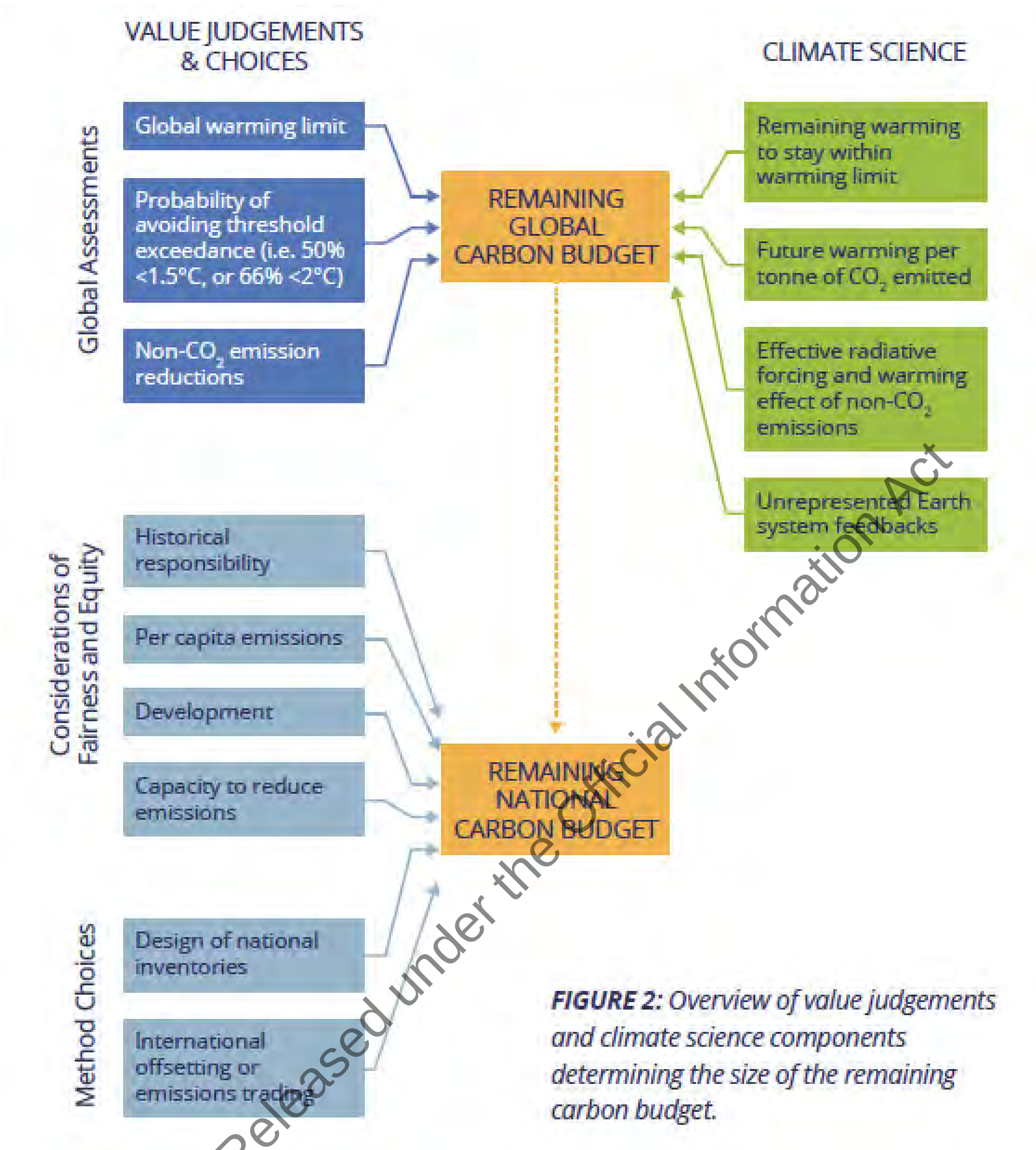

Figure 7: *Methodological, fairness and equity choices when creating national carbon budgets from the global remaining carbon budget. Figure 2 from the 2019 CONSTRAIN report https://constrain-eu.org/. See also Rogelj et al. (2019a).*

When comparing national emission pathways, it is important to consider different national starting points. The same '1.5C consistent' mitigation actions measured by cost or other measure of effort could result in different rates of emissions reductions in different regions depending on national circumstances and their respective capabilities to cut emissions. This includes the share of hard-to-abate emissions within a country profile today. For example, if the energy sector is already mostly decarbonised, the national emissions might not fall as quickly as the global average, whose rapid decline over the 2020s in 1.5°C scenarios is associated primarily with the rapid removal of coal from the electricity generation mix. Assessing whether a nation is taking the '1.5C consistent' actions with its planned emissions reduction pathway needs to be more nuanced than a simple comparison with the global average reductions. It also needs to consider additional effort, outside of the domestic emissions account that a country might be undertaking to support the global transition (e.g. climate finance provision, purchase of credits through international markets, technology transfer etc.) to form a holistic picture of whether planned action to 2030 is 1.5°C-aligned.

Summary and conclusions

Section 1,presented a brief update of the science on past and future warming from greenhouse gases. Section 2 illustrated global tradeoff considerations in strong mitigation emission pathways and Section 3 considered implications for deriving national strategies.

In the further development of policy towards New Zealand's contribution to the global effort of achieving the Paris Temperature Goals, our report has highlighted several issues and choices that would benefit from consideration. These are outlined below:

4.1 Evolving science

As knowledge is being developed and assessment reports are being published, it is important to be clear and transparent about what is used as the basis for the policy design; i.e. which values and which definitions are adopted and used and how they might be revised as science understanding evolves.

4.2 Defining net zero

There are different choices to how net zero is defined both in terms of allowable sinks, in terms of which gases are included in the target and any emission metric choice. Also important is the boundary of the system and if consumption or territorial emissions are addressed and emission trading is allowed.

The SR1.5 used two main indicators of net zero emissions: 1) a CO_2 only and 2) an aggregate of GHGs expressed as CO_2-equivalent emissions based on GWP100. See e.g Table 2.4 in SR1.5. As shown in the table, net zero emissions are typically achieved several years later for the aggregated net zero GHG as compared to the CO_2-only net zero.

Choices of approach not only need to consider the physical science uncertainty but also need to consider the overall objectives of the climate policy and the practicalities of usage and communication. As illustrated in Section 3.1, the selection of greenhouse gases and as well as the emission metric used will have a significant effect on timing and efforts to achieve net zero and on the resulting global warming. The UK legislated for a net zero target in terms of GWP100 emissions. One of the reasons given was that such a target would actively decrease its future warming commitment over time (see Section 2.1 and 3.1). For New Zealand to continue to decrease its future warming commitment after 2050, additional CH_4 reductions and/or negative emissions of CO_2 would be needed (Section 3.1).

Emission metrics are used for comparing and trading of emissions of gases with different physical characteristics on a common scale. GWP100 has been widely adopted for aggregating emission of gases to so-called 'CO_2-equivalent emissions'. But different mixes of long and short lived gases included in the same amount of CO_2-equivalent emissions will give different temperature outcomes over time, and the use of the concept therefore introduces ambiguity in temperature outcome. New metric concepts have been presented in the literature after AR5; e.g., the GWP* concept which approximates the temperature response over time from emission paths. Which metric is chosen and the rationale for the choice needs consideration and clear communication of which purpose and goal it is meant to serve. As shown in Section 2.2, an alternative approach based on the emergent relation between CH_4 emissions prior to temperature peak and cumulative CO_2 and N_2O could be considered as an alternative or supplement, depending on the policy objectives.

The Paris Agreement aims for a net-zero type target on a global basis. In the development of mitigation strategies for a single country it is important to consider how the plans for net zero might be achieved internationally and how a nation's plan fits into the international effort (i.e., which countries might achieve net negative, net zero or net positive emissions, and how international trading is used).

4.3 Life after net-zero

As shown in the pathways in SR1.5, achieving net zero GHG is just one part of the challenge in limiting future warming. Plans for the further path of emissions of the individual gases after net zero target is achieved also need to be addressed and communicated, particularly how greenhouse gas removal can be sustained given finite and competing interest for land resources (see Section 3.1).

4.3 Defining national high-ambition pathways

Which fairness and equity principles that are applied as rationale for New Zealand's efforts are important to communicate as a part of a mitigation strategy. As New Zealand's starting position in terms of sectoral emissions is different from other nations, a high ambition emission reduction trajectory might look quite different to a high ambition pathway from another country. In particular, many countries are expected to rapidly decarbonise their power sector out to 2030, leading to large national emission reductions in the 2020s. Countries such as New Zealand (and the UK) where the power sector is already mostly decarbonised, urgent actions are needed on other sectors such as buildings and transport for mitigation compatible with Paris Agreement ambitions, that might take longer to manifest themselves in emissions trends. Therefore relatively modest emissions reductions might suffice in the 2020s to keep warming to 1.5°C, compared to what is required by the world as a whole. These could still be seen as ambitious provided the groundwork is laid for large reductions in the 2030s (see Section 3.2).

References

Allen, M. R., K. P. Shine, J. S. Fuglestvedt, R. J. Millar, M. Cain, D. J. Frame, and A. H. Macey, 2018 : A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Nature npj Climate and Atmospheric Science*, 1(2018-16), , doi: 10.1038/s41612-018-0026-8.

Allen M.R. et al. 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change,* **6,** 773-776, doi: 10.1038/nclimate2998

Collins, W.J.,C.P. Webber, P.M. Cox, C. Huntingford, J. Lowe, S. Sitch, S.E. Chadburn, E. Comyn-Platt, A.B. Harper, G. Hayman and T. Powell, 2018: Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters*, 13(5), doi:10.1088/1748-9326/aab89c.

Danison S., Forster P.M., Smith C.J., 2019: Guidance on emissions metrics for nationally determined contributions under the Paris Agreement. *Environmental Research Letters*, 10 (7-10), doi:10.1038/s41558-019-0660-0.

Foster P.M., A.C. Maycock, C.M. McKenna and C.J. Smith, 2020: Latest climate models confirm need for urgent mitigation. *Nature Climate Change*, 1–14, doi:10.1007/s11027-017-9762-z.

Fuglestvedt J.S., J. et al., 2018: Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philosophical Transaction of the Royal Society A*, 376(2119),

doi:10.1098/rsta.2016.0445.

Fuglestvedt J.S., Berntsen T.K. and Skodvin T., 2000: Climate implications of GWP-based reductions in greenhouse gas emissions. *Geophysical Research Letters*, 27(3), 409–412, doi:10.1029/1999GL010939.

Fuglestvedt J.S., Berntsen T.K., Godal O., Sausen R., Shine K.P. and Skovin T., 2003 Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. *Climatic Change*, 58, 267-331, doi:10.1023/A:1023905326842 .

Gasser T. et al., 2016: Accounting for the climate–carbon feedback in emission metrics. *Earth System Dynamics*, 8, 235-253, doi: 10.5194/esd-8-235-2017.

Grubler A. et al., 2018: A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, 3, 515-527, doi:10.1038/s41560-018-0172-6 .

Hawkins E. et al., 2017: Estimating Changes in Global Temperature since the Preindustrial Period. *American Meteorological Society*, 98(9), 1841-1856, doi:10.1175/BAMS-D-16-0007.1.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J.-I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geosci. Model Dev., 11, 369–408, https://doi.org/10.5194/gmd-11-369-2018, 2018

Hodnebrog Ø. Et.al., 2020: Updated Global Warming Potentials and Radiative Efficiencies of Halocarbons and Other Weak Atmospheric Absorbers. *Reviews of Geophysics*, 58(3), doi:10.1029/2019RG000691.

Kennedy J.J. et al.,, 2019: An Ensemble Data Set of Sea Surface Temperature Change From 1850: The Met Office Hadley Centre HadSST.4.0.0.0 Data Set. *JGR Atmospheres*, **124(14)**, 7719-7763, doi:10.1029/2018JD029867.

Lauder, A. R., I. G. Enting, J. O. Carter, N. Clisby, A. L. Cowie, B. K. Henry, and M. R. Raupach, 2013: Offsetting methane emissions—An alternative to emission equivalence metrics. *Int. J. Greenh. Gas*

Control, 12, 419–429.

Lynch J.. et al., 2020: Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environmental Research Letters*, 15(4), doi:10.1088/1748-9326/ab6d7e .

Myhre G.. et al., 2013: Radiative forcing [Stocker, T.F. et al. (eds.)]. Cambridge University Press, pp. 659-740.

MacDougall A.H. et al., 2020 Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2.*Biogeoscience*, 17(11), doi: 10.5194/bg-17-2987-2020.

Nicholls Z.R.J. et al., 2020: Reduced complexity model intercomparison project phase 1: Protocol, results and initial observations. *Geoscientific Model Development*, doi: 10.5194/gmd-2019-375.

Popp et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change,* Volume 42, January 2017, Pages 331-345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Rogelj J. and Schleussner C.F., 2019: Unintentional unfairness when applying new greenhouse gas emissions metrics at country level. *Environmental Research Letters*, 14(11), doi:10.1088/1748-9326/ab4928 .

Rogelj J. er al., 2018: Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, 571, 335-342, doi:10.1038/s41586-019-1368-z

Rogelj J. et al., 2019: A new scenario logic for the Paris Agreement long-term temperature goal. *Nature*, 573, 357-363, doi:10.1038/s41586-019-1541-4 .

Richardson T.B. et al., 2019: Efficacy of Climate Forcings in PDRMIP Models. *JGR Atmospheres*, 124(23), 12824-12844, doi:10.1029/2019JD030581 .

Sherwood S.C. et al., 2020: An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*, 58(4), e2019RG000678, doi:10.1029/2019RG000678 .

Samset B.H. et al, 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical Research Letters*, 45, 408-411, doi:10.1002/2017GL076079 .

Shindell D. and Smith J., 2019: Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature*, 573(sup1), 408-411, doi: 10.1038/s41586-019-1554-z

Smith C.J.. et al., 2019: Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming. *Nature Communications*, 10(101), doi: 10.1038/s41467-018-07999-w.

Smith C.J. et al., 2018: Understanding Rapid Adjustments to Diverse Forcing Agents *Geophysical Research Letters*,**16(21)**,12023-12031, doi: 10.1029/2018GL079826

Steffen W. et al., 2018: Trajectories of the Earth System in the Anthropocene. *PNAS*, 115(33), 8252,8259,

doi:10.1073/pnas.1810141115.

Tanaka K. and O'Neil B.C., 2018: The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets. *Nature Climate Change*, 8, 319-324, doi:10.1038/s41558-018-0097-x.

Tebaldi C. et al., 2020: Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth System Dynamics*, , doi: 10.5194/esd-2020-68.

Thornhill G. et al., 2019: Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models *Atmospheric Chemistry and Physics*, doi: 0.5194/acp-2019-1207.

Turetsky M.R. et al., 2020: Carbon release through abrupt permafrost thaw. *Nature Geoscience*, 13, 138-143, doi:10.1038/s41561-019-0526-0.

UK Committee on Climate Change: Net Zero – The UK's contribution to stopping global warming, https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

van Vuuren D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, 8, 391-397, doi:10.1038/s41558-018-0119-8.

Wang Y and Huang Y., 2020: The Surface Warming Attributable to Stratospheric Water Vapor in CO_2-Caused Global Warming. *JGR Atmospheres*, 125(17), e2020JD032752, doi: 10.1029/2020JD032752.

Zickfeld K. et al., 2017: Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. *PNAS*, doi: 10.1073/pnas.1612066114.

Climate science considerations of global mitigation pathways and implications for New Zealand mitigation pathways

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Version 8 January 2021

This report interprets how the global surface temperature responds to mitigation of long lived greenhouse gases and short-lived greenhouse gases using the latest climate science. It puts these findings in the context of global mitigation pathways and New Zealand specific emission pathways. With a concerted effort to reduce biogenic methane emission and other greenhouse gases, New Zealand can substantially reduce its contribution to global warming out to 2100. Further, reaching net zero long-lived greenhouse gases is essential to limit New Zealand's contribution to global warming in the longer term.

Introduction

This report gives a brief overview of the current scientific understanding of emissions reductions needed to achieve the global temperature goal of the Paris Agreement. It builds on the findings in the Intergovernmental Panel of Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR1.5) and Special Report on Climate change and Land, as well as recent updates in the scientific literature. It focuses on the main characteristics of global emissions pathways and tradeoffs between reductions of emissions of different greenhouse gases. We also discuss how different choices affect the prospects of meeting the Paris temperature goals and how New Zealand's future emissions pathway relate to global temperature outcomes.

1. Climate response to emissions of different GHGs

This first section examines how much global warming has occurred and how much past and future emissions commit the world to further warming.

Based on the literature and knowledge available at the time, SR1.5 concluded that past emissions alone are unlikely to commit the world to global warming in excess of 1.5°C. Does this conclusion still hold? Since 2018 (the date of IPCC-SR1.5 publication) there have additional warm years observed in 2019 and 2020, and updates to the methodologies used to construct global surface temperature timeseries from past observations. There is new science emerging on estimates of the 'locked-in' or 'committed' warming from past carbon dioxide (CO_2) emissions alone, the zero emission commitment (ZEC).[1] Future warming also depends on the amount of warming coming from *future* greenhouse gas (GHG) emissions and on emission changes in short lived greenhouse gases such as methane and in non-greenhouse gas pollutants, as well as cumulative emissions of longer-lived GHGs, such as (CO_2) and nitrous oxide (N_2O). The sections below detail how understanding of each of these has progressed since SR1.5.

1.1 Historical warming

SR1.5 estimated that the human-induced warming[2] had reached around 1°C (with a 0.8°C to 1.2°C *likely*[3] range) above pre-industrial levels by the end of 2017. This was based on averaging the four prominent global (land and sea) datasets with peer-reviewed methodology (summarized in Table 1.1 of IPCC-SR1.5). Since then these global temperature datasets have been updated and improved to reflect the latest understanding of how to incorporate a range of historical climate data into a single timeseries and to improvements to methods to produce globally representative values (Morice et al., 2020). These latest revisions will lead to a slight increase in the estimated level of warming above pre-industrial levels relative to the versions of the datasets available to IPCC-SR1.5 (e.g., Kennedy et al. 2019, Kadow et al. 2020). These changes arise from updates in the methodologies for constructing global temperature records and not because climate change today is worse than expected by recent IPCC reports. The trend in global temperature over recent decades are robust, consistent with the years since the publication of IPCC-SR1.5 being among the hottest in the instrumental record.

Definitions of globally average surface temperature for the purpose of estimating remaining global carbon budgets was addressed in Chapter 2 of SR1.5. Chapter 2 employed two estimates of the warming to date. The traditional measure of global-mean surface temperature (GMST) is based on observations that use a combination of near surface air temperature over land and sea-ice regions and sea-surface temperature over open ocean regions. The second measure is one that infers global surface air temperature (GSAT) changes across the globe based on a scaling factor from complex climate models. The latter choice was there estimated to lead to 10% higher levels compared to GMST based on climate models and therefore a smaller remaining carbon budget than estimates based on GMST. More recent work suggests that increasing GMST by 10% to estimate GSAT may not be borne out in real-world observations comparing night-time marine air temperature to sea-surface temperature data (e.g., Kennedy et al. 2019).

IPCC SR1.5 used the average over the period 1850-1900, the earliest period then available in the direct observational record with reliable estimates of the global average temperature, to

[1] This is estimated using idealised scenarios in climate models in which emissions are reduced to zero instantaneously. This scenario isn't directly relevant to scenarios that could be realised in the global economy but is informative for identifying physically-based lower limits of the minimum amount of 'inevitable' additional future increases in global temperature.

[2] This is a measure of the increase in global temperature above pre-industrial levels resulting from human activity (e.g., GHG emissions and emissions of aerosols) only. Temporary *natural* effects (e.g. temporary cooling due to volcanic eruptions or natural climate cycles), that temporarily increase or decrease total warming relative to this human-induced level, are excluded.

[3] Here *likely* means at least a 66% chance that the true value lies within this interval – consistent with how this term is used across IPCC reports.

approximate pre-industrial levels. There has been discussion in the scientific literature of the dependence of global emissions reduction ambition needed to achieve the Paris Agreement on the a choice of this 1850-1900 period to approximate the pre-industrial baseline or an earlier period such as 1750. Using 1750 as a pre-industrial baseline could increase today's level of the global average temperature rise above preindustrial level by around 0.05°C above the level when using the 1850-1900 period, but this is not estimated to be statistically significant (Hawkins et al., 2017).

In summary, we might expect further revisions and updates of the order one tenth of a degree to the historical surface temperature change since preindustrial times and these would have knock on effects for estimates of the remaining global carbon budget consistent with the Paris Agreement. Note that by altering the historical temperature we are implicitly altering the applied relationship between the level of global temperature rise above pre-industrial levels and aggregate climate impacts. As an example, if we were to revise the present day historical warming upwards from 1.0°C to 1.1°C, the present day climate impacts being experienced now do not alter, we instead would associate temperature levels (e.g. 1.1°C or 1.5°C) with lower levels of climate impact than previously, so avoiding 1.5°C of warming becomes a more stringent target (associated with a lower level of aggregate climate impacts than it was previously), rather than the revision pushing us closer to higher levels of future climate impact.

1.2 Future warming

1.2.1 Committed warming from greenhouse gases

This section demonstrates to what extent past and future emissions of specific gases (chiefly CO_2 and CH_4) commit to future changes in global temperature, and hence the extent to which the levels of global temperature above pre-industrial levels in a given year (e.g. around 2050 to reflect when peak warming under many 1.5°C scenarios) is a historic liability and what amount is the result of future emissions that haven't yet occurred.

For emissions of *long-lived GHGs* (LLGHG) (CO_2, N_2O, some fluorinated-gases)[4] their global temperature impact is largely determined by their *cumulative* emissions. Nitrous oxide (N_2O) has a finite single perturbation lifetime unlike CO_2, and consequently behaves differently in the very long term, but can be treated as approximately equivalent to a certain amount of CO_2 emissions (e.g. using conventional metrics from equivalence between GHGs; see section 2.4) when thinking about impacts of its emission on global temperature for this century. As shown in SR1.5 (Table 2.4) and the scientific literature, these emissions need to come down to below net zero (aggregated by the global warming potential with time horizon of 100 years - GWP_{100}) in scenarios compatible with 1.5°C warming. As some level of residual long-lived greenhouse gas emissions are expected to be unavoidable, active removal of CO_2 from the atmosphere is expected to be required to achieve net-zero LLGHG emissions. Removal of non-CO_2 greenhouse gases from the ambient atmosphere has been considered at a conceptual level in the scientific literature but has not generally been considered in the same level of techno-economic detail as active removal of

[4] These are GHGs that result in raised atmospheric concentrations of the gas for many decades after the emission occurred.

CO_2, for which demonstration-scale plants of some engineered removals methods already exist today (De Richter et al., 2017; Jackson et al., 2019).

For CO_2, MacDougall et al. (2020) looked at the evidence from idealized simulations with complex global climate models to conclude that the most likely value of the zero-emission commitment (ZEC)[5] on multi-decadal timescales is close to zero, consistent with previous model experiments and theory, but at the same time pointing to the large uncertainty related to constraining this effect. The right panels on Figure 1 show that the ZEC can be of either sign, but is generally less than +0.5°C across models, with a best estimate, based on current evidence of close to zero. Similarly, for other LLGHGs it is reasonable to assume that the past warming contribution is largely governed by past cumulative emissions and, for timescales under 100 years, there is little further warming or cooling due to past emissions. Likewise, future warming will be governed by future cumulative emissions.

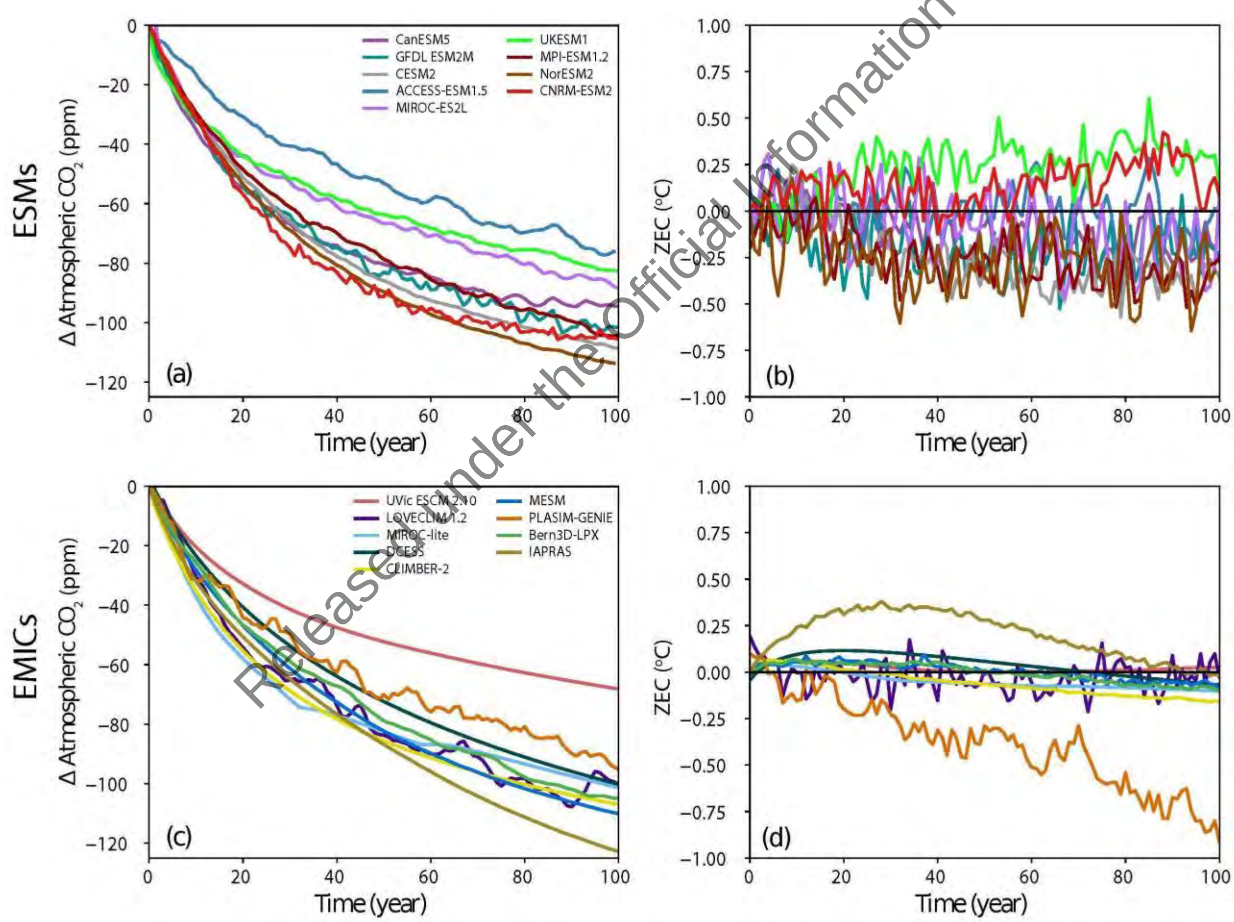

Figure 1: *Atmospheric* CO_2 *concentration anomaly and (b, d) Zero Emissions Commitment following the cessation of emissions during the experiment wherein 1000 PgC was emitted according to the methods in the 1% experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. The top row shows the output for Earth*

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[5] The amount of additional warming that occurs when global CO_2 emissions are instantaneously brought to net-zero.

