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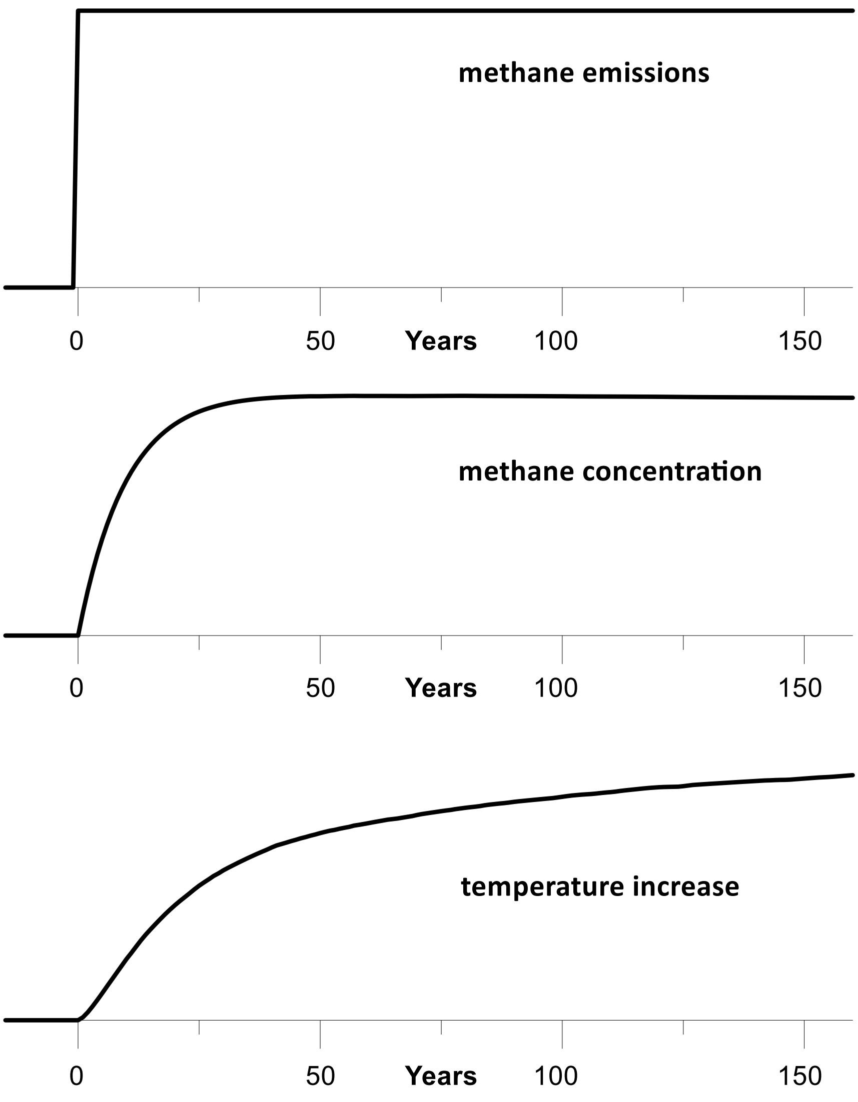
The contribution of methane emissions from New Zealand livestock to global warming



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The contribution of methane emissions from New Zealand livestock to global warming

Report to the Parliamentary Commissioner for the Environment

August 2018

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Summary haiku:

Methane is short-lived

but its warming lingers on:

Earth adjusts slowly

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Table of Contents

Executive summary

This report provides information on the global warming that might occur from future emissions of methane from livestock in New Zealand under different assumptions and scenarios. Specifically, the report seeks to answer three main questions, namely:

- Given our past emissions, what would be the warming contribution of future methane emissions in New Zealand if they were held steady at current levels?
- Given the most recent projected emissions of methane in New Zealand what additional warming might be expected?
- What annual reductions in methane emissions would be required to avoid any additional warming contribution from New Zealand methane emissions by 2030 or by 2050?

The answers to these questions are highly relevant as New Zealand is considering what emission target(s) it might set for different greenhouse gases as part of its contribution to the objectives of the Paris Agreement.

These questions are answered by developing estimates of historical emissions of methane from livestock husbandry in New Zealand back to the 19th century, and combining such estimates with more recent data from the national greenhouse gas emissions inventory and projections by the Ministry for Primary Industries. These past and future emission estimates, which have contributed to the increase in global methane concentrations, were then fed into a simple climate model that has been used widely internationally to simulate the climate change resulting from different emission scenarios. The indirect climate effects of methane emissions are included in the simulations, and the effect of uncertainties in key parameters are considered. The climate model, called MAGICC, is based on the physics and chemistry of greenhouse gases and their fate in the atmosphere, including the relatively short lifetime of methane. The model can be calibrated to simulate results from a range of much more complex climate models and is thus also able to provide insight into model-based uncertainties of future projections.

The main finding from this study is that if New Zealand were to hold its livestock methane emissions constant at 2016 levels, the amount of methane in the atmosphere due to those emissions would level out within a decade, but warming from this methane would still increase for well over a century, albeit at a gradually declining rate. This ongoing additional warming is largely due to the inertia of the climate system, which is still responding to the historical increase in methane emissions from New Zealand since the 19th century and results in a long-lasting component of warming from methane despite the relatively short lifetime of the gas itself. It would take several hundred years of constant methane emissions before warming due to those emissions ceases to increase entirely.

If New Zealand's methane emissions were held constant from today onwards, the additional warming in 2050 would be about 10-20% above the warming that has been caused by New Zealand's methane emissions to date. By 2100, the additional warming would increase to about 25-40%, and to about 40-55% by 2200. The ranges reflect the fact that the warming effect exerted by New Zealand's methane emissions depends on global methane concentrations. Hence the actions taken by other countries during this period to address climate change, including through reducing their methane emissions, will influence the warming caused by on-going methane emissions from New Zealand.

If New Zealand wished to ensure that its livestock methane emissions cause <u>no</u> additional future warming relative to the warming caused by those emissions to date, it would have to reduce those methane emissions by about 10-22% below current levels by the year 2050, and 20-27% by 2100. The ranges in the emission reductions are due to different assumptions regarding actions taken by other countries that will influence future concentrations of greenhouse gases, and represent best estimates based on a range of different climate models. As a general rule, the greater the assumed action globally to reduce methane from the extraction, transport and use of fossil fuels (coal, oil and gas), the lower global methane concentrations and hence the more effective the warming caused by remaining sources of methane becomes.

Even though this study demonstrates that constant methane emissions result in some additional future warming, this does not mean that methane has the same long-lasting impact on climate as carbon dioxide. Continued emissions of carbon dioxide by New Zealand at today's level would eventually result in greater additional warming than continued emissions of methane, given the long lifetime of carbon dioxide and its resulting accumulation in the atmosphere. Warming due to long-lived greenhouse gases will continue to increase until their net emissions reach zero. Reducing net emissions of long-lived greenhouse gases to zero is therefore a physical necessity if New Zealand wishes to halt its further contribution to climate change.

By contrast, reducing New Zealand's livestock methane emissions by 22% (as a best estimate) below today's levels would avoid additional warming from those emissions in 2050 relative to today, if the world as a whole undertakes actions consistent with the Paris Agreement. Additional reductions would be needed beyond 2050 to maintain this level of warming into the more distant future. Reducing New Zealand's emissions by more than 22% below today's levels by 2050 would reduce the warming caused by New Zealand's livestock methane emissions below today's levels. However, how much New Zealand can and wants to reduce its emissions to reduce its overall contribution to warming will depend on complex economic, social and other environmental considerations that physical metrics can inform but not answer.

1. Purpose and Context of this Report

The New Zealand Parliamentary Commissioner for the Environment requested a report examining the global warming expected to result from future livestock-related methane emissions from New Zealand under various scenarios. This report seeks to answer three main questions:

- Given New Zealand's past methane emissions from livestock, what would be the warming contribution of future methane emissions from livestock in New Zealand if they were held steady at current levels?
- Given the most recent projected emissions of methane from livestock in New Zealand, what additional warming might be expected?
- What annual reductions in these methane emissions would be required to avoid any additional warming contribution from New Zealand methane emissions by 2030 or by 2050?

This information is relevant as New Zealand is considering what emission target(s) it might set as part of its contribution to the objectives of the Paris Agreement. The Paris Agreement seeks to limit the increase in global average temperature to well below 2°C, and pursue efforts to limit warming to 1.5°C, above pre-industrial levels. Global temperatures have already risen by around 1°C, and the most recent (fifth) assessment by the Intergovernmental Panel on Climate Change (IPCC) found that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC 2013). Achieving the temperature goal of the Paris Agreement will require major efforts to reduce emissions globally and across all sectors as far and as quickly as possible to minimise overall warming.

Multiple greenhouse gases from a range of human activities have contributed to the warming and will continue to do so over the 21st century and beyond (IPCC 2013). However, their contributions to warming differ widely, owing to their different abilities to absorb infrared (heat) radiation and different lifetimes in the atmosphere.

Emissions of long-lived greenhouse gases, predominantly carbon dioxide (CO_2) but also nitrous oxide (N_2O), persist in the atmosphere for hundreds to thousands of years. Every tonne of carbon dioxide emitted creates warming that lasts for many centuries and that adds to the stock of carbon dioxide currently in the atmosphere. Consequently, if global warming is to be limited at any level considered to avoid dangerous climate change, net emissions of long-lived greenhouse gases have to be reduced to zero. Until such net zero emissions are achieved, any further net emissions of long-lived greenhouse gases will continue to add additional warming to that already experienced to date.

Some greenhouse gases, including methane, have a much shorter lifetime in the atmosphere, as various chemical processes in the atmosphere remove them within a few decades. An emission pulse of methane persists in the atmosphere on average for 12 years, but a small fraction persists for longer.[1] Methane is a powerful greenhouse gas, so an emission pulse results in significant warming over the first few decades, but this warming gradually decays again, with most of the warming gone within a century. As a result, emissions of short-lived greenhouse gases do not have to be reduced to zero to avoid additional warming, since the warming caused by ongoing emissions to a large extent simply maintains, rather than adds to, the warming caused by previous emissions.

1 A lifetime of 12 years does not mean that all methane has disappeared after 12 years, as methane follows an exponential decay curve. Some molecules in one kg of methane emitted into the atmosphere will disappear within one second or the first year, while others will last for 50 or even 100 years. After 50 years, less than 2% of the original emission remain. See Section 3 for some graphs that illustrate how a pulse of methane decays over time.

As a growing number of countries around the world are setting and updating long-term (2050 and beyond) emission reduction targets, these differences become highly relevant. Every tonne emitted of any greenhouse gas makes the world warmer than it would have been otherwise, and thus avoiding the emission of any greenhouse gas brings a benefit to the climate – but because of the differing contributions to cumulative warming from the different gases, the long term goals for emissions reductions of each gas may differ.

The emission reduction target for long-lived greenhouse gases globally is unambiguously dictated by basic physics: net emissions of long-lived greenhouse gases must go to zero if the global average temperature is to be stabilised. By contrast, physical climate considerations alone are insufficient to set a target for short-lived gases: emissions of short-lived gases do not have to go to zero, but the lower they go, the less they will contribute to the overall warming the world will experience.

The interplay between emission reductions of short- and long-lived gases can be illustrated by comparing global net emissions of carbon dioxide and methane under different scenarios (see Figure 1). The default pathway shown in Figure 1 (black) represents a scenario used widely as a benchmark in the scientific literature to limit warming below 2°C (van Vuuren et al. 2011b). In this scenario, net global carbon dioxide emissions become negative by 2080 (i.e. global removal of carbon dioxide outweighs any remaining emissions). This is technically challenging and could represent major risks for food security and environmental integrity, given that most currently viable carbon dioxide removal processes require land, water and/or energy that could compete with food production and other ecosystem functions (Azar 2011; Humpenöder et al. 2018). In that same scenario, methane emissions are reduced rapidly largely because any emissions associated with fossil fuel exploration and use, as well as emissions from waste, are almost eliminated, and emissions from agriculture reduced significantly below business-as-usual trends.

The red and blue lines represent hypothetical alternative emission pathways that would result in nearly identical warming trends. The red scenario assumes no reduction in methane emissions. This requires a significantly more rapid reduction in carbon dioxide emissions and greater net negative emissions towards the end of the 21st century, thus magnifying the challenges and risks in remaining below the 2°C limit. The blue scenario assumes additional reductions in methane emissions, which would allow carbon dioxide emissions to be reduced at a slightly lesser pace and would almost entirely avoid net carbon dioxide emissions having to become negative during the 21st century.

Note that the red and blue scenarios are not economically-optimised scenarios; they are simply thought experiments to demonstrate the global-scale interplay between methane and carbon dioxide. They show that methane reductions cannot substitute for the need for carbon dioxide emissions to reach net zero – but the *pace* at which carbon dioxide emissions have to be reduced to (and below) zero[2] does depend on the future *sustained rate* of methane emissions. This trade-off between a finite carbon budget and a sustained rate of methane emissions can be captured by the GWP* metric proposed recently (Allen et al. 2016; Allen et al. 2018).

The upshot of the interaction between a finite budget of carbon dioxide emissions and a sustained rate of methane emissions is that it is impossible to determine based on physical climate conside-rations alone how low global methane emissions have to go, but rely inevitably also on economic and social considerations. If methane emissions could be reduced very cheaply, it would make sense for methane to go as close to zero as possible as this would reduce the overall contribution to

[2] In other words, the total allowable carbon dioxide emissions budget consistent with a given temperature goal

warming from methane, and thus allow a greater carbon dioxide budget to remain within the same overall warming limit. By contrast, if substantial methane emission reductions are very expensive or socially not feasible, these emissions could remain even at today's levels without rendering the Paris temperature goals physically impossible, but this would rely on even more rapid reductions of global carbon dioxide emissions that equally could encounter economic, social and environmental limits.

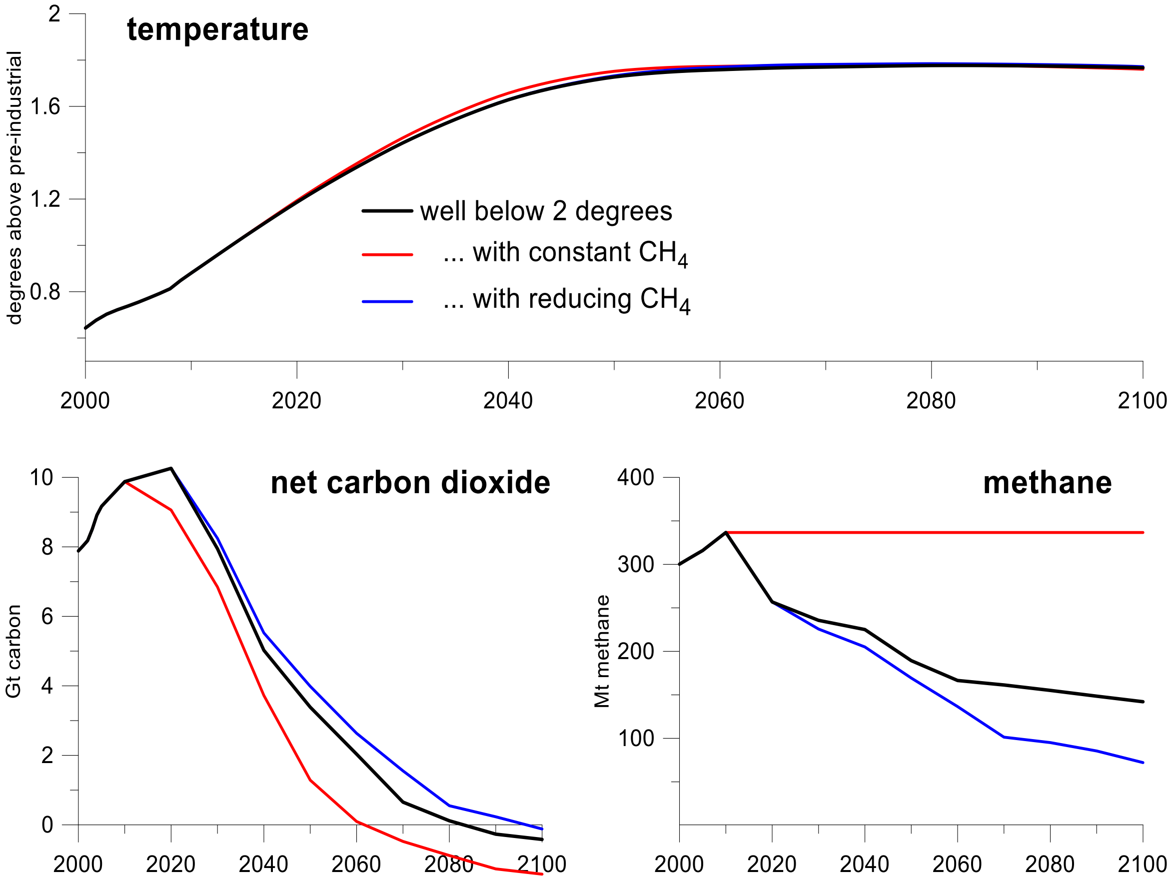

Figure 1. Three alternative scenarios for global emissions of carbon dioxide and methane that limit the rise in global average temperatures to below 2°C in the best estimate. For details, see text. Note that for scenarios that limit warming to 1.5°C, net carbon dioxide emissions would have to reach zero globally as early as 2050 and become negative after that.

These considerations are highly relevant to New Zealand, which has an unusually high share of methane in its emissions profile and hence where the question of what to do about methane is particularly pressing. The above global-scale considerations indicate that it is defensible from a climate perspective for New Zealand's methane emissions to remain above zero, but this doesn't answer the question *how much* above zero.

One potentially useful benchmark to answer this question could be to ask how much methane emissions would need to drop to result in *no additional* warming over and above the warming caused by our methane emissions already.

The short answer is that as methane is a short-lived greenhouse gas, maintaining a constant rate of emissions will result in a constant methane concentration, and a constant methane concentration will *eventually* result in a stable amount of warming (see e.g. Hollis et al. 2016).

However, this short-hand characterisation merges significant differences in time frames. For example, if the concentrations of all greenhouse gases had been held constant at levels reached in the year 2000, we would still have expected another 0.6°C of warming to occur by the year 2100, in addition to the 0.74°C warming that occurred over the preceding century (IPCC 2007). This ongoing warming reflects the inertia of the climate system, which adjusts only slowly to an increase in the radiative blanket formed by increased greenhouse gases in the atmosphere long after the thickness of the blanket has stabilised.

It takes about 50 years after the beginning of a constant rate of methane emissions for methane concentrations to stabilise (see Section 3). It then takes several hundreds of years for temperatures to stabilise in response to the increased methane concentrations, owing to both the inertia of the climate system and various feedbacks that further enhance the warming that comes from methane alone (see Sections 2 and 3). Some of these feedbacks are unique to the chemical characteristics of methane, while others are common to all greenhouse gases. While the statement that a constant flow of methane emissions results in a constant amount of warming is true from a geological perspective that measures time in centuries to millennia, it does not hold if the goal is to halt the rise in global average temperature within the 21st century and if methane emissions have risen rapidly during the previous century. The climate system will continue to adjust to the increase in methane (as well as any other greenhouse gases) over the 21st century and beyond, even if the concentrations of all greenhouse gases were held constant from now on.

The purpose of this report is therefore to explore in more scientific detail the time frames over which a constant rate of methane emissions would affect global temperature. More specifically, this report discusses how much additional warming we could expect from New Zealand's methane emissions if they were to continue under "business-as-usual", if they were held constant at today's levels[3], and how much they might need to be reduced if the goal was to ensure no additional warming from New Zealand's methane emissions above the warming caused already.

It needs to be emphasised that knowing what level of methane emissions would result in a constant amount of warming from today onwards can only serve as a reference point, it does not necessarily constitute an appropriate emissions target. The absolute amount of warming caused by a gas to date and in future, as well as the potential to reduce its future emissions to limit total warming, are also important. These perspectives are explored further for New Zealand's livestock methane emissions in Appendix II.[4]

How far New Zealand in fact can and wants to lower its methane emissions and the warming they have caused to date and will continue to contribute to in future will depend on complex judgements about the economic, social and environmental consequences of such reductions. This includes judgements on how New Zealand wishes to position itself relative to actions and expectations by the rest of the world. A physical estimate of *relative* temperature changes compared to today can only provide a reference point but cannot answer these much bigger social and economic questions.

