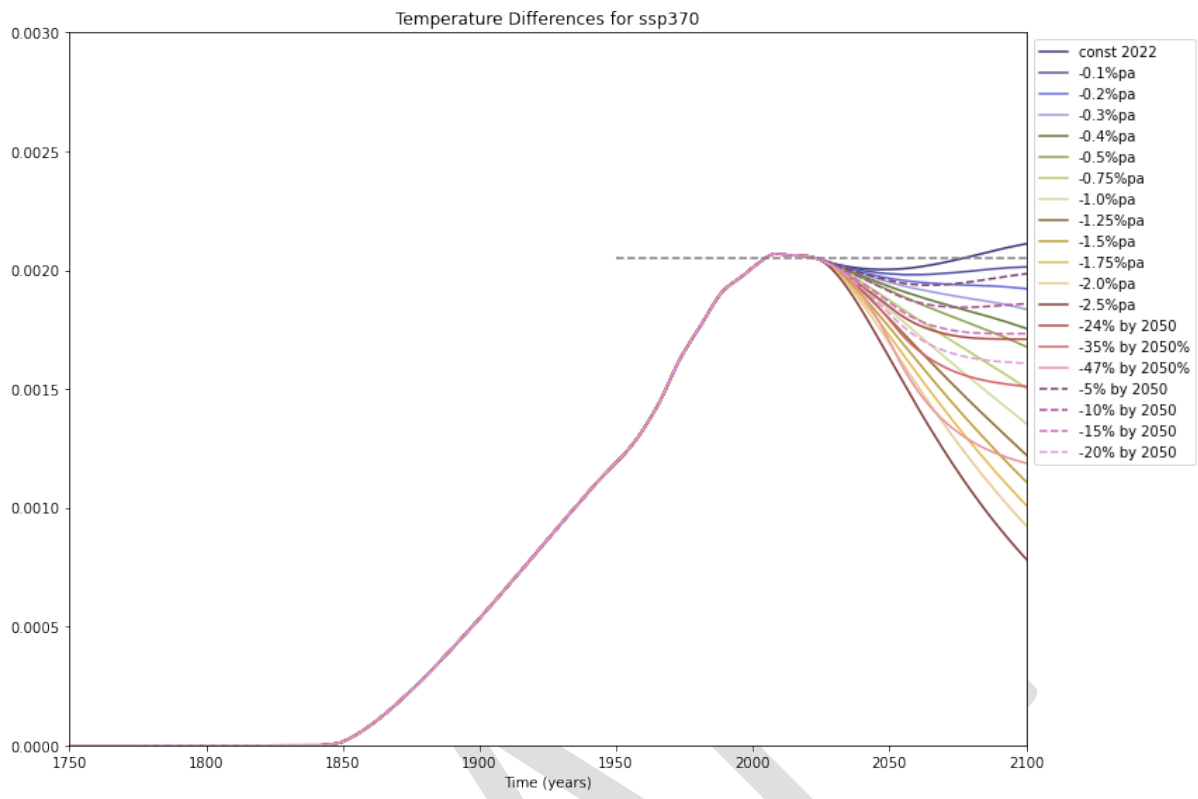
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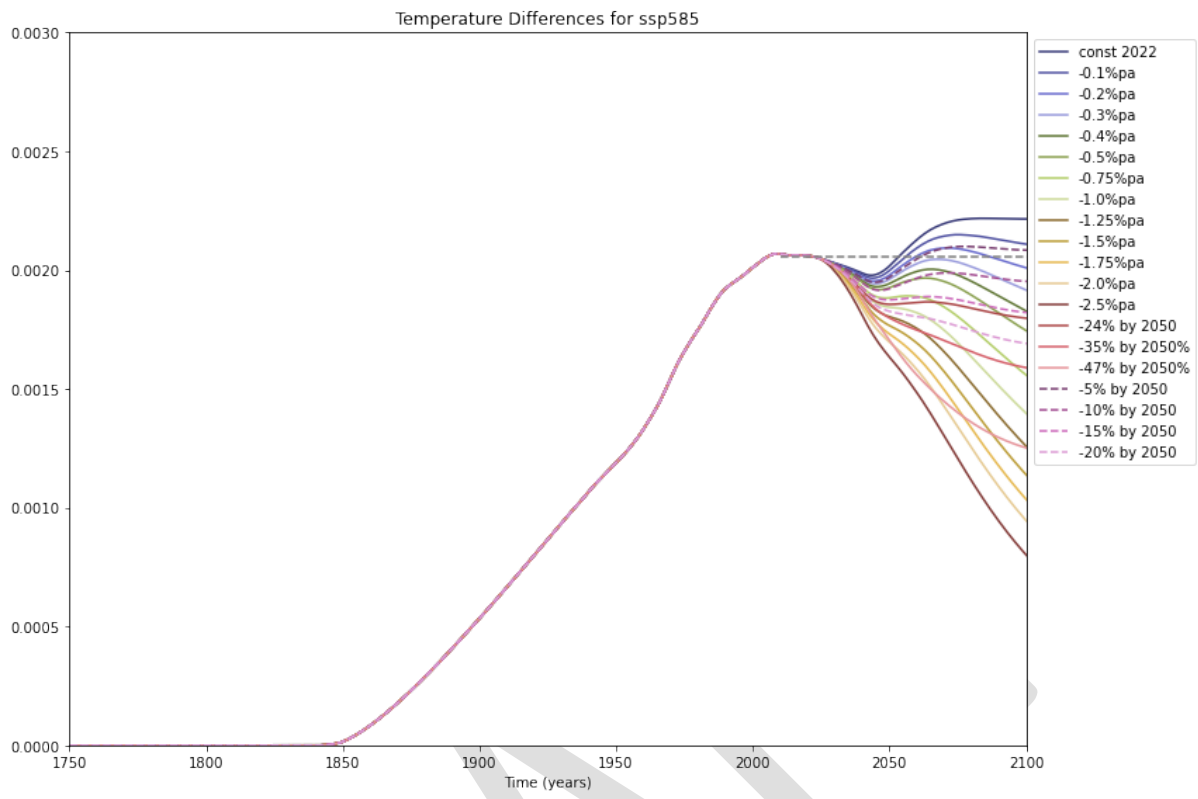
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