System Models (ESMs), and the bottom row shows the output for Earth System Models of Intermediate Complexity (EMICs) (MacDougall et al., 2020).

The current evidence across the scientific literature therefore suggests that we do not expect significant additional warming above that seen already due to past long-lived GHG emissions. However, important uncertainties still remain, including through processes that are difficult to accurately simulate within the current generation of complex climate models, such as the role of future thawing of the permafrost and future wildfires. Nevertheless, some of the more dire warnings of tipping points (e.g., Steffen et al. 2018) are not born out in more careful assessments (e.g., Turetsky et al., 2020). It remains likely that the future amount of GHG emissions from the global economy emitted on the pathway to net-zero emissions will be significantly more important to future levels of warming realized than the warming arising from changes in natural carbon sinks this century due to feedbacks from Earth system processes that aren't typically included within carbon budget estimates. Nevertheless, estimates of these additional feedbacks can be factored into remaining carbon budget estimates (e.g. Table 2.2 in Chapter 2 of SR1.5), although it is difficult to estimate exactly how quickly or slowly these additional emissions might enter the atmosphere. It is unlikely that all of these Earth system emissions would have occurred by the time global CO_2 emissions must have reached net-zero by around 2050 and warming peaked to keep to the temperature level of the Paris Agreement long-term temperature goal (see SR1.5 Chapter 2, Rogelj et al., 2018a,b and Rogelj et al., 2019).

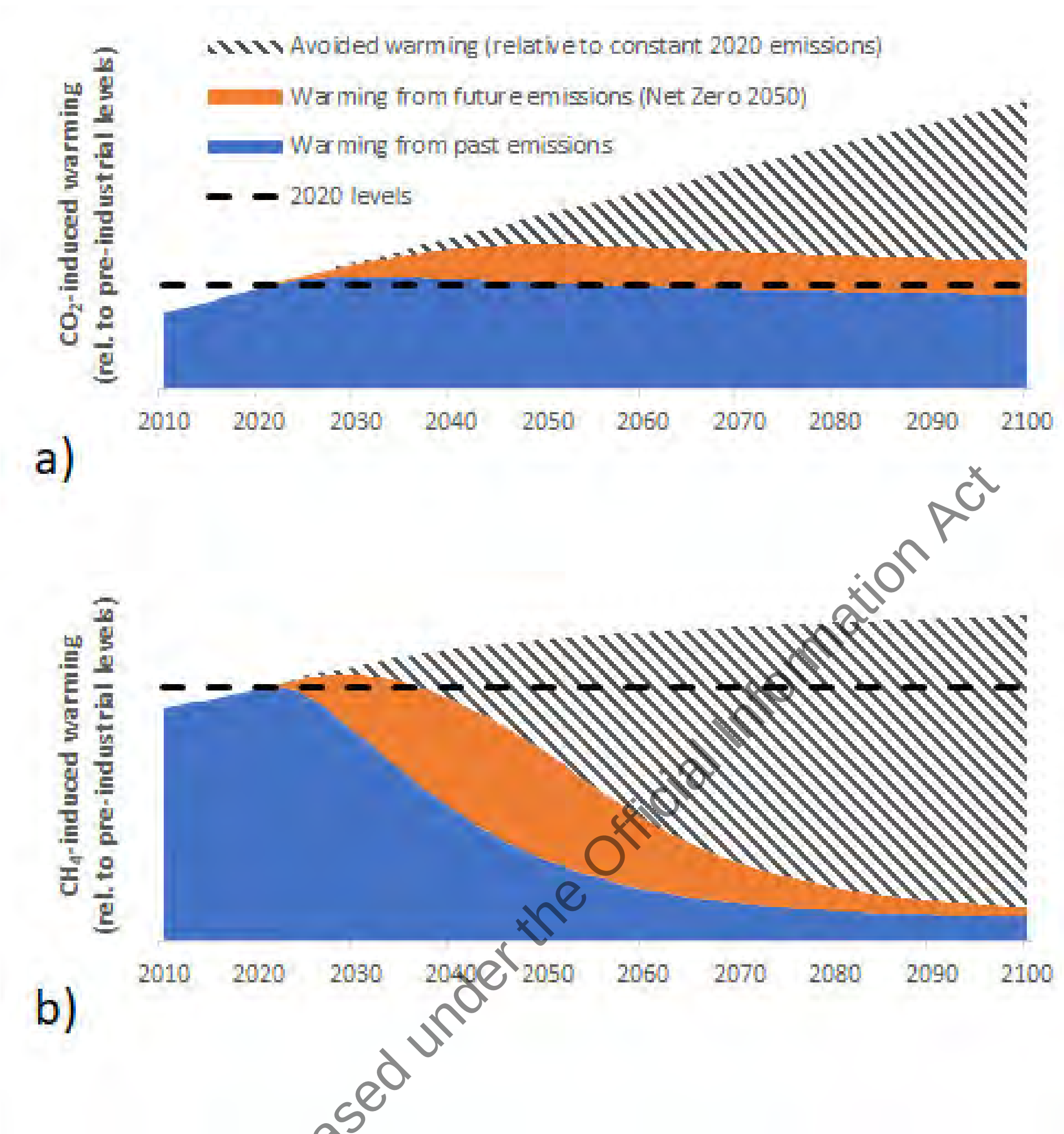

Figure 2: *A stylised illustration of commitment from past emissions to future warming and how much future global temperature is dependent on future and past emissions – for two gases CO_2 (top) and CH_4 (bottom). The blue area represents a case with an instant drop in emission to zero after 2020, illustrating the commitment from past emissions only on future global temperatures . The orange area shows the warming arising only from future emissions in a scenario in which CO_2/CH_4 emissions decline linearly from 2020 to (net-) zero emissions in 2050. The hatched area shows the avoided warming wedge between the case with declined emission to zero in 2050 (orange case) and a case with constant future emission at 2020 levels. The dashed lines show levels of global temperature rise above pre-industrial levels from CO_2/CH_4 emissions in 2020.*

For *Short Lived GHGs* (SLGHG) (CH_4, some F-gases) their global temperature impact depends (as a first order approximation) on the sustained *rate* of emissions. In contrast to the long-lived gases their emissions need only to be gradually reduced and not stopped altogether to prevent further contributions to ever increasing global temperature. An increase in their emission rate, not simply continued emissions will add to future warming. It is important to note that any level of sustained short-lived GHG emissions would still sustain raised global temperature above pre-industrial levels (as does achieving net zero CO_2). Therefore, to reduce their historical contribution to temperature change SLGHG emissions rates need to be reduced whereas net negative emissions of LLGHGs are needed to reduce historical contribution to global temperature from LLGHG emissions. The lower the emissions rate of SLGHGs the lower the contribution of sustained SLGHG emissions to global temperature. Furthermore, emissions of SLGHGs also have longer-term climate impacts through their impact on carbon cycle (e.g., Gasser et al. 2017) and on other climate variables (e.g., sea level rise - Zickfeld et al., 2017), that are not reversed simply by reducing their sustained emissions rates

The different lifetimes of the two gases (CO_2 and CH_4) is fundamental for understanding how past emissions of these gases affect future warming and the role of additional future emissions on top of the committed warming from past emissions. Figure 2 shows in a stylised way the different behavior of these two gases. While for CO_2 the warming from pre-2020 emission remains approximately constant over the century, the warming from past emissions of CH_4 decays over the coming decades (although doesn't disappear entirely). These differences are also important to bear in mind when different metrics are used for comparing effects of emissions (see Section 2.4). In spite of the very different warming profiles, reducing emissions of both gases will significantly contribute to reduced future warming and would help achieve the long-term temperature goal. For CO_2, this abatement comes from avoiding future emissions that add to the committed historical warming from past emissions. For CH_4, this principally comes from emissions reductions that reduce the level of global temperature rise above preindustrial levels that would have been sustained if emissions were kept at current rates.

In summary, both long and short-lived greenhouse gas emissions contribute to keeping global temperatures above pre-industrial levels, but they do so in different ways. For short-lived gases it is via their emission rates. For long-lived gases it is via their cumulative emissions. Abatement from emissions of both short- and long-lived gases benefit the global climate.

1.2.2 Non greenhouse gas emission changes

Changes in emissions that affect aerosol and those that affect ozone concentrations change future temperature and how close we are to temperature targets. Although generally 20-30 years of near-term warming is expected from reducing aerosol pollution following a combination of climate mitigation policies and air quality policies (Smith et al. 2018a; Samset et al. 2018), near term warming can be limited with well-designed policies targeting both short and long-lived pollutants (Shindell and Smith, 2019). Forster et al. (2020) and Weber et al. (2020) examined the climate response to COVID-19 restrictions and showed that some of the short term warming from reduced SO_2 emissions and less aerosol cooling was offset globally by a large near-term reduction in NOx and ozone from reduced transport emissions. This suggests reducing road transport emissions at the same time as SO_2 emissions would lessen any near-term warming.

1.3 Scientific developments

Since the IPCC 5th Assessment Report (AR5), scientific knowledge has developed further with improved understanding of several key processes in the climate system, and longer and improved observation series. The adoption of the Paris Agreement increased the focus on differences between 2°C and 1.5°C in terms of climate responses and impacts, as well as emission pathways compatible with the Paris Agreement ambitions, summarized in the recent IPCC Special Reports. Their assessments also confirm that the fundamental understanding of the climate system has remained largely the same since AR5. From consistency across these reports, there is a robust understanding of what needs to happen to global emissions to meet the temperature goal of the Paris Agreement. This requires reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing (primarily driven by the rate of SLGHG emissions) to halt anthropogenic global warming.

In spite of the fundamental understanding remaining largely unchanged, uncertainties in radiative forcing and climate sensitivity affect the relationship between emissions and surface temperature change, and there have been some relevant developments in these areas which are discussed below.

1.3.1 Climate sensitivity

The latest generation of climate models from the sixth climate model intercomparison exercise (CMIP6) warm more than the previous generation and generally have greater equilibrium climate sensitivities (Forster et al. 2019). However, a five-year assessment of climate sensitivity comparing estimates using paleoclimate evidence, physical process evidence and the evidence from the 1850-2018 period (Sherwood et al., 2020) finds a much more constrained likely range for the equilibrium climate sensitivity that is robustly within 2.3 to 4.5°C. These estimates did not directly rely on the new generation of climate models so provides an independent assessment against which the new generation of complex climate models can be compared. This comparison suggests that the high warming estimates from some of the climate models are unlikely but cannot be ruled out entirely (Forster et al., 2019).

This updated evidence on the climate sensitivity indicates that the likely range of global warming projections due to uncertainty in the climate system response for projections of future climate changes under different global GHG emissions scenarios would have a narrower range than similarly presented ranges in SR1.5 and AR5. As this revised uncertainty in the Earth’s climate sensitivity largely affects the tails of the distribution, the central estimates of projected warming for the same emission scenario would likely still remain similar to those shown in SR1.5 and AR5 (see Figure 3). The low estimates of warming have firmed up and are slightly larger than before, whereas the high-end estimate remains somewhat uncertain.

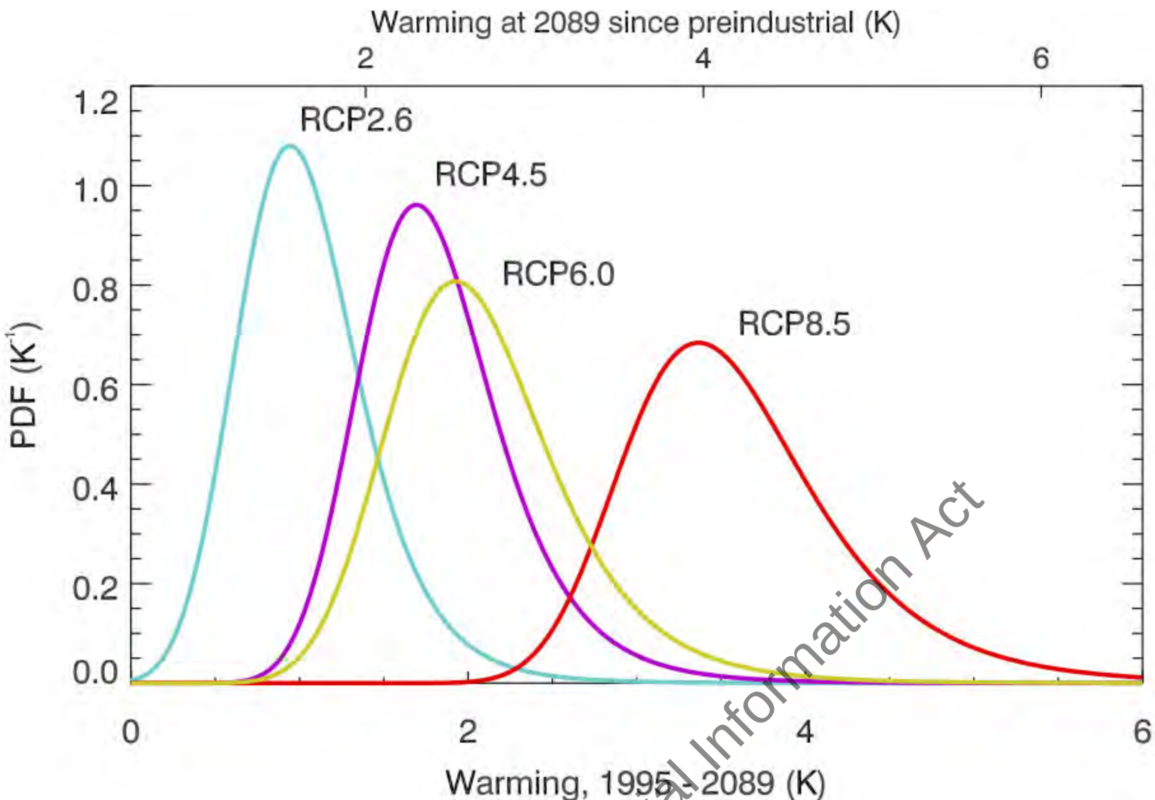

***Figure 3**: Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).*

1.3.2. Radiative Forcing and Global Warming Potentials

The Effective Radiative Forcing (ERF) introduced in IPCC AR5 has now become the accepted way to compare the magnitude of different climate change mechanisms (Richardson et al., 2020). The ERF includes cloud related adjustments to the more traditional stratospherically adjusted radiative forcing, allowing a better comparison of the effect on global surface temperature across forcing agents.

The establishment of ERF as the standard measure of forcing can help improve the estimates of GHG metrics (such as the GWP), including for methane. A number of other factors studied in recent publications may also influence the GWP value for methane:

- Moving to ERF increases CO_2 radiative forcing but leads to a decrease in methane radiative forcing from cloud adjustments (Smith et al. 2018).
- Etminan et al. (2016) include the shortwave forcing from methane and updates to the water vapour continuum and account for the overlaps between carbon dioxide and nitrous oxide.
- Thornhill et al. (2020) quantify the indirect effect of methane on ozone radiative forcing based on several models and strengthen the knowledge basis about indirect effects of methane.
- The results of Wang and Huang (2020) show that due to high cloud changes the stratospheric water contribution to methane GWP-100 which was 15% in AR5 might be

closer to zero in the ERF framework. This change would be additional to the adjustments outlined in Smith et al. (2018b) and in of itself it would *decrease* the GWP.

- Gasser et al. (2017) and Sterner and Johansson (2017) give descriptions of how to account for climate carbon cycle feedbacks in emission metrics. AR5 Working Group I included this feedback for non-CO_2 gases, which up to then was only included for the reference gas CO_2, and imply an underestimation of GWP values for non-CO_2 gases. Due to lack of sufficient literature at the time of writing AR5, the inclusion of this feedback effect was presented as tentative.

Studies have not yet applied these results or combined these analyses for an overall estimate of methane GWP. At this stage it is difficult to be more quantitative regarding the net result, but the IPCC Sixth Assessment Report will attempt to assess these and other studies, bringing different lines of evidence together to form a new comprehensive assessment.

For CH_4, the GWP value also depends on whether the carbon is of biogenic or fossil origin. When oxidised, fossil methane will introduce additional CO_2 to the atmosphere. The metric value for fossil methane will therefore be slightly higher than for biogenic methane. Thus, AR5 Working Group I gave two values for the methane GWP-100; i.e., 28 for biogenic and 30 for fossil methane. It was pointed out that "In applications of these values, inclusion of the CO_2 effect of fossil methane must be done with caution to avoid any double-counting because CO_2 emissions numbers are often based on total carbon content. Methane values without the CO_2 effect from fossil methane are thus appropriate for fossil methane sources for which the carbon has been accounted for elsewhere, or for biospheric methane sources for which there is a balance between CO_2 taken up by the biosphere and CO_2 produced from CH_4 oxidization."

Other updates are also available in the literature, e.g., Hodnebrog et al. (2020) gives an update of radiative efficiency and GWP and GTP values for halocarbons. New radiative efficiencies calculations are presented for more than 400 compounds in addition to the previously assessed compounds, and GWP calculations are given for around 250 compounds. Present-day radiative forcing due to halocarbons and other weak absorbers was estimated to be 0.38 [0.33–0.43] W m^{-2}, compared to 0.36 [0.32–0.40] W m^{-2} in IPCC AR5 (Myhre et al., 2013), which is about 18% of the current CO_2 forcing.

1.3.3 Surface temperature projection estimates

Climate model emulators such as FaIR and MAGICC (employed in SR1.5) are often used to estimate global warming futures across multiple scenarios. Such reduced complexity climate models can either be set up to mimic the behaviour of global-mean surface temperature change from more complex models or can be set up in probabilistic form to match the assessed range of climate sensitivity and effective radiative forcing from other assessments or lines of evidence. Due to the prominent role of such models in projecting net zero scenarios in SR1.5, an intercomparison is currently underway (**https://www.rcmip.org/)** between a variety of these reduced complexity models. Preliminary results from this show that such models generally work well for projections of global surface temperature (Nicholls et al. 2020). Such models based on updated estimates of ERF and climate sensitivity can provide the basis for calculating national emissions contributions to global temperature changes and could also be used to understand the direct global temperature impacts of New Zealand's emissions (see Section 3.1).

2. Trade-offs in global emissions pathways to keep warming to 1.5°C

At a global level, different combinations of future long-lived and shorter-lived GHG emissions trajectories can be consistent with achieving the long-term temperature goal of the Paris Agreement. This section looks at the understanding of possible combinations of cumulative long-lived GHG emissions and sustained emissions rates of shorter-lived GHGs that could be consistent with an overall global temperature trajectory consistent with the Paris Agreement.

2.1 Understanding GHG trade-offs determining the level of peak warming reached

Physically, warming could be kept to 'well-below' 2°C or below 1.5°C with a range of possible combinations of global future cumulative LLGHG emissions and global SLGHG emissions rates.

Fundamentally, there are three key contributions from future emissions to the level of peak warming reached:

1. The level of global temperature increase above pre-industrial levels arising from future cumulative LLGHG emissions between now and the timing of reaching net zero. This warming is additional to that caused by past-emissions of LLGHGs.[6]
2. The level of global temperature increase sustained by the rate of SLGHG emissions over the couple of decades prior to peak warming. Depending on whether the global emissions rates are higher or lower than values over the recent past, the level of global temperature rise above pre-industrial levels sustained by global SLGHG emissions could be greater, the same, or lower than the level of global temperature rise above pre-industrial levels sustained by these emissions today.
3. Changes in the levels of global temperature decrease below pre-industrial levels that are sustained by global human emissions of aerosols (which have a net cooling effect on the climate). These emissions are also shorter-lived meaning that the contribution from these emissions to peak warming largely depends on the emissions rate of the aerosols. Some aerosols emissions are often co-emitted with GHG emissions, so efforts to reduce emissions in the future and improve air quality mean that global emissions of aerosols are expected to be reduced in the future, meaning that they are expected to suppress less the GHG induced warming at the time of peak warming than they do today.

Variations in any one of these three factors has implications for the combinations of the other two that would be consistent with a given climate outcome. Emissions of aerosols are not formally regulated under climate policy frameworks (such as the Paris Agreement) so changes in aerosol

[6] Nitrous oxide emissions have a perturbation lifetime of ~100 years in the atmosphere, meaning that, unlike carbon dioxide, some of the warming caused by past nitrous oxide emissions early in the historical record will have decayed away. For the purposes of future nitrous oxide emissions over the next several decades, nitrous oxide can be treated largely analogous to CO_2 when converted through the GWP-100 metric to CO_2-equivalent emissions.

emissions are often considered as exogenous to climate policy considerations on the balance of GHG emissions, despite not being entirely independent.

Overall, the higher the global rates of SLGHG emissions the lower the cumulative total of LLGHG emissions that would be consistent with keeping expected peak warming to any level and vice versa the lower the global rate of SLGHG emissions the greater the cumulative total of LLGHG emissions. These physically-based trade-offs have been illustrated in the literature through the use of simple climate models (e.g. Leahy et al. 2020) and summarised by the IPCC in Figure SPM1 of the Special Report on Global Warming of 1.5°C.

Alongside the use of simple climate models, the relationship between different futures for global cumulative long-lived GHG emissions and reductions/increases in the rate of global short-lived GHG emissions for can be explored for a wide range of situations using new emission metrics (see Section 2.4); e.g., proposed metrics that more directly measure the 'warming-equivalence' between long-lived and short-lived GHG emissions (Allen et al., 2016, Allen et al., 2018, Collins et al., 2018, Cain et al., 2019, Collins et al., 2020).[7] An application of these metrics to approximate trade-offs between global methane emission futures and futures of long-lived GHGs are shown in Figure 4.

Table 1 provides conversion factors to approximate the amount of cumulative carbon dioxide emissions that would create the same warming as a sustained change in the emissions rate of a shorter-lived GHG such as methane. Whilst there is some variation across time horizons for these factors, the fractional variation is significantly reduced relative to conventional metrics (e.g., global warming potential - Section 2.4), suggesting that comparing pulses of LLGHGs and sustained emissions rates of SLGHGs provides the most robust approximation for the effects on global temperature across a range of timescales, and could be used to explore a wide range of scenarios.

[7] Collins et al. (2018), applied a process-based approach to assess the importance of methane reductions for the 1.5°C target. Their modelling approach included indirect effects of methane on tropospheric ozone, stratospheric water vapour and the carbon cycle. They find a robust relationship between decreased CH_4 concentration at the end of the century and increased amount of cumulative CO_2 emissions up to 2100. This relationship is independent of climate sensitivity and temperature pathway. In terms of relation between end of the century emission changes in CH_4 and CO_2, their results achieve similar results as those obtained by Allen et al., 2016 in a GWP* context. Collins et al., 2018, also point out that the non-climate benefits of mitigating CH_4 can be significantly larger than indicated by IAM studies.

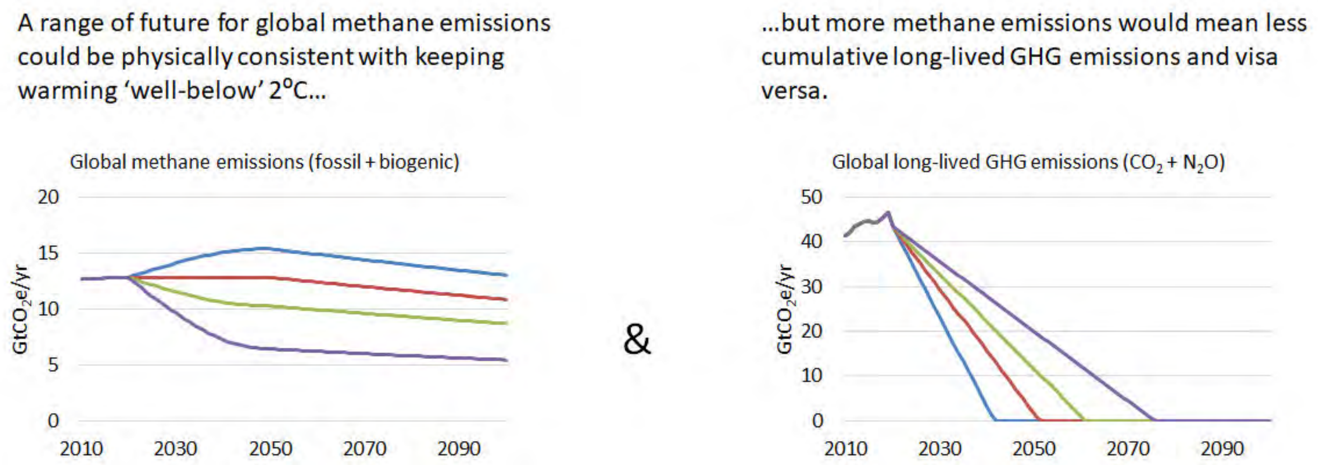

Figure 4: *Stylised trajectories that illustrate the trade-off between global trajectories for anthropogenic methane emissions (fossil and biogenic sources) and long-lived GHG emissions using the framework of Cain et al. (2019). Trajectories are constructed to keep expected peak warming to approximately 1.75°C above pre-industrial levels.*[8]

Table 1: Equivalence between CO_2 and CH_4 emissions under the combined global temperature potential (CGTP) metric of Collins et al. (2020).