The remainder of this report is structured as follows: Section 2 provides an overview of the global methane emissions and concentrations, the chemical processes that control the lifetime of methane

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[3] In this report, "today's levels" generally refers to emissions in the year 2016, which is the most recent year for which emissions estimates are available from New Zealand's national greenhouse gas emissions inventory.

[4] Based on the metric devised by Allen et al. (2016), the overall warming effect (relative to pre-industrial levels) from sustaining New Zealand's livestock methane emissions at today's levels (1,156 kt CH_4) is roughly the same as that from a one-off historical emission of 3.2 Gt CO_2. By comparison, the total cumulative fossil CO_2 emissions from 1840 to 2016 are estimated to be about 1.8 Gt CO_2 (historical emission estimate based on Ausseil et al. 2013), and about 2.4 Gt CO_2 if fossil CO_2 emissions are phased out by 2050. This indicates that sustaining New Zealand's methane emissions would contribute more to total warming relative to pre-industrial conditions than New Zealand's fossil CO_2 emissions, provided that these are phased out within the 21st century. For additional details, see Appendix II.

in the atmosphere, and the various mechanisms by which methane emissions contribute to global warming. Section 3 provides a set of simple conceptual graphs that demonstrate the warming resulting from a single short burst (pulse) and a sustained rate of methane emissions, and how this contrasts with the warming from a pulse and sustained rate of carbon dioxide emissions. The indirect climate effects of methane emissions are included in the simulations, and the effect of uncertainties in key parameters are considered. Section 4 then tackles the question of how much additional warming can be expected from New Zealand's methane emissions under a range of scenarios, taking into account historical methane emissions, climate model uncertainties and ongoing changes in the global atmosphere. This report focuses on methane from livestock only, as this constitutes by far the largest fraction of total methane emissions in New Zealand. Section 5 summarises and concludes the results.

The detailed modelling of the atmospheric responses to methane emissions was undertaken using the climate model MAGICC. This model is used widely to assess the climatic consequences of different emission scenarios, and can be calibrated to reproduce results from much more complex climate and carbon cycle models. It therefore is also a useful tool to explore model-based uncertainties. Appendix I gives an overview of the model and how it was used in this report.

2. Warming caused by methane emissions: key mechanisms

2.1 Global methane emissions and concentrations

Methane (CH_4) is a relatively short-lived greenhouse gas with a current lifetime in the atmosphere of just over 12 years.[5] Methane is highly effective at absorbing infrared (heat) radiation, and an increasing concentration of methane in the atmosphere means that Earth loses less heat into space, resulting in a gradual warming.

Global methane concentrations have increased from about 700 parts-per-billion (ppb) at the beginning of the industrial revolution to more than 1,850 ppb in 2017, a more than 2.5-fold increase (see Figure 2). This substantial increase occurred despite the short lifetime of methane because rapidly increasing emissions from human activities (mainly from agriculture, fossil fuel extraction, transport and use, and waste) have outpaced the natural loss processes for methane (Saunois et al. 2016a; Saunois et al. 2016b). There has been considerable discussion about why methane concentrations stopped growing between about 1999 and 2006, and the causes for the sustained increase since 2007 that can be seen in Figure 2. The detailed reasons remain subject to scientific debate. Closure of leaky gas pipelines in the former Soviet Union have been considered as plausible reason for the slow-down in the early 2000s, although some studies also pointed to slowing emissions growth from rice and cattle production. The renewed increase in methane concentrations since 2006 is considered to be most likely due to increased emissions mainly from tropical agriculture and tropical wetlands, with a possible contribution also from increased fossil-fuel related emissions. There is also some evidence that atmospheric loss processes for methane may have slowed down over the past decade although details remain unresolved (Royal Society 2017).

Overall, global methane emissions (from both biogenic and fossil sources), including their consequences for other atmospheric constituents that influence the global climate, are estimated to have contributed more than 40% of the total warming effect (radiative forcing) from all human

5 In this report, the lifetime of methane is the so-called 'perturbation lifetime' that takes into account the indirect effect of the gas on its own residence time (Myhre et al. 2013).

activities between 1750 and 2011. About two thirds of this is estimated to come from methane itself, and the other third from indirect effects triggered by methane emissions (see Section 2.4 below; Myhre et al. 2013: Table 8.17).

Methane decays naturally in the atmosphere through a series of photochemical reactions, breaking down ultimately into water vapour (H_2O) and carbon dioxide (CO_2). Whether the end product CO_2 has to be considered in the total warming depends on the origin of the methane emission.

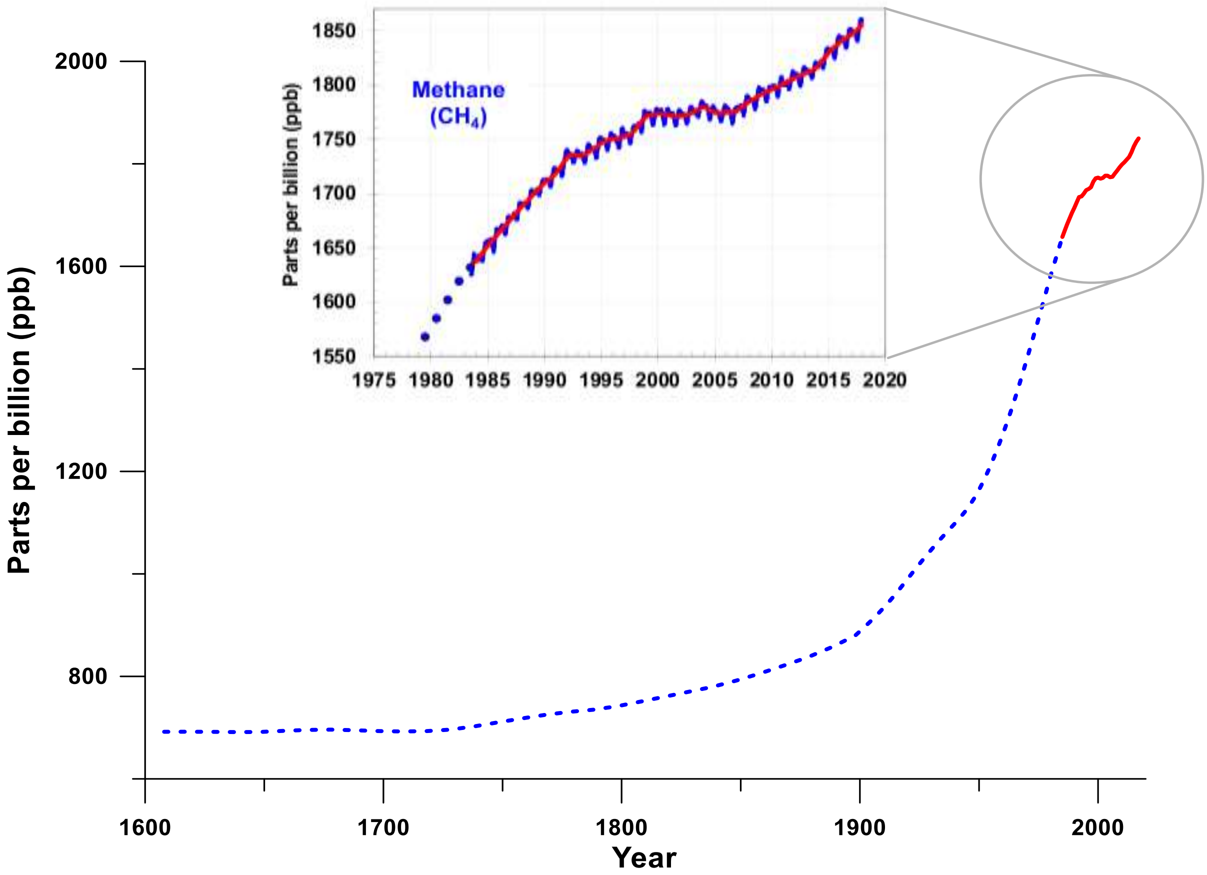

Figure 2: Global methane concentrations. Data up to 1984 (blue dotted lines) are from Greenland and Antarctic ice cores (Etheridge et al. 1998); data from 1984 onwards (red full lines) are from the US National Oceanic and Atmospheric Administration (NOAA Earth System Research Laboratory global air sampling network (http://www.esrl.noaa.gov/gmd/). The inset shows monthly average values (blue solid lines) as well as annual average (red solid lines) from the NOAA network.

If methane is produced by biological processes (such as enteric fermentation or manure management in agriculture, or in the decay of biological products in landfills and wastewater), it can be assumed that for each molecule of CO_2 produced in the decay of methane, one molecule of CO_2 would recently have been absorbed from the atmosphere through the growth of plant matter. For example (see Figure 3), as grass grows it absorbs carbon dioxide from the atmosphere. A cow then eats the grass, and through its digestion turns the carbon contained in the grass either back into carbon dioxide that is exhaled through its breath, or into manure that quickly decays into CO_2 through microbial activity. Carbon contained in products such as meat and milk is then consumed by humans, who in turn convert these products into carbon dioxide through respiration and through microbial degradation of human excreta. A small fraction of the carbon eaten by the cow gets converted into methane, which ultimately again breaks down into carbon dioxide.

For this reason, for so-called biogenic methane (created by living organisms), the carbon dioxide into which methane decays can be ignored since generally the original removal of carbon dioxide from the atmosphere by short-lived organic matter is also ignored. As far as carbon dioxide is concerned, the production and decay of short-lived organic matter is a closed cycle (even though for methane from landfills, this cycle can potentially stretch over a decade or more between production of organic material and its decay). It is only when some of the carbon contained in organic matter is transformed into the form of methane that an additional warming effect occurs.

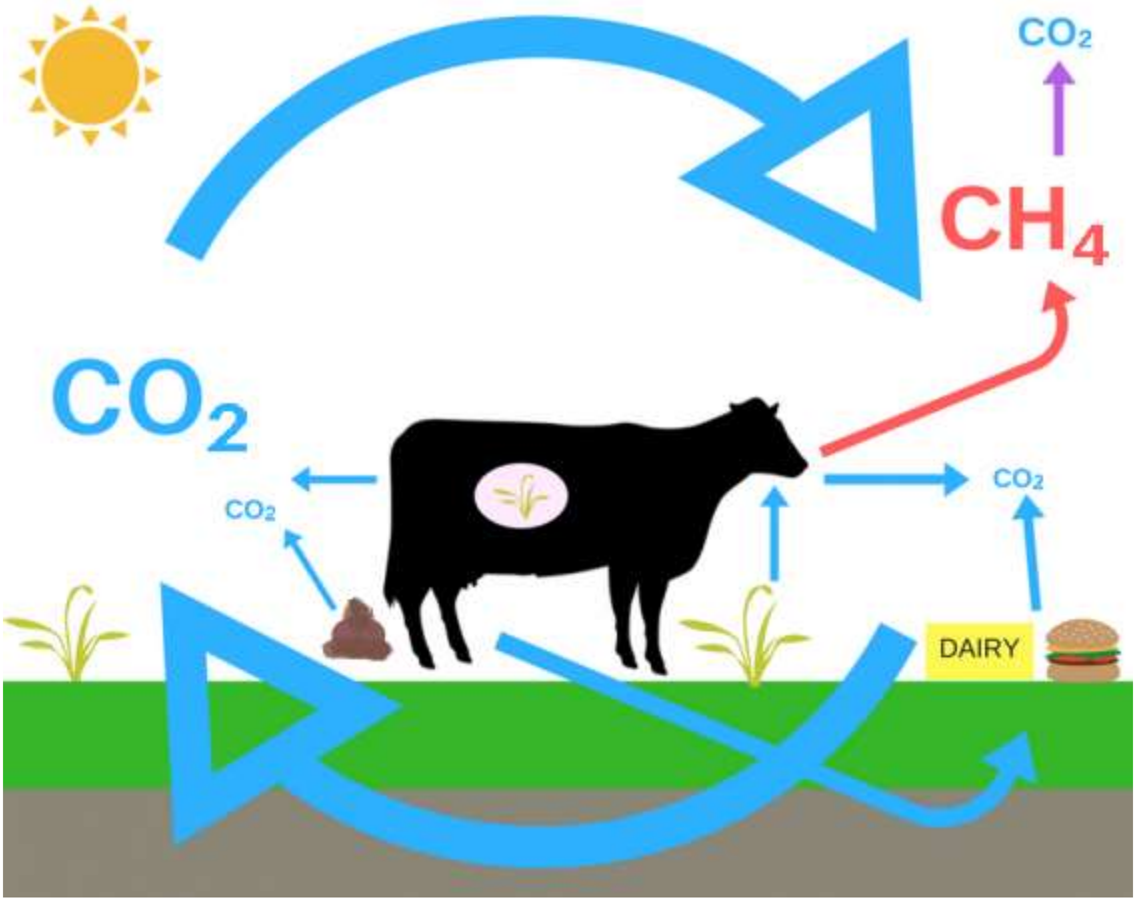

Figure 3. Schematic diagram of the carbon cycle for a pastoral system. Source: www.nzagrc.org.nz.

The situation is markedly different for fossil methane released in the course of the extraction, transport and use of fossil fuels such as coal, oil and gas. The carbon dioxide that fossil methane decays into has not been in the atmosphere for hundreds of thousands and possibly millions of years. From a human perspective, this carbon dioxide is therefore additional to that already in our atmosphere. As a result, emitting fossil methane causes warming first when methane enters the atmosphere and second after it has broken down into carbon dioxide. The additional warming caused by the remaining carbon dioxide is much smaller year-on-year because methane is a far more effective at absorbing heat radiation than carbon dioxide – but the carbon dioxide will then remain in the atmosphere for centuries to millennia. Taking this into account increases the warming contribution from a pulse of fossil methane by 5-10% over 100 years (Boucher et al. 2009), but contributes less than 1% to total global greenhouse gas emissions from human activities (Gillenwater 2008).

By contrast, the water vapour produced in the decay of methane in the troposphere (the bottom 10-15 km of the atmosphere) does not add to global warming even though water vapour is a strong and important greenhouse gas. This is because most of the methane decays in the troposphere, where the concentration of water vapour is controlled strongly by ambient temperature (i.e. the evaporation and condensation of water vapour from its liquid form, and sublimation from solid ice). Additional emissions of water vapour therefore have virtually no effect on the overall water vapour concentration in the troposphere, where most of the atmosphere's water vapour resides.

2.2 Methane chemistry

The decay of methane in the atmosphere is controlled largely by the presence of the hydroxyl radical (OH), a very short-lived chemical component that is constantly generated and destroyed by sunlight entering the Earth's atmosphere and subsequent chemical reactions with a variety of gases. While the amount of hydroxyl radicals appears to have been reasonably stable over the past century, there is considerable uncertainty over how it might change in future as the composition of Earth's atmosphere continues to change rapidly due to human activities. Some studies suggest that part of the acceleration of the growth rate of atmospheric methane since 2006 may indeed be attributable to a reduction in the concentration of the hydroxyl radical, but this has not been proven unequivocally (Prather and Holmes 2017; Rigby et al. 2017; Turner et al. 2017).

The perturbation lifetime of methane is likely to change over time as the emission of other gases affect the presence of hydroxyl radicals. Some of these chemical processes also depend on temperature, meaning that ongoing climate change itself can alter the lifetime of methane and hence the contribution that a single emission of methane will make to overall warming. For this report, the basic equations described in the IPCC Third Assessment Report (Ehhalt et al. 2001) have been used as part of the MAGICC model. While the approach compares reasonably well with more complex models (Ocko et al. 2018) and the most recent IPCC assessment (Myhre et al. 2013), novel scientific insights could result in significant revisions of the future lifetime of methane and hence the contribution of methane emissions to global warming (Holmes 2018; Manning and Reisinger 2011).

2.3 Radiative forcing of methane

As with all greenhouse gases, an increasing concentration of methane in the atmosphere results in an imbalance between incoming and outgoing radiation. This imbalance is also referred to as radiative forcing (warming effect). The greater the increase in the concentration of a greenhouse gas, the greater its radiative forcing and hence warming effect on the climate.

However, the relationship between methane concentration and the radiative forcing this exerts is not constant. This is because the capacity of an additional amount of methane to absorb infrared (heat) radiation becomes smaller the more methane there already is in the atmosphere. Also, nitrous oxide (N_2O) and methane partly absorb the same frequencies of infrared radiation and as a result, a given amount of methane in the atmosphere exerts lower radiative forcing the more nitrous oxide is in the atmosphere (Etminan et al. 2016; Ramaswamy et al. 2001).

As a consequence, the radiative forcing (warming effect) of an additional methane emission pulse depends on how much methane and nitrous oxide there will be in the global atmosphere in future. If the world reduces methane emissions rapidly (a substantial part of methane emissions would be avoided as co-benefit of reduced fossil fuel extraction, transport and use; see Rogelj et al. 2014) then the warming effect from any remaining methane emissions will be higher for each kg emitted than today. By contrast, if the world continues to increase its methane emissions, then the warming effect of a given rate of methane emissions will reduce relative to today. The magnitude of this effect is illustrated further below in this report in Section 3.3 (see in particular Figure 12).

This has important implications for understanding the warming resulting from a constant rate of methane emissions from New Zealand, because the efficacy of New Zealand's emissions in warming the Earth will depend on how much methane there will be in the future atmosphere from all other emission sources globally (see Section 4 for details and examples).

The radiative forcing of methane is, as most physical parameters, not known precisely but only within a range based on measurements and understanding of the vibrational and rotational modes of the methane molecule. A recent study (Etminan et al. 2016) indicates a significant (25%) upward revision of the radiative forcing from methane, but is awaiting confirmation through other studies and assessment by the IPCC. An upward revision of the radiative forcing would increase the absolute amount of warming from a given methane emission, but would have a very limited effect on how this warming evolves over time as it would enhance the warming by the same relative amount in any year following an emission. For this reason and for the purpose of this report, the radiative forcing for methane used in previous IPCC assessments (Forster et al. 2007; Myhre et al. 2013; Ramaswamy et al. 2001) has been used to allow comparability with other studies.

2.4 Indirect warming effects of methane

Methane causes warming not only through its own presence in the atmosphere, but also through several indirect effects. These also need to be taken into account to fully understand the warming that a given methane emission will cause.

2.4.1 Indirect effects relating to the chemistry of methane

One effect is that the reaction of methane with hydroxyl radicals reduces the concentration of hydroxyl radicals; hence increasing methane emissions results in an increasing methane lifetime in the atmosphere. The often-stated (perturbation) lifetime of just over 12 years (Myhre et al. 2013)already takes this interaction into account but is correct only for current methane concentrations; increasing methane concentrations resulting from increasing emissions would result in a gradual lengthening of the lifetime of methane, which needs to be considered in model studies (Holmes 2018; Prather and Holmes 2017).

A second indirect effect is that the decay of methane produces tropospheric ozone. This is itself a greenhouse gas and also a powerful oxidant that can affect plant growth and, in high-enough concentrations, human health. Since methane emissions directly increase global ozone concentrations, this represents an indirect warming effect from methane emissions. The secondary effect of this increased ozone on plant growth, which can reduce the ability of plants to absorb and store carbon dioxide, is more uncertain and not generally considered in warming estimates for methane. Some studies suggest that this secondary effect could be relevant especially in the context of ambitious mitigation goals (Collins et al. 2018; Cox and Jeffery 2010).

A third indirect effect is that a fraction of methane emitted at the ground will eventually reach the stratosphere (a layer of the atmosphere extending between about 12 and 50 km), where the more intense sunlight results in a rapid decay. In the stratosphere, the water vapour produced by the decay of methane is no longer buffered by a liquid pool. As a result, the decay of methane emissions does increase the overall concentration of water vapour in the stratosphere, which results in an additional warming effect. These indirect feedback effects are well established (even though their magnitude is subject to continuous scientific revision) and are generally included in estimates of the overall warming effect from methane emissions (Myhre et al. 2013).

A range of other indirect effects on the climate arising from the chemical interactions of methane with other atmospheric constituents have been discussed (for an overview, see Ciais et al. 2013; Myhre et al. 2013). Some of these effects could significantly increase the net warming effect from methane, for example the interaction between methane and aerosols (Shindell et al. 2009). They are not included routinely in model-based estimates because their magnitude is too uncertain and/or the processes are not replicated readily in all models. In this report, only the first three indirect effects (effect on hydroxyl concentrations, tropospheric ozone, and stratospheric water vapour) are included as these are well established and quantified within reasonably robust ranges.

2.4.1 Indirect effects arising from climate-carbon cycle coupling

A fourth important indirect warming effect from methane emissions arises not from the chemical reactions and decay products of methane, but because the warming caused by methane and its immediate decay products affects the global carbon cycle.

It is well understood that carbon constantly cycles through the atmosphere, ocean and biosphere, through a range of chemical and biological exchange mechanisms. For example, carbon dioxide emitted by the burning of fossil fuels may be taken up by a growing tree through photosynthesis, but this tree also respires carbon dioxide during the night. Leaves and branches fall to the ground where microbes eat them and produce carbon dioxide in the process, and eventually the entire tree will meet the same fate. Microbes in soil assimilate carbon but also respire carbon dioxide as part of their metabolism. Similarly, carbon dioxide is absorbed by the surface of the ocean, and some organisms living in the ocean may take it up further, but the ocean also releases excess carbon dioxide back into the ocean. These processes collectively constitute the global carbon cycle. Most of these processes are influenced by temperature, and this interdependence between the climate and the carbon cycle is referred to as climate-carbon cycle coupling.

Naturally, given the complexity of processes involved, the magnitude of the climate-carbon cycle coupling is not known with certainty, but there is robust evidence that greater warming means more carbon remains in the atmosphere and hence adds further to warming, and a lesser fraction is stored in the biosphere and ocean. For summaries and ranges of model results for the 21st century, see e.g. Ciais et al. (2013); Friedlingstein et al. (2006); Friedlingstein et al. (2013); Zickfeld et al. (2011).

The existence of feedbacks between the climate and carbon cycle means that the emission of a greenhouse gas will not only result in warming from the gas itself, but also because it increases the fraction of carbon dioxide that will remain airborne from all other emissions.[6] While this effect is well established and is used routinely in the calculation of the warming effect from carbon dioxide itself (Joos et al. 2013), it is becoming recognised increasingly that this also affects the contribution to warming from the emission of other greenhouse gases such as methane (Gillett and Matthews 2010; Myhre et al. 2013).

The emission of methane results in initial warming, and this warming causes carbon dioxide that is already in the atmosphere (from any source) to remain there for longer, and for additional carbon dioxide to be released from the biosphere and ocean. The magnitude of this additional warming is substantial, with estimates ranging from about 15 to 25% additional warming averaged over 100 years following a methane emission (Collins et al. 2013b; Gasser et al. 2016; Gillett and Matthews 2010; Sterner and Johansson 2017). More importantly for the questions addressed in this report, the additional warming caused by this climate-carbon cycle feedback continues for more than a century, well after the methane emission itself has decayed. These studies estimate the warming that is still in place 100 years after a methane emission occurred to be two or three times the warming caused by methane and its chemical decay products alone. While the total warming 100 years after a methane emission is much smaller than the warming caused in the first two to three decades, it does add an additional long-lived component to the warming caused by this short-lived gas.

The Global Warming Potential (GWP), which is a common metric to compare the climatic effect of the emission of different gases, is defined as the integrated radiative forcing caused by a single pulse of a non-CO_2 gas to the radiative forcing caused by a pulse of CO_2. However, the GWP has historically been inconsistent in how it treated climate-carbon cycle feedbacks. Such feedbacks have long been included in estimating the warming due to carbon dioxide, but not for the warming from non-CO_2 gases. The most recent IPCC report recognised this inconsistency and reported GWPs with and without climate-carbon cycle feedbacks for non-CO_2 gases. To illustrate the importance of this, the

[6] Note that this is not related to the carbon dioxide formed in the chemical decay of methane, but affects any carbon dioxide that is already in the atmosphere regardless of its source.

GWP for methane for a time horizon of 100 years is 28 if climate-carbon cycle feedbacks are excluded, but is estimated tentatively as high as 34 if they are included (Myhre et al. 2013).[7]

Subsequent studies have explored different approaches, giving results for the GWP_{100} of methane that range from 31 to 35 (Gasser et al. 2016; Sterner and Johansson 2017). While model uncertainty clearly is important for the quantification of this feedback, its substantial contribution to the overall warming effect resulting from a methane emission indicates that it does need to be taken into account if the contribution of methane emissions to global warming are to be fully understood. A recent programme led by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) concluded that climate-carbon cycle feedbacks should be included by default in climate change lifecycle assessments (Levasseur et al. 2016).

The remainder of this report explores the implications of these findings for the warming caused by a single pulse and a steady rate of methane emissions (Section 3), and what this means specifically for the warming caused by New Zealand's historical and future methane emissions (Section 4).

3. Warming from idealised methane emissions

This section presents the warming caused by a single pulse of methane emissions, as well as the warming from a constant rate of methane emissions. These idealised emissions scenarios are presented as they help to understand the fate of methane in the atmosphere and its contribution to warming in principle, before assessing the warming due to New Zealand's actual historical and potential future emissions in Section 4.

3.1 Illustrative results for pulse and sustained emissions

Figure 4 shows the concentrations and warming resulting from a single pulse of methane emitted in a single year, with the consequences of a similar pulse of carbon dioxide shown for comparison. The decay of methane and carbon dioxide, radiative forcing and resulting warming were simulated using MAGICC (see Appendix I for details), assuming an atmosphere with constant background concentrations of all greenhouse gases. The model has been calibrated to reproduce the relative warming effects of methane and carbon dioxide based on a range of other model studies as assessed in the most recent IPCC report (Myhre et al. 2013).

Figure 4 illustrates that methane itself decays relatively quickly, with most of the increase in concentration gone after about 50 years. Nonetheless, the warming caused by the initial concentration spike is 'stretched out' in time and persists for much longer, with noticeable warming (about 9% of the peak warming) remaining after 100 and some warming remaining even 200 years (about 4% of the peak warming). Some of this extended warming effect reflects the inertia of the climate system (i.e. the initial temperature shock takes a long time to subside again as heat becomes distributed from the atmosphere through the ocean and back into the atmosphere), but an increasing fraction of the long-term warming is due to climate-carbon cycle feedbacks. The magnitude of the warming due to climate-carbon cycle feedbacks lies within the range estimated by

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7 The continued revisions in both the direct radiative forcing from methane and re-assessment of its various indirect warming effects have resulted in significant revisions of the GWP of methane over time in successive IPCC reports. The GWP_{100} was estimated as 21 in the IPCC's Second Assessment Report (IPCC 1996) which formed the basis of the Kyoto Protocol, but was revised to 25 in the IPCC's Fourth Assessment Report (IPCC 2007), and to 28-34 in the IPCC's Fifth Assessment Report (IPCC 2013). If the updated absorption calculations by (Etminan et al. 2016) are confirmed, this could result in an estimated GWP_{100} of about 31-38 in the next IPCC assessment.

other studies (Gasser et al. 2016; Sterner and Johansson 2017). Figure 4 shows only the median estimate from MAGICC, uncertainties are explored and quantified later in Section 3.2.

In strong contrast to methane, a pulse of carbon dioxide does not decay to zero, but a significant fraction remains in the atmosphere for many centuries (Joos et al. 2013). Similar to methane, the temperature response is also ‘stretched out’ further compared to the slow decline in concentrations, resulting in an almost constant amount of warming from a single pulse of carbon dioxide that persists over many centuries.

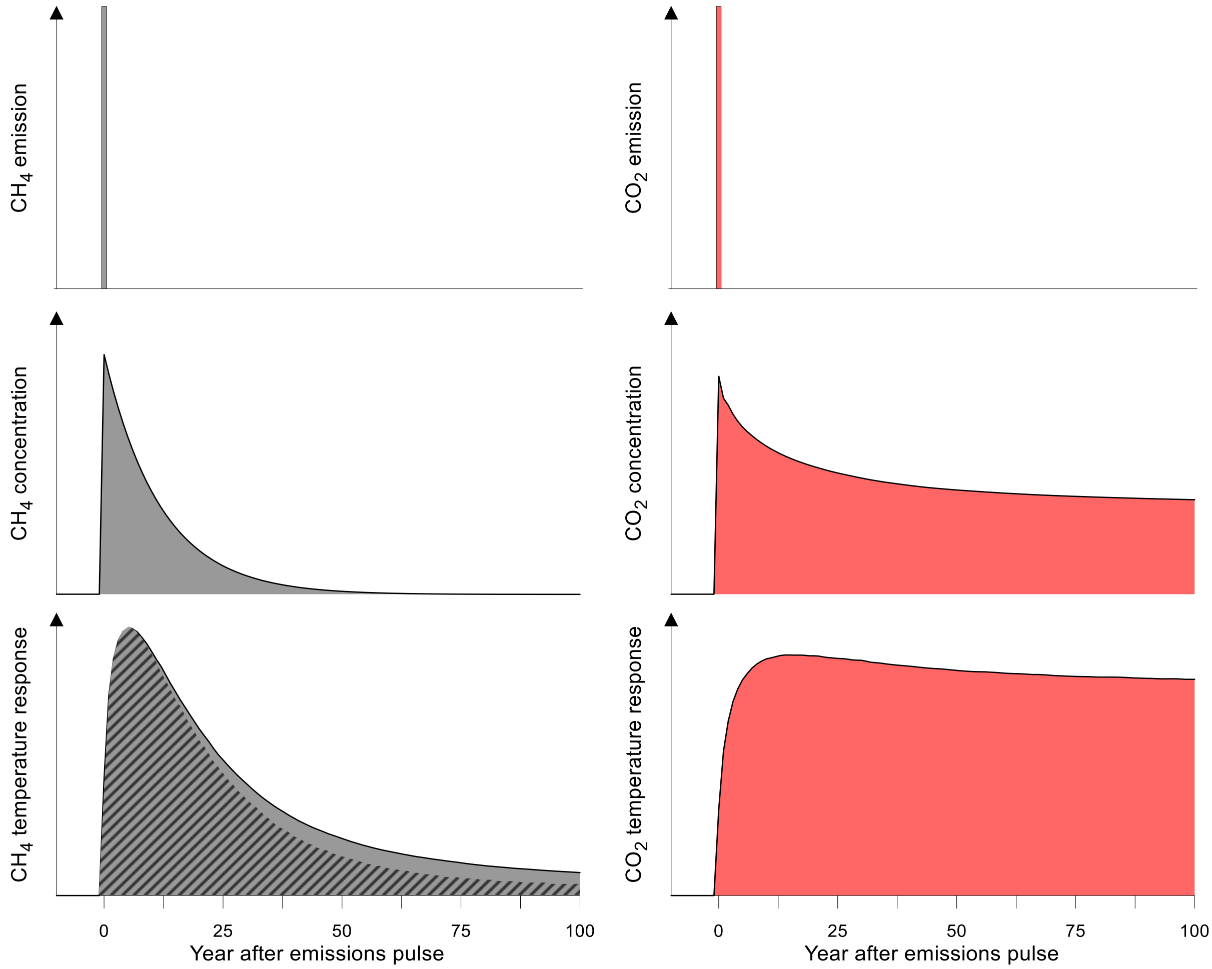

Figure 4. Concentration and warming resulting from a single pulse of methane (left) and carbon dioxide (right) in a single year. The hatched grey area illustrates the warming caused by methane directly as well as tropospheric ozone and stratospheric water vapour, while the solid grey area indicates the total warming including climate-carbon cycle feedbacks. For carbon dioxide, climate-carbon cycle feedbacks are automatically included in the calculation of the decay in carbon dioxide concentration and resulting warming. Note the vertical axes do not use the same scales, they are intended to illustrate the concepts only.

A constant rate of emissions can be conceptualised simply as a sequence of individual pulses of methane or carbon dioxide, with a new pulse released each year and the resulting concentration increase and warming in each year being added to the concentration or warming remaining from emissions in the preceding years. The result are shown in Figure 5.

Figure 5 demonstrates that for an idealised scenario where methane emissions start from zero and are then sustained at a constant rate, methane concentrations reach a stable level about 50 years after emissions started, but temperature keeps climbing upwards for much longer than this. Part of this continued climb in temperature is due to the inertia of the climate system, but an increasing fraction (illustrated in Figure 5) fraction is due to additional warming from climate-carbon cycle feedbacks. The warming due to climate-carbon cycle feedbacks, as illustrated in Figure 4, means that a small part of the warming caused from a methane emission accumulates and results in temperatures continuing to climb long after methane concentrations have stabilised. One hundred years after emissions started, climate-carbon cycle feedbacks increase the resulting warming by about 16% above the warming caused by methane and its immediate indirect effects only (see Figure 5). The magnitude of this effect demonstrates the importance of including those feedbacks if the climatic impact of a sustained rate of methane emissions is to be fully understood.

The warming from a sustained rate of carbon dioxide emissions is markedly different. Both concentration and warming rise nearly linearly over time, since the warming from each emission pulse remains in the atmosphere for many centuries and subsequent emission pulses continue adding to those. Even though methane does cause some ongoing warming long after emissions and concentrations have stabilised, this warming begins to level off within the first century. By contrast, the warming from a sustained rate of carbon dioxide emissions continues to climb.

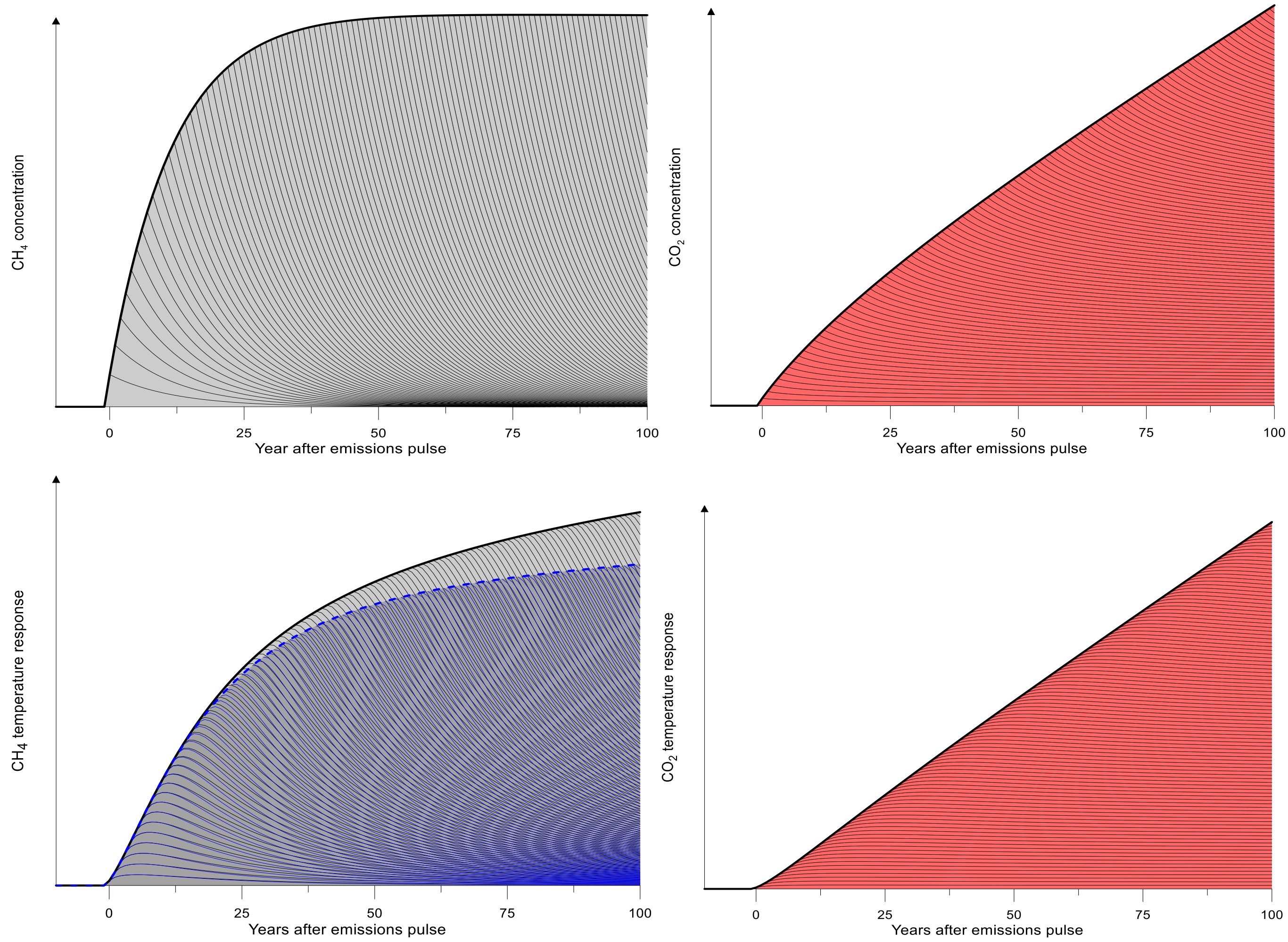

Figure 5. Concentration (top panels) and warming (bottom panels) resulting from a constant rate of methane (left panels) and carbon dioxide (right panels) emissions, using a simple superposition of the responses to individual pulses shown in Figure 4. The bottom panel shows the warming resulting caused by methane directly as well as tropospheric ozone and stratospheric water vapour, while the solid grey area indicates the total warming including climate-carbon cycle feedbacks. For carbon dioxide, climate-carbon cycle feedbacks are automatically included in the calculation of the decay in carbon dioxide concentration and resulting warming.

The linearly increasing warming with constant carbon dioxide emission has given rise to the concept of the carbon budget, i.e. that warming from carbon dioxide is related primarily to the total, cumulative emissions (Allen et al. 2009). The same approach clearly cannot be used for methane, as only a fraction of the warming from methane accumulates but most of the overall warming is related to the ongoing rate of emissions.

The difference in warming from a constant rate of emissions are illustrated in Figure 6. This figure now compares the absolute amount of warming from both gases at the same scale. For this Figure, the rate of carbon dioxide emissions is set at 3.3 Gt CO_2 per year, while that of methane is 100 Mt CH_4 per year, i.e. emissions of carbon dioxide are 33 times greater than of methane. The warming due to carbon dioxide continues to increase linearly with the constant flow of emissions, given that the stock of this gas continues to accumulate, whereas the warming due to methane gradually begins to level off (but does not become stable within at least 200 years since the start of the emissions, and is greater than the warming due to carbon dioxide for the first 100 years).

The cross-over point in warming from the two gases at the quantities chosen is around 100 years. This is not a coincidence, since it was shown early on in the development of greenhouse gas metrics that the relative warming from a sustained rate of greenhouse gases is similar to the GWP metric for that same time horizon (Shine et al. 2005 and references therein). The GWP for methane with a time horizon of 100 years, when climate-carbon cycle feedbacks are included, is in the range of 31-35 (Gasser et al. 2016; Gillett and Matthews 2010; Myhre et al. 2013; Sterner and Johansson 2017) and 33 in our model set-up. This confirms the general relationships set out in Shine et al. (2005) also hold approximately when climate-carbon cycle feedbacks are included in the definition of these GHG metrics.