Time horizon	50 years	75 years	100 years
Size of pulse of CO_2 emissions ($GtCO_2$) with equivalent warming effect to a sustained 1 $MtCH_4$/yr change in CH_4 emissions rates depending on time horizon	3.3	3.7	4.0

2.2 Tradeoffs between GHGs after peak warming

Section 2.1 summarized how the trajectories of SLGHGs and LLGHGs relate to each other prior to peak warming for efforts to keep warming to below a particular level. After reaching peak warming the evolution of both long-lived and short-lived GHGs will also be important for whether temperatures remain constant or fall from their peak.

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[8] These trajectories assume a present-day (2020) warming of around 1.2°C, consistent with the definition of present-day warming (GSAT) used for carbon-budget calculations in IPCC-SR1.5, and a TCRE of 0.45°C/$TtCO_2$ consistent with IPCC SR1.5 Ch2. A contribution to future warming from aerosols is approximated through a 0.4Wm^{-2} increase in net aerosol forcing between 2020 and mid-century consistent with typical modelled global emissions pathways that keep warming to 1.5°C with no or low overshoot. Methane emissions trajectories are specified to fall at approximately the rate required to not add to further warming after 2050. Emissions are expressed as CO_2-equivalent values using the Global Warming Potential metrics (time horizon of 100 years) from the IPCC 5th Assessment Report (including carbon-climate feedbacks).

Reductions in global temperature after peak warming could occur due to either net anthropogenic removals of long-lived GHG emissions from the atmosphere (e.g., direct air capture of carbon and storage) or through permanent falls in the annual rate of short-lived GHG emissions after the time at which peak temperature is reached whilst long-lived GHG emissions remain at net-zero. Table 1 provides a way to estimate the magnitude in the reduction of the annual global CH_4 emissions rate below the levels at the timing of peak warming that would be required to achieve a given level of cooling over a specific period. Based on mid-range estimate of the transient climate response to cumulative emissions (TCRE) of 0.45^{o}C/TtCO_2 a cooling of around 0.2^{o}C over 50 years after temperature peaked would require a cumulative net active removal of CO_2 from the atmosphere of around 445 GtCO_2 over this 50 year period[9]. Table 1 indicates that this same cooling effect could also be created by a permanent reduction in the rate of global methane emissions by around 135 MtCH_4/yr below the levels over the couple of decades prior to the timing of peak warming.

2.3 Modelled economic least-cost global pathways

Global GHG emissions trajectories consistent with the Paris Agreement are often studied using Integrated Assessment Models (IAMs). These models of the energy and land-use systems allocate emissions reductions across sectors, countries, and gases to keep the overall 'net present cost' of the emissions reduction pathway as low as possible whilst constraining global emissions to pathways expected to be consistent with a specified global temperature goal.[10] These modelled pathways, regularly summarised and applied in the IPCC assessment reports and intergovernmental documents such as the 'Emissions Gap' reports from UN Environment, can be useful indicators of what an idealised 'cost-effective' global emissions pathways might look like across sectors, gases and regions, but do not explicitly incorporate additional considerations of fairness, political will or institutional capability which will all be important additional determinants of how reductions are shared across sectors, gases and regions in the real world.

The balance of effort between reductions in different GHGs across the full range of pathways produced by international modelling groups used in the IPCC Special Report on Global Warming of 1.5°C is summarised in Table 2, with trajectories for LLGHGs (CO_2 and N_2O) and biogenic CH_4 from these simulations shown in Figure 5.[11] As now relatively widely known, these pathways require significant deviations in the historical trends of global emissions. Whilst technological progress (including the falling costs of renewable power generation) has helped shift projected future emissions trajectories away from the highest emissions futures, expected emissions at the global level out to 2030 remain far from these trajectories (UNEP, 2020).

This scenario set is not a statistically well-defined set of simulations and should not be treated as such. It includes simulations where particular technologies are explicitly excluded as contributing to the emissions reductions (e.g., nuclear) and come from a wide set of models with varying levels

[9] Assuming a perfectly symmetric global temperature response to positive and negative CO_2 emissions.
[10] In many IAMs this is achieved using a 'shadow value of carbon' for all emissions. This is typically applied to non-CO_2 GHG emissions using the global warming potential (GWP) metric for a 100-year time horizon.
[11] Methane emissions from the energy sector are not included within these plots but are an important source of emissions at the global level.

of detail regarding the representation of energy system technologies, varying assumptions regarding their relative costs, and varying assumptions about global developments (e.g., population, economic growth and development) in the absence of climate policies or impacts. Some scenarios also impose specific behavioural change (e.g., diet preferences) future exogenous to the modelling framework (van Vuuren et al., 2018). Differences in the evolution of the global energy systems can be larger between different models as it can between different levels of climate ambition within the same model. Although the differing assumptions and outcomes in the land and agriculture sector have been studied (Popp et al., 2017), it is difficult to clearly identify the drivers of differences between the high-level global emissions outcomes without additional targeted experiments, and the fundamental drivers of different balances between reductions in biogenic methane and LLGHGs within these modelling frameworks in pursuit of ambitious climate objectives remain poorly understood.

Table 2. *Summary statistics of global cost-optimal pathways (median is given, with max and min in parentheses - long-lived GHG emissions include only CO_2 and N_2O aggregated using GWP-100 value of 298). 'Biogenic' methane is here approximated as all non-energy sources including both agricultural and waste sources. Globally biogenic methane emissions rates were estimated to be around 220 $MtCH_4$/yr in 2015 from observationally-based datasets (Hoesly et al., 2018).*

Scenario grouping	Cumulative LLGHG emissions from 2020 to 2050 - $GtCO_2e$	Cumulative LLGHG emissions from 2020 to peak warming - $GtCO_2e$	Rate of LLGHG emissions at 2030 - $GtCO_2e$/yr	Rate of LLGHG emissions at 2050 - $GtCO_2e$/yr	Rates of biogenic CH_4 emission at 2030 - $MtCH_4$/yr	Rates of biogenic CH_4 emission at 2050 $MtCH_4$/yr	Rates of biogenic CH_4 emission over 20 years prior to peak warming $MtCH_4$/yr
1.5ºC (~50% probability)	545 (325 - 705)	535 (360 - 810)	23 (14 - 28)	2.3 (-8.3 - 12)	180 (110 - 230)	140 (60 - 200)	175 (100 - 240)
<2ºC (~66% probability)	790 (580 - 1060)	930 (625 - 1430)	30 (20 - 46)	12 (1.9 - 20)	190 (160 - 300)	155 (115 - 205)	155 (100 - 245)

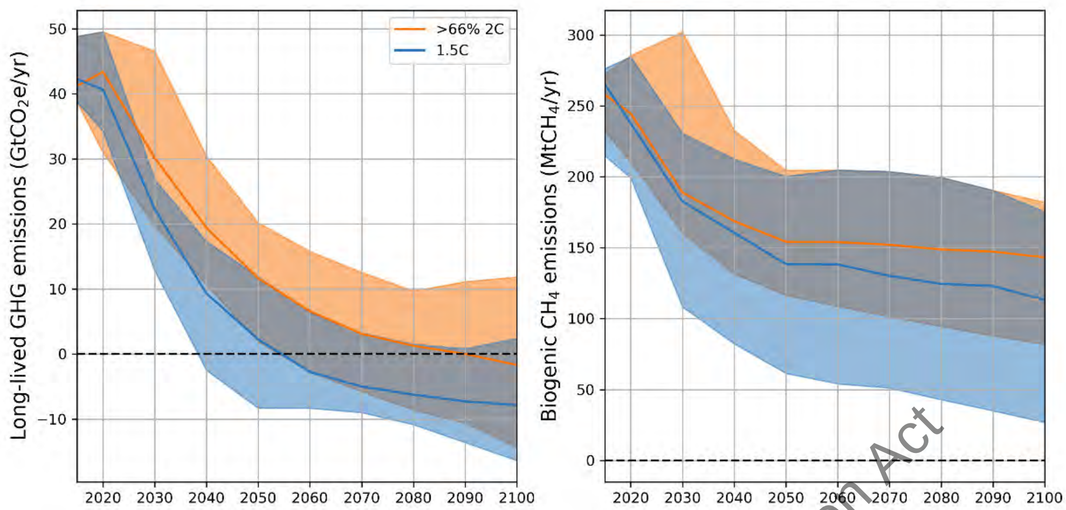


Figure 5: *The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for Long-lived GHGs (CO_2 and N_2O) and biogenic CH_4. Solid lines denote the median of the scenario set.*

Figure 5 illustrates the different roles the gases CO_2, CH_4 and N_2O can play in future model-based emissions pathways that are compatible with the temperature ambitions of the Paris Agreement. The global emissions of CO_2 have to go to net zero around the middle or second half of the century, depending on level of temperature ambition. Large reductions in CH_4 and N_2O are also generally found in these modelled pathways but there is more variation. The model studies found that strong reductions in methane are simulated in all pathways, but zero CH_4 is not achieved in any pathway. This non-zero global residual CH_4 emission is due to the assumed cost of reducing the remaining CH_4 emissions not because of its physical properties (Harmsen et al. 2019). For N_2O, the pathways show smaller reductions or even modest increases depending on the degree of future fertilizer use. N_2O emission pathways also do not reach net-zero. The large spread in possible pathways for emissions of CH_4 and N_2O are worth noting, reflecting different assumptions about abatement costs including potential for demand-side changes. However, in the vast majority of these modelled least economic cost global pathways, biogenic CH_4 emissions are seen to decline strongly by mid-century. This reduces the level of global average CH_4-induced warming relative to the warming these emissions are causing at present.

Peak warming generally occurs around 2050 in scenarios that keep warming to 1.5°C with ~50% probability - approximately corresponding with the date of global net-zero CO_2 emissions (Figure 2.6 in UK CCC, 2019). Although net long-lived GHG emissions remain positive at the time of peak warming (due to some residual N_2O emissions in all scenarios), the effect of falling methane emissions over the decades prior to 2050 (which reduces CH_4-induced levels of global

temperature rise) temporarily acts to offset some of the temperature implications of these residual long-lived GHG emissions, sufficient to bring global temperature to a peak.[12]

Many of these scenarios continue to reduce CO_2 emissions further so that global CO_2 (and long-lived GHG) emissions go net-negative. This has the effect of reducing temperatures after peak warming has been reached, but doesn't significantly contribute to the level of peak warming achieved. In many scenarios that peak warming at around 1.5°C (or less than 0.1°C of overshoot) by 2050 the net-negative CO_2 emissions largely contribute to temperatures declining from their peak to around 1.3°C by 2100. Alternative pathways exist that would avoid these net-negative emissions - for example Rogelj et al. (2019) shows that pathways which reach net-zero CO_2 emissions around 2040 and then maintain this level still achieve a peak temperature around 1.5°C with warming remaining around this level out to 2100, in part due to the continued reduction of global methane emissions after warming peaks acting to offset any increases in the level of global temperature due to non-zero residual (non-CO_2) long-lived GHG emissions. In the long-term (centennial timescales) it may be necessary to have a certain amount of net negative global CO_2 emissions even to sustain global temperature at a constant level. This is to counter any slow Earth System feedbacks such as permafrost thawing which would add to atmospheric concentrations (and therefore warming) over long-timescales (see Section 1).

After the completion of SR1.5, new scenarios have been developed by various scenario groups. These may give more insight to cost optimal emissions pathways for these gases and provide a stronger knowledge basis for options to reach the temperature goals.

2.4 Emission metrics

The Global Warming Potential (GWP) is defined as the time-integrated radiative forcing (RF) due to a pulse emission of a non-CO_2 gas, relative to a pulse emission of an equal mass of CO_2. It is used for expressing the effects of different emissions on a common scale; so-called 'CO_2 equivalent emissions'. The GWP was presented in the First IPCC Assessment, where it was stated that "It must be stressed that there is no universally accepted methodology for combining all the relevant factors into a single global warming potential for greenhouse gas emissions. A simple approach has been adopted here to illustrate the difficulties inherent in the concept, …".

Since then, the GWP has become a widely used metric for aggregation of different gases to 'CO_2 equivalent emissions' in the context of reporting emissions as well as in designing and assessing climate policies. The GWP for a time horizon of 100 years was adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol.

[12] This compensatory effect of falling methane emissions could only temporarily offset the additional warming from continued positive emissions of long-lived GHGs, as falling methane emissions could not be maintained forever, ultimately keeping warming constant would require net-zero long-lived GHG emissions to be reached, necessitating net-negative emissions of CO_2 as some level of residual positive agricultural N_2O emissions are expected to be unavoidable.

The numerical values for GWP have been updated in the successive IPCC reports, as a consequence of updated science but also due to the changes occurring in the atmosphere; in particular the CO_2 concentration to which the radiative forcing has a non-linear relation.

Since its introduction, the concept has been evaluated and tested for use in design of mitigation policies. IPCC AR4 stated that "Although it has several known shortcomings, a multi-gas strategy using GWPs is very likely to have advantages over a CO_2-only strategy (O'Neill, 2003). Thus, GWPs remain the recommended metric to compare future climate impacts of emissions of long-lived climate gases." In IPCC AR5, the assessment concluded that "The choice of metric and time horizon depends on the particular application and which aspects of climate change are considered relevant in a given context. Metrics do not define policies or goals but facilitate evaluation and implementation of multi-component policies to meet particular goals. All choices of metric contain implicit value-related judgements such as type of effect considered and weighting of effects over time."

The Paris Agreement text does not explicitly specify any emission metric for aggregation of GHGs, but under the Paris rulebook adopted at COP 24 in Katowice [Decision 18/CMA.1, annex, paragraph 37], parties have agreed to use GWP-100 values from the IPCC AR5 or GWP-100 values from a subsequent IPCC assessment to report aggregate emissions and removals of GHGs and for accounting under NDCs. In addition, it is also stated that parties may use other metrics to report supplemental information on aggregate emissions and removals of greenhouse gases.

After IPCC AR5, new metric concepts have been published; some of them building on the similarity in behaviour of a sustained change in SLGHG and pulse of CO_2 (Allen et al., 2016), similar to the approach explored earlier by Lauder et al. (2013).

This new approach for comparing emissions, denoted GWP*, uses the same GWP values, but apply rate of change in emissions of the short-lived gas, e.g., methane. Cain et al. (2019) refined the concept to better represent the relationship between cumulative CO_2-warming-equivalent emissions and modelled warming in diverse CH_4 mitigation scenarios by taking into account the delayed warming impact of past methane emission increases. Lynch et al. (2020) demonstrated this for idealized cases. Collins et al. (2020) take an analytical approach and derive the combined global temperature change potential (CGTP) metric for calculating an equivalence between a sustained step-change in SLGHG emissions and a CO_2 emissions pulse. Collectively, these metrics that represent SLGHG emissions with a rate of emissions of CO_2 that would have the same impact on global temperatures are known as "warming-equivalent".

These mixed step-pulse metrics can be used to aggregate SLGHG together with CO_2 and approximate the development of temperature relative to a reference year. In this way, the mixed step-pulse metrics allow for inclusion of SLGHG into the relation between cumulative CO_2-equivalent emissions and temperature change.

It is important to note that the two metric concepts GWP* and GWP measure different things. GWP measures the warming effect from emissions of a gas (e.g., CH_4) relative to the absence of that emission, whereas GWP* measures the warming effect from that emission relative to the warming from a reference emissions level. Thus, the physical quantity that is being compared for SLGHGs emissions relative to the warming from CO_2 is different for the two metrics. The differences are shown in the stylised example in Figure 2. For both LLGHGs and SLGHGs their past emissions contribute to global temperatures remaining above preindustrial levels in the future. For LLGHGs the contribution from past emissions persists at current levels for centuries. For SLGHGs their past contribution to temperature change above preindustrial decays over the next few decades (compare blue segments in Figure 2a and 2b). Therefore, the global temperature change contributed by post-2020 CH_4 emissions is quite different to the change in the global temperature level, comparing the 2020 reference level to the level at a future date, unlike for CO_2. This is because the contribution of CH_4 to warming from past emissions will decay over time (Figure 2b).

The fundamental science underlying these metrics is well established and much of the ongoing debate is about the framing and applications of metrics for various questions and contexts.

Metrics can also be used for assessing the concept "GHG balance" as used in Article 4 in the Paris Agreement. Fuglestvedt et al. (2018) tested metrics for calculation of temperature response to various composition of GHGs and found that balance determined using GWP* imply approximately constant temperatures once the balance has been achieved, whereas a balance based on GWP implies slowly declining temperatures when the mix of GHGs contains a significant positive contribution from SLGHGs[13]. This raises issues related to consistency between Article 4 and Article 2 in the Paris Agreement and what the ultimate temperature goal of the agreement is (Fuglestvedt et al. 2018; Schleussner et al., 2019). Tanaka and O'Neill (2018) find that net zero GHG emissions (in terms of GWP-100) are not necessarily required to remain below 1.5°C or 2°C, assuming either target can be achieved without temporarily overshooting these warming levels.

It is useful to consider how trading emissions under GWP-100 affects surface temperature change. Different combinations of LLGHGs and SLGHGs can give the same overall CO_2 equivalent emission trajectory (when aggregated using GWP-100 values) (e.g., Fuglestvedt et a., 2000, Fuglestvedt et al., 2003; Myhre et al., 2013; Allen et al., 2016; Allen et al., 2018). Globally the ambiguity generated for realistic strong mitigation pathways has been found to be important at the 10% level (or 0.17°C) (Denison et al., 2020). However, larger ambiguities could exist at sector and country level; e.g., in countries where methane emissions represent a larger fraction of total greenhouse gas emissions.

Figure 6 illustrates the temperature responses for different and purely hypothetical scenarios for New Zealand. The blue and green lines (or the purple and red) are contributions from pathways with the same total CO_2 equivalent emission trajectory (based on GWP-100) but different trajectories of CO_2 and biogenic CH_4 emissions comprising it. The green pathway has 47% biogenic CH_4 reductions by 2050 but at the expense of extra CO_2 emissions (to match the CO_2-equivalent emissions of the blue line) and does not reach net zero CO_2 emissions by 2050, which happens in the blue pathway. Over this century the extra biogenic CH_4 reduction under the GWP-100 CO_2 equivalent assumption (green line) leads to lower contributions to global temperature than scenarios with identical aggregated GWP-100 emissions but lower cumulative CO_2

[13] Balance based on GWP could theoretically lead to a warming effect if SLGHG removal is used to balance ongoing CO_2 emissions on a large scale.

emissions. However, after 2100, the long-term warming effect of the extra CO_2 emissions dominate (substituted for CH_4) and give a continuing warming trend due to not achieving net-zero CO_2 emissions. Similarly, the purple line includes extra CO_2 emission reduction on top of the 24% CH_4 reduction scenario to match the GWP-100 trend in the 47% scenario. This scenario results in a continued long-term reduction in the contribution to global temperature due to the sustained net-negative CO_2 emissions. Generally, these results show that if New Zealand were to specify a single CO_2-equivalent emission reduction target based on GWP-100, there could be significant difference in the resulting global warming trajectory over century timescales. This is illustrated by the pairs of curves (green and blue, purple and red) in Figure 6 where differences give the scale of the ambiguity introduced and show how these change through time. Put simply, if you mitigate CO_2 as a substitute for CH_4 emissions you get long term benefits (a lower long-term temperature level), and if you mitigate CH_4 and a substitute for CO_2 emissions you get cooling for several decades (at the expense of longer term benefits).

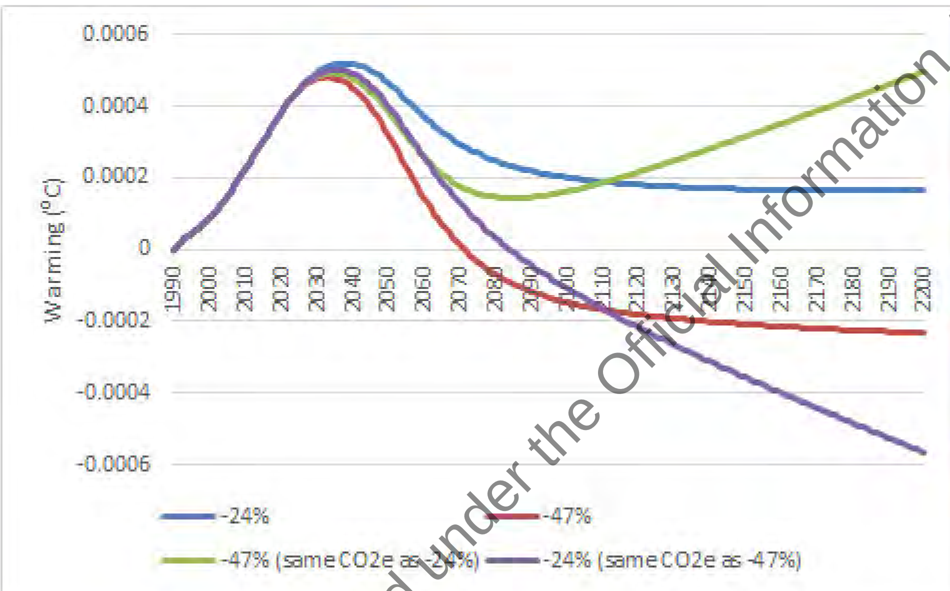


Figure 6: *An illustration of New Zealand's contribution to global warming (relative to the level of its contribution in 1990). The blue and red pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel CH_4, and have either 24% (blue) or 47% (red) reductions in biogenic CH_4 from 2017 levels to 2050. The green line has 47% biogenic CH_4 reduction but additional emissions of CO_2 to match the CO_2e emissions of the blue line based on IPCC AR4 GWP-100 values. The purple line has 24% CH_4 reduction but has extra CO_2 emission reduction to match the CO_2-equivalent emission within the 47% scenario. Emissions from 2050 do not alter. See Section 3.1 for the methodology.*

3. Considerations for national pathways consistent with keeping warming to 1.5°C

Section 2 considered the tradeoffs between mitigation of different greenhouse gases. This section discusses other considerations that could be taken into account in national pathways. There is no fundamental physical reason why a national pathway should follow either the global temperature or the global emissions trajectory, given different national circumstances and different mix of sectors with different long-lived and short-lived greenhouse gases.

3.1 National contribution to global warming.

New Zealand's historic contribution to global warming is estimated to be above 0.01 °C, from large-scale deforestation prior to 1840 (Reisinger and Leahy, 2019). The warming is estimated to be around 0.003 °C from biogenic methane emissions, nitrous oxide and fossil fuel CO_2 (Figure 7). There are also small contributions from F-gases and fossil fuel methane, which are not included in the Figure.