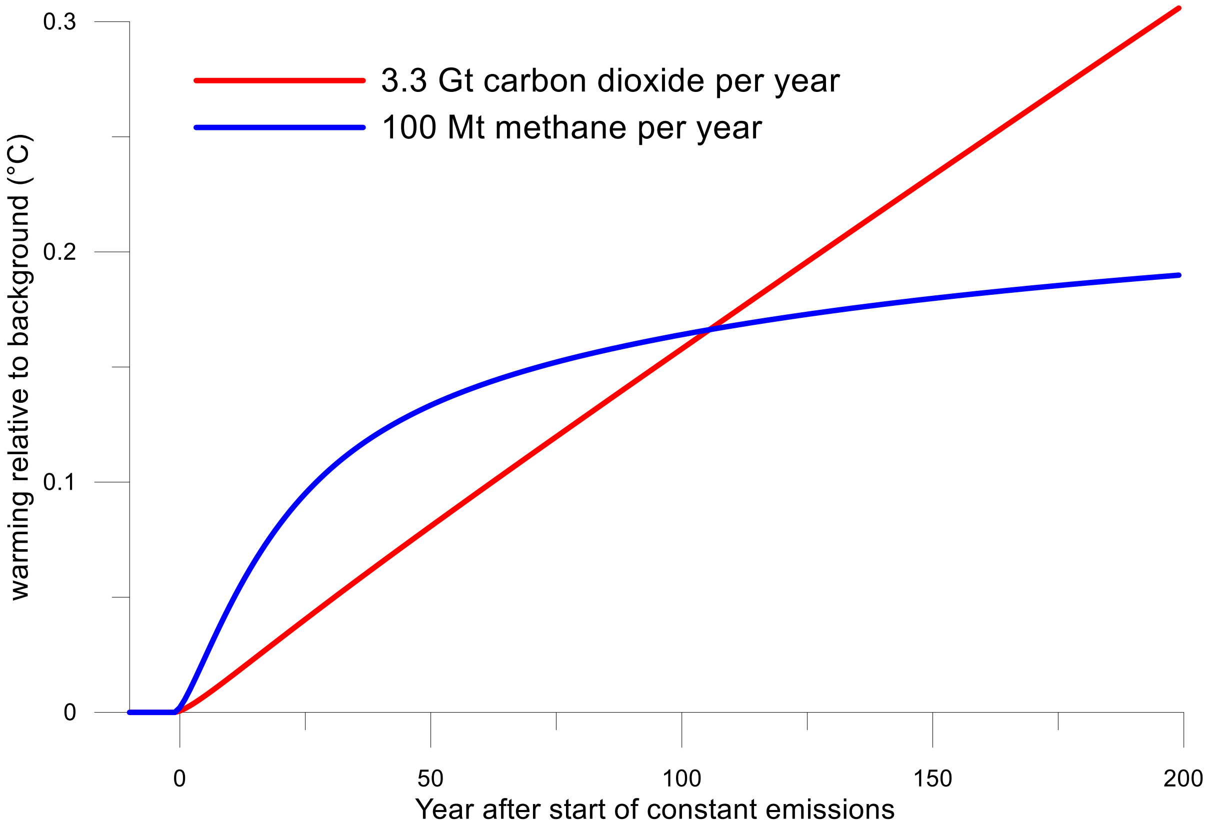

Figure 6. Comparison of the warming resulting from a sustained rate of emissions of both methane and carbon dioxide, using a superposition of the response functions to individual pulses. The flow of emissions is set to 100 Mt CH_4 and 3.3 Gt CO_2 per annum (i.e. the rate of carbon dioxide emissions in this Figure is 33 times the rate of methane emissions).

3.2 Probabilistic results for constant background concentrations

The preceding section demonstrated qualitatively the warming responses to pulse and sustained methane emissions and compared them with those from carbon dioxide. However, this simple approach ignores second-order effects (such as how the increasing concentrations of methane and carbon dioxide will affect their own radiative efficacy, and the rising temperatures will affect the lifetimes of gases). This section now explores uncertainties around the results and tests how the results could differ under alternative scenarios for the 21st century. These more detailed model simulations were undertaken for methane emissions only, as these form the focus of this report.

To estimate uncertainties, the MAGICC model was run in a probabilistic mode that systematically samples uncertainties in key physical parameters. The model is run 1200 times with different parameter sets such as the overall climate sensitivity, the imperfectly known radiative forcing from a given increase in methane, or the fact that the rate with which the ocean transports heat from the surface to deeper layers is known only imprecisely. The span of results can be taken to represent the range of uncertainty resulting from uncertain parameters as well as differences in carbon cycle models (for more details, see Appendix I; also see Meinshausen et al. 2009 for a key application of this approach).

Figure 7 shows the simulated temperature response for a single 100 Mt methane emission pulse set in the year 2011, with background emissions of all greenhouse gases adjusted so that their background concentrations would remain constant at year 2011 levels.[8] The left hand panel shows the warming if climate-carbon cycle feedbacks are ignored, while the right hand panel shows the warming if they are included. The light shaded area indicates the 10 to 90 percentile range of model results, while the dark shaded area indicates the 25 to 75 percentile range. The black line indicates the median across all model runs (used also in Figures 3 and 4).

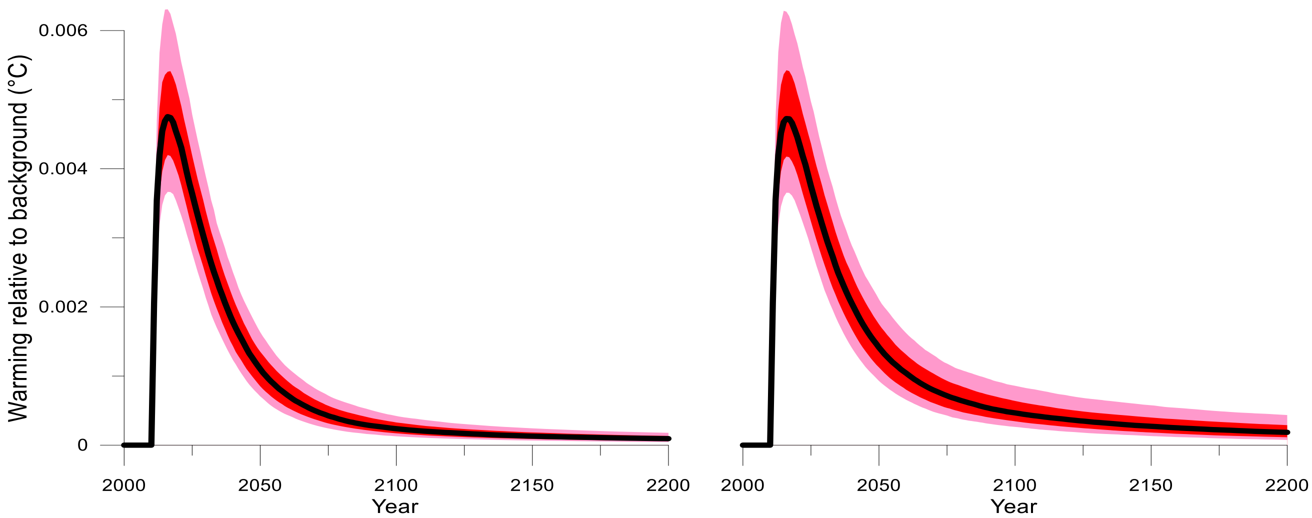

Figure 7. Probabilistic results using MAGICC for the warming from a single 100 Mt pulse of methane, placed in the atmosphere of the year 2011 with constant background concentrations from 2011 onwards, without (left) and with (right) climate-carbon cycle feedbacks. While the overall shape of the two curves does not look very different, the warming decays more slowly with climate-carbon cycle feedbacks included (right) and after 100 years is almost twice the magnitude of the warming without climate-carbon cycle feedbacks (left). For details, see text.

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8 The size of this emissions pulse, which represents just under a third of current annual emissions globally, was chosen to minimise numerical rounding errors in the model simulations.

It can be seen that including climate-carbon cycle feedbacks increases temperatures significantly from about 50 years following the emission, but also increases the spread of model results. This reflects the range of differing assumptions made in the different carbon cycle models that MAGICC has been calibrated to for the probabilistic evaluation. However, all parameter combinations increase the long-term warming if climate-carbon cycle feedbacks are included. Notably though, even if climate-carbon cycle feedbacks are not included, temperatures remain above zero even 200 years after the emission of a methane pulse, indicating that the inertia of the climate system alone is responsible for a strong lag in the warming effect from a single methane emissions pulse.

The magnitude of the climate-carbon cycle feedback is shown separately in Figure 8, which presents the difference in temperature between model runs with and without climate-carbon cycle feedbacks for each parameter combination sampled by the model. The magnitude and time response of the warming (particularly the gradual decline over time) is consistent with the results obtained by Sterner and Johansson (2017) and Gasser et al. (2016) when using more detailed physics-based models. The advantage of the probabilistic approach taken in this report is that the range of uncertainties can be clearly demonstrated across a range of complex models: all model and parameter combinations result in additional warming in the long term due to climate-carbon cycle feedbacks, but the magnitude of this warming spans a considerable range.

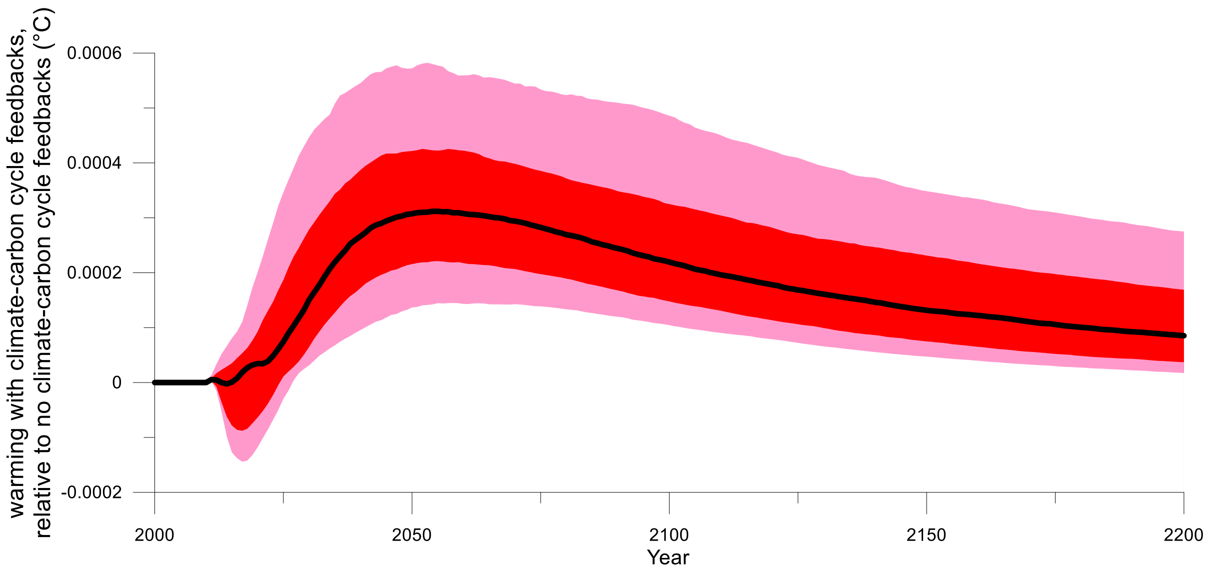

Figure 8. Probabilistic results using MAGICC for the warming induced via climate-carbon cycle feedbacks from a single pulse of 100 Mt methane. The warming shown is the difference between the warming with and without climate-carbon cycle feedbacks for each parameter combination run by the model.

The same full range of model calibrations can now also be used to explore the warming resulting from a constant additional flow of methane emissions of 100 Mt every year. For this model simulation, the flow of methane emissions is started in the year 1990 and continues indefinitely. Figure 9 shows the resulting warming as for Figure 7 without (left) and with (right) climate-carbon cycle feedbacks included. The left hand panel of Figure 9 shows that the inertia of the climate system alone results in a gradual further rise in temperatures for at least 200 years following the start of a steady rate of methane emissions. The rate of increase slows down markedly after about 2040 as methane concentrations will have stabilised about 50 years after the flow of emissions started (see Figure 5), but warming continues well beyond 2040. When climate-carbon cycle feedbacks are included, the warming continues more steadily but still slows down over time.

If climate-carbon cycle feedbacks are included, the median warming in 2090, 100 years after the start of a steady rate of emissions, is 25% greater than the warming realised in 2040, 50 years after the start emissions. By the year 2190, the warming is 45% greater, and by the year 2290 (i.e. 300 years after the emission has started) the warming is 55% greater than in the year 2040. The 10 percentile range of models exhibiting the least amount of overall warming show only 20% and 38% more warming 100 and 200 years compared to 50 years, while the 90 percentile range of models shows 30% and 62% more warming in 100 and 200 years compared to 50 years.

If climate-carbon cycle feedbacks are excluded, the warming 100 and 200 years after the start of emissions is 15% and 27% greater than after 50 years. For the 10 percentile of models exhibiting the least warming, the additional warming is 14% and 23% for 100 and 200 years, while for the 90 percentile it is 18% and 31%.

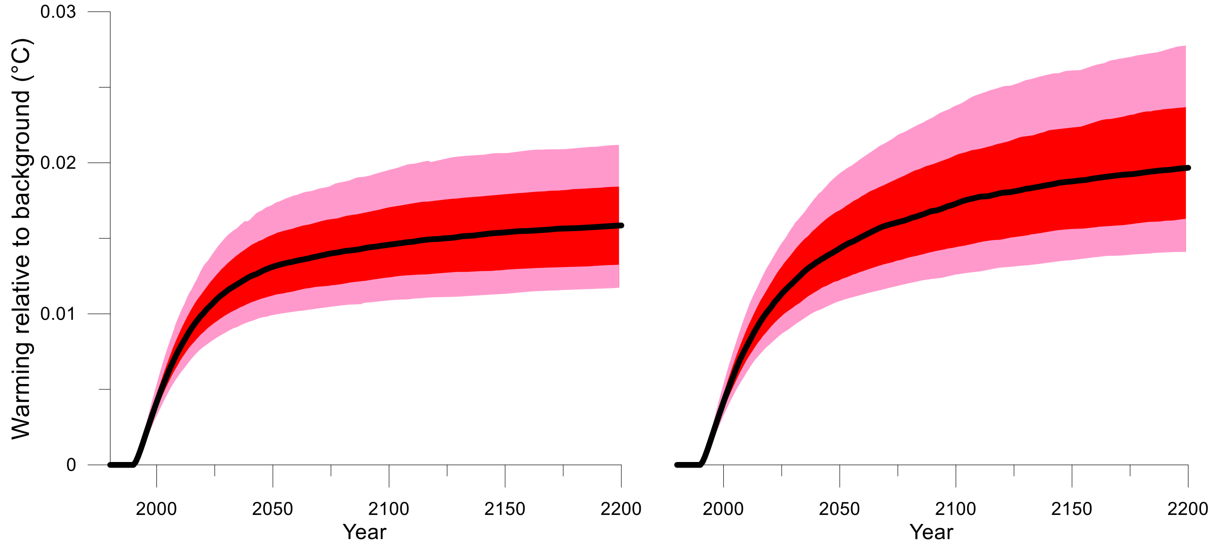

Figure 9. Probabilistic results using MAGICC for the warming from a continuous rate of 100 Mt methane emitted every year from the year 2011 onwards, without (left) and with (right) climate-carbon cycle feedbacks. For details, see text.

Figure 10 shows the additional warming caused by climate-carbon cycle feedbacks alone for the constant flow of methane starting in 1990. The warming increases over time, but at a slowing rate (given that much of the warming from a single pulse disappears again within a few centuries, as seen in Figure 8). By the year 2200, the median additional warming due to climate-carbon cycle feedbacks amounts to about 20% of the warming induced by a constant flow of methane (along with the production of tropospheric ozone and stratospheric water vapour) alone.

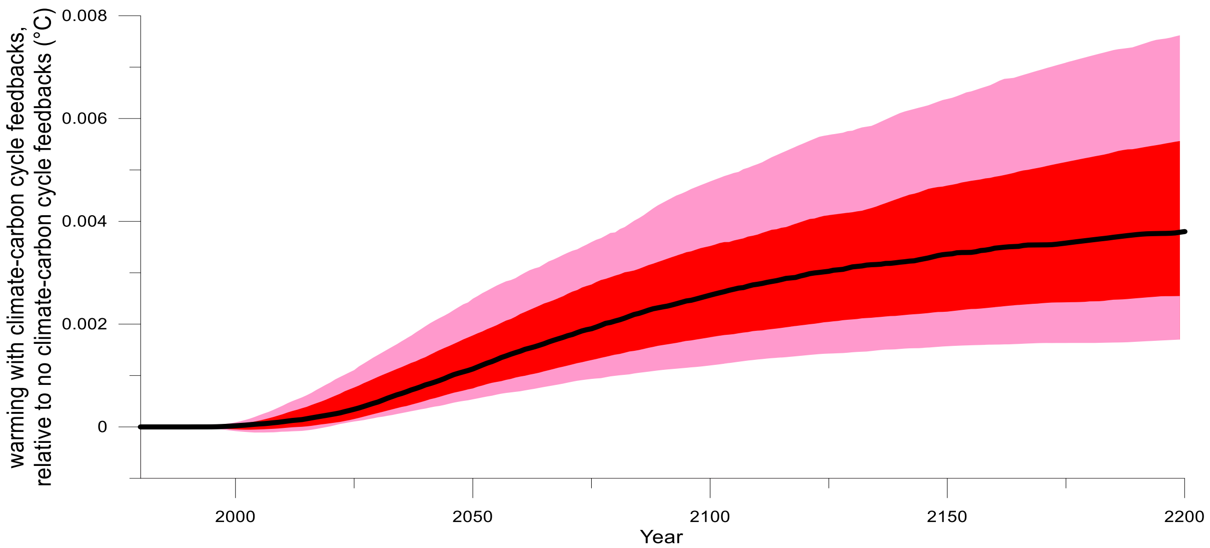

Figure 10. Additional warming due to climate-carbon cycle feedbacks for a constant rate of 100 Mt methane emitted from the year 2011 onwards, simulated using MAGICC in probabilistic mode.

To summarise, the key conclusions from this conceptual analysis are that:

- A constant flow of methane emissions results in a constant methane concentration within about 50 years, but temperatures do not stabilise for many centuries.
- The reasons for this ongoing increase are twofold:
  a) The inertia of the climate system means that temperature continues to adjust slowly to the increased radiative forcing from increased methane concentration
  b) The warming caused by methane and its immediate decay products triggers climate-carbon cycle feedbacks, which lead to an increase in background carbon dioxide concentrations and additional warming. This warming is long-lived in nature and results in a more continuous increase in temperatures than would be observed in the absence of such feedbacks.
- To illustrate the magnitude of these effects, the median warming realized 100 and 200 years after the start of a steady rate of emissions in 1990, if global background concentrations of all greenhouse gases are held constant from 2011 onwards, is 25% and 45% greater than the warming realized after 50 years if climate-carbon cycle feedbacks are included, and 15% and 27% if they are excluded.
- The amount of additional warming depends on imperfectly known aspects of the global carbon cycle. Across the range of uncertainties sampled in this study, the additional warming after 100 and 200 years, relative to the warming after 50 years, ranges from 20% and 38% for the 10 percentile range of models, to 30% and 62% for the 90 percentile of models.

3.3 The influence of varying background concentrations

If the goal is to understand how much warming could result from a steady flow of methane emissions, then uncertainties across models and physical parameters representing the response of the climate system to increased greenhouse gas emissions are not the only source of uncertainty.

The key other source of uncertainty is the changing state of our atmosphere and climate as a result of ongoing global greenhouse gas emissions. As discussed in Section 2, the efficacy with which a given *additional* amount of methane absorbs infrared radiation depends on how much methane there is in the atmosphere already. The more methane there is already, the less an additional quantity of methane will absorb additional infrared radiation. The less methane there is, the more an additional quantity will absorb additional infrared radiation. The actual warming that can be expected to result from a constant flow of methane emissions over time will therefore depend on whether and how much the global background concentrations of methane will change.[9]

The scientific community developed a set of four global scenarios of future greenhouse gas concentrations and associated emissions, called the Representative Concentration Pathways (RCPs). These scenarios are used widely to inform climate modelling and impact studies; they are not predictions nor are they comprehensive, but they span a wide range of possible futures (van Vuuren et al. 2011a). Figure 11 shows the global methane concentrations under the four different RCPs, which reflect widely differing assumptions about global extraction and use of fossil fuels, agriculture,

[9] To illustrate the magnitude of this effect: the warming effect from a constant flow of methane emissions would be reduced by about 30% if methane concentration doubled compared to today's level, and increase by more than 40% if methane emissions halved compared to today's levels.

land-use and waste and resulting methane emissions. They cover both business-as-usual scenarios (RCP8.5 and RCP6.0) as well as moderate (RCP4.5) and stringent (RCP2.6) mitigation scenarios.[10]

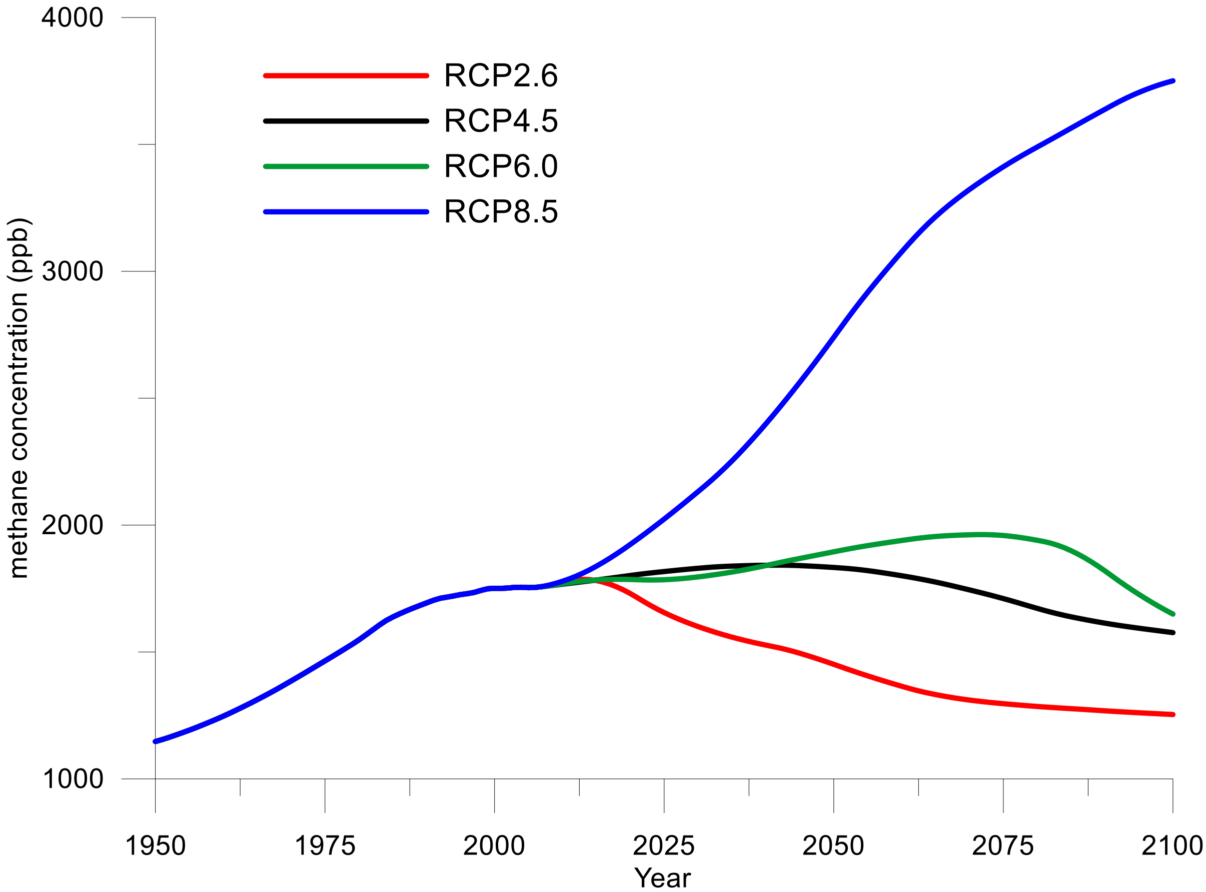

Figure 11. Scenarios of global methane concentrations under the Representative Concentration Pathways. Source: Meinshausen et al. (2011b).

The RCP with the lowest emissions, RCP2.6, would result in a more than 30% drop in methane concentrations below today's levels as a result of rapid reductions in methane emissions (especially related to fossil fuels), reaching concentrations in 2100 similar to 1950-1970. At the other extreme, the RCP with the highest emissions (RCP8.5) that aggressively pursues further fossil fuel exploitation would see a doubling of methane concentrations by the end of the 21st century relative to today.

These different future background concentrations have a noticeable influence on the additional warming effect that an additional amount of methane emitted each year would make. Figure 12 shows the median concentrations, radiative forcing from methane only, and the realized warming resulting from a constant flow of 100 Mt methane emissions per annum started in the year 1990, under the four different Representative Concentration Pathways as well as a scenario where the background concentrations of greenhouse gases would remain constant after 2011 (as in Figure 9).

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10 The number attached to an RCP indicates the total radiative forcing that would arise under this scenario in the year 2100, in Watts per square metre. Conceptually, RCP2.6 would be consistent with a world that rapidly reduces greenhouse gas emissions and limits warming to below 2°C, whereas most "business-as-usual" scenarios that assume no dedicated climate policies at all fall in the range between RCP6.0 and RCP8.5.

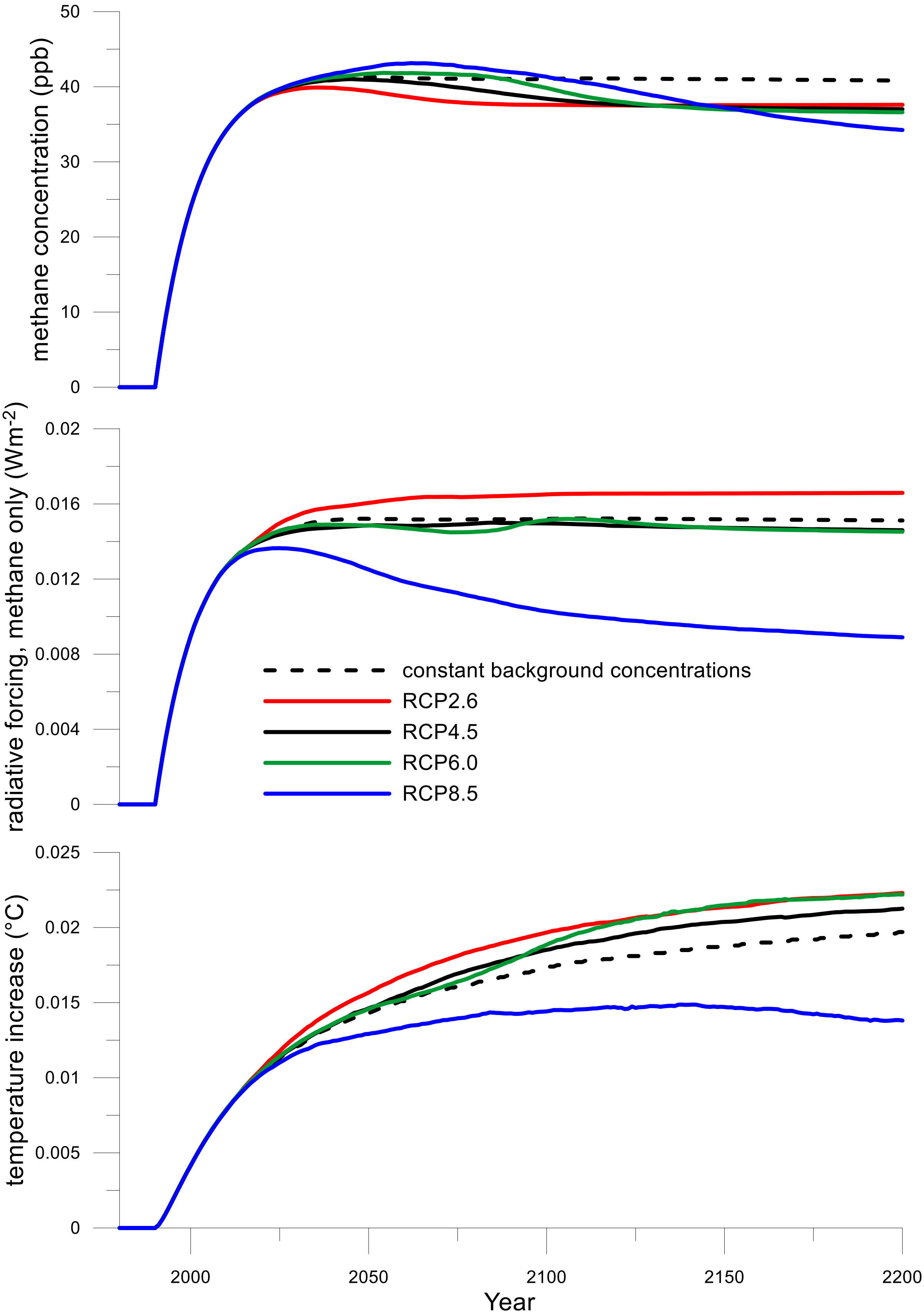

Figure 12. Increase in methane concentrations (top panel), radiative forcing (middle panel) and warming (bottom panel) resulting from a constant flow of 100 Mt methane emissions per year, starting in 1990, under the four different Representative Concentration Pathways. The solid lines represent medians of probabilistic model runs for each RCP. The dashed line represents a scenario where global background concentrations would remain constant after the year 2011.

Several key conclusions stand out from this Figure. One is that the increase in methane concentrations resulting from a constant flow of methane emissions depends on the concentration of other gases in the atmosphere. This is not surprising, given the chemical reactions responsible for the natural decay of methane, in particular the concentration of hydroxyl radicals in the atmosphere, depends on the concentrations of other gases and on global average temperature. The variations between the methane concentrations for the different RCPs are not large, but noticeable. More relevant is that the change in radiative forcing, shown in the middle panel, goes in the opposite direction to the change in concentrations. This is because under RCP2.6, the background concentrations of methane decline by about 30% by 2100, and as a result, the radiative forcing exerted by a constant flow of 100 Mt methane per year is higher than under all other RCPs. In stark contrast, RCP8.5 exhibits the lowest radiative forcing from an additional flow of methane because there is twice as much methane in the atmosphere by 2100 than today, so that an additional 100 Mt emission absorbs much less additional infrared radiation.

These characteristics are also carried through into the realized temperature: the actual warming realised from a constant rate of 100 Mt methane per year in the RCP8.5 scenario is significantly less than under all other RCPs. For the other RCPs, differences in temperature are less pronounced.

The spread in realised warming is 19% for the model means in 2050, rising to 29% in 2100 and 43% in 2200. Most of this spread comes from the extreme nature of the scenario RCP8.5, with results across the other three scenarios differing by only 5-7% (in part because of counteracting effects arising from changes in different atmospheric trace gases in these scenarios). Nonetheless, the results indicate that future emissions by the world as a whole influence how much warming would result from a specific additional, constant rate of methane emissions.

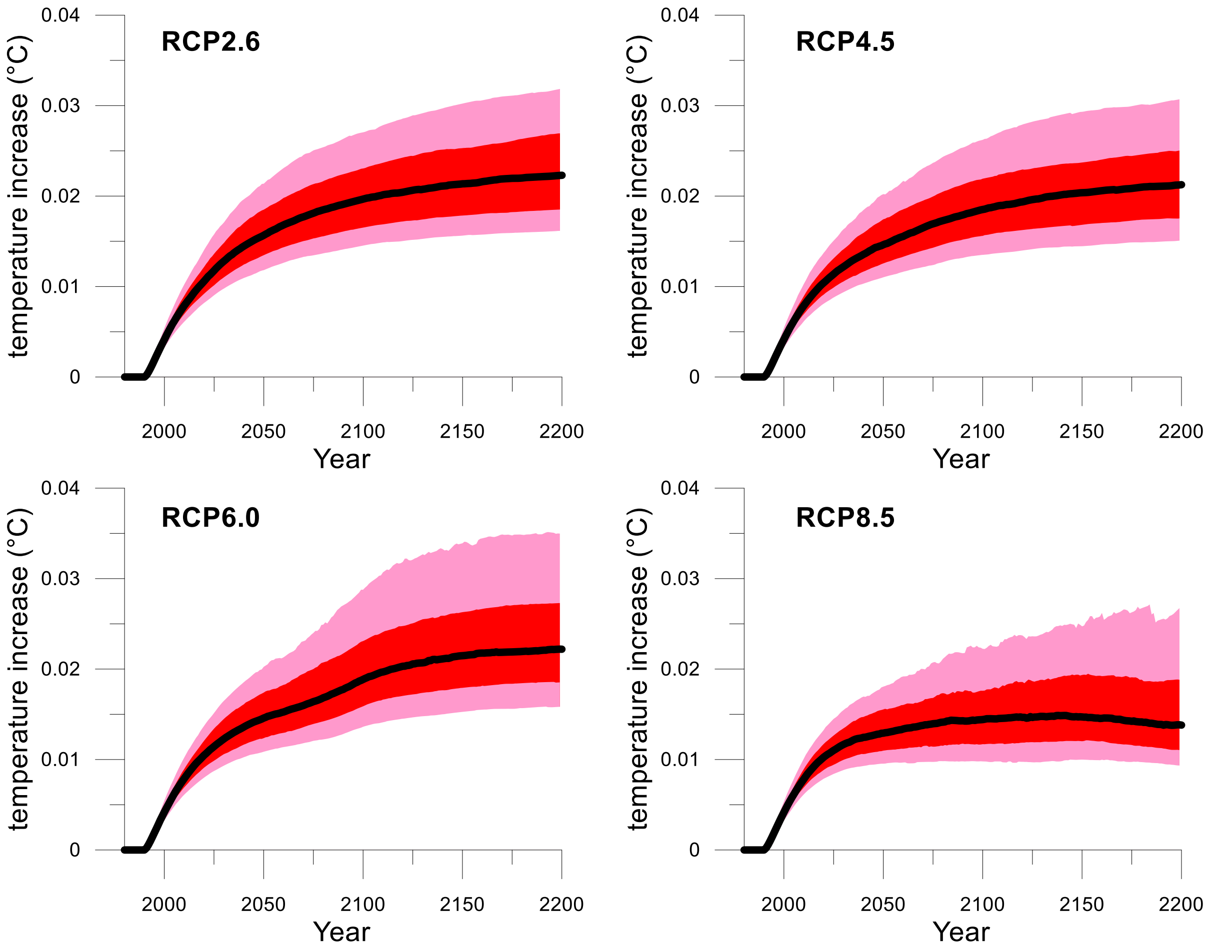

Figure 13. Probabilistic estimates of warming for each of the four Representative Concentration Pathways arising from an additional constant flow of 100 Mt methane emissions per year from 1990 onwards.

The spread in warming arising from model uncertainties (shown for each global emissions scenario in Figure 13) is greater for the high-emissions scenarios RCP6.0 and RCP8.5, because the high rates of emissions of other trace gases such as carbon monoxide, nitrogen oxides, and volatile non-methane hydrocarbons, add to the uncertainty in the future radiative forcing and consequent warming from a constant rate of methane emissions. The high rates of warming in these scenarios also amplify temperature feedbacks, adding to the total uncertainty range.

4. Warming from New Zealand's livestock methane

New Zealand methane emissions reported to the United Nations Framework Convention on Climate Change were 1,351 kilotonnes (kt) in the year 2016 (MfE 2018). The great majority of these emissions (85.7%) came from agriculture, almost entirely from enteric fermentation by ruminant livestock (82.2%) and manure management (3.4%). The remainder of New Zealand's methane emissions came from waste disposed in landfills and wastewater treatment (11.0%) and the extraction and use of fossil fuels for energy generation and in other industrial processes (3.1%).

This report focuses on methane emissions from New Zealand's livestock sector only, given that emissions from this sector constitute by far the largest source of New Zealand's total methane emissions. The conclusions from this work hold qualitatively also for waste, which is New Zealand's next biggest source of methane, even though the absolute amount of warming caused by those emissions is obviously much smaller than that from livestock agriculture.

4.1 Reconstruction of historical methane emissions

The model results from Section 3 demonstrated that the history of methane emissions matters for the amount of additional warming that is to be expected when emissions are held constant. If emissions had started only in 1990, the additional future warming under constant future emission would be significant. If emissions have been roughly constant for many decades already, then the residual future warming will be smaller.

For this report, we therefore constructed a time series of historical methane emissions from New Zealand livestock. This is challenging given the paucity of good data on livestock especially prior to about 1920, but the much smaller magnitude of emissions during the 19th and early 20th century would have only a minor effect on the key conclusions from this study.

Agricultural methane emissions from New Zealand are comprised predominantly of methane produced in the rumen of animals through enteric fermentation (currently ~96% of total agricultural methane emissions). Enteric methane emissions are estimated in the national greenhouse gas emissions inventory using population data and data on animal size and animal performance (i.e. milk yield, growth rates and slaughter weights). This information is used to infer the amount of feed that animals must have consumed to achieve these performance levels (which have changed considerably over time). Total methane emissions are then estimated by multiplying feed intake (expressed as dry matter intake) with a constant factor (based on actual measurements) to give the total methane production. The current published time series based on the national inventory runs from 1990 to 2016 (MfE 2018). Estimating emissions from before 1990 using this method are severely constrained by the absence of comprehensive data. However, it is possible to use the 1990-2016 time series and available historical data to estimate pre-1990 emissions.

4.1.1 Data sources

Beef + Lamb NZ collate and publish comprehensive data on the New Zealand agricultural sector. This includes data on population and total product output. On request they kindly provided population data for the four main species of farmed ruminants in New Zealand. For beef, sheep and dairy cattle the provided data from 1930 through to 2016. For deer the time series start in 1979 since this was the start of the domestic deer industry. These data do not necessarily correspond exactly to the data on population numbers obtainable from Statistics New Zealand since the latter data refer to populations at a particular date, June 30th each year. Beef + Lamb New Zealand also provided data on the total annual product output. For sheep and beef this was meat output and for dairy cattle total milk solids output. The time series available for meat production was for 1964 – 2016 and for milk solids production from 1951 to 2016.

From these population and production data the nominal meat/milk production per animal was calculated for the years when data was available. To estimate meat/milk production per animal for those years in which data were not available linear/non-linear regression was used; relationships between time and milk/meat production per animal were derived from the actual data and values fitted for those years in which actual data were unavailable.

4.1.2 Estimating methane emissions

As methane emissions are primarily driven by animal numbers and animal performance, a simple approach relating Beef + Lamb numbers and performance to estimated emissions prior to 1990 was adopted that mimics the approach underlying the national inventory. For each animal species, multiple regression was used to derive relationships between population number, production per animal and annual methane emissions based on the detailed information in the national inventory from 1990 to 2016. These multiple regression equations were then used with the actual (population and some performance data) and re-constructed (some performance data) to estimate annual methane emissions for the years 1930-1990.

The biggest drawback of this method is that the equations relating population and animal performance to annual methane emissions are used to estimate values well outside the range of values used to obtain the predictive algorithms themselves. There is therefore a tacit assumption that the relationships don't change with time. The relationships between population/performance and methane emissions for the 1990 – 2016 period are very strong ($R^2 > 0.95$ for sheep and dairy cattle), but weaker for beef cattle ($R^2 \approx 0.74$). A possible factor in this is that the structure of the beef industry changed from about 1998 onwards when beef breeding cow numbers stated to decline and more beef was provided from surplus animals from a growing dairy sector. Prior to 1990 the dairy industry had much less influence on beef production. The relationship between animal numbers, production and emissions derived from the period 1990-2016 may therefore have limited applicability to the pre-1990 situation. However, the error inherent in this approach is limited since the dominant influence on methane emissions is animal numbers, and this information is consistent across time. In the fitted relationships, animal population was always the dominant term and in fact estimated pre-1990 emission values using linear regression and population numbers alone to predict emissions differed little from the multiple regression approach eventually adopted.

Even though this simple methodology clearly has limitations, the time series of methane does pass what might be termed the common sense test. They rise steadily from the 1930's and peak when animal numbers peak in the early 1980's. In the rest of the 1980's they fall due to the shock of the changes in agricultural support payments and then start to rise again influenced strongly by a rise in dairy populations and rapid increases in production per animal generally across the sector. Our estimates are consistent with the simpler approach adopted by Ausseil et al. (2013) but show slightly higher emissions in the 1970s and 1980s. Prior to 1930, we used the estimates from Ausseil et al. (2013) to 1861. Prior to 1861, we arbitrarily assumed that emissions rose linearly from zero in 1840 to the first data value in 1861. Methane from animal waste was assumed to scale proportionally to enteric methane emissions prior to 1990.

For projections of future emissions, the most recent government forecasts were used up to 2030 (MfE 2017), with extension to 2050 based on Reisinger et al. (2018). Emissions are held constant thereafter at 2050 levels. The complete time series derived in this way is shown in Figure 14, along with an alternative scenario that holds future emissions constant at 2016 levels.