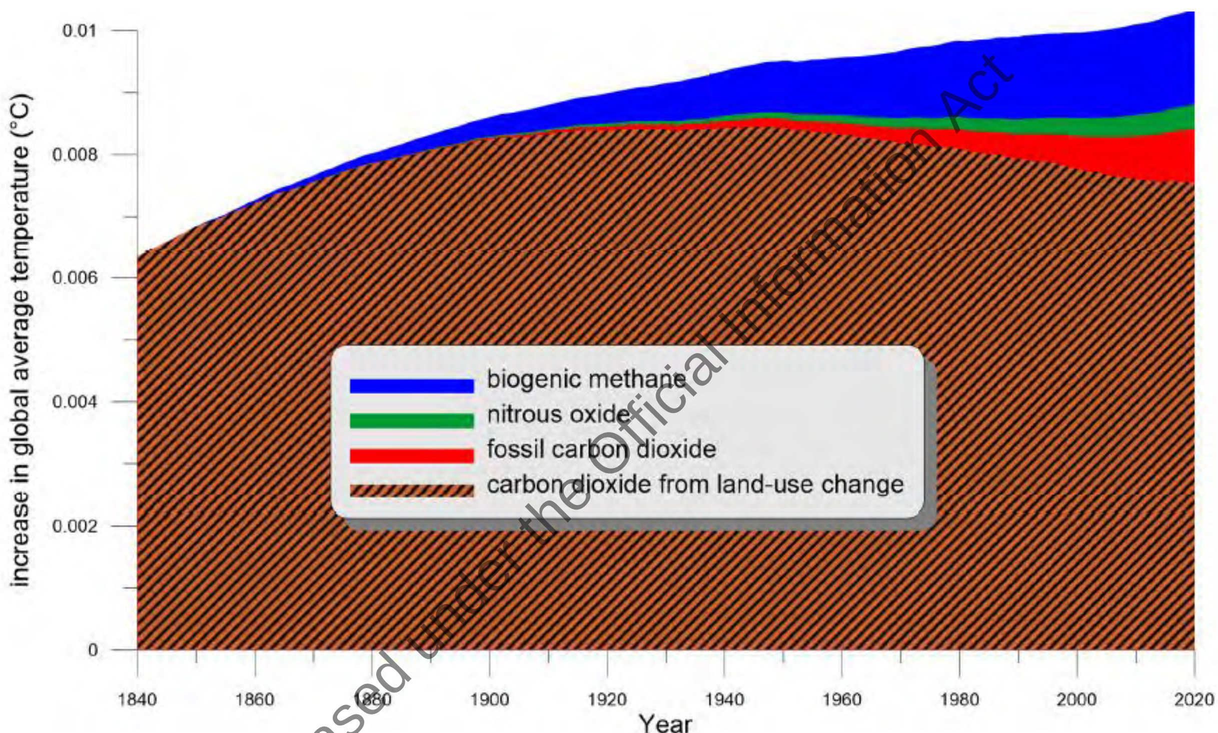


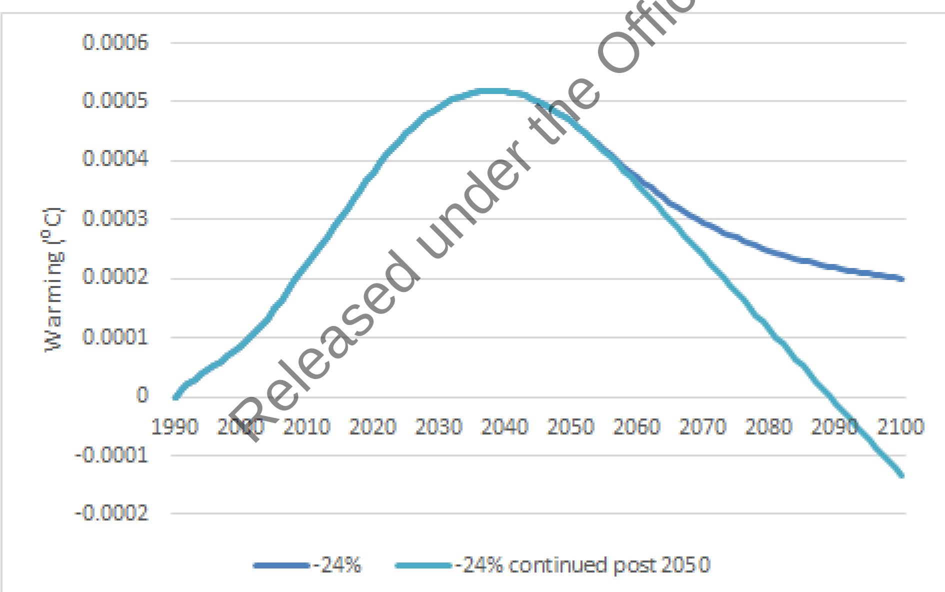
Figure 7: *Estimate of New Zealand's contribution to global warming from emissions until the end of 2019. Figure is taken from Reisinger and Leahy (2019).*

Figure 8 focuses on estimates of New Zealand's future contribution to global warming from emissions since 1990. New Zealand emissions from 1990-2018 are taken from New Zealand's greenhouse gas inventory and before that are taken from Reisinger and Leahy (2019) using Ausseil et al. (2013). They combine fossil fuel emissions, land-use change and biogenic emissions. The estimates of temperature change use the impulse response functions provided in the IPCC 5th Assessment Report for calculating GHG metrics as a simple climate model. Non-GHG contributions to warming (e.g. aerosol emissions) are not part of these scenarios.

The blue and red curves in Figure 8 approximate the range of New Zealand's possible future contributions to global warming under current policies, with a range of idealised assumptions after 2050. Under both 24% and 47% biogenic CH_4 reduction policies, New Zealand is beginning to reverse its contribution to global warming by around 2040. Under 24% reduction policies, the 2050 contribution to the level of global warming from New Zealand's emission since 1990 matches today's level of New Zealand's contribution to the level of global warming. Under 47% biogenic CH_4 reduction policies, the 2050 level of global warming from New Zealand's emissions approximately matches that from 2015.

Contributions to global temperature rise are sensitive to the shape of the emissions reduction profile as well as the end point reached in 2050 or any other year when mitigation approaches might change. This is particularly so for LLGHG pollutants, but less so for SLGHGs. Early reductions in LLGHGs have lower cumulative LLGHG emissions and overall less climate impact in the longer term (see Section 2.3). However, the most relevant factor for New Zealand's contribution to global temperatures rise above pre-industrial levels over most of this century will be the level of reduction of SLGHGs.

What happens to emissions after 2050 is important for the longer term contribution to global temperatures (see Sections 2.3 and 4.2). This is theoretically explored in Figure 8, which keeps net-zero CO_2 emissions at zero after 2050 and compares options for stable or continued biogenic methane emission reductions. These results illustrate that although the choices of biogenic emission pathway up until 2040 do influence New Zealand's contribution to global warming, the benefits of choosing 47% biogenic CH_4 abatement become more visible after 2040, when pathways are reversing New Zealand's historical contribution to global warming.



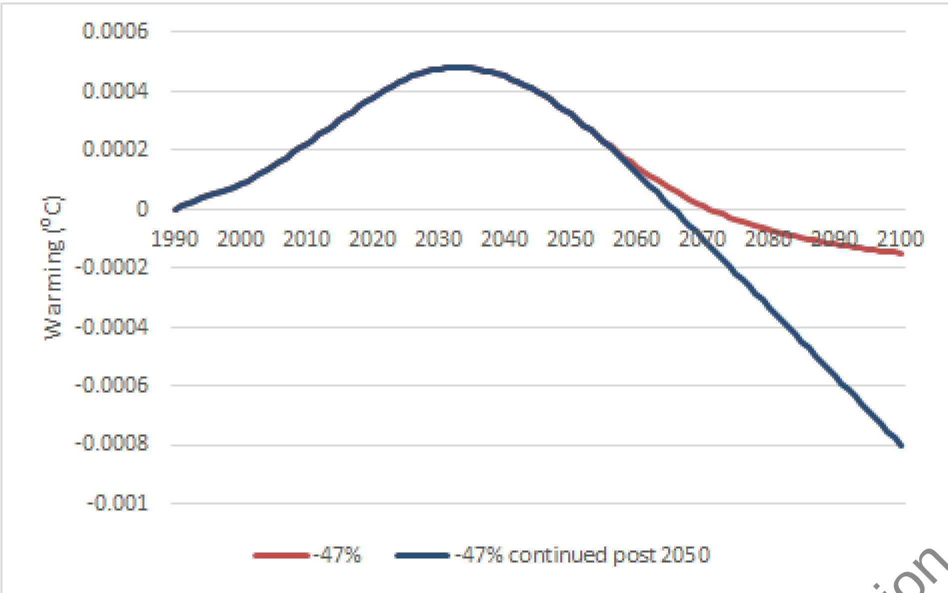


Figure 8: *As Figure 6, except emissions reductions continue beyond 2050. 24% biogenic CH_4 reduction by 2050, shown in the top panel and 47% reduction in the bottom panel. The panels have two scenarios: emissions unchanged after 2050, matching Figure 6, and the biogenic methane reduction rate continuing after 2050.*

Figure 9 explores a scenario where the 47% biogenic CH_4 reduction pathway is planned but biogenic CH_4 abatement does not prove possible, so CO_2 abatement is substituted assuming GWP-100 based equivalence. This pathway would give some more warming in the short term but eventually lead to less warming overall. Continued biogenic CH_4 reductions (as shown in Figure 8) and/or net negative CO_2 emissions (as shown in Figure 9) have a large effect on how much New Zealand's warming contribution is reversed.

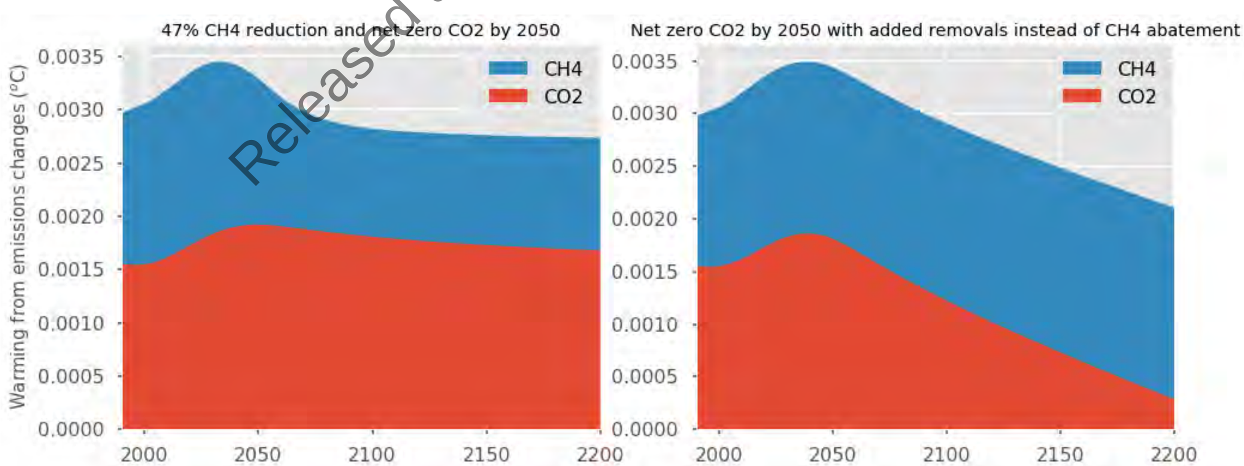


Figure 9: *Changes to warming contributions (above pre-industrial levels excluding emissions from historical land-use change) from different abatement strategies. The left plot shows the 47% biogenic CH_4 reduction scenario until 2050 reaching net zero CO_2 emissions at the same time.*

The right plot shows a scenario where additional CO_2 abatement is substituted for the CH_4 reduction assuming GWP-100 equivalence.

3.2 Fairness and equity

When determining either net zero targets dates or proportioning the remaining carbon budget into national quotas, choices have to be made regarding fairness, equity and burden sharing. These are obviously not straightforward and can have a large effect on levels of ambition for mitigation reduction (see Figure 3.9 from the UK CCC, 2019). It is not possible to include methane emissions scaled by GWP-100 within carbon budget estimates. However, similar equity principles could be applied to CH_4 emissions rates and cumulative CO_2 emissions.

When comparing national emission pathways, it is important to consider different national starting points. The same '1.5°C consistent' mitigation actions measured by cost or other measure of effort could result in different rates of emissions reductions in different regions depending on national circumstances and their respective capabilities to cut emissions. This includes the share of hard-to-abate emissions within a country profile today. For example, if the energy sector is already mostly decarbonised, the national emissions might not fall as quickly as the global average, whose rapid decline over the 2020s in 1.5°C scenarios is associated primarily with the rapid removal of coal from the electricity generation mix. Assessing whether a nation is taking the '1.5°C consistent' actions with its planned emissions reduction pathway may need to be more nuanced than a simple comparison with the global average reductions. It may also consider additional effort, outside of the domestic emissions account that a country might be undertaking to support the global transition (e.g. climate finance provision, purchase of credits through international markets, technology transfer etc.) to form a holistic picture of whether planned action to 2030 is 1.5°C-aligned.

3.3 Net Zero in the context of New Zealand

New Zealand currently plan to reach net zero GHG emissions by 2050 excluding biogenic methane for which a range of reductions in emissions rate by 2050 is being considered. Whether net zero GHG is reached is dependent on the emission metric choice in the way that net zero GHG is defined. As discussed in Fuglestvedt et al. (2018), it can be defined as a balance between anthropogenic emissions and removals, aggregated across gases by a chosen emission metric. The UK and the EU have set net-zero GHG targets based on GWP-100 which would be expected to lead to steadily declining temperatures if achieved globally. The New Zealand goal would not reach net zero GHGs under GWP-100 but would still lead to declining temperatures. Using the GWP* emission metric to assess if national pathways achieve net zero, both the UK and New Zealand goals would be seen as achieving net-negative GHG emissions.

Summary and conclusions

Section 1 presented a brief update of the science on past and future warming from greenhouse gases. Section 2 illustrated global trade-off considerations in strong mitigation emission pathways and Section 3 considered implications for deriving national strategies.

In the further development of policy towards New Zealand's contribution to the global effort of achieving the Paris temperature goals, our report has highlighted several issues and choices that would benefit from consideration. These are outlined below:

4.1 Evolving science

As knowledge is being developed and assessment reports are being published, it is important to be clear and transparent about what is used as the basis for the policy design; i.e. which parameter values and which definitions are adopted and used and how they might be revised as science understanding evolves.

4.2 Abatement choices

Choices of approach not only need to consider the physical science uncertainty but also need to consider the overall objectives of the climate policy and the practicalities of usage and communication. As illustrated in Section 3.1, the selection of greenhouse gases and as well as the emission metric used will have a significant effect on timing and efforts to achieve net zero and on the resulting global warming. The UK legislated for a net zero target in terms of GWP-100 emissions. One of the reasons given was that such a target would actively decrease its future warming commitment over time (see Section 2.1 and 3.1). For New Zealand to continue to decrease its future warming commitment after 2050, additional CH_4 reductions and/or negative emissions of CO_2 would be needed (Section 3.1).

New Zealand, by employing a two-target approach, one for biogenic methane and one for other greenhouse gases, largely avoids complications to do with emission metrics discussed in Section 2.4. However, if at a future date biogenic CH_4 and CO_2 abatements were traded as illustrated in Figure 9, the way of doing this trading would need to be considered. Using a GWP-100 metric would lead to long term additional cooling effect but shorter term additional warming when using carbon dioxide removal as a substitute for methane abatement (see Figure 9). However, other metric choices for trading between the gases could be considered. More generally, Sections 2.2 and 3.1, showed how it is possible to reverse the global warming trend and/or a nation's contribution to it by either a net removal of cumulative CO_2 emissions or by a permanent reduction in the rate of methane emissions below the levels at the time of peak warming. Where 445 $GtCO_2$ removal would have the same cooling effect as a permanent reduction in the rate of global methane emissions by around 135 $MtCH_4$/yr.

The Paris Agreement aims for a net-zero type target on a global basis. In the development of mitigation strategies for a single country it is important to consider how the plans for net zero might be achieved internationally and how a nation's plan fits into the international effort (i.e., which countries might achieve net negative, net zero or net positive emissions, and how international trading is used).

4.3 Pathways after net-zero

As shown in the pathways in SR1.5, achieving net zero CO_2 is just one part of the challenge in limiting future warming. Plans for the further path of emissions of the individual gases after net zero target is achieved also need to be addressed and communicated, particularly how greenhouse gas removal can be sustained given finite and competing interest for land resources (see Section 3.1).

4.4 Defining national high-ambition pathways

Which fairness and equity principles that are applied as rationale for New Zealand's efforts are important to communicate as a part of a mitigation strategy. As New Zealand's starting position in terms of sectoral emissions is different from other nations, a high ambition emission reduction trajectory might look quite different to a high ambition pathway from another country. In particular, many countries are expected to rapidly decarbonise their power sector out to 2030, leading to large national emission reductions in the 2020s. In countries such as New Zealand (and the UK) where the power sector is already mostly decarbonised, urgent actions are needed on other sectors such as agriculture, buildings and transport for mitigation compatible with Paris Agreement ambitions. Policy actions in these areas might take longer to manifest themselves in emissions trends. Such a pathway was presented for the UK 6th carbon budget (UK CCC, 2020), where actions over 2020-2025 only produced modest emission reduction by laying the groundwork for march larger emission reductions at the end of the 2020s.

New Zealand, by getting to net zero CO_2 as soon as possible with concerted action to substantially reduce biogenic CH_4 emissions as much as possible, can limit the contribution it makes to global warming which is expected to peak around 2040 and then begin to reverse. If actions continue to 2050 and beyond, New Zealand could substantially reduce its historic contribution to global warming from fossil fuel emissions, nitrous oxide and biogenic methane by the end of the century.

References

Allen M.R. et al. 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change*, **6,** 773-776, doi: 10.1038/nclimate2998

Allen, M. R., K. P. Shine, J. S. Fuglestvedt, R. J. Millar, M. Cain, D. J. Frame, and A. H. Macey, 2018 : A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Nature npj Climate and Atmospheric Science*, **1(2018-16)**, , doi: 10.1038/s41612-018-0026-8.

Ausseil A-GE, Kirschbaum MUF, Andrew RM, McNeill S, Dymond JR, Carswell F, Mason NWH 2013 Climate regulation in New Zealand: contribution of natural and managed ecosystems. In Dymond JR ed. Ecosystem services in New Zealand – conditions and trends. Manaaki Whenua Press, Lincoln, New Zealand.

Cain, M., Lynch, J., Allen, M. R., Fuglestvedt, J. S., Frame, D. J., and Macey, A. H. (2019). Improved calculation of warming-equivalent emissions for short-lived climate pollutants. NPJ Clim. Atmos. Sci. 2, 1–7. doi:10.1038/s41612-019-0086-4.

Collins, W.J.,C.P. Webber, P.M. Cox, C. Huntingford, J. Lowe, S. Sitch, S.E. Chadburn, E. Comyn-Platt, A.B. Harper, G. Hayman and T. Powell, 2018: Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters*, **13(5)**, doi:10.1088/1748-9326/aab89c.

Collins, W. J. , Frame, D. J., Fuglestvedt, J., and Shine, K. P. (2020). Stable climate metrics for emissions of short and long-lived species – combining steps and pulses. Environ. Res. Lett. doi:10.1088/1748-55 9326/ab6039.

UK Climate Change Committee, 2020, Sixth CArbon Budget Report, https://www.theccc.org.uk/publication/sixth-carbon-budget/

Denison S., Forster P.M., Smith C.J., 2019: Guidance on emissions metrics for nationally determined contributions under the Paris Agreement. *Environmental Research Letters*, **10** (7-10), doi:10.1038/s41558-019-0660-0.

Etminan, M., Myhre, G., Highwood, E. J., and Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophys. Res. Lett. 43, 12,614-12,623. doi:10.1002/2016GL071930.

Forster P.M., A.C. Maycock, C.M. McKenna and C.J. Smith, 2020: Latest climate models confirm need for urgent mitigation. *Nature Climate Change*, 1–14, doi:10.1007/s11027-017-9762-z.

Forster, P. M., Forster, H. I., Evans, M. J., Gidden, M. J., Jones, C. D., Keller, C. A., et al. (2020a). Current and future global climate impacts resulting from COVID-19. *Nature Climate Change*. oi:10.1038/s41558-020-0883-0.

Fuglestvedt J.S., Rogelj, R. J. Millar, M. Allen, O. Boucher, M. Cain, P. M. Forster, E. Kriegler and D. Shindell., 2018: Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philosophical Transaction of the Royal Society A*, **376(2119)**, doi:10.1098/rsta.2016.0445.

Fuglestvedt J.S., Berntsen T.K. and Skodvin T., 2000: Climate implications of GWP-based reductions in greenhouse gas emissions. *Geophysical Research Letters*, **27(3)**, 409–412, doi:10.1029/1999GL010939.

Fuglestvedt J.S., Berntsen T.K., Godal O., Sausen R., Shine K.P. and Skovin T., 2003 Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. *Climatic Change*, **58**, 267-331, doi:10.1023/A:1023905326842 .

Gasser T. et al., 2016: Accounting for the climate–carbon feedback in emission metrics. *Earth System Dynamics*, **8**, 235-253, doi: 10.5194/esd-8-235-2017.

Grubler A. et al., 2018: A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, **3**, 515-527, doi:10.1038/s41560-018-0172-6 .

Hawkins E. et al., 2017: Estimating Changes in Global Temperature since the Preindustrial Period. *American Meteorological Society*, **98(9)**, 1841-1856, doi:10.1175/BAMS-D-16-0007.1.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J.-I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geosci. Model Dev., 11, 369–408, https://doi.org/10.5194/gmd-11-369-2018, 2018

Hodnebrog Ø. Et.al., 2020: Updated Global Warming Potentials and Radiative Efficiencies of Halocarbons and Other Weak Atmospheric Absorbers. *Reviews of Geophysics*, **58(3)**, doi:10.1029/2019RG000691.

Jackson, R.B., Solomon, E.I., Canadell, J.G. *et al.* Methane removal and atmospheric restoration. *Nat Sustain* **2,** 436–438 (2019). https://doi.org/10.1038/s41893-019-0299-x

Kadow, C., Hall, D. M., and Ulbrich, U. (2020). Artificial intelligence reconstructs missing climate information. *Nat. Geosci*. 13, 408–413. doi:10.1038/s41561-020-0582-5.

Kennedy J.J. et al.,, 2019: An Ensemble Data Set of Sea Surface Temperature Change From 1850: The Met Office Hadley Centre HadSST.4.0.0.0 Data Set. *JGR Atmospheres*, 124(14), 7719-7763, doi:10.1029/2018JD029867.

Lauder, A. R., I. G. Enting, J. O. Carter, N. Clisby, A. L. Cowie, B. K. Henry, and M. R. Raupach, 2013: Offsetting methane emissions—An alternative to emission equivalence metrics. *Int. J. Greenh. Gas Control*, 12, 419–429.

Leahy, S. C., H. Clark, and A. Reisinger, 2020: Challenges and prospects for agricultural greenhouse gas mitigation pathways consistent with the Paris Agreement. *Front. Sustain. Food Syst*., 1–15, https://doi.org/10.3389/fsufs.2020.00069.

Lynch J. et al., 2020: Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environmental Research Letters*, **15(4)**, doi:10.1088/1748-9326/ab6d7e .

Myhre G.. et al., 2013: Radiative forcing [Stocker, T.F. et al. (eds.)]. Cambridge University Press, pp. 659-740.

MacDougall A.H. et al., 2020 Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2.*Biogeoscience*, 17(11)**,** doi: 10.5194/bg-17-2987-2020.

Morice C.P., J. J. Kennedy N. A. Rayner J. P. Winn E. Hogan R. E. Killick R. J. H. Dunn T. J. Osborn P. D. Jones I. R. Simpson. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. JGR Atmospheres. 15 December 2020. https://doi.org/10.1029/2019JD032361

Nicholls Z.R.J. et al., 2020: Reduced complexity model intercomparison project phase 1: Protocol, results and initial observations. *Geoscientific Model Development*, doi: 10.5194/gmd-2019-375.

O'Neill, B., 2003: Economics, natural science, and the costs of global warming potentials. *Clim. Change,* 58, 251–260.

Popp et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change,* Volume 42, January 2017, Pages 331-345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Reisinger, A. and Leahy, S., 2019: Scientific aspects of New Zealand's 2050 emission targets, New Zealand Agricultural and Greenhouse Research Centre Technical Report, available at https://www.nzagrc.org.nz/user/file/1941/Scientific%20aspects%20of%202050%20methane%20targets.pdf

Renaud de_Richter, Tingzhen Ming, Philip Davies, Wei Liu, Sylvain Caillol, Removal of non-CO2 greenhouse gases by large-scale atmospheric solar photocatalysis, Progress in Energy and Combustion Science, Volume 60, 2017, Pages 68-96, ISSN 0360-1285, https://doi.org/10.1016/j.pecs.2017.01.001.

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, M. V. Vilariño, 2018a, Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

Rogelj J. et al., 2018b: Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, **571**, 335-342, doi:10.1038/s41586-019-1368-z

Rogelj J. et al., 2019: A new scenario logic for the Paris Agreement long-term temperature goal. *Nature*, **573**, 357-363, doi:10.1038/s41586-019-1541-4 .

Richardson T.B. et al., 2019: Efficacy of Climate Forcings in PDRMIP Models. *JGR Atmospheres*, 124(23), 12824-12844, doi:10.1029/2019JD030581 .

Schleussner, C.-F., Nauels, A. , Schaeffer, M., Hare, W. and Rogelj, J.: 2019: Inconsistencies when applying novel metrics for emissions accounting to the Paris agreement. *Environ. Res. Lett*. 14 (2019) 124055 https://doi.org/10.1088/1748-9326/ab56e7

Sherwood S.C. et al., 2020: An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*, **58(4)**, e2019RG000678, doi:10.1029/2019RG000678 .

Samset B.H. et al, 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical Research Letters*, **45**, 408-411, doi:10.1002/2017GL076079 .

Shindell D. and Smith J., 2019: Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature*, **573(sup1)**, 408-411, doi: 10.1038/s41586-019-1554-z

Smith C.J.. et al., 2019: Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming. *Nature Communications*, **10(101)**, doi: 10.1038/s41467-018-07999-w.

Smith C.J. et al., 2018: Understanding Rapid Adjustments to Diverse Forcing Agents *Geophysical Research Letters*,**16(21)**,12023-12031, doi: 10.1029/2018GL079826

Steffen W. et al., 2018: Trajectories of the Earth System in the Anthropocene. *PNAS*, **115(33)**, 8252,8259, doi:10.1073/pnas.1810141115.

Sterner, E. and Johansson D., 2017: The effect of climate–carbon cycle feedbacks on emission Metrics. *Environ. Res. Lett*. 12 034019

Tanaka K. and O'Neil B.C., 2018: The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets. *Nature Climate Change*, **8**, 319-324, doi:10.1038/s41558-018-0097-x.

Thornhill G. et al., 2019: Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models *Atmospheric Chemistry and Physics*, doi: 0.5194/acp-2019-1207.

Turetsky M.R. et al., 2020: Carbon release through abrupt permafrost thaw. *Nature Geoscience*, **13**, 138-143, doi:10.1038/s41561-019-0526-0.

UNEP 2020 Emissions Gap Report, https://www.unenvironment.org/emissions-gap-report-2020.

UK Committee on Climate Change: Net Zero – The UK's contribution to stopping global warming, https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

van Vuuren D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8**, 391-397, doi 10.1038/s41558-018-0119-8.

Weber, J., Shin , Y.M, Staunton Sykes, J., Archer-Nicholls, S., Abraham, N. L., Archibald, A.,: 2020: Minimal Climate Impacts From Short-Lived Climate Forcers Following Emission Reductions Related to the COVID-19 Pandemic. *Geophys. Res. Let.,* 13 October 2020. https://doi.org/10.1029/2020GL090326

Wang Y and Huang Y., 2020: The Surface Warming Attributable to Stratospheric Water Vapor in CO_2-Caused Global Warming. *JGR Atmospheres*, **125(17)**, e2020JD032752, doi: 10.1029/2020JD032752.

Zickfeld K. et al., 2017: Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. *PNAS*, doi: 10.1073/pnas.1612066114.

Climate science considerations of global mitigation pathways and implications for New Zealand mitigation pathways

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Version 8 January 2021

This report interprets how the global surface temperature responds to mitigation of long lived greenhouse gases and short-lived greenhouse gases using the latest climate science. It puts these findings in the context of global mitigation pathways and New Zealand specific emission pathways. With a concerted effort to reduce biogenic methane emission and other greenhouse gases, New Zealand can substantially reduce its contribution to global warming out to 2100. Further, reaching net zero long-lived greenhouse gases is essential to limit New Zealand's contribution to global warming in the longer term.

Introduction

This report gives a brief overview of the current scientific understanding of emissions reductions needed to achieve the global temperature goal of the Paris Agreement. It builds on the findings in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR1.5) and Special Report on Climate change and Land, as well as recent updates in the scientific literature. It focuses on the main characteristics of global emissions pathways and tradeoffs between reductions of emissions of different greenhouse gases. We also discuss how different choices affect the prospects of meeting the Paris temperature goals and how New Zealand's future emissions pathway relate to global temperature outcomes.

1. Climate response to emissions of different GHGs

This first section examines how much global warming has occurred and how much past and future emissions commit the world to further warming.

Based on the literature and knowledge available at the time, SR1.5 concluded that past emissions alone are unlikely to commit the world to global warming in excess of 1.5°C. Does this conclusion still hold? Since 2018 (the date of IPCC-SR1.5 publication) there have additional warm years observed in 2019 and 2020, and updates to the methodologies used to construct global surface temperature timeseries from past observations. There is new science emerging on estimates of the 'locked-in' or 'committed' warming from past carbon dioxide (CO_2) emissions alone, the zeroemission commitment (ZEC).[1] Future warming also depends on the amount of warming coming from *future* greenhouse gas (GHG) emissions and on emission changes in short lived greenhouse gases such as methane and in non-greenhouse gas pollutants, as well as cumulative emissions of longer-lived GHGs, such as (CO_2) and nitrous oxide (N_2O). The sections below detail how understanding of each of these has progressed since SR1.5.

1.1 Historical warming

SR1.5 estimated that the human-induced warming[2] had reached around 1°C (with a 0.8°C to 1.2°C *likely*[3] range) above pre-industrial levels by the end of 2017. This was based on averaging the four prominent global (land and sea) datasets with peer-reviewed methodology (summarized in Table 1.1 of IPCC-SR1.5). Since then these global temperature datasets have been updated and improved to reflect the latest understanding of how to incorporate a range of historical climate data into a single timeseries and to improvements to methods to produce globally representative values (Morice et al., 2020). These latest revisions will lead to a slight increase in the estimated level of warming above pre-industrial levels relative to the versions of the datasets available to IPCC-SR1.5 (e.g., Kennedy et al. 2019, Kadow et al. 2020). These changes arise from updates in the methodologies for constructing global temperature records and not because climate change today is worse than expected by recent IPCC reports. The trend in global temperature over recent decades are robust, consistent with the years since the publication of IPCC-SR1.5 being among the hottest in the instrumental record.

Definitions of globally average surface temperature for the purpose of estimating remaining global carbon budgets was addressed in Chapter 2 of SR1.5. Chapter 2 employed two estimates of the warming to date. The traditional measure of global-mean surface temperature (GMST) is based on observations that use a combination of near surface air temperature over land and sea-ice regions and sea-surface temperature over open ocean regions. The second measure is one that infers global surface air temperature (GSAT) changes across the globe based on a scaling factor from complex climate models. The latter choice was there estimated to lead to 10% higher levels compared to GMST based on climate models and therefore a smaller remaining carbon budget than estimates based on GMST. More recent work suggests that increasing GMST by 10% to estimate GSAT may not be borne out in real-world observations comparing night-time marine air temperature to sea-surface temperature data (e.g., Kennedy et al. 2019).

[1] This is estimated using idealised scenarios in climate models in which emissions are reduced to zero instantaneously. This scenario isn't directly relevant to scenarios that could be realised in the global economy but is informative for identifying physically-based lower limits of the minimum amount of 'inevitable' additional future increases in global temperature.

[2] This is a measure of the increase in global temperature above pre-industrial levels resulting from human activity (e.g., GHG emissions and emissions of aerosols) only. Temporary *natural* effects (e.g. temporary cooling due to volcanic eruptions or natural climate cycles), that temporarily increase or decrease total warming relative to this human-induced level, are excluded.

[3] Here *likely* means at least a 66% chance that the true value lies within this interval – consistent with how this term is used across IPCC reports.

IPCC SR1.5 used the average over the period 1850-1900, the earliest period then available in the direct observational record with reliable estimates of the global average temperature, to approximate pre-industrial levels. There has been discussion in the scientific literature of the dependence of global emissions reduction ambition needed to achieve the Paris Agreement on the choice of this 1850-1900 period to approximate the pre-industrial baseline or an earlier period such as 1750. Using 1750 as a pre-industrial baseline could increase today's level of the global average temperature rise above preindustrial level by around 0.05°C above the level when using the 1850-1900 period, but this is not estimated to be statistically significant (Hawkins et al., 2017).

In summary, we might expect further revisions and updates of the order one tenth of a degree to the historical surface temperature change since preindustrial times and these would have knock on effects for estimates of the remaining global carbon budget consistent with the Paris Agreement. Note that by altering the historical temperature we are implicitly altering the applied relationship between the level of global temperature rise above pre-industrial levels and aggregate climate impacts. As an example, if we were to revise the present day historical warming upwards from 1.0°C to 1.1°C, the present day climate impacts being experienced now do not alter, we instead would associate temperature levels (e.g. 1.1°C or 1.5°C) with lower levels of climate impact than previously, so avoiding 1.5°C of warming becomes a more stringent target (associated with a lower level of aggregate climate impacts than it was previously), rather than the revision pushing us closer to higher levels of future climate impact.

1.2 Future warming

1.2.1 Committed warming from greenhouse gases

This section demonstrates to what extent past and future emissions of specific gases (chiefly CO_2 and CH_4) commit to future changes in global temperature, and hence the extent to which the levels of global temperature above pre-industrial levels in a given year (e.g. around 2050 to reflect when peak warming under many 1.5°C scenarios) is a historic liability and what amount is the result of future emissions that haven't yet occurred.

For emissions of *long-lived GHGs* (LLGHG) (CO_2, N_2O, some fluorinated-gases)[4] their global temperature impact is largely determined by their *cumulative* emissions. Nitrous oxide (N_2O) has a finite single perturbation lifetime unlike CO_2, and consequently behaves differently in the very long term, but can be treated as approximately equivalent to a certain amount of CO_2 emissions (e.g. using conventional metrics from equivalence between GHGs; see section 2.4) when thinking about impacts of its emission on global temperature for this century. As shown in SR1.5 (Table 2.4) and the scientific literature, these emissions need to come down to below net zero (aggregated by the global warming potential with time horizon of 100 years - GWP_{100}) in scenarios compatible with 1.5°C warming. As some level of residual long-lived greenhouse gas emissions are expected to be unavoidable, active removal of CO_2 from the atmosphere is expected to be required to achieve net-zero LLGHG emissions. Removal of non-CO_2 greenhouse gases from the

[4] These are GHGs that result in raised atmospheric concentrations of the gas for many decades after the emission occurred.

ambient atmosphere has been considered at a conceptual level in the scientific literature but has not generally been considered in the same level of techno-economic detail as active removal of CO_2, for which demonstration-scale plants of some engineered removals methods already exist today (De Richter et al., 2017; Jackson et al., 2019).

For CO_2, MacDougall et al. (2020) looked at the evidence from idealized simulations with complex global climate models to conclude that the most likely value of the zero-emission commitment (ZEC)[5] on multi-decadal timescales is close to zero, consistent with previous model experiments and theory, but at the same time pointing to the large uncertainty related to constraining this effect. The right panels on Figure 1 show that the ZEC can be of either sign, but is generally less than +0.5°C across models, with a best estimate, based on current evidence of close to zero. Similarly, for other LLGHGs it is reasonable to assume that the past warming contribution is largely governed by past cumulative emissions and, for timescales under 100 years, there is little further warming or cooling due to past emissions. Likewise, future warming will be governed by future cumulative emissions.

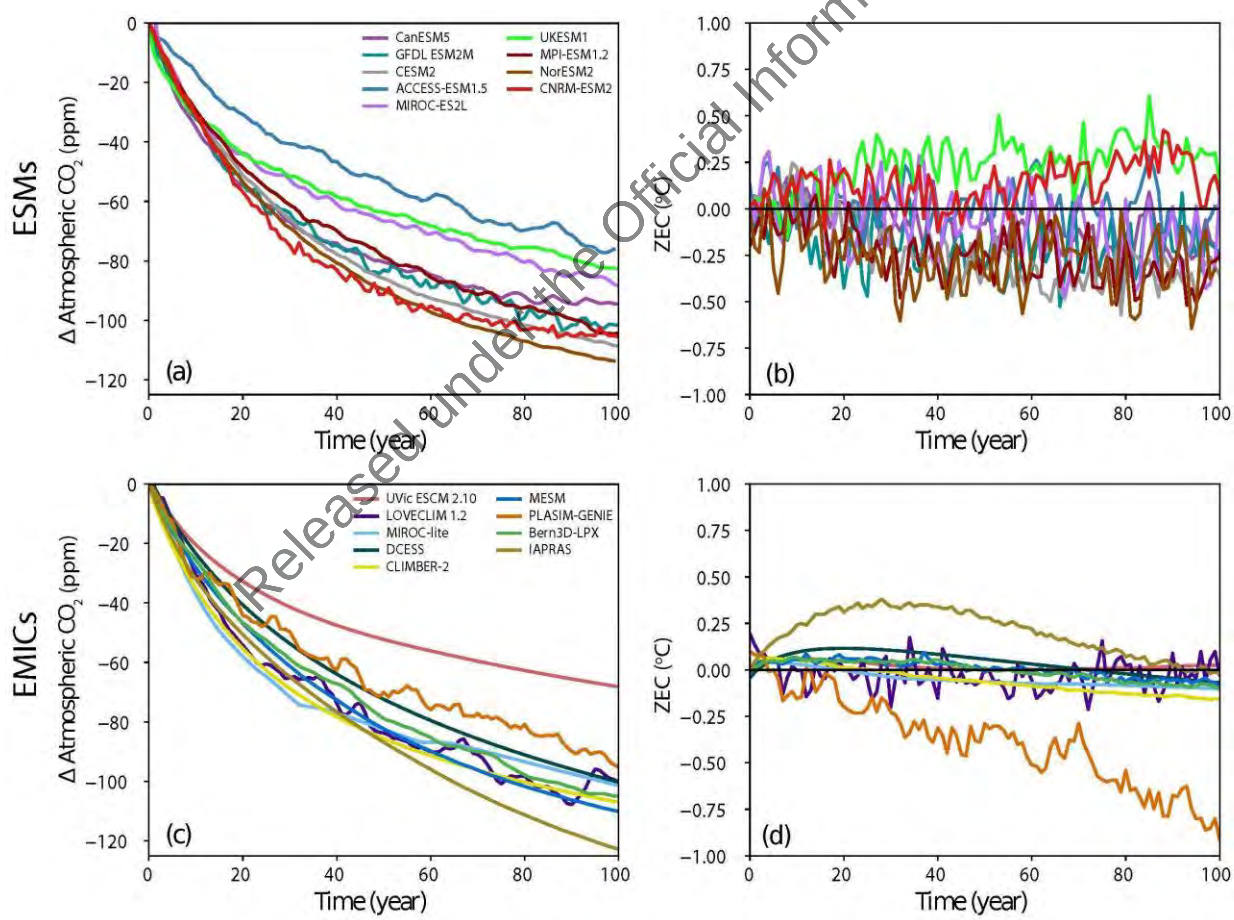

Figure 1: *Atmospheric* CO_2 *concentration anomaly and (b, d) Zero Emissions Commitment*

[5] The amount of additional warming that occurs when global CO_2 emissions are instantaneously brought to net-zero.

following the cessation of emissions during the experiment wherein 1000 PgC was emitted according to the methods in the 1% experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. The top row shows the output for Earth System Models (ESMs), and the bottom row shows the output for Earth System Models of Intermediate Complexity (EMICs) (MacDougall et al., 2020).

The current evidence across the scientific literature therefore suggests that we do not expect significant additional warming above that seen already due to past long-lived GHG emissions. However, important uncertainties still remain, including through processes that are difficult to accurately simulate within the current generation of complex climate models, such as the role of future thawing of the permafrost and future wildfires. Nevertheless, some of the more dire warnings of tipping points (e.g., Steffen et al., 2018) are not born out in more careful assessments (e.g., Turetsky et al., 2020). It remains likely that the future amount of GHG emissions from the global economy emitted on the pathway to net-zero emissions will be significantly more important to future levels of warming realized than the warming arising from changes in natural carbon sinks this century due to feedbacks from Earth system processes that aren't typically included within carbon budget estimates. Nevertheless, estimates of these additional feedbacks can be factored into remaining carbon budget estimates (e.g., Table 2.2 in Chapter 2 of SR1.5), although it is difficult to estimate exactly how quickly or slowly these additional emissions might enter the atmosphere. It is unlikely that all of these Earth system emissions would have occurred by the time global CO_2 emissions must have reached net-zero by around 2050 and warming peaked to keep to the temperature level of the Paris Agreement long-term temperature goal (see SR1.5 Chapter 2, Rogelj et al., 2018a,b and Rogelj et al., 2019).

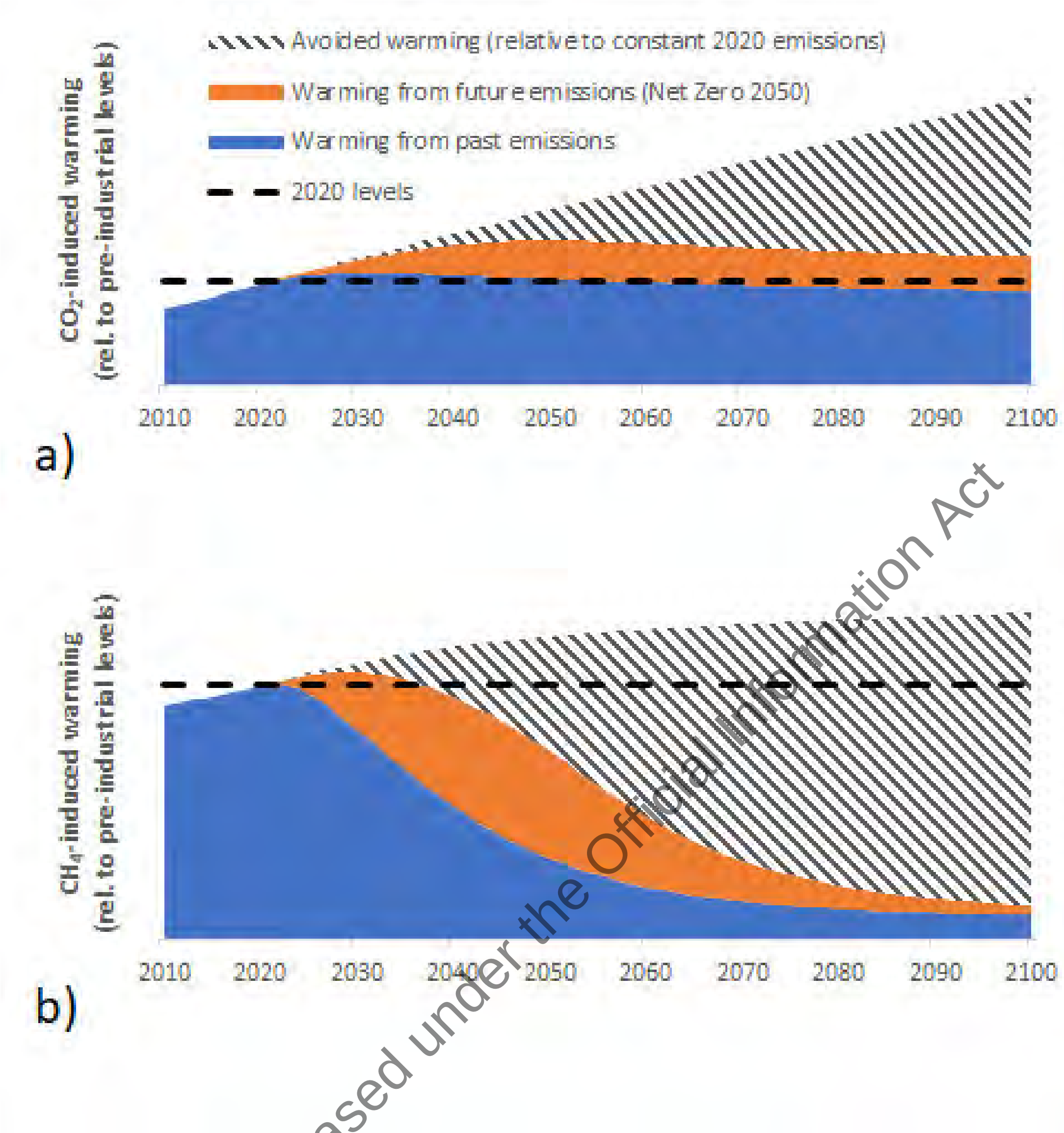

Figure 2: *A stylised illustration of commitment from past emissions to future warming and how much future global temperature is dependent on future and past emissions – for two gases CO_2 (top) and CH_4 (bottom). The blue area represents a case with an instant drop in emission to zero after 2020, illustrating the commitment from past emissions only on future global temperatures. The orange area shows the warming arising only from future emissions in a scenario in which CO_2/CH_4 emissions decline linearly from 2020 to (net-) zero emissions in 2050. The hatched area shows the avoided warming wedge between the case with declined emission to zero in 2050 (orange case) and a case with constant future emission at 2020 levels. The dashed lines show levels of global temperature rise above pre-industrial levels from CO_2/CH_4 emissions in 2020.*

For *Short Lived GHGs* (SLGHG) (CH_4, some F-gases) their global temperature impact depends (as a first order approximation) on the sustained *rate* of emissions. In contrast to the long-lived gases their emissions need only to be gradually reduced and not stopped altogether to prevent further contributions to ever increasing global temperature. An increase in their emission rate, not simply continued emissions will add to future warming. It is important to note that any level of sustained short-lived GHG emissions would still sustain raised global temperature above pre-industrial levels (as does achieving net zero CO_2). Therefore, to reduce their historical contribution to temperature change SLGHG emissions rates need to be reduced whereas net negative emissions of LLGHGs are needed to reduce historical contribution to global temperature from LLGHG emissions. The lower the emissions rate of SLGHGs the lower the contribution of sustained SLGHG emissions to global temperature. Furthermore, emissions of SLGHGs also have longer-term climate impacts through their impact on carbon cycle (e.g., Gasser et al. 2017) and on other climate variables (e.g., sea level rise - Zickfeld et al., 2017), that are not reversed simply by reducing their sustained emissions rates.

The different lifetimes of the two gases (CO_2 and CH_4) is fundamental for understanding how past emissions of these gases affect future warming and the role of additional future emissions on top of the committed warming from past emissions. Figure 2 shows in a stylised way the different behavior of these two gases. While for CO_2 the warming from pre-2020 emission remains approximately constant over the century, the warming from past emissions of CH_4 decays over the coming decades (although doesn't disappear entirely). These differences are also important to bear in mind when different metrics are used for comparing effects of emissions (see Section 2.4). In spite of the very different warming profiles, reducing emissions of both gases will significantly contribute to reduced future warming and would help achieve the long-term temperature goal. For CO_2, this abatement comes from avoiding future emissions that add to the committed historical warming from past emissions. For CH_4, this principally comes from emissions reductions that reduce the level of global temperature rise above preindustrial levels that would have been sustained if emissions were kept at current rates.

In summary, both long and short-lived greenhouse gas emissions contribute to keeping global temperatures above pre-industrial levels, but they do so in different ways. For short-lived gases it is via their emission rates. For long-lived gases it is via their cumulative emissions. Abatement from emissions of both short- and long-lived gases benefit the global climate.

1.2.2 Non greenhouse gas emission changes

Changes in emissions that affect aerosol and those that affect ozone concentrations change future temperature and how close we are to temperature targets. Although generally 20-30 years of near-term warming is expected from reducing aerosol pollution following a combination of climate mitigation policies and air quality policies (Shindell and Smith 2019; Samset et al. 2018), near term warming can be limited with well-designed policies targeting both short and long-lived pollutants (Shindell and Smith, 2019). Forster et al. (2020) and Weber et al. (2020) examined the climate response to COVID-19 restrictions and showed that some of the short term warming from reduced SO_2 emissions and less aerosol cooling was offset globally by a large near-term reduction in NOx and ozone from reduced transport emissions. This suggests reducing road transport emissions at the same time as SO_2 emissions would lessen any near-term warming.

1.3 Scientific developments

Since the IPCC 5th Assessment Report (AR5), scientific knowledge has developed further with improved understanding of several key processes in the climate system, and longer and improved observation series. The adoption of the Paris Agreement increased the focus on differences between 2°C and 1.5°C in terms of climate responses and impacts, as well as emission pathways compatible with the Paris Agreement ambitions, summarized in the recent IPCC Special Reports. Their assessments also confirm that the fundamental understanding of the climate system has remained largely the same since AR5. From consistency across these reports, there is a robust understanding of what needs to happen to global emissions to meet the temperature goal of the Paris Agreement. This requires reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing (primarily driven by the rate of SLGHG emissions) to halt anthropogenic global warming.

In spite of the fundamental understanding remaining largely unchanged, uncertainties in radiative forcing and climate sensitivity affect the relationship between emissions and surface temperature change, and there have been some relevant developments in these areas which are discussed below.

1.3.1 Climate sensitivity

The latest generation of climate models from the sixth climate model intercomparison exercise (CMIP6) warm more than the previous generation and generally have greater equilibrium climate sensitivities (Forster et al., 2019). However, a five-year assessment of climate sensitivity comparing estimates using paleoclimate evidence, physical process evidence and the evidence from the 1850-2018 period (Sherwood et al., 2020) finds a much more constrained likely range for the equilibrium climate sensitivity that is robustly within 2.3 to 4.5°C. These estimates did not directly rely on the new generation of climate models so provides an independent assessment against which the new generation of complex climate models can be compared. This comparison suggests that the high warming estimates from some of the climate models are unlikely but cannot be ruled out entirely (Forster et al., 2019).

This updated evidence on the climate sensitivity indicates that the likely range of global warming projections due to uncertainty in the climate system response for projections of future climate changes under different global GHG emissions scenarios would have a narrower range than similarly presented ranges in SR1.5 and AR5. As this revised uncertainty in the Earth's climate sensitivity largely affects the tails of the distribution, the central estimates of projected warming for the same emission scenario would likely still remain similar to those shown in SR1.5 and AR5 (see Figure 3). The low estimates of warming have firmed up and are slightly larger than before, whereas the high-end estimate remains somewhat uncertain.

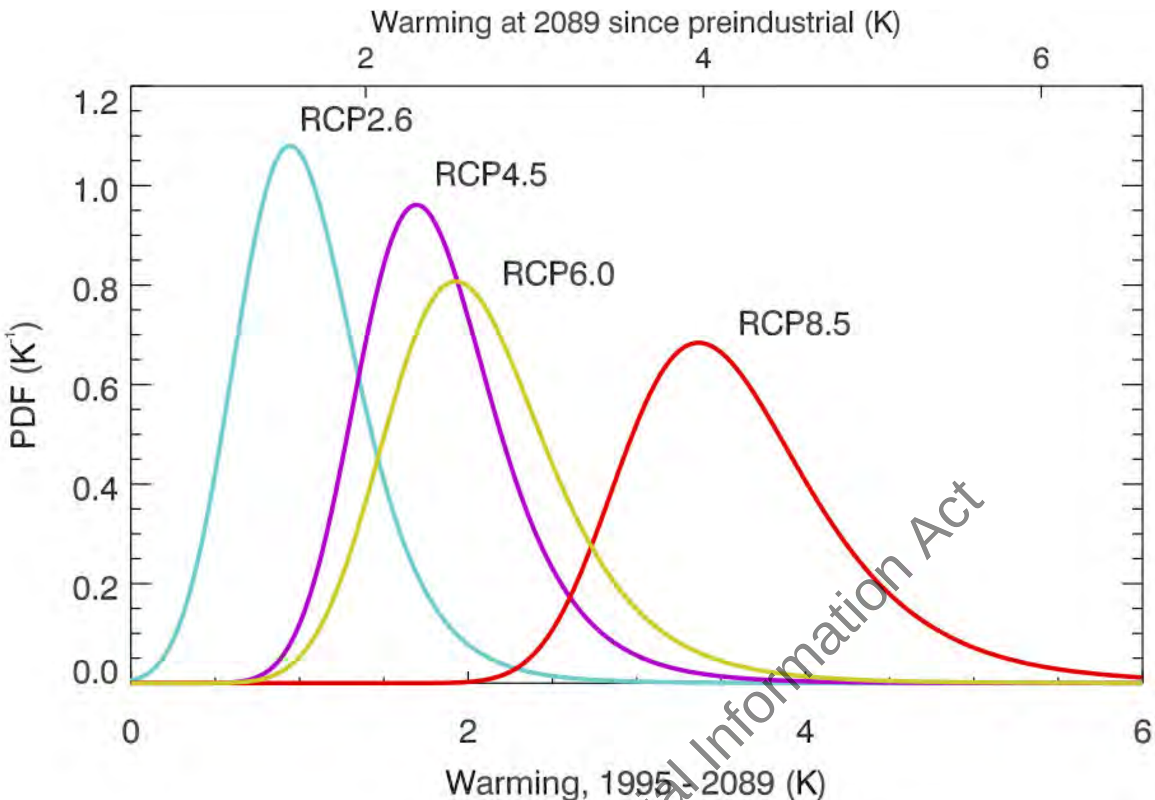

***Figure 3**: Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).*

1.3.2. Radiative Forcing and Global Warming Potentials

The Effective Radiative Forcing (ERF) introduced in IPCC AR5 has now become the accepted way to compare the magnitude of different climate change mechanisms (Richardson et al., 2019). The ERF includes cloud related adjustments to the more traditional stratospherically adjusted radiative forcing, allowing a better comparison of the effect on global surface temperature across forcing agents.