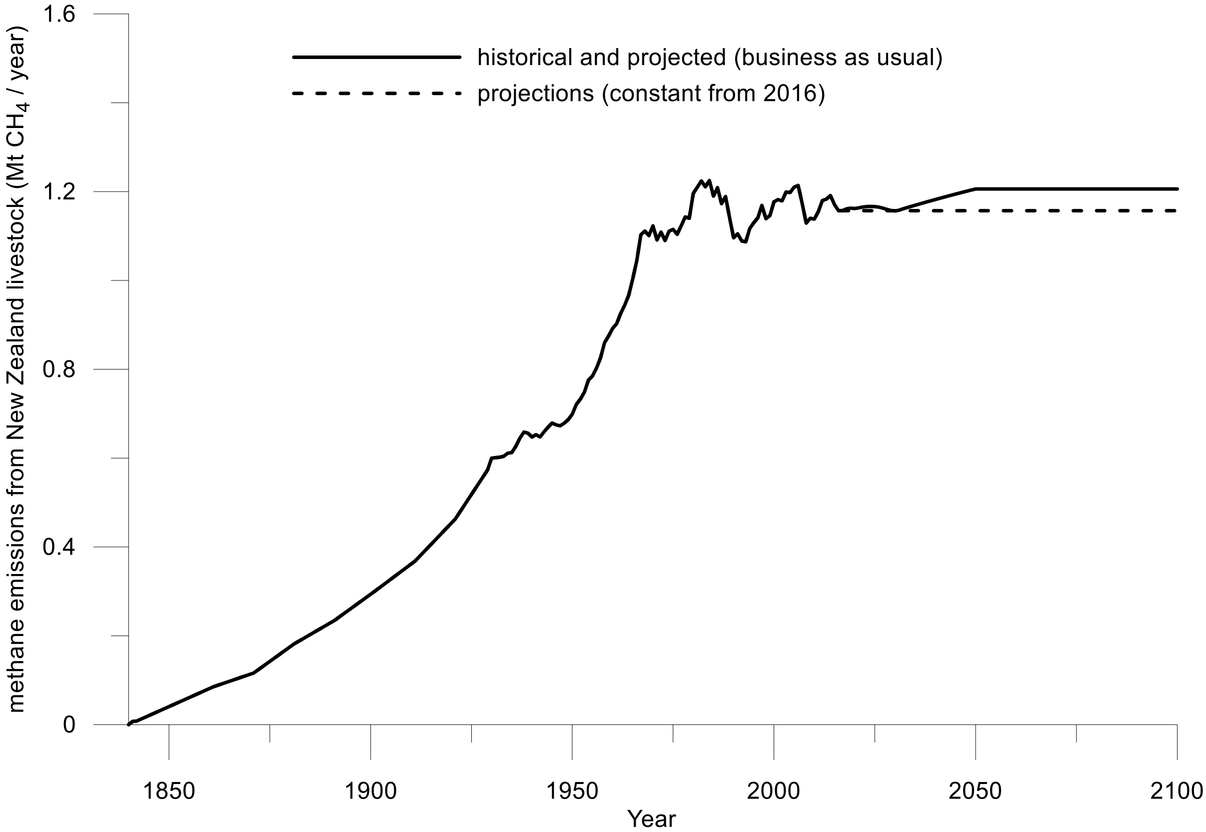

Figure 14. Historical and projected methane emissions from New Zealand livestock. For details, see text. Also shown is a hypothetical scenario with emissions held constant at 2016 levels from that date onwards.

4.2 Warming from New Zealand's livestock methane emissions

These historical time series and future projections were used to estimate the historical and future warming attributable to New Zealand's livestock methane emissions, using the same modelling approach and for the same global emissions scenarios (Representative Concentration Pathways) as in Section 3. Figure 15 shows the historical and projected future warming from New Zealand's livestock methane emissions if the global background concentrations of all greenhouse gases were otherwise held constant from 2011 onwards. It can be seen that a noticeable residual warming would be expected to occur, even if climate-carbon cycle feedbacks were excluded from the model, but the ongoing warming is more pronounced if they are included.

As shown in in Section 3.3, the evolution of global atmospheric methane concentrations matters for the warming effect exerted by an additional flow of methane. Figure 16 illustrates this, using the same New Zealand emissions and showing the modelled median warming for constant background concentrations as well as RCP2.6 and RCP4.5 (which could be loosely described as scenarios where the world achieves the goals of the Paris Agreement (RCP2.6) and one where the world fails to achieve the Paris Agreement but has tried (RCP4.5)).

In both RCP scenarios, the warming exceeds that expected if global methane emissions were held constant at 2011 levels, because in both scenarios global methane concentrations drop below today's levels (shortly after 2020 in the case of RCP2.6, and in the second half of the 21st century in the case of RCP4.5). The lower global methane concentrations mean that a given additional quantity of methane in the atmosphere would have a greater warming effect than it has today, resulting in additional warming.

Figure 16 also shows the warming that would be expected if New Zealand livestock CH_4 emissions follow the government's current "business-as-usual" scenario, extended out to 2050 (Reisinger et al. 2018) and remain constant thereafter. Up to about 2040, there would be little difference in warming compared to a scenario where New Zealand's livestock methane emissions are held constant at 2016 levels, but a beginning divergence from 2050 onwards. This is because this business-as-usual scenario envisages a growth in methane emissions after 2030 (see Figure 14), resulting in a higher flow of methane in the second half of the 21st century and hence higher warming.

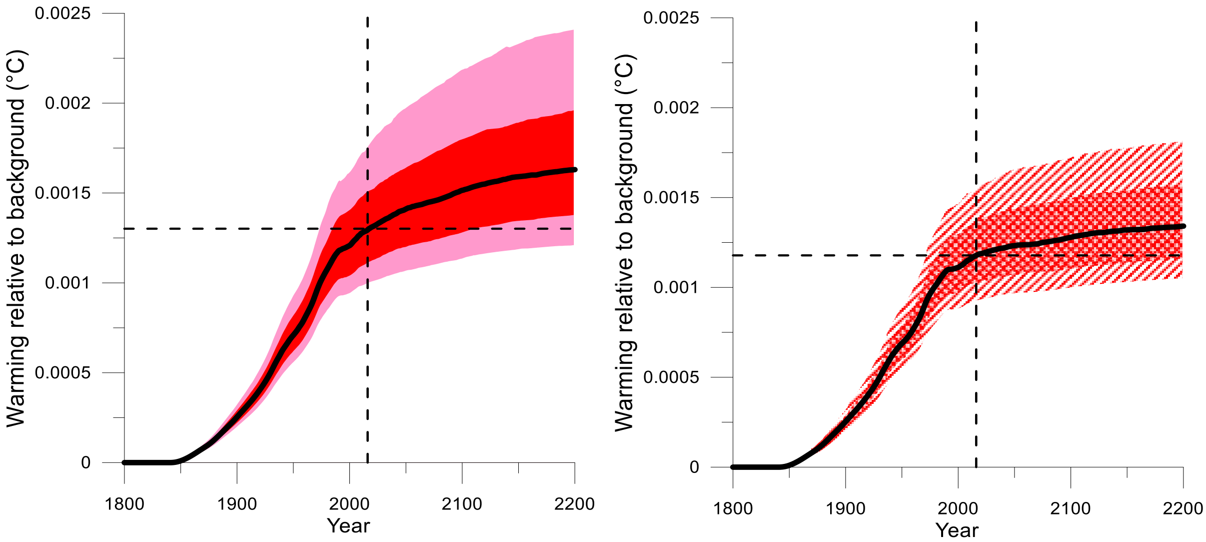

Figure 15. Modelled warming from New Zealand livestock methane emissions, with the effect of climate-carbon cycle feedbacks included (left panel, solid shading) and excluded (right panel, hashed shading). Global background concentrations were assumed to be constant from 2011 onwards. Dashed lines indicate the warming estimated to have occurred due to New Zealand's methane emissions by the year 2016.

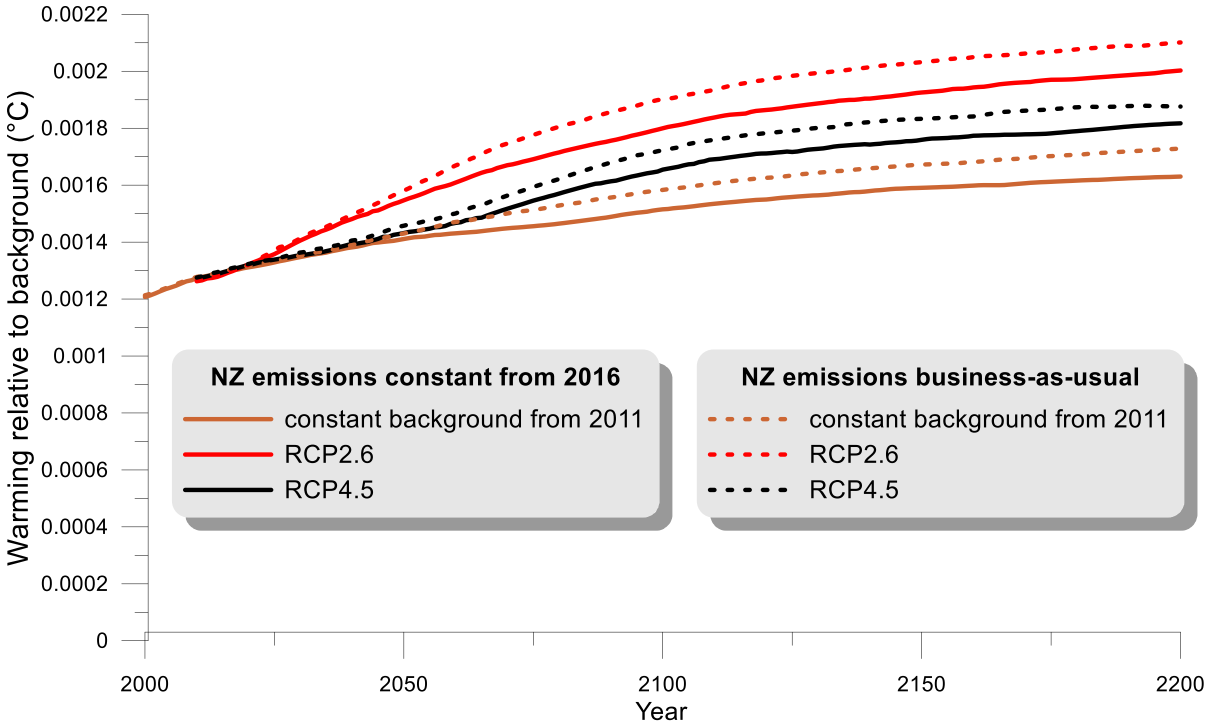

Figure 16. Modelled median warming from New Zealand livestock methane emissions for different scenarios of global atmospheric methane concentrations, and with New Zealand emissions held constant from 2016 onwards (solid lines) and using business-as-usual projections to 2050 and constant emissions afterwards (dashed lines).

Table 1 summarises the additional warming that could be expected under those two scenarios, relative to the warming estimated to have been caused by New Zealand's livestock methane emissions by the year 2016. If New Zealand livestock methane emissions were held constant at 2016 levels, the warming due to those emissions would be expected to be 10-20% greater in 2050 than it was in 2016, and 12-22% greater if emissions follow a business-as-usual trajectory, for the two Representative Concentration Pathways RCP2.6 and RCP4.5. Other global concentration pathways were not modelled for this report on the assumption that the world would make at least some significant effort towards meeting the objectives of the Paris Agreement. By 2100, the additional warming relative to 2016 would reach 27-39% for constant emissions, and 32-47% for business-as-usual followed by constant emissions from 2050. These estimates are based on median model results; uncertainties in climate models and climate-carbon cycle feedbacks give a slightly wider spread, especially for RCP4.5 which has higher emissions of other gases that interact with methane chemistry and which add to the overall uncertainty of the warming effect.

Table 1. Summary of modelled mean warming from New Zealand livestock methane emissions under three alternative global scenarios, and for different assumptions about future New Zealand emissions. Warming is given as a percentage increase of the warming in 2050, 2100 and 2200, relative to the warming realized in the year 2016.

global scenario [1]	**constant emissions from 2016** [2]			**business-as-usual to 2050, constant emissions from 2050** [2]		
	temperature increase [3]			temperature increase [3]		
	2050/2016	2100/2016	2200/2016	2050/2016	2100/2016	2200/2016
CONSTANT	9 [7-10]%	17 [14-21]%	26 [21-34]%	10 [9-12]%	22 [20-26]%	33 [29-41]%
RCP2.6	20 [18-20]%	39 [38-45]%	55 [48-62]%	22 [20-23]%	47 [44-50]%	62 [60-69]%
RCP4.5	10 [7-14]%	27 [21-33]%	40 [31-48]%	12 [9-13]%	32 [27-36]%	44 [40-52]%

1 The global scenarios assume that global greenhouse gas concentrations remain constant at 2011 levels (CONSTANT), or follow the Representative Concentration Pathways RCP2.6 or RCP4.5.

2 Future New Zealand emissions are assumed to either remain constant at 2016 levels, or follow business-as-usual to 2050 and then remain constant at 2050 levels.

3 Temperatures are median model results, with the central 66 percentile (i.e. 17th to 83rd percentile, corresponding to the IPCC *likely* range) given in square brackets, based on probabilistic MAGICC simulations (see Appendix I, and text).

4.3 Reductions in New Zealand's livestock methane emissions that would avoid additional warming above today's levels

This section presents estimates of the reductions in New Zealand's livestock methane emissions that would result in no additional warming due to those emissions occurs, relative to the warming already realised from those emissions in the year 2016.

The emissions reductions were estimated manually and iteratively. An initial emission reduction was inferred from the warming shown in Table 1 (i.e. if warming increases by 10% in 2050 relative to 2016, it was assumed that methane emissions might have to be reduced by 10% in 2050 relative to 2016 to achieve a constant level of warming). These initial reduction estimates were then re-adjusted based on iterative model simulations to better approximate the desired outcome to avoid any additional warming after 2016, and to account for non-linear behaviours and inertia of the climate system. These simulations were undertaken for median warming only. Figure 17 shows the resulting estimated emission pathways that would result in no additional warming from New Zealand's livestock CH_4 emissions, for different assumptions about global methane concentrations (RCP2.6, RCP4.5, and constant concentrations from 2011 onwards) and if climate-carbon cycle feedbacks are included or ignored.

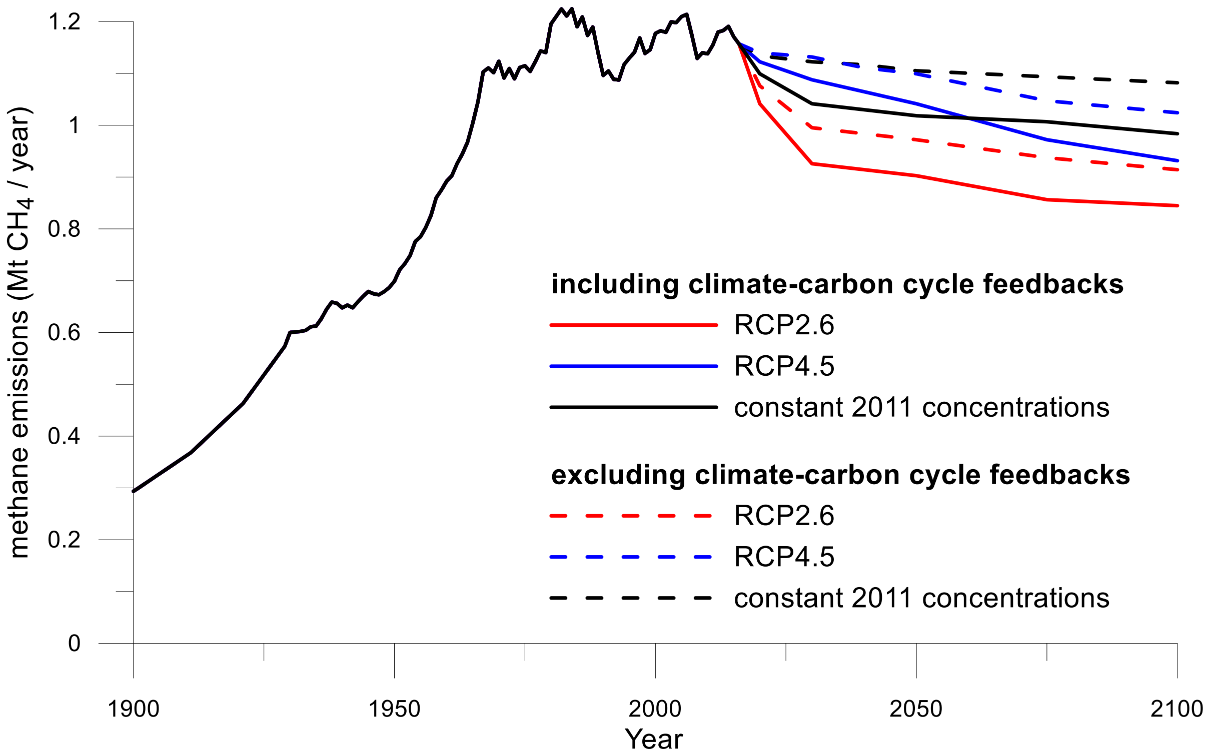

Figure 17. Approximate methane emissions from New Zealand livestock that would result in no additional warming in 2050 and 2100 relative to the warming from those emissions in 2016, based on median MAGICC model results. Solid lines indicate emissions reductions consistent with no additional warming if climate-carbon cycle feedbacks are included in the simulations, and dashed lines show emissions reductions if climate-carbon cycle feedbacks are ignored.

Emission reductions prior to 2050 were set such that the warming does not exceed current levels at any time between now and 2050; given the non-linear adjustment of the climate system, this required a more rapid reduction between now and 2030 and a lesser rate of reduction between 2030 and 2050. Further reductions beyond 2050 are required to ensure warming remains stable during the second half of the 21st century. Taking climate-carbon cycle feedbacks into account requires an about five to six percentage points greater reduction of emissions than if they are ignored; i.e. for RCP4.5, the reductions in 2050 are 5% below today's levels without climate-carbon cycle feedbacks and 10% with climate-carbon cycle feedbacks, and 16% versus 22% for RCP2.6.

Because of the non-linear change in emissions to ensure warming does not exceed the current level at any time in future, the necessary reductions cannot be easily expressed as simple annual rates. A linear decline in emissions would result in additional warming over the next two decades and then declining warming back to today's levels by 2050. If this temporary overshoot were considered acceptable, this would equate to a linear emissions reduction of about 0.3-0.6% per year between 2016 and 2050, and a further decline by about 0.2-0.3% per year between 2050 and 2100.

Figure 18 illustrates the actual warming from New Zealand's livestock methane emissions simulated for two of those scenarios, including climate model uncertainties. The Figure shows that temperatures are not exactly constant after 2016, which largely reflects that emissions were only adjusted manually to give an *approximately* stable temperature. Uncertainties arising from different climate model parameterisations affect the total amount of warming, but have a more limited influence on whether warming increases or decreases relative to today's warming. Only for models belonging in the 75th percentile and above of the warmest models would there be a noticeable ongoing warming trend for the chosen emission reduction scenarios (reflecting model parameterisations where climate-carbon cycle feedbacks are particularly strong).

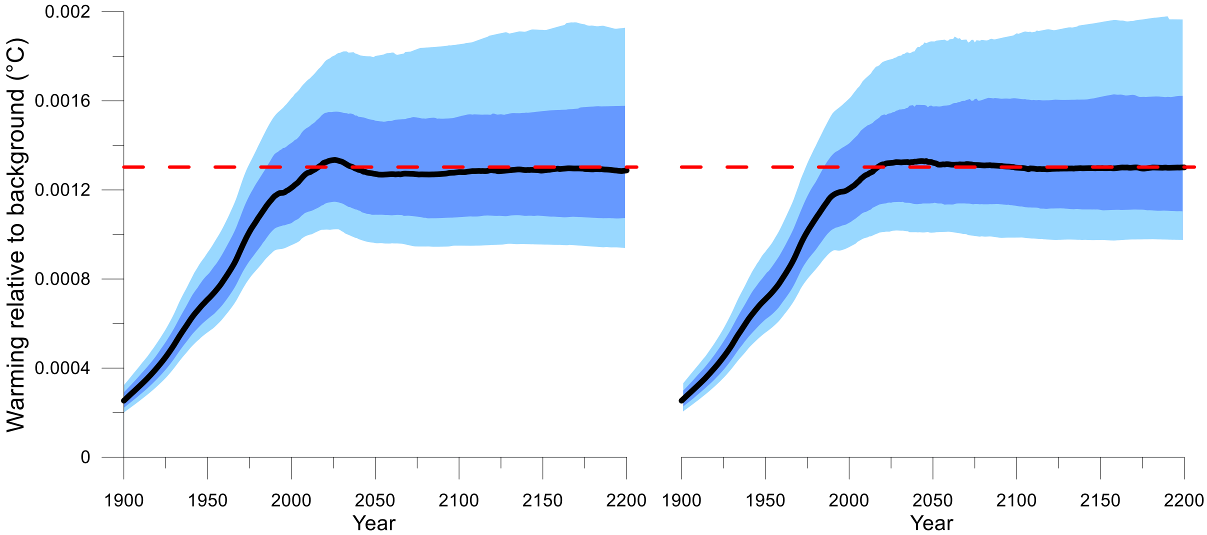

Figure 18. Illustrative warming from methane emissions from New Zealand livestock, for emission reduction scenarios that seek to ensure no additional warming above the warming caused by those emissions in 2016. The two panels are for scenarios where the global background methane concentrations follow the RCP2.6 (left panel) and RCP4.5 (right panel) scenario. The results demonstrate that actual warming from New Zealand's livestock methane emissions would indeed be approximately constant from 2016 onwards for the different emissions reductions shown in Figure 17.