The establishment of ERF as the standard measure of forcing can help improve the estimates of GHG metrics (such as the GWP), including for methane. A number of other factors studied in recent publications may also influence the GWP value for methane:

- Moving to ERF increases CO_2 radiative forcing but leads to a decrease in methane radiative forcing from cloud adjustments (Smith et al. 2018).
- Etminan et al. (2016) include the shortwave forcing from methane and updates to the water vapour continuum and account for the overlaps between carbon dioxide and nitrous oxide.
- Thornhill et al. (2020) quantify the indirect effect of methane on ozone radiative forcing based on several models and strengthen the knowledge basis about indirect effects of methane.

- The results of Wang and Huang (2020) show that due to high cloud changes the stratospheric water contribution to methane GWP-100 which was 15% in AR5 might be closer to zero in the ERF framework. This change would be additional to the adjustments outlined in Smith et al. (2018) and in of itself it would *decrease* the GWP.
- Gasser et al. (2017) and Sterner and Johansson (2017) give descriptions of how to account for climate carbon cycle feedbacks in emission metrics. AR5 Working Group I included this feedback for non-CO_2 gases, which up to then was only included for the reference gas CO_2, and imply an underestimation of GWP values for non-CO_2 gases. Due to lack of sufficient literature at the time of writing AR5, the inclusion of this feedback effect was presented as tentative.

Studies have not yet applied these results or combined these analyses for an overall estimate of methane GWP. At this stage it is difficult to be more quantitative regarding the net result, but the IPCC Sixth Assessment Report will attempt to assess these and other studies, bringing different lines of evidence together to form a new comprehensive assessment.

For CH_4, the GWP value also depends on whether the carbon is of biogenic or fossil origin. When oxidised, fossil methane will introduce additional CO_2 to the atmosphere. The metric value for fossil methane will therefore be slightly higher than for biogenic methane. Thus, AR5 Working Group I gave two values for the methane GWP-100; i.e., 28 for biogenic and 30 for fossil methane. It was pointed out that "In applications of these values, inclusion of the CO_2 effect of fossil methane must be done with caution to avoid any double-counting because CO_2 emissions numbers are often based on total carbon content. Methane values without the CO_2 effect from fossil methane are thus appropriate for fossil methane sources for which the carbon has been accounted for elsewhere, or for biospheric methane sources for which there is a balance between CO_2 taken up by the biosphere and CO_2 produced from CH_4 oxidization."

Other updates are also available in the literature, e.g., Hodnebrog et al. (2020) gives an update of radiative efficiency and GWP and GTP values for halocarbons. New radiative efficiencies calculations are presented for more than 400 compounds in addition to the previously assessed compounds, and GWP calculations are given for around 250 compounds. Present-day radiative forcing due to halocarbons and other weak absorbers was estimated to be 0.38 [0.33–0.43] W m^{-2}, compared to 0.36 [0.32–0.40] W m^{-2} in IPCC AR5 (Myhre et al., 2013), which is about 18% of the current CO_2 forcing.

1.3.3 Surface temperature projection estimates

Climate model emulators such as FaIR and MAGICC (employed in SR1.5) are often used to estimate global warming futures across multiple scenarios. Such reduced complexity climate models can either be set up to mimic the behaviour of global-mean surface temperature change from more complex models or can be set up in probabilistic form to match the assessed range of climate sensitivity and effective radiative forcing from other assessments or lines of evidence. Due to the prominent role of such models in projecting net zero scenarios in SR1.5, an intercomparison is currently underway (https://www.rcmip.org/) between a variety of these reduced complexity models. Preliminary results from this show that such models generally work well for projections of global surface temperature (Nicholls et al., 2020). Such models based on updated estimates of ERF and climate sensitivity can provide the basis for calculating national emissions contributions to global temperature changes and could also be used to understand the direct global temperature impacts of New Zealand's emissions (see Section 3.1).

2. Trade-offs in global emissions pathways to keep warming to 1.5°C

At a global level, different combinations of future long-lived and shorter-lived GHG emissions trajectories can be consistent with achieving the long-term temperature goal of the Paris Agreement. This section looks at the understanding of possible combinations of cumulative long-lived GHG emissions and sustained emissions rates of shorter-lived GHGs that could be consistent with an overall global temperature trajectory consistent with the Paris Agreement.

2.1 Understanding GHG trade-offs determining the level of peak warming reached

Physically, warming could be kept to 'well-below' 2°C or below 1.5°C with a range of possible combinations of global future cumulative LLGHG emissions and global SLGHG emissions rates.

Fundamentally, there are three key contributions from future emissions to the level of peak warming reached:

1. The level of global temperature increase above pre-industrial levels arising from future cumulative LLGHG emissions between now and the timing of reaching net zero. This warming is additional to that caused by past-emissions of LLGHGs.[6]
2. The level of global temperature increase sustained by the rate of SLGHG emissions over the couple of decades prior to peak warming. Depending on whether the global emissions rates are higher or lower than values over the recent past, the level of global temperature rise above pre-industrial levels sustained by global SLGHG emissions could be greater, the same, or lower than the level of global temperature rise above pre-industrial levels sustained by these emissions today.
3. Changes in the levels of global temperature decrease below pre-industrial levels that are sustained by global human emissions of aerosols (which have a net cooling effect on the climate). These emissions are also shorter-lived meaning that the contribution from these emissions to peak warming largely depends on the emissions rate of the aerosols. Some aerosols emissions are often co-emitted with GHG emissions, so efforts to reduce emissions in the future and improve air quality mean that global emissions of aerosols are expected to be reduced in the future, meaning that they are expected to suppress less the GHG induced warming at the time of peak warming than they do today.

[6] Nitrous oxide emissions have a perturbation lifetime of ~100 years in the atmosphere, meaning that, unlike carbon dioxide, some of the warming caused by past nitrous oxide emissions early in the historical record will have decayed away. For the purposes of future nitrous oxide emissions over the next several decades, nitrous oxide can be treated largely analogous to CO_2 when converted through the GWP-100 metric to CO_2-equivalent emissions.

Variations in any one of these three factors has implications for the combinations of the other two that would be consistent with a given climate outcome. Emissions of aerosols are not formally regulated under climate policy frameworks (such as the Paris Agreement) so changes in aerosol emissions are often considered as exogenous to climate policy considerations on the balance of GHG emissions, despite not being entirely independent.

Overall, the higher the global rates of SLGHG emissions the lower the cumulative total of LLGHG emissions that would be consistent with keeping expected peak warming to any level and vice versa the lower the global rate of SLGHG emissions the greater the cumulative total of LLGHG emissions. These physically-based trade-offs have been illustrated in the literature through the use of simple climate models (e.g. Leahy et al. 2020) and summarised by the IPCC in Figure SPM1 of the Special Report on Global Warming of 1.5°C.

Alongside the use of simple climate models, the relationship between different futures for global cumulative long-lived GHG emissions and reductions/increases in the rate of global short-lived GHG emissions for can be explored for a wide range of situations using new emission metrics (see Section 2.4); e.g., proposed metrics that more directly measure the 'warming-equivalence' between long-lived and short-lived GHG emissions (Allen et al., 2016, Allen et al., 2018, Collins et al., 2018, Cain et al., 2019, Collins et al., 2020).[7] An application of these metrics to approximate trade-offs between global methane emission futures and futures of long-lived GHGs are shown in Figure 4.

Table 1 provides conversion factors to approximate the amount of cumulative carbon dioxide emissions that would create the same warming as a sustained change in the emissions rate of a shorter-lived GHG such as methane. Whilst there is some variation across time horizons for these factors, the fractional variation is significantly reduced relative to conventional metrics (e.g., global warming potential - Section 2.4), suggesting that comparing pulses of LLGHGs and sustained emissions rates of SLGHGs provides the most robust approximation for the effects on global temperature across a range of timescales, and could be used to explore a wide range of scenarios.

[7] Collins et al. (2018), applied a process-based approach to assess the importance of methane reductions for the 1.5°C target. Their modelling approach included indirect effects of methane on tropospheric ozone, stratospheric water vapour and the carbon cycle. They find a robust relationship between decreased CH_4 concentration at the end of the century and increased amount of cumulative CO_2 emissions up to 2100. This relationship is independent of climate sensitivity and temperature pathway. In terms of relation between end of the century emission changes in CH_4 and CO_2, their results achieve similar results as those obtained by Allen et al., 2016 in a GWP* context. Collins et al., 2018, also point out that the non-climate benefits of mitigating CH_4 can be significantly larger than indicated by IAM studies.

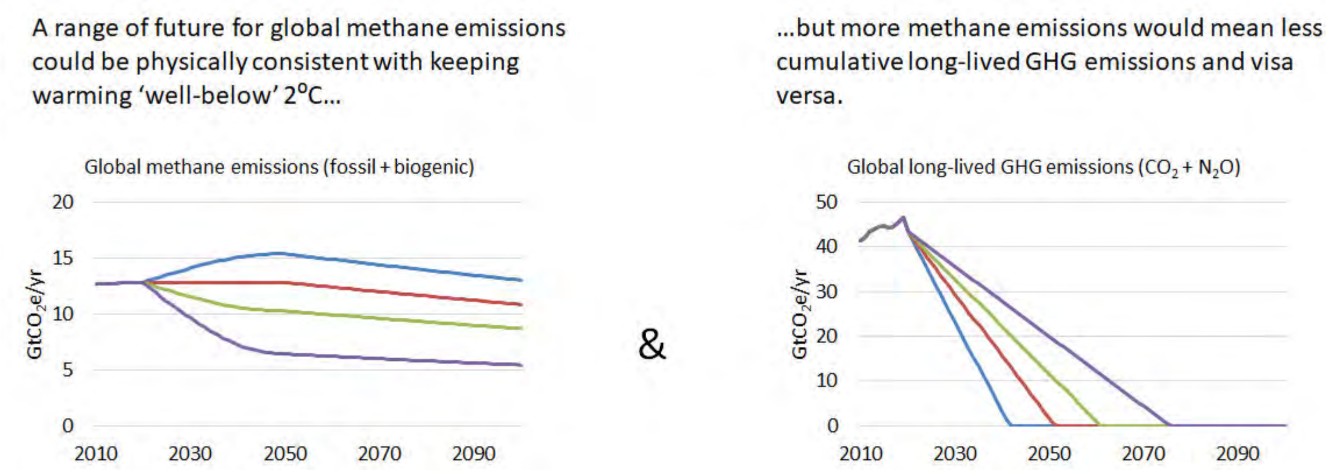

Figure 4: *Stylised trajectories that illustrate the trade-off between global trajectories for anthropogenic methane emissions (fossil and biogenic sources) and long-lived GHG emissions using the framework of Cain et al. (2019). Trajectories are constructed to keep expected peak warming to approximately 1.75°C above pre-industrial levels.*[8]

Table 1: Equivalence between CO_2 and CH_4 emissions under the combined global temperature potential (CGTP) metric of Collins et al. (2020).

Time horizon	50 years	75 years	100 years
Size of pulse of CO_2 emissions ($GtCO_2$) with equivalent warming effect to a sustained 1 $MtCH_4$/yr change in CH_4 emissions rates depending on time horizon	3.3	3.7	4.0

2.2 Tradeoffs between GHGs after peak warming

Section 2.1 summarized how the trajectories of SLGHGs and LLGHGs relate to each other prior to peak warming for efforts to keep warming to below a particular level. After reaching peak warming the evolution of both long-lived and short-lived GHGs will also be important for whether temperatures remain constant or fall from their peak.

[8] These trajectories assume a present-day (2020) warming of around 1.2°C, consistent with the definition of present-day warming (GSAT) used for carbon-budget calculations in IPCC-SR1.5, and a TCRE of 0.45°C/TtCO_2 consistent with IPCC SR1.5 Ch2. A contribution to future warming from aerosols is approximated through a 0.4Wm^{-2} increase in net aerosol forcing between 2020 and mid-century consistent with typical modelled global emissions pathways that keep warming to 1.5°C with no or low overshoot. Methane emissions trajectories are specified to fall at approximately the rate required to not add to further warming after 2050. Emissions are expressed as CO_2-equivalent values using the Global Warming Potential metrics (time horizon of 100 years) from the IPCC 5th Assessment Report (including carbon-climate feedbacks).

Reductions in global temperature after peak warming could occur due to either net anthropogenic removals of long-lived GHG emissions from the atmosphere (e.g., direct air capture of carbon and storage) or through permanent falls in the annual rate of short-lived GHG emissions after the time at which peak temperature is reached whilst long-lived GHG emissions remain at net-zero. Table 1 provides a way to estimate the magnitude in the reduction of the annual global CH_4 emissions rate below the levels at the timing of peak warming that would be required to achieve a given level of cooling over a specific period. Based on mid-range estimate of the transient climate response to cumulative emissions (TCRE) of 0.45°C/TtCO_2 a cooling of around 0.2°C over 50 years after temperature peaked would require a cumulative net active removal of CO_2 from the atmosphere of around 445 GtCO_2 over this 50 year period[9]. Table 1 indicates that this same cooling effect could also be created by a permanent reduction in the rate of global methane emissions by around 135 MtCH_4/yr below the levels over the couple of decades prior to the timing of peak warming.

2.3 Modelled economic least-cost global pathways

Global GHG emissions trajectories consistent with the Paris Agreement are often studied using Integrated Assessment Models (IAMs). These models of the energy and land-use systems allocate emissions reductions across sectors, countries, and gases to keep the overall 'net present cost' of the emissions reduction pathway as low as possible whilst constraining global emissions to pathways expected to be consistent with a specified global temperature goal.[10] These modelled pathways, regularly summarised and applied in the IPCC assessment reports and intergovernmental documents such as the 'Emissions Gap' reports from UN Environment, can be useful indicators of what an idealised 'cost-effective' global emissions pathways might look like across sectors, gases and regions, but do not explicitly incorporate additional considerations of fairness, political will or institutional capability which will all be important additional determinants of how reductions are shared across sectors, gases and regions in the real world.

The balance of effort between reductions in different GHGs across the full range of pathways produced by international modelling groups used in the IPCC Special Report on Global Warming of 1.5°C is summarised in Table 2, with trajectories for LLGHGs (CO_2 and N_2O) and biogenic CH_4 from these simulations shown in Figure 5.[11] As now relatively widely known, these pathways require significant deviations in the historical trends of global emissions. Whilst technological progress (including the falling costs of renewable power generation) has helped shift projected future emissions trajectories away from the highest emissions futures, expected emissions at the global level out to 2030 remain far from these trajectories (UNEP, 2020).

This scenario set is not a statistically well-defined set of simulations and should not be treated as such. It includes simulations where particular technologies are explicitly excluded as contributing

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[9] Assuming a perfectly symmetric global temperature response to positive and negative CO_2 emissions.
[10] In many IAMs this is achieved using a 'shadow value of carbon' for all emissions. This is typically applied to non-CO_2 GHG emissions using the global warming potential (GWP) metric for a 100-year time horizon.
[11] Methane emissions from the energy sector are not included within these plots but are an important source of emissions at the global level.

to the emissions reductions (e.g., nuclear) and come from a wide set of models with varying levels of detail regarding the representation of energy system technologies, varying assumptions regarding their relative costs, and varying assumptions about global developments (e.g., population, economic growth and development) in the absence of climate policies or impacts. Some scenarios also impose specific behavioural change (e.g., diet preferences) future exogenous to the modelling framework (van Vuuren et al., 2018). Differences in the evolution of the global energy systems can be larger between different models as it can between different levels of climate ambition within the same model. Although the differing assumptions and outcomes in the land and agriculture sector have been studied (Popp et al., 2017), it is difficult to clearly identify the drivers of differences between the high-level global emissions outcomes without additional targeted experiments, and the fundamental drivers of different balances between reductions in biogenic methane and LLGHGs within these modelling frameworks in pursuit of ambitious climate objectives remain poorly understood.

Table 2. *Summary statistics of global cost-optimal pathways (median is given, with max and min in parentheses - long-lived GHG emissions include only CO_2 and N_2O aggregated using GWP-100 value of 298). 'Biogenic' methane is here approximated as all non-energy sources including both agricultural and waste sources. Globally biogenic methane emissions rates were estimated to be around 220 $MtCH_4$/yr in 2015 from observationally-based datasets (Hoesly et al., 2018).*

Scenario grouping	Cumulative LLGHG emissions from 2020 to 2050 - $GtCO_2e$	Cumulative LLGHG emissions from 2020 to peak warming - $GtCO_2e$	Rate of LLGHG emissions at 2030 - $GtCO_2e$/yr	Rate of LLGHG emissions at 2050 - $GtCO_2e$/yr	Rates of biogenic CH_4 emission at 2030 - $MtCH_4$/yr	Rates of biogenic CH_4 emission at 2050 $MtCH_4$/yr	Rates of biogenic CH_4 emission over 20 years prior to peak warming $MtCH_4$/yr
1.5ºC (~50% probability)	545 (325 - 705)	535 (360 - 810)	23 (14 - 28)	2.3 (-8.3 - 12)	180 (110 - 230)	140 (60 - 200)	175 (100 - 240)
<2ºC (~66% probability)	790 (580 - 1060)	930 (625 - 1430)	30 (20 - 46)	12 (1.9 - 20)	190 (160 - 300)	155 (115 - 205)	155 (100 - 245)

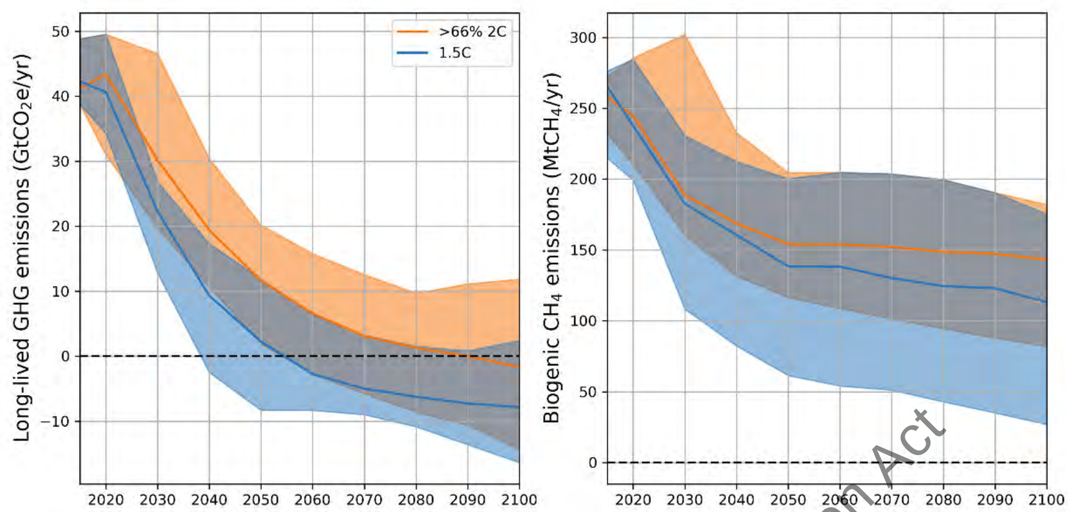


***Figure 5:** The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for Long-lived GHGs (CO_2 and N_2O) and biogenic CH_4. Solid lines denote the median of the scenario set.*

Figure 5 illustrates the different roles the gases CO_2, CH_4 and N_2O can play in future model-based emissions pathways that are compatible with the temperature ambitions of the Paris Agreement. The global emissions of CO_2 have to go to net zero around the middle or second half of the century, depending on level of temperature ambition. Large reductions in CH_4 and N_2O are also generally found in these modelled pathways but there is more variation. The model studies found that strong reductions in methane are simulated in all pathways, but zero CH_4 is not achieved in any pathway. This non-zero global residual CH_4 emission is due to the assumed cost of reducing the remaining CH_4 emissions not because of its physical properties (Harmsen et al., 2019). For N_2O, the pathways show smaller reductions or even modest increases depending on the degree of future fertilizer use. N_2O emission pathways also do not reach net-zero. The large spread in possible pathways for emissions of CH_4 and N_2O are worth noting, reflecting different assumptions about abatement costs including potential for demand-side changes. However, in the vast majority of these modelled least economic cost global pathways, biogenic CH_4 emissions are seen to decline strongly by mid-century. This reduces the level of global average CH_4-induced warming relative to the warming these emissions are causing at present.

Peak warming generally occurs around 2050 in scenarios that keep warming to 1.5°C with ~50% probability - approximately corresponding with the date of global net-zero CO_2 emissions (Figure 2.6 in UK CCC, 2019). Although net long-lived GHG emissions remain positive at the time of peak warming (due to some residual N_2O emissions in all scenarios), the effect of falling methane emissions over the decades prior to 2050 (which reduces CH_4-induced levels of global

temperature rise) temporarily acts to offset some of the temperature implications of these residual long-lived GHG emissions, sufficient to bring global temperature to a peak.[12]

Many of these scenarios continue to reduce CO_2 emissions further so that global CO_2 (and long-lived GHG) emissions go net-negative. This has the effect of reducing temperatures after peak warming has been reached, but doesn't significantly contribute to the level of peak warming achieved. In many scenarios that peak warming at around 1.5°C (or less than 0.1°C of overshoot) by 2050 the net-negative CO_2 emissions largely contribute to temperatures declining from their peak to around 1.3°C by 2100. Alternative pathways exist that would avoid these net-negative emissions - for example Rogelj et al. (2019) shows that pathways which reach net-zero CO_2 emissions around 2040 and then maintain this level still achieve a peak temperature around 1.5°C with warming remaining around this level out to 2100, in part due to the continued reduction of global methane emissions after warming peaks acting to offset any increases in the level of global temperature due to non-zero residual (non-CO_2) long-lived GHG emissions. In the long-term (centennial timescales) it may be necessary to have a certain amount of net negative global CO_2 emissions even to sustain global temperature at a constant level. This is to counter any slow Earth System feedbacks such as permafrost thawing which would add to atmospheric concentrations (and therefore warming) over long timescales (see Section 1).

After the completion of SR1.5, new scenarios have been developed by various scenario groups. These may give more insight to cost optimal emissions pathways for these gases and provide a stronger knowledge basis for options to reach the temperature goals.

2.4 Emission metrics

The Global Warming Potential (GWP) is defined as the time-integrated radiative forcing (RF) due to a pulse emission of a non-CO_2 gas, relative to a pulse emission of an equal mass of CO_2. It is used for expressing the effects of different emissions on a common scale; so-called 'CO_2 equivalent emissions'. The GWP was presented in the First IPCC Assessment, where it was stated that "It must be stressed that there is no universally accepted methodology for combining all the relevant factors into a single global warming potential for greenhouse gas emissions. A simple approach has been adopted here to illustrate the difficulties inherent in the concept, …".

Since then, the GWP has become a widely used metric for aggregation of different gases to 'CO_2 equivalent emissions' in the context of reporting emissions as well as in designing and assessing climate policies. The GWP for a time horizon of 100 years was adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol.

[12] This compensatory effect of falling methane emissions could only temporarily offset the additional warming from continued positive emissions of long-lived GHGs, as falling methane emissions could not be maintained forever, ultimately keeping warming constant would require net-zero long-lived GHG emissions to be reached, necessitating net-negative emissions of CO_2 as some level of residual positive agricultural N_2O emissions are expected to be unavoidable.

The numerical values for GWP have been updated in the successive IPCC reports, as a consequence of updated science but also due to the changes occurring in the atmosphere; in particular the CO_2 concentration to which the radiative forcing has a non-linear relation.

Since its introduction, the concept has been evaluated and tested for use in design of mitigation policies. IPCC AR4 stated that "Although it has several known shortcomings, a multi-gas strategy using GWPs is very likely to have advantages over a CO_2-only strategy (O'Neill, 2003). Thus, GWPs remain the recommended metric to compare future climate impacts of emissions of long-lived climate gases." In IPCC AR5, the assessment concluded that "The choice of metric and time horizon depends on the particular application and which aspects of climate change are considered relevant in a given context. Metrics do not define policies or goals but facilitate evaluation and implementation of multi-component policies to meet particular goals. All choices of metric contain implicit value-related judgements such as type of effect considered and weighting of effects over time."

The Paris Agreement text does not explicitly specify any emission metric for aggregation of GHGs, but under the Paris rulebook adopted at COP 24 in Katowice [Decision 18/CMA.1, annex, paragraph 37], parties have agreed to use GWP-100 values from the IPCC AR5 or GWP-100 values from a subsequent IPCC assessment to report aggregate emissions and removals of GHGs and for accounting under NDCs. In addition, it is also stated that parties may use other metrics to report supplemental information on aggregate emissions and removals of greenhouse gases.