The emission reductions for the various scenarios of New Zealand livestock methane emissions are summarised in Table 2, for model simulations with and without climate-carbon cycle feedbacks. The results indicate that a reduction of about 22% below 2016 levels by 2050, and 27% by 2100, would ensure (based on the median model results) that the warming does not exceed 2016 levels regardless of the assumed global scenario and resulting global methane concentration. Lesser emission reductions of 10% could achieve the goal if the world follows the RCP4.5 pathway, but not if it follows the RCP2.6 pathway.

Table 2 also demonstrates that lesser reductions of 5-16%, rather than 10-22%, would be consistent with the goal of keeping the warming from New Zealand's livestock methane constant if climate-carbon cycle feedbacks are ignored. However, this information is provided for completeness only since climate-carbon cycle feedbacks are undoubtedly a part of the climate system.

Table 2. Summary of emissions of methane from New Zealand livestock to achieve no additional warming in 2050, 2100 and 2200, relative to the warming from those emissions in the year 2016. Results are approximate, with an uncertainty of at least one percentage point, based on the median of probabilistic model simulations. Reductions are shown for model simulations with and without climate-carbon cycle feedbacks included. For details, see text.

global scenario [1]	**with climate-carbon cycle feedbacks** [2]			**without climate-carbon cycle feedbacks** [2]		
	emission reductions relative to 2016 [3]			emission reductions relative to 2016 [3]		
	2050	2100	2200	2050	2100	2200
CONSTANT	12%	15%	18%	4.5%	6.5%	9%
RCP2.6	22%	27%	29%	16%	21%	23%
RCP4.5	10%	20%	21%	5.0%	11%	13%

5. Conclusions

This report sought to clarify the extent to which a constant flow of methane emission results in a stable temperature, and the time scales over which such a stabilisation would be achieved. This conceptual approach was then used to test whether stabilisation of methane emissions from New Zealand's livestock sector would result in stable or additional warming, and by what amount those emissions would have to be reduced to achieve a stable level of warming.

The study used a widely used climate model of reduced complexity (MAGICC version 6.3) to test a variety of scenarios and to explore the extent to which the answer could depend on differences between climate models. The MAGICC model has been shown to be able to emulate results from more complex and detailed models, and is therefore well suited to test the effect of uncertainties arising from different models as well as results under differing global emission scenarios.

The analysis in this report demonstrates that if New Zealand were to hold its methane emissions constant at 2016 levels, the amount of methane in the atmosphere due to New Zealand's emissions would level out rapidly, but warming from this methane would still increase over timescales of decades to centuries, albeit at a gradually declining rate. This ongoing additional warming is largely due to the inertia of the climate system, which is still responding to the historical increase in methane emissions from New Zealand since the 19th century and results in a long-lasting component of warming from methane despite the relatively short lifetime of the gas itself. Additionally, the release of methane triggers various feedbacks that result in additional warming over and above that directly caused by methane itself. It would take several hundred years of constant methane emissions before warming due to those emissions ceases to increase entirely. Note that even though there is on-going warming from constant methane emissions, the situation would be very different for long-lived greenhouse gases such as carbon dioxide or nitrous oxide, where warming would continue to increase linearly year-on-year if emissions remain constant.

The time scale over which a fully stable temperature would be reached has not been analysed in this report, in part because MAGICC has only been calibrated to complex models over timescales of one or two centuries. Confidence in its results therefore decrease for simulations extending over many centuries. Climate simulations using more complex models indicate that it would take about a millennium for temperatures to fully stabilise in response to a constant additional radiative forcing, with most of the additional warming realised within the first three centuries after radiative forcing has become constant (Collins et al. 2013a). The simulations carried out for this report indicate that 300 years after a constant rate of methane emissions has started, the warming is more than twice as high than the warming after 50 years.

This report developed an estimated historical time series of methane emissions from New Zealand livestock. This time series, along with a range of possible future emissions, was used to simulate the warming attributable to those methane emissions.

The results show that if New Zealand's methane emissions were held constant from today onwards, the additional warming in 2050 would be about 10-20% above the warming that has been caused by New Zealand's methane emissions to date, and this would increase further to 27-39% by 2100. These ranges reflect the fact that the warming impact of New Zealand's methane emissions depends on global methane concentrations, which will influence the warming effect exerted by New Zealand's additional methane emissions. In other words, the warming from New Zealand's emissions depends to some extent on the actions taken by other countries to address climate change.

If New Zealand wished to ensure that its livestock methane emissions cause no additional future warming relative to the warming caused by those emissions to date, it would have to reduce those methane emissions by about 10-22% below current levels by the year 2050, and more by 2100. The ranges in the emission reductions are due to different assumptions regarding future concentrations of greenhouse gases (particularly methane), and represent best estimates based on simulations across a range of different climate models. As a general rule, the greater the assumed action globally to reduce methane from the extraction, transport and use of fossil fuels (coal, oil and gas), the more significant the warming contribution from other sources of methane becomes. If the world reduces long-lived greenhouse gases to zero or below, and simultaneously takes stringent actions to also reduce methane emissions (as in the RCP2.6 global Representative Concentration Pathway), this would increase the warming effect exerted by New Zealand's methane emissions. In this case, New Zealand's livestock methane emissions would need to be reduced by about 22% relative to today to avoid any additional warming from those emissions. If the world takes less stringent actions (as in the RCP4.5 global Representative Concentration Pathway), global methane concentrations would fall less and New Zealand would only have to reduce its livestock methane emissions by only 10% relative to today to avoid additional warming from those emissions.

Even though this study demonstrates that constant methane emissions result in some additional future warming, this does not mean that methane has the same long-lasting impact on climate as carbon dioxide. Continued emissions of carbon dioxide from New Zealand at today's level would eventually result in greater additional warming than continued emissions of methane from New Zealand, given the long lifetime of carbon dioxide and its resulting accumulation in the atmosphere. Warming due to long-lived greenhouse gases will continue to increase until their net emissions reach zero, whereas the warming from constant methane emissions levels off within a few centuries. Reducing net emissions of long-lived greenhouse gases to zero is therefore a physical necessity if New Zealand wishes to halt its further contribution to climate change. By contrast, the results presented in this report demonstrated that a much lesser reduction in methane emissions would ensure that methane emissions do not add further to warming.

It needs to be emphasised that knowing what level of methane emissions would result in a constant amount of warming from today onwards can only serve as a benchmark, it does not necessarily constitute an appropriate emissions target. The absolute amount of warming caused by a gas to date, as well as the potential to reduce its emissions and hence total contribution to warming in future, are also important. New Zealand might wish to reduce its methane emissions by more than the 10-22% range indicated in this report to reduce the overall contribution from this gas to global warming below where it is today. How far New Zealand in fact can and wants to lower its methane emissions and the warming they have caused to date and will continue to contribute to in future will depend on complex judgements about the economic, social and environmental consequences of such reductions. This includes judgements on how New Zealand wishes to position itself relative to actions and expectations by the rest of the world. A physical estimate of additional temperature changes relative to today can only provide a reference point but cannot answer these much bigger social and economic questions.

Appendix I – MAGICC model description and setup

MAGICC is a reduced-complexity climate model that has been used widely for climate scenario studies (Wigley and Raper 1992) and in IPCC assessment reports. The model simulates the basic physics of the climate system, including an upwelling-diffusive ocean and a simple carbon cycle model including CO_2 fertilization and temperature feedback parameterisations of the terrestrial biosphere and oceanic uptake. The model has been updated repeatedly to incorporate updated scientific insights. For this study, MAGICC version 6.3 has been used (see Meinshausen et al. 2011a; Meinshausen et al. 2011c for a detailed description).

To simulate the behaviour of methane in the atmosphere, MAGICC uses a simple atmospheric chemistry module that includes separate loss processes for reaction with the hydroxyl radical in the troposphere (the dominant loss process), as well as destruction of methane in the stratosphere and by methanotroph (methane digesting) bacteria in soils. The concentration of hydroxyl radicals and resulting loss rate depends on the global concentration of methane as well as carbon monoxide, nitrogen oxides, and volatile non-methane hydrocarbons; and each of those loss rates depend on temperature. The default parameters describing these reactions and their temperature dependence are taken from the IPCC Third Assessment Report (Ehhalt et al. 2001). More recent assessments have clarified uncertainty ranges for some of those parameters but have not fundamentally changed the reactions and their dependence on concentrations of other gases and temperature (Myhre et al. 2013). In contrast to many other simple climate models that rely on fixed pulse-response functions to simulate the decay of greenhouse gases in the atmosphere, the relatively sophisticated treatment of methane in MAGICC thus makes the model suitable to answer the questions asked of this report, and a recent comparison of MAGICC with a detailed atmospheric chemistry model has confirmed the ability of MAGICC to reproduce the key features of methane chemistry (Ocko et al. 2018).

Similarly, the decay of carbon dioxide in the atmosphere is simulated explicitly through various carbon pools representing living biomass, litter, and uptake in the ocean in several layers, with the exchange between each pool dependent on temperature. As a result, MAGICC is able to reproduce key features of the global carbon cycle, and the coupling between the carbon cycle and the climate system, and matches well the results from more complex Earth System Models (Joos et al. 2013).

A key feature of the model is that the parameters that describe the response of the climate system to key drivers such as changes in greenhouse gas concentrations, but also parameters describing the chemistry of greenhouse gases or the carbon cycle, can be calibrated against simulations from more complex Earth System and General Circulation Models. This allows the model to emulate the results from much more complex models at global scales; and because of the limited computing power needed to run the model, many different parameter combinations can be explored and thus be used to estimate the range of uncertainty in results arising from different climate and carbon cycle models. The calibrated model has been shown to be consistent with the range of results from more complex climate and carbon cycle models (Joos et al. 2013; Meinshausen et al. 2011a).

In addition, a set of 82 parameters in MAGICC can be varied randomly in a Monte-Carlo type approach to sample not only the range of uncertainties presented by an ensemble of models but also by known constraints on key physical parameters that control energy balance, gas-phase chemistry, and radiative forcing including its spatial distribution. Detailed descriptions of this approach can be found in Meinshausen et al. (2009) and Reisinger et al. (2010). One parameter in this set is the global equilibrium climate sensitivity (the long-term warming resulting from a doubling of carbon dioxide concentrations, which has been estimated to be likely between 1.5 and 4.5°C).

For this study, we used the Monte-Carlo approach with the parameter set described in (Meinshausen et al. 2009), along with parameter settings that emulate a set of 9 different climate-carbon cycle models (Friedlingstein et al. 2006). The parameter representing the equilibrium climate sensitivity follows the distribution given by Frame et al. (2006). Additional details can be found in (Reisinger et al. 2010).

The parameter set was updated for this study only to reflect the revised indirect forcing from a methane emissions via tropospheric ozone as described in the IPCC 5th Assessment Report (Ciais et al. 2013). Other than this, the calibration set from the IPCC 4th Assessment was used, which was considered adequate for this study given that the projected climate change response to a given amount of forcing has changed relatively little over the past 20 years (Rogelj et al. 2012).

With this slightly updated setting, the simulated GWP100 of methane using the probabilistic (Monte-Carlo) approach is 28 for the model median if climate-carbon cycle feedbacks are excluded, and 33 if they are included, in broad agreement with the findings from the IPCC 5th Assessment Report (Myhre et al. 2013). The projected model mean warming (representing the median across a set of 1200 Monte Carlo simulations that include the full range of equilibrium climate sensitivity) is 1.0°C under the RCP2.6 scenario and 4.0°C under the RCP8.5 scenario in 2081-2100 relative to 1986-2005. This corresponds well to the warming of 1.0 (0.3–1.7)°C and 3.7 (2.6–4.8)°C for these same scenarios given in the IPCC 5th Assessment Report based on a range of complex climate models (IPCC 2013). The slightly 'warmer' median model result from MAGICC under the high-emissions scenario RCP8.5 is consistent with the slight downward revision of the lower *likely* range for the equilibrium climate sensitivity in the IPCC 5th Assessment Report compared to the 4th Assessment Report. A similar result was observed in a recent study (Leach et al. 2018). However, these minor differences in overall warming rates do not affect the utility of the MAGICC model for the purpose of this study, since the primary question in this report is not the absolute amount of warming caused by New Zealand's methane emissions, but the relative change over time, which is much less affected.

To simulate the warming effect from a pulse or constant rate of emission of methane or carbon dioxide, the model is first run in inverse mode to determine the background greenhouse gas emissions that would give rise to a prescribed set of global background concentrations of greenhouse gases and other relevant trace gases. The model is then run in forward mode without and with the additional emission; the differences between these two model runs gives the changes in greenhouse gas concentrations, radiative forcing, and temperature attributable to the additional emission. This approach allows carbon dioxide concentrations to respond via climate-carbon cycle feedbacks to the warming caused by methane emissions. To determine the warming if such feedbacks are excluded, the global carbon dioxide concentrations are fixed to their background levels. The model is run in a Monte Carlo approach 1200 times, sampling twice a set of 600 alternative climate parameter combinations cross-matched randomly with one out of nine different global carbon cycle model parameterisations. For details, see (Meinshausen et al. 2009).

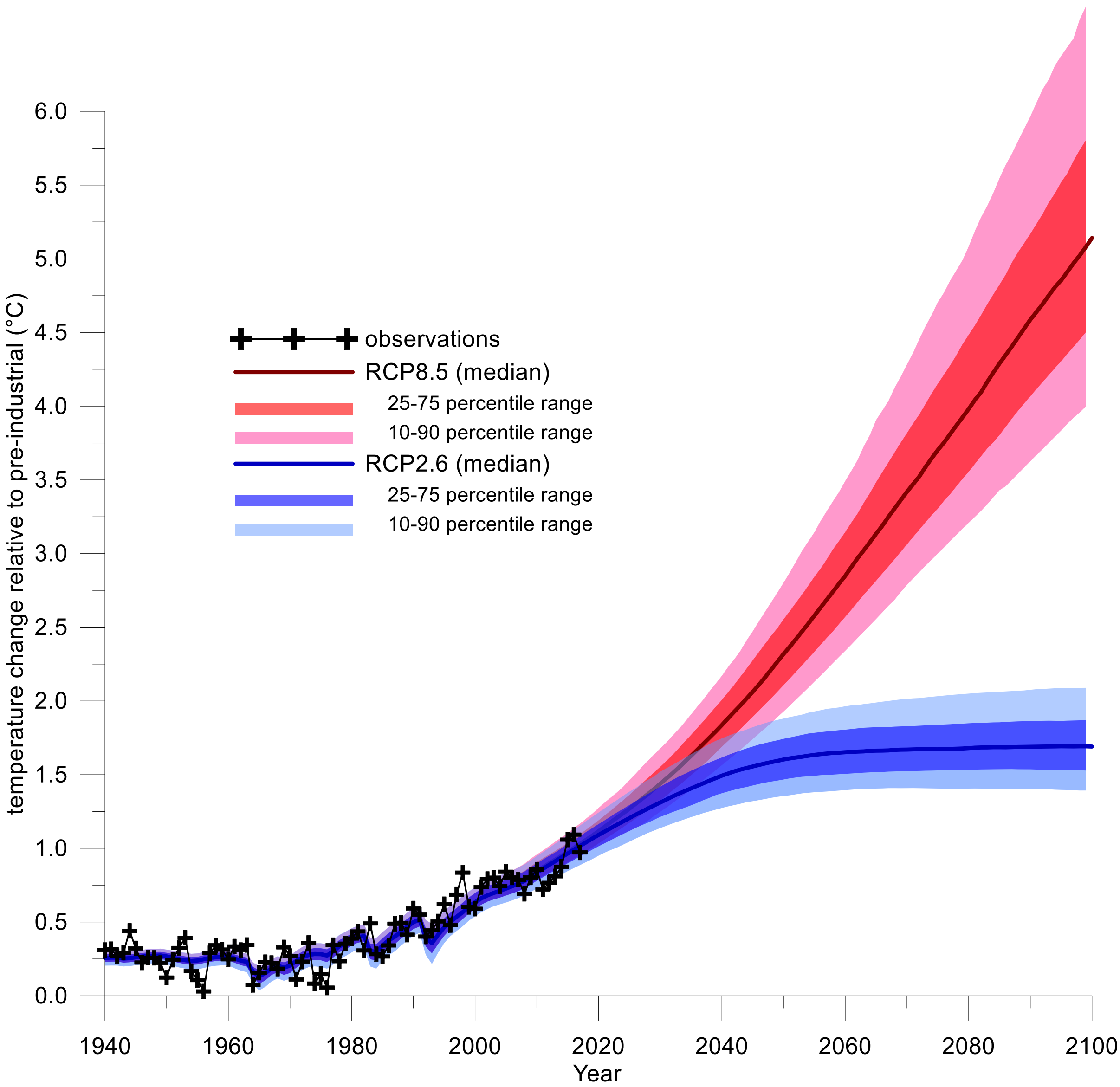

Figure 19. Simulated historical and projected future change in global average temperature using the probabilistic (Monte-Carlo) approach for MAGICC, for two alternative future global greenhouse gas concentration scenarios (RCP2.6 and RCP8.5). Historical data are from the Hadley Centre global temperature dataset HADCrut4 (Morice et al. 2012), shifted to match the MAGICC median temperatures for the period 1986-2005.

Appendix II – Estimated total warming from historical and future New Zealand livestock methane and fossil CO_2 emissions

The focus of this report is on the *additional* warming caused by future methane emissions from New Zealand's livestock sector, relative to the warming from historical emissions inferred for the year 2016. This Appendix sets this *additional* warming into broader context by providing estimates of the *total* warming (i.e. relative to pre-industrial conditions) caused by historical and future livestock methane emissions from New Zealand, and comparing this warming with the total warming caused by historical and future fossil carbon dioxide emissions from New Zealand.

A reconstruction of New Zealand's historical livestock methane emissions is presented in the body of the report (see Section 4.1) and reproduced in Figure 20. Historical fossil carbon dioxide emissions from New Zealand are based on the dataset from Ausseil et al. (2013). The reconstructed emissions date only back to 1881; for this study, emissions were linearly extrapolated to start at zero in 1840.

For the projections discussed here, future fossil carbon dioxide emissions are assumed either to be constant from 2016 onwards or to decline to zero by 2050 or 2100. Methane emissions are assumed to be constant from 2016 onwards or reduced such that no additional warming results after 2016. The alternative emission scenarios are shown in Figure 20.

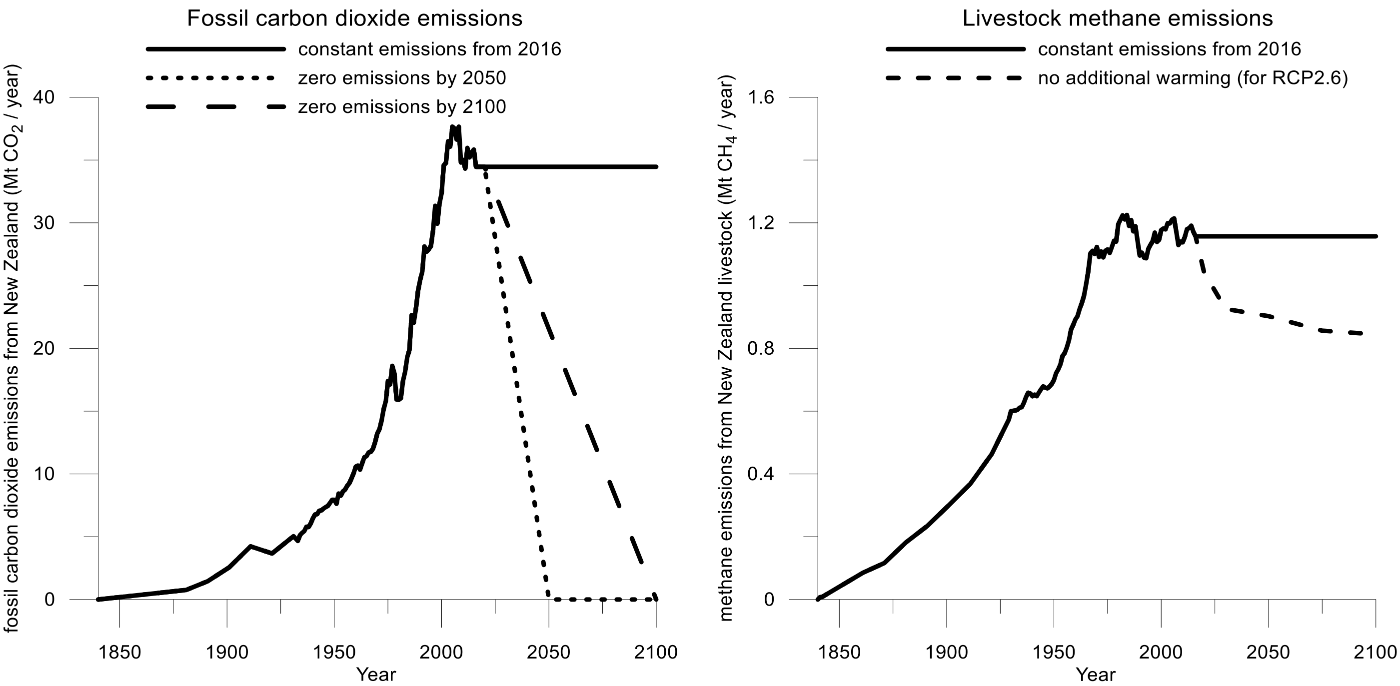

Figure 20. Historical and alternative future emissions of fossil carbon dioxide and livestock methane from New Zealand. Historical emissions were reconstructed from 1840 to 2016, using published national inventory data for the period 1990 to 2016. Future emissions follow simplified alternative scenarios. For details, see text.

These emissions of fossil carbon dioxide and livestock methane were used in MAGICC simulations to estimate the resulting historical and future total temperature change out to the year 2100. For these illustrative examples, it was assumed that emissions from the rest of the world fall sufficiently rapidly to limit the increase in global average temperature change to less than 2°C relative to pre-industrial levels (i.e. the RCP2.6 pathway – see Section 3.3). The results are shown in Figure 21, separately for each gas and for the combination of both gases, for median model results using a probabilistic modelling approach (see Appendix I).

Figure 21 shows that the total warming up to 2016 attributable to historical livestock methane emissions is about twice as large as the warming from historical fossil carbon dioxide emissions, but the warming from carbon dioxide is currently increasing about twice as fast as that from methane.

If fossil carbon dioxide continues to be emitted at a constant rate at 2016 levels, the resulting warming would continue to rise linearly. By about 2070, the total warming from fossil carbon dioxide emissions would exceed the total warming from constant methane emissions and continue to rise thereafter, whereas the warming due to constant methane emissions would gradually flatten out.

If fossil carbon dioxide emissions were reduced to zero by 2050 or 2100, warming due to those emissions would continue to increase, at a gradually declining rate, until emissions reach zero. The *additional* warming from those carbon dioxide emissions between now and 2050 or 2100 would be greater than the *additional* warming from constant methane emissions.

At the same time, Figure 21 illustrates that the *total* amount of warming from New Zealand's livestock methane at any time during the 21st century, if those emissions were sustained at current levels, would be greater than the *total* warming from New Zealand's fossil carbon dioxide emissions, as long as those emissions are brought to zero before 2100.

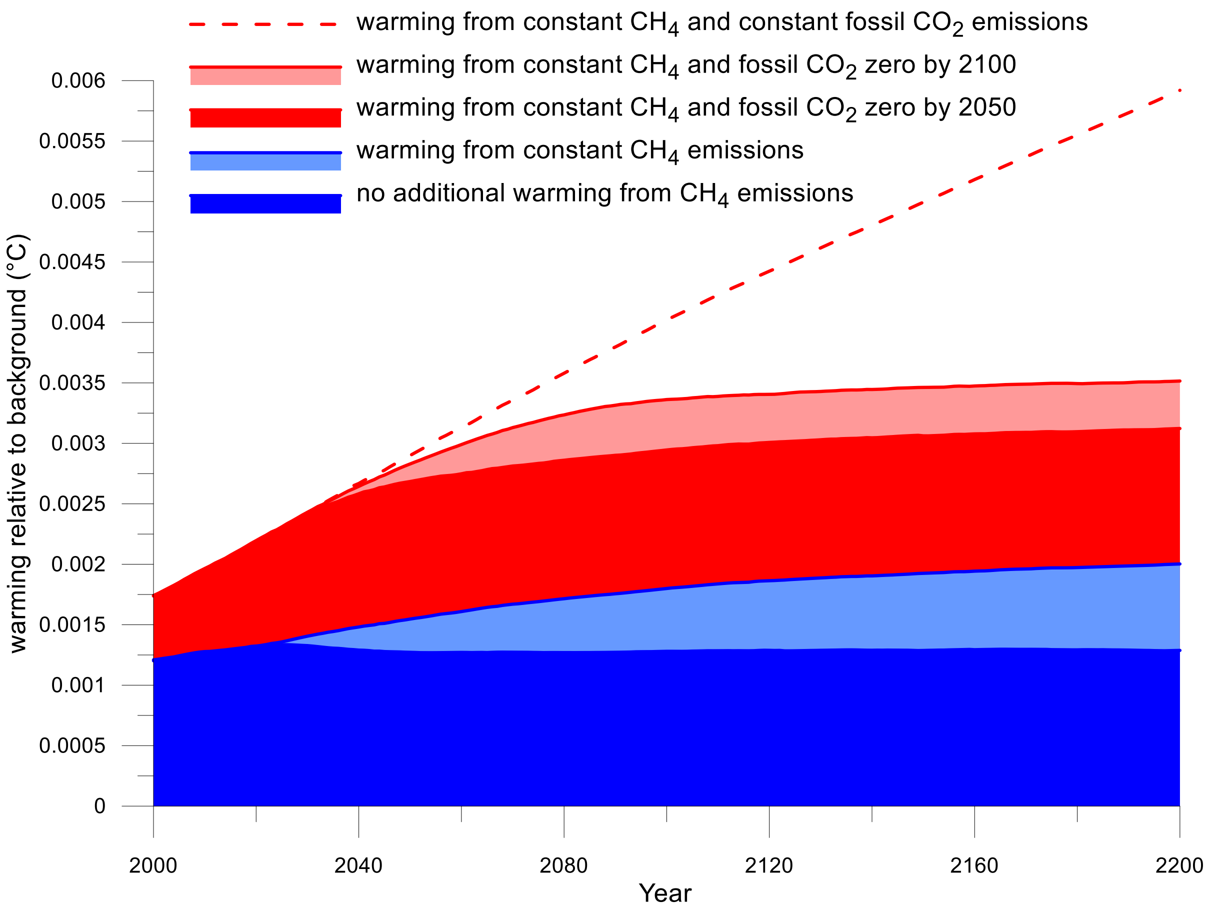

Figure 21. Total warming from New Zealand livestock methane and fossil carbon dioxide emissions from 2000 to 2200. The dark blue shaded area indicates the total warming if methane emissions are reduced such that no additional warming results after 2016; the light blue shaded area indicates the additional warming that would result if methane emissions were held constant from 2016 onwards. The dark red area indicates the total warming from fossil carbon dioxide emissions, added to the total warming from methane emissions, if fossil carbon dioxide emissions were reduced to zero by 2050, and the light red shaded area indicates the warming that would result if fossil carbon dioxide emissions were reduced to zero by 2100. The red dashed line indicates the total warming that would result if both livestock methane and fossil carbon dioxide emissions were held constant at year 2016 levels. Levels of warming represent the best estimate (median) result of probabilistic MAGICC simulations (see Appendix I).

Given the long atmospheric lifetime of carbon dioxide, the amount of future warming from this gas is the result of both historical and future emissions. By contrast, most of the *future* total warming from methane will be caused by *future* methane emissions. Reducing future methane emissions as far as possible (rather than only to a level where they do not cause *additional* warming), could therefore substantially reduce New Zealand's overall contribution to future climate change – provided this is done in addition to, rather than instead of, reducing carbon dioxide to zero. However, how much methane emissions can be reduced will depend on the future cost of emission reductions as well as the broader economic, social and environmental consequences of doing so.

These detailed model results are consistent with and demonstrate the utility of the GWP* metric proposed by Allen et al. (2016). Based on this metric, a sustained emission of 1.156 Mt CH_4 (the rate of livestock methane emissions in 2016) has an approximately equivalent effect on global radiative forcing as a cumulative carbon dioxide emission of 3.2 Gt CO_2 (using a GWP_{100} for methane of 28, excluding climate-carbon cycle feedbacks). By comparison, the reconstructed cumulative fossil carbon dioxide emissions from New Zealand between 1840 and 2016 are 1.74 Gt CO_2.[11] Taking future carbon dioxide emissions into account, the cumulative fossil carbon dioxide emissions from 1840 to 2100 would be 4.7 Gt CO_2 for constant emissions, and 2.4 and 3.2 Gt CO_2 for emissions declining to zero by 2050 and 2100, respectively.

The GWP* metric therefore predicts that the total warming effect from constant methane emissions is about 1.3 times greater than that from fossil carbon dioxide emissions, provided those emissions reach zero by 2050, and about the same if fossil carbon dioxide emissions reach zero by 2100. This is in reasonable agreement with the detailed model results shown in Figure 21. The modelled actual temperature change is slightly greater than that indicated by the GWP* metric because the metric ignores the warming due to climate-carbon cycle feedbacks from methane emissions.

It should be noted that the above model calculations and estimates do not provide a complete picture of New Zealand's past and future contribution to climate change, since emissions of other gases (most notably nitrous oxide) and emissions and removals of carbon dioxide via historical deforestation, and more recent afforestation, are not included. In addition, it appears almost impossible to reduce fossil carbon dioxide emissions to zero by 2050 as assumed in the above model simulations; some unavoidable emissions of fossil carbon dioxide will need to be compensated for by carbon removals e.g. through forestry, to achieve net zero carbon dioxide emissions.

The model simulations presented here have not attempted to capture these aspects nor explored uncertainties related to historical and future emissions and removals of carbon dioxide from land-use change. They can therefore only give an indicative answer regarding the importance of future methane emissions for New Zealand's overall future contribution to climate change.

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[11] Minor changes in the start date have only a minor influence on the cumulative historical fossil carbon dioxide emissions: if it is assumed that fossil carbon dioxide emissions started in 1800, the cumulative fossil carbon dioxide emissions from 1800 to 2016 would be 1.75 Gt CO_2.

References

Allen MR, Frame DJ, Huntingford C et al (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458(7242): 1163-1166

Allen MR, Fuglestvedt JS, Shine KP et al (2016) New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nature Clim. Change advance online: DOI: 10.1038/nclimate2998

Allen MR, Shine KP, Fuglestvedt JS et al (2018) A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. npj Climate and Atmospheric Science advance online: DOI: 10.1038/s41612-018-0026-8

Ausseil A-G, Kirschbaum MUF, Andrew RM et al (2013) Climate regulation in New Zealand: contribution of natural and managed ecosystems. In: Dymond J (eds) *Ecosystem services in New Zealand – conditions and trends*. Manaaki Whenua Press, Lincoln. pp386-399

Azar C (2011) Biomass for energy: a dream come true… or a nightmare? Wiley Interdisciplinary Reviews: Climate Change 2(3): 309-323

Boucher O, Friedlingstein P, Collins B et al (2009) The indirect global warming potential and global temperature change potential due to methane oxidation. Environmental Research Letters 4(4): 044007

Ciais P, Sabine C, Bala G et al (2013) Carbon and Other Biogeochemical Cycles. In: Stocker TF, Qin D, Plattner G-K et al (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp465–570

Collins M, Knutti R, Arblaster J et al (2013a) Long-term Climate Change: Projections, Commitments and Irreversibility. In: Stocker TF, Qin D, Plattner G-K et al (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp1029–1136

Collins WJ, Fry MM, Yu H et al (2013b) Global and regional temperature-change potentials for near-term climate forcers. Atmos. Chem. Phys. 13(5): 2471-2485

Collins WJ, Webber CP, Cox PM et al (2018) Increased importance of methane reduction for a 1.5 degree target. Environmental Research Letters 13(5): 054003

Cox PM, Jeffery HA (2010) Methane radiative forcing controls the allowable CO2 emissions for climate stabilization. Current Opinion in Environmental Sustainability 2(5-6): 404-408

Ehhalt D, Prather M, Dentener F et al (2001) Atmosperic chemistry and greenhouse gases. In: Houghton JT, Ding Y, Griggs DJ et al (eds) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Etheridge DM, Steele LP, Francey RJ et al (1998) Atmospheric methane between 1000 A.D. and present: Evidence of anthropogenic emissions and climatic variability. Journal of Geophysical Research: Atmospheres 103(D13): 15979-15993

Etminan M, Myhre G, Highwood EJ et al (2016) Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophysical Research Letters 43(24): 12,614-12,623

Forster P, Ramaswamy V, Artaxo P et al (2007) Changes in Atmospheric Constituents and Radiative Forcing. In: Solomon S, Qin D, Manning M et al (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Frame DJ, Stone DA, Stott PA et al (2006) Alternatives to stabilization scenarios. Geophys. Res. Lett. 33(14): L14707

Friedlingstein P, Cox P, Betts R et al (2006) Climate-Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison. Journal of Climate 19(14): 3337-3353

Friedlingstein P, Meinshausen M, Arora VK et al (2013) Uncertainties in CMIP5 Climate Projections due to Carbon Cycle Feedbacks. Journal of Climate 27(2): 511-526

Gasser T, Peters GP, Fuglestvedt JS et al (2016) Accounting for the climate-carbon feedback in emission metrics. Earth Syst. Dynam. Discuss. 2016: 1-29

Gillenwater M (2008) Forgotten carbon: indirect CO2 in greenhouse gas emission inventories. Environmental Science & Policy 11(3): 195-203

Gillett NP, Matthews HD (2010) Accounting for carbon cycle feedbacks in a comparison of the global warming effects of greenhouse gases. Environmental Research Letters 5(3): 034011

Hollis M, de Klein C, Frame D et al (2016) Cows, Sheep and Science: A Scientific Perspective on Biological Emissions from Agriculture. Motu Working Paper 16-17. Motu Economic and Policy Research, Wellington. pp48.

Holmes CD (2018) Methane Feedback on Atmospheric Chemistry: Methods, Models, and Mechanisms. Journal of Advances in Modeling Earth Systems 10(4): 1087-1099

Humpenöder F, Popp A, Bodirsky BL et al (2018) Large-scale bioenergy production: how to resolve sustainability trade-offs? Environmental Research Letters 13(2): 024011

IPCC (1996) Climate Change 1995: The Science of Climate Change. Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Houghton JT, Filho LGM, Callander BA et al (eds). Cambridge University Press, Cambridge, UK,

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M et al (eds). Cambridge University Press, Cambridge, UK,

IPCC (2013) Climate Change 2013: The Physical Science Basis. Stocker TF, Qin D, Plattner G-K et al (ed) Cambridge University Press, Cambridge, UK, and New York, USA,

Joos F, Roth R, Fuglestvedt JS et al (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos. Chem. Phys. 13(5): 2793-2825

Leach NJ, Millar RJ, Haustein K et al (2018) Current level and rate of warming determine emissions budgets under ambitious mitigation. Nature Geoscience 11(8): 574-579

Levasseur A, Cavalett O, Fuglestvedt JS et al (2016) Enhancing life cycle impact assessment from climate science: review of recent findings and recommendations for application to LCA. Ecological Indicators 71: 163-174

Manning M, Reisinger A (2011) Broader perspectives for comparing different greenhouse gases. Proceedings of the Royal Society A 369(1943): 1891-1905

Meinshausen M, Meinshausen N, Hare W et al (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458(7242): 1158-1162

Meinshausen M, Raper SCB, Wigley TML (2011a) Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. Atmos. Chem. Phys. 11(4): 1417-1456

Meinshausen M, Smith S, Calvin K et al (2011b) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109(1-2): 213-241

Meinshausen M, Wigley TML, Raper SCB (2011c) Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: Applications. Atmos. Chem. Phys. 11(4): 1457-1471

MfE (2017) New Zealand's Third Biennial Report Under the United Nations Framework Convention on Climate Change. Report ME 1339. Ministry for the Environment, Wellington.

MfE (2018) New Zealand's Greenhouse Gas Inventory 1990–2016. Publication ME 1351. Ministry for the Environment, Wellington. pp519.

Morice CP, Kennedy JJ, Rayner NA et al (2012) Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. Journal of Geophysical Research: Atmospheres 117(D8): D08101

Myhre G, Shindell D, Bréon F-M et al (2013) Chapter 8: Anthropogenic and Natural Radiative Forcing. In: Stocker TF, Qin D, Plattner G-K et al (eds) *Climate Change 2013: The scientific basis*. Cambridge University Press, Cambridge, UK, and New York, USA

Ocko IB, Naik V, Paynter D (2018) Rapid and reliable assessment of methane impacts on climate. Atmos. Chem. Phys. Discuss. 2018: 1-23

Prather MJ, Holmes CD (2017) Overexplaining or underexplaining methane's role in climate change. Proceedings of the National Academy of Sciences 114(21): 5324-5326

Ramaswamy V, Boucher O, Haigh J et al (2001) Radiative forcing of climate change. In: Houghton JT, Ding Y, Griggs DJ et al (eds) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK. pp349-416

Reisinger A, Meinshausen M, Manning M et al (2010) Uncertainties of global warming metrics: CO_2 and CH_4. Geophys. Res. Lett. 37(14): L14707

Reisinger A, Clark H, Abercrombie R et al (2018) Future options to reduce biological GHG emissions on-farm: critical assumptions and national-scale impact. Report prepared for the Biological Emissions Reference Group. Ministry for Primary Industries, Wellington. pp80.

Rigby M, Montzka SA, Prinn RG et al (2017) Role of atmospheric oxidation in recent methane growth. Proceedings of the National Academy of Sciences 114(21): 5373-5377
Rogelj J, Meinshausen M, Knutti R (2012) Global warming under old and new scenarios using IPCC climate sensitivity range estimates. Nature Clim. Change 2(4): 248-253
Rogelj J, Schaeffer M, Meinshausen M et al (2014) Disentangling the effects of CO2 and short-lived climate forcer mitigation. Proceedings of the National Academy of Sciences:
Royal Society (2017) Climate Updates: What have we learnt since the IPCC 5th Assessment Report? The Royal Society, London, UK. pp34.
Saunois M, Bousquet P, Poulter B et al (2016a) The global methane budget 2000–2012. Earth Syst. Sci. Data 8(2): 697-751
Saunois M, Jackson RB, Bousquet P et al (2016b) The growing role of methane in anthropogenic climate change. Environmental Research Letters 11(12): 120207
Shindell DT, Faluvegi G, Koch DM et al (2009) Improved Attribution of Climate Forcing to Emissions. Science 326(5953): 716-718
Shine K, Fuglestvedt J, Hailemariam K et al (2005) Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. Climatic Change 68(3): 281-302
Sterner EO, Johansson DJA (2017) The effect of climate–carbon cycle feedbacks on emission metrics. Environmental Research Letters 12(3): 034019
Turner AJ, Frankenberg C, Wennberg PO et al (2017) Ambiguity in the causes for decadal trends in atmospheric methane and hydroxyl. Proceedings of the National Academy of Sciences 114(21): 5367-5372
van Vuuren D, Edmonds J, Kainuma M et al (2011a) The representative concentration pathways: an overview. Climatic Change 109(1-2): 5-31
van Vuuren D, Stehfest E, den Elzen M et al (2011b) RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. Climatic Change 109(1): 95-116
Wigley TML, Raper SCB (1992) Implications for climate and sea level of revised IPCC emissions scenarios. Nature 357(6376): 293-300
Zickfeld K, Eby M, Matthews HD et al (2011) Nonlinearity of Carbon Cycle Feedbacks. Journal of Climate 24(16): 4255-4275