After IPCC AR5, new metric concepts have been published; some of them building on the similarity in behaviour of a sustained change in SLGHG and pulse of CO_2 (Allen et al., 2016), similar to the approach explored earlier by Lauder et al. (2013).

This new approach for comparing emissions, denoted GWP*, uses the same GWP values, but apply rate of change in emissions of the short-lived gas, e.g., methane. Cain et al. (2019) refined the concept to better represent the relationship between cumulative CO_2-warming-equivalent emissions and modelled warming in diverse CH_4 mitigation scenarios by taking into account the delayed warming impact of past methane emission increases. Lynch et al. (2020) demonstrated this for idealized cases. Collins et al. (2020) take an analytical approach and derive the combined global temperature change potential (CGTP) metric for calculating an equivalence between a sustained step-change in SLGHG emissions and a CO_2 emissions pulse. Collectively, these metrics that represent SLGHG emissions with a rate of emissions of CO_2 that would have the same impact on global temperatures are known as "warming-equivalent".

These mixed step-pulse metrics can be used to aggregate SLGHG together with CO_2 and approximate the development of temperature relative to a reference year. In this way, the mixed step-pulse metrics allow for inclusion of SLGHG into the relation between cumulative CO_2-equivalent emissions and temperature change.

It is important to note that the two metric concepts GWP* and GWP measure different things. GWP measures the warming effect from emissions of a gas (e.g., CH_4) relative to the absence of that emission, whereas GWP* measures the warming effect from that emission relative to the warming from a reference emissions level. Thus, the physical quantity that is being compared for SLGHGs emissions relative to the warming from CO_2 is different for the two metrics. The differences are shown in the stylised example in Figure 2. For both LLGHGs and SLGHGs their past emissions contribute to global temperatures remaining above preindustrial levels in the future. For LLGHGs the contribution from past emissions persists at current levels for centuries. For SLGHGs their past contribution to temperature change above preindustrial decays over the next few decades (compare blue segments in Figure 2a and 2b). Therefore, the global temperature change contributed by post-2020 CH_4 emissions is quite different to the change in the global temperature level, comparing the 2020 reference level to the level at a future date, unlike for CO_2. This is because the contribution of CH_4 to warming from past emissions will decay over time (Figure 2b).

The fundamental science underlying these metrics is well established and much of the ongoing debate is about the framing and applications of metrics for various questions and contexts.

Metrics can also be used for assessing the concept "GHG balance" as used in Article 4 in the Paris Agreement. Fuglestvedt et al. (2018) tested metrics for calculation of temperature response to various composition of GHGs and found that balance determined using GWP* imply approximately constant temperatures once the balance has been achieved, whereas a balance based on GWP implies slowly declining temperatures when the mix of GHGs contains a significant positive contribution from SLGHGs[13]. This raises issues related to consistency between Article 4 and Article 2 in the Paris Agreement and what the ultimate temperature goal of the agreement is (Fuglestvedt et al. 2018; Schleussner et al., 2019). Tanaka and O'Neill (2018) find that net zero GHG emissions (in terms of GWP-100) are not necessarily required to remain below 1.5°C or 2°C, assuming either target can be achieved without temporarily overshooting these warming levels.

It is useful to consider how trading emissions under GWP-100 affects surface temperature change. Different combinations of LLGHGs and SLGHGs can give the same overall CO_2 equivalent emission trajectory (when aggregated using GWP-100 values) (e.g., Fuglestvedt et a., 2000, Fuglestvedt et al., 2003; Myhre et al., 2013; Allen et al., 2016; Allen et al., 2018). Globally the ambiguity generated for realistic strong mitigation pathways has been found to be important at the 10% level (or 0.17°C) (Denison et al., 2019). However, larger ambiguities could exist at sector and country level; e.g., in countries where methane emissions represent a larger fraction of total greenhouse gas emissions.

Figure 6 illustrates the temperature responses for different and purely hypothetical scenarios for New Zealand. The blue and green lines (or the purple and red) are contributions from pathways with the same total CO_2 equivalent emission trajectory (based on GWP-100) but different trajectories of CO_2 and biogenic CH_4 emissions comprising it. The green pathway has 47% biogenic CH_4 reductions by 2050 but at the expense of extra CO_2 emissions (to match the CO_2-equivalent emissions of the blue line) and does not reach net zero CO_2 emissions by 2050, which

[13] Balance based on GWP could theoretically lead to a warming effect if SLGHG removal is used to balance ongoing CO_2 emissions on a large scale.

happens in the blue pathway. Over this century the extra biogenic CH_4 reduction under the GWP-100 CO_2 equivalent assumption (green line) leads to lower contributions to global temperature than scenarios with identical aggregated GWP-100 emissions but lower cumulative CO_2 emissions. However, after 2100, the long-term warming effect of the extra CO_2 emissions dominate (substituted for CH_4) and give a continuing warming trend due to not achieving net-zero CO_2 emissions. Similarly, the purple line includes extra CO_2 emission reduction on top of the 24% CH_4 reduction scenario to match the GWP-100 trend in the 47% scenario. This scenario results in a continued long-term reduction in the contribution to global temperature due to the sustained net-negative CO_2 emissions. Generally, these results show that if New Zealand were to specify a single CO_2-equivalent emission reduction target based on GWP-100, there could be significant difference in the resulting global warming trajectory over century timescales. This is illustrated by the pairs of curves (green and blue, purple and red) in Figure 6 where differences give the scale of the ambiguity introduced and show how these change through time. Put simply, if you mitigate CO_2 as a substitute for CH_4 emissions you get long term benefits (a lower long-term temperature level), and if you mitigate CH_4 and a substitute for CO_2 emissions you get cooling for several decades (at the expense of longer term benefits).

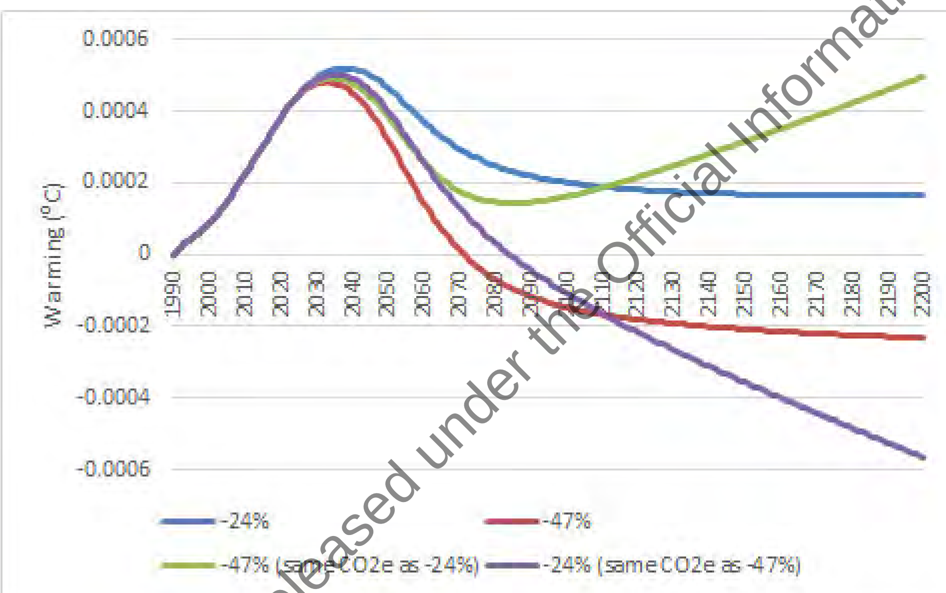


Figure 6: *An illustration of New Zealand's contribution to global warming (relative to the level of its contribution in 1990). The blue and red pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel CH_4, and have either 24% (blue) or 47% (red) reductions in biogenic CH_4 from 2017 levels to 2050. The green line has 47% biogenic CH_4 reduction but additional emissions of CO_2 to match the CO_2e emissions of the blue line based on IPCC AR4 GWP-100 values. The purple line has 24% CH_4 reduction but has extra CO_2 emission reduction to match the CO_2-equivalent emission within the 47% scenario. Emissions from 2050 do not alter. See Section 3.1 for the methodology.*

3. Considerations for national pathways consistent with keeping warming to 1.5°C

Section 2 considered the tradeoffs between mitigation of different greenhouse gases. This section discusses other considerations that could be taken into account in national pathways. There is no fundamental physical reason why a national pathway should follow either the global temperature or the global emissions trajectory, given different national circumstances and different mix of sectors with different long-lived and short-lived greenhouse gases.

3.1 National contribution to global warming.

New Zealand's historic contribution to global warming is estimated to be above 0.01 °C, from large-scale deforestation prior to 1840 (Reisinger and Leahy, 2019). The warming is estimated to be around 0.003 °C from biogenic methane emissions, nitrous oxide and fossil fuel CO_2 (Figure 7). There are also small contributions from F-gases and fossil fuel methane, which are not included in the Figure.

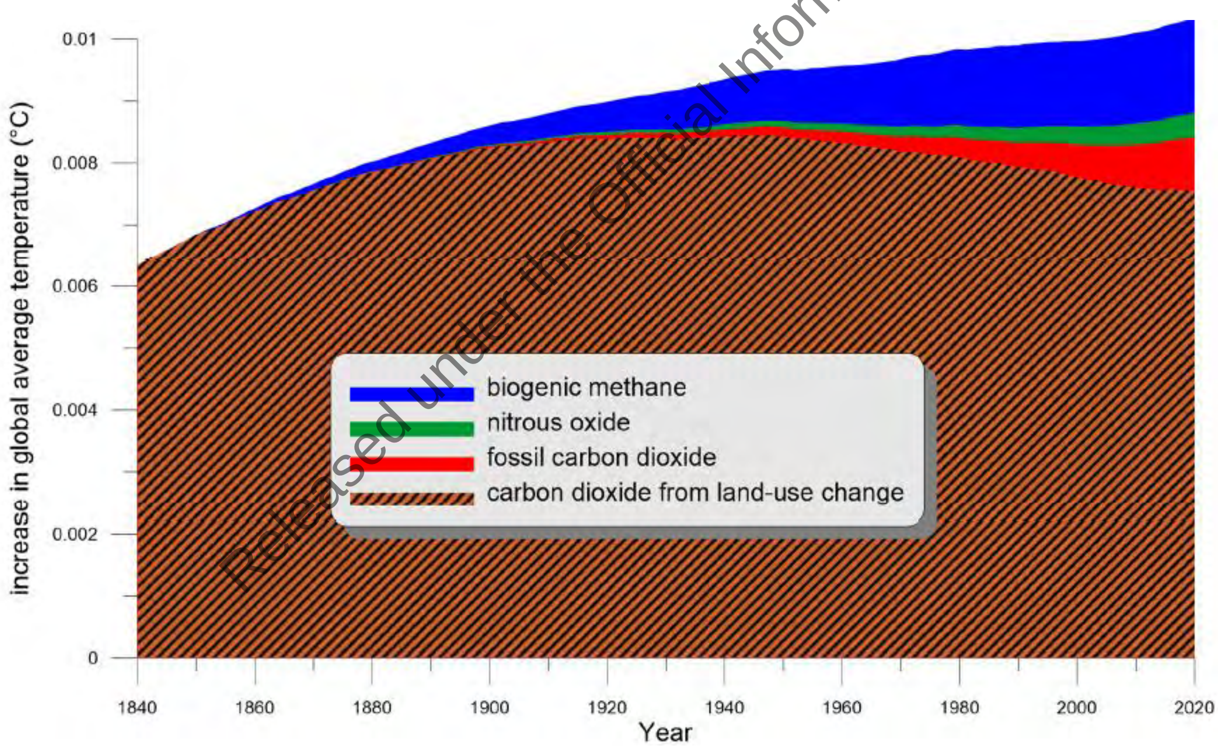


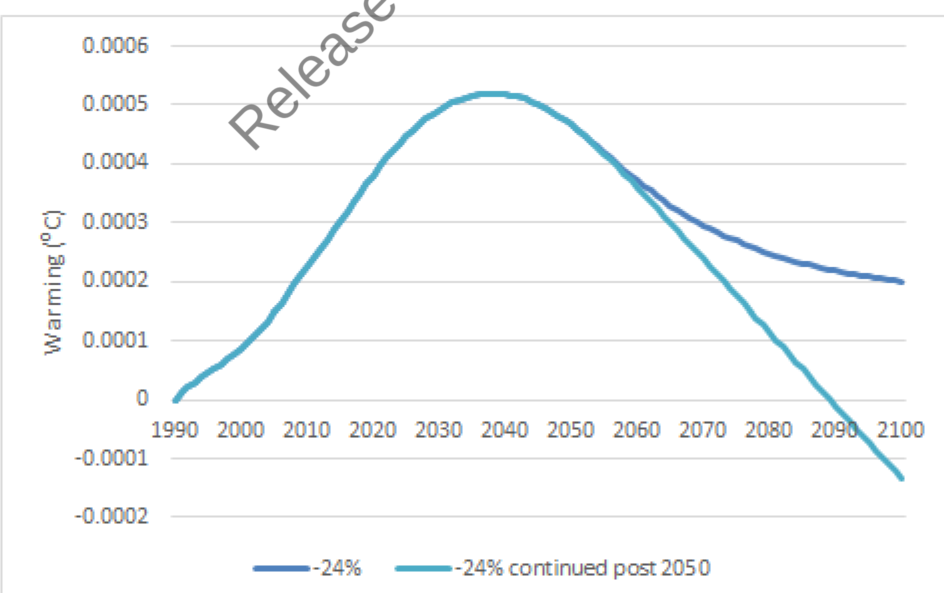
***Figure 7:** Estimate of New Zealand's contribution to global warming from emissions until the end of 2019. Figure is taken from Reisinger and Leahy (2019).*

Figure 8 focuses on estimates of New Zealand's future contribution to global warming from emissions since 1990. New Zealand emissions from 1990-2018 are taken from New Zealand's greenhouse gas inventory and before that are taken from Reisinger and Leahy (2019) using Ausseil et al. (2013). They combine fossil fuel emissions, land-use change and biogenic emissions. The estimates of temperature change use the impulse response functions provided in the IPCC 5th Assessment Report for calculating GHG metrics as a simple climate model. Non-GHG contributions to warming (e.g., aerosol emissions) are not part of these scenarios.

The blue and red curves in Figure 8 approximate the range of New Zealand's possible future contributions to global warming under current policies, with a range of idealised assumptions after 2050. Under both 24% and 47% biogenic CH_4 reduction policies, New Zealand is beginning to reverse its contribution to global warming by around 2040. Under 24% reduction policies, the 2050 contribution to the level of global warming from New Zealand's emission since 1990 matches today's level of New Zealand's contribution to the level of global warming. Under 47% biogenic CH_4 reduction policies, the 2050 level of global warming from New Zealand's emissions approximately matches that from 2015.

Contributions to global temperature rise are sensitive to the shape of the emissions reduction profile as well as the end point reached in 2050 or any other year when mitigation approaches might change. This is particularly so for LLGHG pollutants, but less so for SLGHGs. Early reductions in LLGHGs have lower cumulative LLGHG emissions and overall less climate impact in the longer term (see Section 2.3). However, the most relevant factor for New Zealand's contribution to global temperatures rise above pre-industrial levels over most of this century will be the level of reduction of SLGHGs.

What happens to emissions after 2050 is important for the longer term contribution to global temperatures (see Sections 2.3 and 4.2). This is theoretically explored in Figure 8, which keeps net-zero CO_2 emissions at zero after 2050 and compares options for stable or continued biogenic methane emission reductions. These results illustrate that although the choices of biogenic emission pathway up until 2040 do influence New Zealand's contribution to global warming, the benefits of choosing 47% biogenic CH_4 abatement become more visible after 2040, when pathways are reversing New Zealand's historical contribution to global warming.



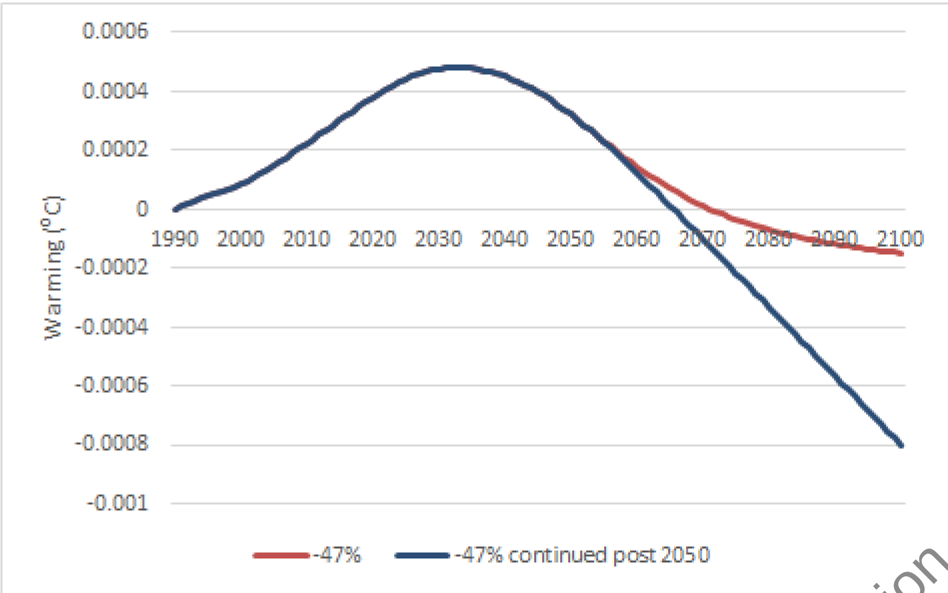


Figure 8: *As Figure 6, except emissions reductions continue beyond 2050. 24% biogenic CH_4 reduction by 2050, shown in the top panel and 47% reduction in the bottom panel. The panels have two scenarios: emissions unchanged after 2050, matching Figure 6, and the biogenic methane reduction rate continuing after 2050.*

Figure 9 explores a scenario where the 47% biogenic CH_4 reduction pathway is planned but biogenic CH_4 abatement does not prove possible, so CO_2 abatement is substituted assuming GWP-100 based equivalence. This pathway would give some more warming in the short term but eventually lead to less warming overall. Continued biogenic CH_4 reductions (as shown in Figure 8) and/or net negative CO_2 emissions (as shown in Figure 9) have a large effect on how much New Zealand's warming contribution is reversed.

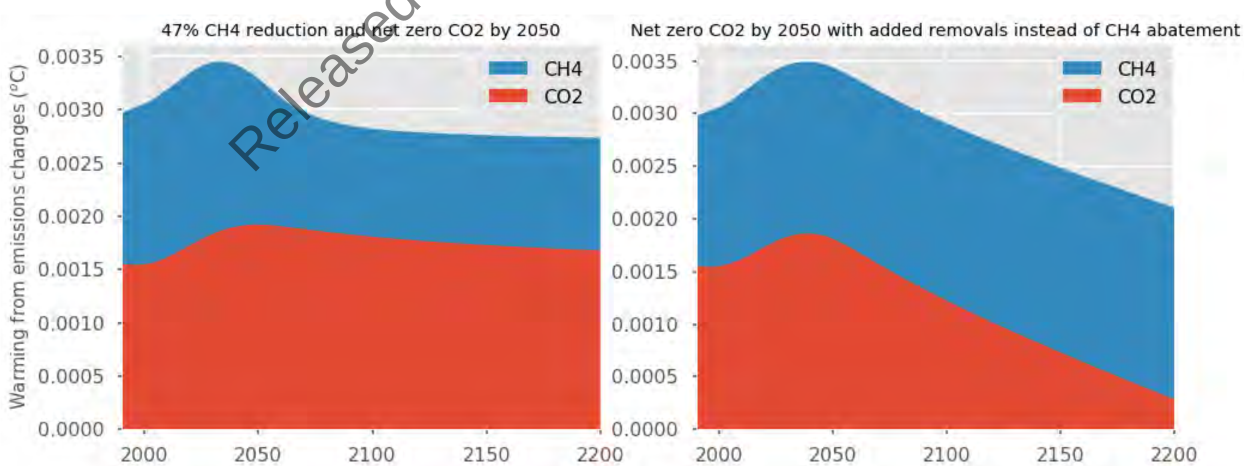


Figure 9: *Changes to warming contributions (above pre-industrial levels excluding emissions from historical land-use change) from different abatement strategies. The left plot shows the 47% biogenic CH_4 reduction scenario until 2050 reaching net zero CO_2 emissions at the same time.*

The right plot shows a scenario where additional CO_2 abatement is substituted for the CH_4 reduction assuming GWP-100 equivalence.

3.2 Fairness and equity

When determining either net zero targets dates or proportioning the remaining carbon budget into national quotas, choices have to be made regarding fairness, equity and burden sharing. These are obviously not straightforward and can have a large effect on levels of ambition for mitigation reduction (see Figure 3.9 from the UK CCC, 2019). It is not possible to include methane emissions scaled by GWP-100 within carbon budget estimates. However, similar equity principles could be applied to CH_4 emissions rates and cumulative CO_2 emissions.

When comparing national emission pathways, it is important to consider different national starting points. The same '1.5°C consistent' mitigation actions measured by cost or other measure of effort could result in different rates of emissions reductions in different regions depending on national circumstances and their respective capabilities to cut emissions. This includes the share of hard-to-abate emissions within a country profile today. For example, if the energy sector is already mostly decarbonised, the national emissions might not fall as quickly as the global average, whose rapid decline over the 2020s in 1.5°C scenarios is associated primarily with the rapid removal of coal from the electricity generation mix. Assessing whether a nation is taking the '1.5°C consistent' actions with its planned emissions reduction pathway may need to be more nuanced than a simple comparison with the global average reductions. It may also consider additional effort, outside of the domestic emissions account that a country might be undertaking to support the global transition (e.g., climate finance provision, purchase of credits through international markets, technology transfer etc.) to form a holistic picture of whether planned action to 2030 is 1.5°C-aligned.

3.3 Net Zero in the context of New Zealand

New Zealand currently plan to reach net zero GHG emissions by 2050 excluding biogenic methane for which a range of reductions in emissions rate by 2050 is being considered. Whether net zero GHG is reached is dependent on the emission metric choice in the way that net zero GHG is defined. As discussed in Fuglestvedt et al. (2018), it can be defined as a balance between anthropogenic emissions and removals, aggregated across gases by a chosen emission metric. The UK and the EU have set net-zero GHG targets based on GWP-100 which would be expected to lead to steadily declining temperatures if achieved globally. The New Zealand goal would not reach net zero GHGs under GWP-100 but would still lead to declining temperatures. Using the GWP* emission metric to assess if national pathways achieve net zero, both the UK and New Zealand goals would be seen as achieving net-negative GHG emissions.

Summary and conclusions

Section 1 presented a brief update of the science on past and future warming from greenhouse gases. Section 2 illustrated global trade-off considerations in strong mitigation emission pathways and Section 3 considered implications for deriving national strategies.

In the further development of policy towards New Zealand's contribution to the global effort of achieving the Paris temperature goals, our report has highlighted several issues and choices that would benefit from consideration. These are outlined below:

4.1 Evolving science

As knowledge is being developed and assessment reports are being published, it is important to be clear and transparent about what is used as the basis for the policy design; i.e. which parameter values and which definitions are adopted and used and how they might be revised as science understanding evolves.

4.2 Abatement choices

Choices of approach not only need to consider the physical science uncertainty but also need to consider the overall objectives of the climate policy and the practicalities of usage and communication. As illustrated in Section 3.1, the selection of greenhouse gases and as well as the emission metric used will have a significant effect on timing and efforts to achieve net zero and on the resulting global warming. The UK legislated for a net zero target in terms of GWP-100 emissions. One of the reasons given was that such a target would actively decrease its future warming commitment over time (see Section 2.1 and 3.1). For New Zealand to continue to decrease its future warming commitment after 2050, additional CH_4 reductions and/or negative emissions of CO_2 would be needed (Section 3.1).

New Zealand, by employing a two-target approach, one for biogenic methane and one for other greenhouse gases, largely avoids complications to do with emission metrics discussed in Section 2.4. However, if at a future date biogenic CH_4 and CO_2 abatements were traded as illustrated in Figure 9, the way of doing this trading would need to be considered. Using a GWP-100 metric would lead to long term additional cooling effect but shorter term additional warming when using carbon dioxide removal as a substitute for methane abatement (see Figure 9). However, other metric choices for trading between the gases could be considered. More generally, Sections 2.2 and 3.1, showed how it is possible to reverse the global warming trend and/or a nation's contribution to it by either a net removal of cumulative CO_2 emissions or by a permanent reduction in the rate of methane emissions below the levels at the time of peak warming. Where 445 $GtCO_2$ removal would have the same cooling effect as a permanent reduction in the rate of global methane emissions by around 135 $MtCH_4$/yr.

The Paris Agreement aims for a net-zero type target on a global basis. In the development of mitigation strategies for a single country it is important to consider how the plans for net zero might be achieved internationally and how a nation's plan fits into the international effort (i.e., which countries might achieve net negative, net zero or net positive emissions, and how international trading is used).

4.3 Pathways after net-zero

As shown in the pathways in SR1.5, achieving net zero CO_2 is just one part of the challenge in limiting future warming. Plans for the further path of emissions of the individual gases after net zero target is achieved also need to be addressed and communicated, particularly how greenhouse gas removal can be sustained given finite and competing interest for land resources (see Section 3.1).

4.4 Defining national high-ambition pathways

Which fairness and equity principles that are applied as rationale for New Zealand's efforts are important to communicate as a part of a mitigation strategy. As New Zealand's starting position in terms of sectoral emissions is different from other nations, a high ambition emission reduction trajectory might look quite different to a high ambition pathway from another country. In particular, many countries are expected to rapidly decarbonise their power sector out to 2030, leading to large national emission reductions in the 2020s. In countries such as New Zealand (and the UK) where the power sector is already mostly decarbonised, urgent actions are needed on other sectors such as agriculture, buildings and transport for mitigation compatible with Paris Agreement ambitions. Policy actions in these areas might take longer to manifest themselves in emissions trends. Such a pathway was presented for the UK 6th carbon budget (UK CCC, 2020), where actions over 2020-2025 only produced modest emission reduction by laying the groundwork for march larger emission reductions at the end of the 2020s.

New Zealand, by getting to net zero CO_2 as soon as possible with concerted action to substantially reduce biogenic CH_4 emissions as much as possible, can limit the contribution it makes to global warming which is expected to peak around 2040 and then begin to reverse. If actions continue to 2050 and beyond, New Zealand could substantially reduce its historic contribution to global warming from fossil fuel emissions, nitrous oxide and biogenic methane by the end of the century.

References

Allen M.R., Fuglestvedt, J.S, Shine, K. P., Reisinger, A., Pierrehumbert, R.T., and Forster, P.M., 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change,* 6, 773-776, doi: 10.1038/nclimate2998

Allen, M. R., K. P. Shine, J. S. Fuglestvedt, R. J. Millar, M. Cain, D. J. Frame, and A. H. Macey, 2018: A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Nature npj Climate and Atmospheric Science*, 1(2018-16), doi: 10.1038/s41612-018-0026-8.

Ausseil A-GE, Kirschbaum MUF, Andrew RM, McNeill S, Dymond JR, Carswell F, Mason NWH 2013 Climate regulation in New Zealand: contribution of natural and managed ecosystems. In Dymond JR ed. Ecosystem services in New Zealand – conditions and trends. Manaaki Whenua Press, Lincoln, New Zealand.

Cain, M., Lynch, J., Allen, M. R., Fuglestvedt, J. S., Frame, D. J., and Macey, A. H. (2019). Improved calculation of warming-equivalent emissions for short-lived climate pollutants. NPJ Clim. Atmos. Sci. 2, 1–7. doi:10.1038/s41612-019-0086-4.

Collins, W.J., C.P. Webber, P.M. Cox, C. Huntingford, J. Lowe, S. Sitch, S.E. Chadburn, E. Comyn-Platt, A.B. Harper, G. Hayman and T. Powell, 2018: Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters*, **13(5)** https://doi.org/10.1088/1748-9326/aab89c

Collins, W. J., Frame, D. J., Fuglestvedt, J., and Shine, K. P. (2020). Stable climate metrics for emissions of short and long-lived species – combining steps and pulses. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ab6039

Denison S., Forster P.M., Smith C.J., 2019: Guidance on emissions metrics for nationally determined contributions under the Paris Agreement. *Environmental Research Letters*, 10 (7-10), https://doi.org/10.1088/1748-9326/ab4df4

de Richter, Tingzhen Ming, Philip Davies, Wei Liu, Sylvain Caillol, Removal of non-CO2 greenhouse gases by large-scale atmospheric solar photocatalysis, Progress in Energy and Combustion Science, Volume 60, 2017, Pages 68-96, ISSN 0360-1285, https://doi.org/10.1016/j.pecs.2017.01.001.

Etminan, M., Myhre, G., Highwood, E. J., and Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophys. Res. Lett. 43, 12,614-12,623. https://doi.org/10.1002/2016GL071930

Forster P.M., A.C. Maycock, C.M. McKenna and C.J. Smith, 2019: Latest climate models confirm need for urgent mitigation. *Nature Climate Change*, 1–14, https://doi.org/10.1038/s41558-019-0660-0

Forster, P. M., Forster, H. I., Evans, M. J., Gidden, M. J., Jones, C. D., Keller, C. A., et al. (2020). Current and future global climate impacts resulting from COVID-19. *Nature Climate Change*. https://doi.org/10.1038/s41558-020-0883-0

Fuglestvedt J.S., Rogelj, R. J. Millar, M. Allen, O. Boucher, M. Cain, P. M. Forster, E. Kriegler and D. Shindell., 2018: Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philosophical Transaction of the Royal Society A*, 376(2119), DOI:https://doi.org/10.1098/rsta.2016.0445

Fuglestvedt J.S., Berntsen T.K. and Skodvin T., 2000: Climate implications of GWP-based reductions in greenhouse gas emissions. *Geophysical Research Letters*, 27(3), 409–412.

Fuglestvedt J.S., Berntsen T.K., Godal O., Sausen R., Shine K.P. and Skodvin T., 2003 Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. *Climatic Change*, **58**, 267-331, doi:10.1023/A:1023905326842 .

Gasser T. et al., 2016: Accounting for the climate–carbon feedback in emission metrics. *Earth System Dynamics*, 8, 235-253, doi: 10.5194/esd-8-235-2017.

Hawkins E. et al., 2017: Estimating Changes in Global Temperature since the Preindustrial Period. *American Meteorological Society*, 98(9**)**, 1841-1856https://doi.org/10.1175/BAMS-D-16-0007.1

Harmsen, J.H.M., Detlef P. van Vuuren, Dali R. Nayak, Andries F. Hof, Lena Höglund-Isaksson, Paul L. Lucas, Jens B. Nielsen, Pete Smith, Elke Stehfest, 2019: Long-term marginal abatement cost curves of non-CO2 greenhouse gases, Environmental Science & Policy, Volume 99, 2019, Pages 136-149, ISSN 1462-9011, https://doi.org/10.1016/j.envsci.2019.05.013.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J.-I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geosci. Model Dev., 11, 369–408, https://doi.org/10.5194/gmd-11-369-2018, 2018

Hodnebrog Ø. Et.al., 2020: Updated Global Warming Potentials and Radiative Efficiencies of Halocarbons and Other Weak Atmospheric Absorbers. *Reviews of Geophysics*, 58(3), doi:10.1029/2019RG000691.

Jackson, R.B., Solomon, E.I., Canadell, J.G. *M. Cargnello & C. B. Field.* Methane removal and atmospheric restoration. *Nat Sustain* **2,** 436–438 (2019). https://doi.org/10.1038/s41893-019-0299-x

Kadow, C., Hall, D. M., and Ulbrich, U. (2020). Artificial intelligence reconstructs missing climate information. *Nat. Geosci*. 13, 408–413. doi:10.1038/s41561-020-0582-5.

Kennedy J.J. et al., 2019: An Ensemble Data Set of Sea Surface Temperature Change From 1850: The

Met Office Hadley Centre HadSST.4.0.0.0 Data Set. *JGR Atmospheres*, 124(14), 7719-7763, doi:10.1029/2018JD029867.

Lauder, A. R., I. G. Enting, J. O. Carter, N. Clisby, A. L. Cowie, B. K. Henry, and M. R. Raupach, 2013: Offsetting methane emissions—An alternative to emission equivalence metrics. *Int. J. Greenh. Gas Control*, 12, 419–429.

Leahy, S. C., H. Clark, and A. Reisinger, 2020: Challenges and prospects for agricultural greenhouse gas mitigation pathways consistent with the Paris Agreement. *Front. Sustain. Food Syst*., 1–15,

Lynch J., Cain, M, Pierrehumbert, R., and Allen, M., 2020: Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environmental Research Letters*, **15(4)**. https://doi.org/10.1088/1748-9326/ab6d7e

MacDougall A.H. et al., 2020 Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2.*Biogeoscience*, 17(11)**,** doi: 10.5194/bg-17-2987-2020.

Morice C.P., J. J. Kennedy, N. A. Rayner J. P. Winn E. Hogan R. E. Killick R. J. H. Dunn T. J. Osborn P. D. Jones I. R. Simpson. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. JGR Atmospheres. 15 December 2020. https://doi.org/10.1029/2019JD032361

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., et al. (2013). Anthropogenic and natural radiative forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (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 (pp. 659–740). Cambridge, UK and New York, NY: Cambridge University Press. https://doi.org/10.1017/ CBO9781107415324.018

Nicholls Z.R.J. et al., 2020: Reduced complexity model intercomparison project phase 1: Protocol, results and initial observations. *Geoscientific Model Development*, doi: 10.5194/gmd-2019-375.

O'Neill, B., 2003: Economics, natural science, and the costs of global warming potentials. *Clim. Change,* 58, 251–260.

Popp et al., 2017: Land-use futures in the shared socio-economic pathways*. Global Environmental Change,* Volume 42, January 2017, Pages 331-345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Reisinger, A. and Leahy, S., 2019: Scientific aspects of New Zealand's 2050 emission targets, New Zealand Agricultural and Greenhouse Research Centre Technical Report, available at https://www.nzagrc.org.nz/user/file/1941/Scientific%20aspects%20of%202050%20methane%20targets.pdf

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, M. V. Vilariño, 2018a, Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

Rogelj J. Forster, P.M., Kriegler, E., Smith, C.J. & Séférian, R., 2018b: Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, **571**, 335-342, doi:10.1038/s41586-019-1368-z

Rogelj J. Huppmann, D., Krey, V, Riahi, K., Clarke, L., Gidden, M., Nicholls, Z., and Meinshausen, M., 2019: A new scenario logic for the Paris Agreement long-term temperature goal. *Nature*, **573**, 357-363, https://doi.org/10.1038/s41586-019-1541-4

Richardson T.B. et al., 2019: Efficacy of Climate Forcings in PDRMIP Models. *JGR Atmospheres*, 124(23), 12824-12844, https://doi.org/10.1029/2019JD030581 .

Samset B.H. et al, 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical Research Letters*, 45, 408-411, https://doi.org/10.1002/2017GL076079

Schleussner, C.-F., Nauels, A., Schaeffer, M., Hare, W. and Rogelj, J.: 2019: Inconsistencies when applying novel metrics for emissions accounting to the Paris agreement. *Environ. Res. Lett*. 14 (2019) 124055 https://doi.org/10.1088/1748-9326/ab56e7

Sherwood S.C. et al., 2020: An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*, 58(4), e2019RG000678, https://doi.org/10.1029/2019RG000678

Shindell D. and Smith J., 2019: Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature*, 573(sup1), 408-411, https://doi.org/10.1038/s41586-019-1554-z

Smith C.J. et al., 2018: Understanding Rapid Adjustments to Diverse Forcing Agents *Geophysical Research Letters*,16(21),12023-12031, doi: 10.1029/2018GL079826

Steffen W. et al., 2018: Trajectories of the Earth System in the Anthropocene. *PNAS*, 115(33), 8252,8259, doi:10.1073/pnas.1810141115.

Sterner, E. and Johansson D., 2017: The effect of climate–carbon cycle feedbacks on emission Metrics. *Environ. Res. Lett*. 12 034019

Tanaka K. and O'Neil B.C., 2018: The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets. *Nature Climate Change*, **8**, 319-324. https://doi.org/10.1038/s41558-018-0097-x

Thornhill G. et al., 2020: Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models *Atmospheric Chemistry and Physics*, https://acp.copernicus.org/preprints/acp-2019-1207/

Turetsky M.R. et al., 2020: Carbon release through abrupt permafrost thaw. *Nature Geoscience*, **13**, 138-143, doi:10.1038/s41561-019-0526-0.

UNEP 2020 Emissions Gap Report, https://www.unenvironment.org/emissions-gap-report-2020.

UK Committee on Climate Change: Net Zero – The UK's contribution to stopping global warming, https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

UK Climate Change Committee, 2020, Sixth Carbon Budget Report, https://www.theccc.org.uk/publication/sixth-carbon-budget/

van Vuuren D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8**, 391-397, doi:10.1038/s41558-018-0119-8.

Weber, J., Shin, Y.M, Staunton Sykes, J., Archer-Nicholls, S., Abraham, N. L., Archibald, A.: 2020: Minimal Climate Impacts From Short-Lived Climate Forcers Following Emission Reductions Related to the COVID-19 Pandemic. *Geophys. Res. Let.,* 13 October 2020. https://doi.org/10.1029/2020GL090326

Wang Y and Huang Y., 2020: The Surface Warming Attributable to Stratospheric Water Vapor in CO_2-Caused Global Warming. *JGR Atmospheres*, 125(17), e2020JD032752, doi: 10.1029/2020JD032752.

Zickfeld K. et al., 2017: Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. *PNAS*, https://doi.org/10.1073/pnas.1612066114

Climate science considerations of global mitigation pathways and implications for New Zealand mitigation pathways

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Version 8 January 2021

This report interprets how the global surface temperature responds to mitigation of long lived greenhouse gases and short-lived greenhouse gases using the latest climate science. It puts these findings in the context of global mitigation pathways and New Zealand specific emission pathways. With a concerted effort to reduce biogenic methane emission and other greenhouse gases, New Zealand can substantially reduce its contribution to global warming out to 2100. Further, reaching net zero long-lived greenhouse gases is essential to limit New Zealand's contribution to global warming in the longer term.

Introduction

This report gives a brief overview of the current scientific understanding of emissions reductions needed to achieve the global temperature goal of the Paris Agreement. It builds on the findings in the Intergovernmental Panel of Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR1.5) and Special Report on Climate change and Land, as well as recent updates in the scientific literature. It focuses on the main characteristics of global emissions pathways and tradeoffs between reductions of emissions of different greenhouse gases. We also discuss how different choices affect the prospects of meeting the Paris temperature goals and how New Zealand's future emissions pathway relate to global temperature outcomes.

1. Climate response to emissions of different GHGs

This first section examines how much global warming has occurred and how much past and future emissions commit the world to further warming.

Based on the literature and knowledge available at the time, SR1.5 concluded that past emissions alone are unlikely to commit the world to global warming in excess of 1.5°C. Does this conclusion still hold? Since 2018 (the date of IPCC-SR1.5 publication) there have additional warm years observed in 2019 and 2020, and updates to the methodologies used to construct global surface temperature timeseries from past observations. There is new science emerging on estimates of the 'locked-in' or 'committed' warming from past carbon dioxide (CO_2) emissions alone, the zero emission commitment (ZEC).[1] Future warming also depends on the amount of warming coming from *future* greenhouse gas (GHG) emissions and on emission changes in short lived greenhouse gases such as methane and in non-greenhouse gas pollutants, as well as cumulative emissions of longer-lived GHGs, such as (CO_2) and nitrous oxide (N_2O). The sections below detail how understanding of each of these has progressed since SR1.5.

1.1 Historical warming

SR1.5 estimated that the human-induced warming[2] had reached around 1°C (with a 0.8°C to 1.2°C *likely*[3] range) above pre-industrial levels by the end of 2017. This was based on averaging the four prominent global (land and sea) datasets with peer-reviewed methodology (summarized in Table 1.1 of IPCC-SR1.5). Since then these global temperature datasets have been updated and improved to reflect the latest understanding of how to incorporate a range of historical climate data into a single timeseries and to improvements to methods to produce globally representative values (Morice et al., 2020). These latest revisions will may lead to a slight increase in the estimated level of warming above pre-industrial levels relative to the versions of the datasets available to IPCC-SR1.5 (e.g., Kennedy et al. 2019, Kadow et al. 2020). These changes arise from updates in the methodologies for constructing global temperature records and not because climate change today is worse than expected by recent IPCC reports. The trend in global temperature over recent decades are robust, consistent with the years since the publication of IPCC-SR1.5 being among the hottest in the instrumental record.

Definitions of globally average surface temperature for the purpose of estimating remaining global carbon budgets was addressed in Chapter 2 of SR1.5. Chapter 2 employed two estimates of the warming to date. The traditional measure of global-mean surface temperature (GMST) is based on observations that use a combination of near surface air temperature over land and sea-ice regions and sea-surface temperature over open ocean regions. The second measure is one that infers global surface air temperature (GSAT) changes across the globe based on a scaling factor from complex climate models. The latter choice was there estimated to lead to 10% higher levels compared to GMST based on climate models and therefore a smaller remaining carbon budget than estimates based on GMST. More recent work suggests that increasing GMST by 10% to estimate GSAT may not be borne out in real-world observations comparing night-time marine air temperature to sea-surface temperature data (e.g., Kennedy et al. 2019).

[1] This is estimated using idealised scenarios in climate models in which emissions are reduced to zero instantaneously. This scenario isn't directly relevant to scenarios that could be realised in the global economy but is informative for identifying physically-based lower limits of the minimum amount of 'inevitable' additional future increases in global temperature.
[2] This is a measure of the increase in global temperature above pre-industrial levels resulting from human activity (e.g., GHG emissions and emissions of aerosols) only. Temporary *natural* effects (e.g. temporary cooling due to volcanic eruptions or natural climate cycles), that temporarily increase or decrease total warming relative to this human-induced level, are excluded.
[3] Here *likely* means at least a 66% chance that the true value lies within this interval – consistent with how this term is used across IPCC reports.

IPCC SR1.5 used the average over the period 1850-1900, the earliest period then available in the direct observational record with reliable estimates of the global average temperature, to approximate pre-industrial levels. There has been discussion in the scientific literature of the dependence of global emissions reduction ambition needed to achieve the Paris Agreement on the a choice of this 1850-1900 period to approximate the pre-industrial baseline or an earlier period such as 1750. Using 1750 as a pre-industrial baseline could increase today's level of the global average temperature rise above preindustrial level by around 0.05°C above the level when using the 1850-1900 period, but this is not estimated to be statistically significant (Hawkins et al., 2017).

In summary, we might expect further revisions and updates of the order one tenth of a degree to the historical surface temperature change since preindustrial times and these would have knock on effects for estimates of the remaining global carbon budget consistent with the Paris Agreement. Note that by altering the historical temperature we are implicitly altering the applied relationship between the level of global temperature rise above pre-industrial levels and aggregate climate impacts. As an example, if we were to revise the present day historical warming upwards from 1.0°C to 1.1°C, the present day climate impacts being experienced now do not alter, we instead would associate temperature levels (e.g. 1.1°C or 1.5°C) with lower levels of climate impact than previously, so avoiding 1.5°C of warming becomes a more stringent target (associated with a lower level of aggregate climate impacts than it was previously), rather than the revision pushing us closer to higher levels of future climate impact.

1.2 Future warming

1.2.1 Committed warming from greenhouse gases

This section demonstrates to what extent past and future emissions of specific gases (chiefly CO_2 and CH_4) commit to future changes in global temperature, and hence the extent to which the levels of global temperature above pre-industrial levels in a given year (e.g. around 2050 to reflect when peak warming under many 1.5°C scenarios) is a historic liability and what amount is the result of future emissions that haven't yet occurred.

For emissions of *long-lived GHGs* (LLGHG) (CO_2, N_2O, some fluorinated-gases)[4] their global temperature impact is largely determined by their *cumulative* emissions. Nitrous oxide (N_2O) has a finite single perturbation lifetime unlike CO_2, and consequently behaves differently in the very long term, but can be treated as approximately equivalent to a certain amount of CO_2 emissions (e.g. using conventional metrics from equivalence between GHGs; see section 2.4) when thinking about impacts of its emission on global temperature for this century. As shown in SR1.5 (Table 2.4) and the scientific literature, these emissions need to come down to below net zero (aggregated by the global warming potential with time horizon of 100 years - GWP_{100}) in scenarios compatible with 1.5°C warming. As some level of residual long-lived greenhouse gas emissions are expected to be unavoidable, active removal of CO_2 from the atmosphere is expected to be

[4] These are GHGs that result in raised atmospheric concentrations of the gas for many decades after the emission occurred.

required to achieve net-zero LLGHG emissions. Removal of non-CO_2 greenhouse gases from the ambient atmosphere has been considered at a conceptual level in the scientific literature but has not generally been considered in the same level of techno-economic detail as active removal of CO_2, for which demonstration-scale plants of some engineered removals methods already exist today (De Richter et al., 2017; Jackson et al., 2019).

For CO_2, MacDougall et al. (2020) looked at the evidence from idealized simulations with complex global climate models to conclude that the most likely value of the zero-emission commitment (ZEC)[5] on multi-decadal timescales is close to zero, consistent with previous model experiments and theory, but at the same time pointing to the large uncertainty related to constraining this effect. The right panels on Figure 1 show that the ZEC can be of either sign, but is generally less than +0.5°C across models, with a best estimate, based on current evidence of close to zero. Similarly, for other LLGHGs it is reasonable to assume that the past warming contribution is largely governed by past cumulative emissions and, for timescales under 100 years, there is little further warming or cooling due to past emissions. Likewise, future warming will be governed by future cumulative emissions.

[5] The amount of additional warming that occurs when global CO_2 emissions are instantaneously brought to net-zero.

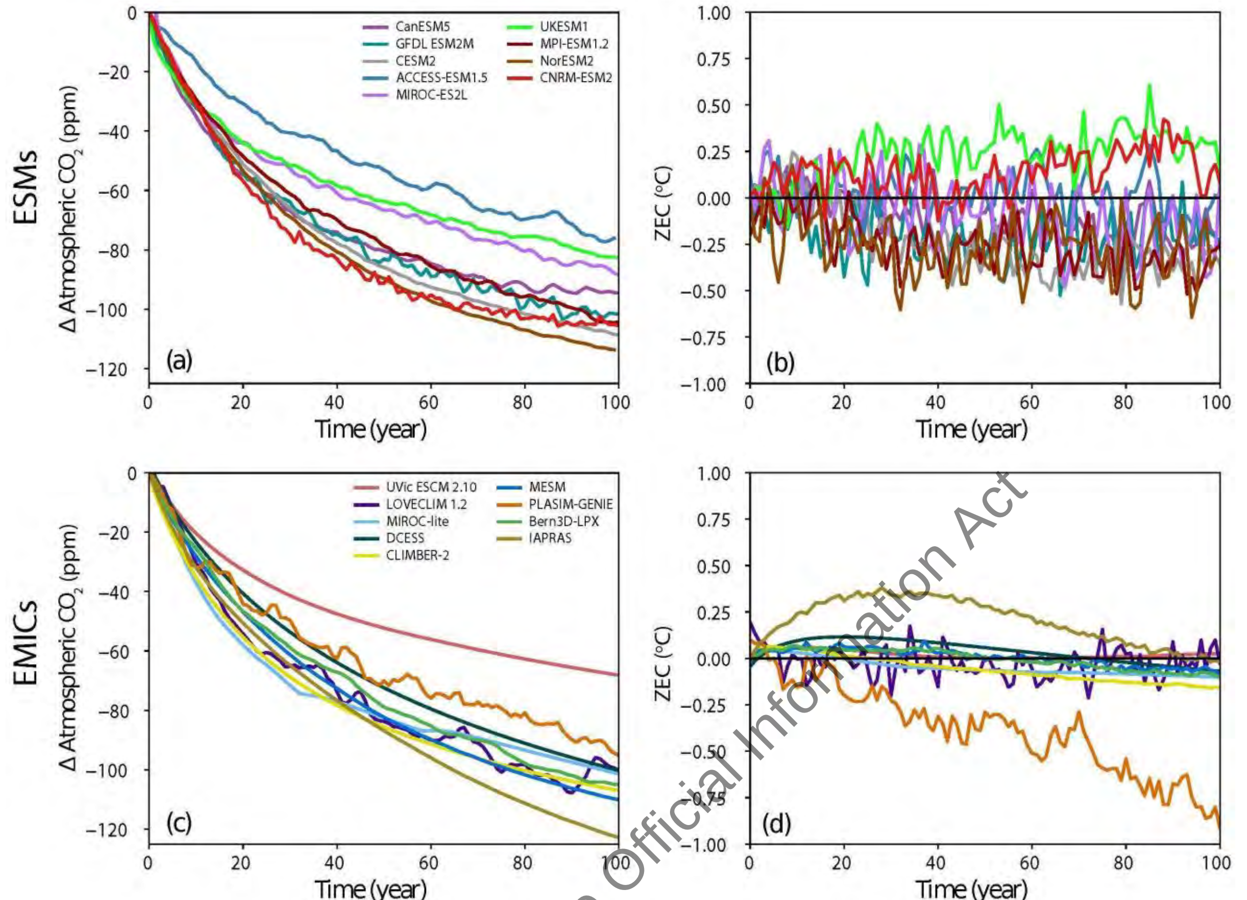

Figure 1: *Atmospheric* CO_2 *concentration anomaly and (b, d) Zero Emissions Commitment following the cessation of emissions during the experiment wherein 1000 PgC was emitted according to the methods in the 1% experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. The top row shows the output for Earth System Models (ESMs), and the bottom row shows the output for Earth System Models of Intermediate Complexity (EMICs) (MacDougall et al., 2020).*

The current evidence across the scientific literature therefore suggests that we do not expect significant additional warming above that seen already to past long-lived GHG emissions. However, important uncertainties still remain, including through processes that are difficult to accurately simulate within the current generation of complex climate models, such as the role of future thawing of the permafrost and future wildfires. Nevertheless, some of the more dire warnings of tipping points (e.g., Steffen et al. 2018) are not born out in more careful assessments (e.g., Turetsky et al., 2020). It remains likely that the future amount of GHG emissions from the global economy emitted on the pathway to net-zero emissions will be significantly more important to future levels of warming realized than the warming arising from changes in natural carbon sinks this century due to feedbacks from Earth system processes that aren't typically included within carbon budget estimates. Nevertheless, estimates of these additional feedbacks can be factored into remaining carbon budget estimates (e.g. Table 2.2 in Chapter 2 of SR1.5), although it is difficult to estimate exactly how quickly or slowly these additional emissions might enter the atmosphere. It is unlikely that all of these Earth system emissions would have occurred by the time global CO_2 emissions must have reached net-zero by around 2050 and warming peaked to keep to the temperature level of the Paris Agreement long-term temperature goal (see SR1.5 Chapter 2, Rogelj et al., 2018a,b and Rogelj et al., 2019).

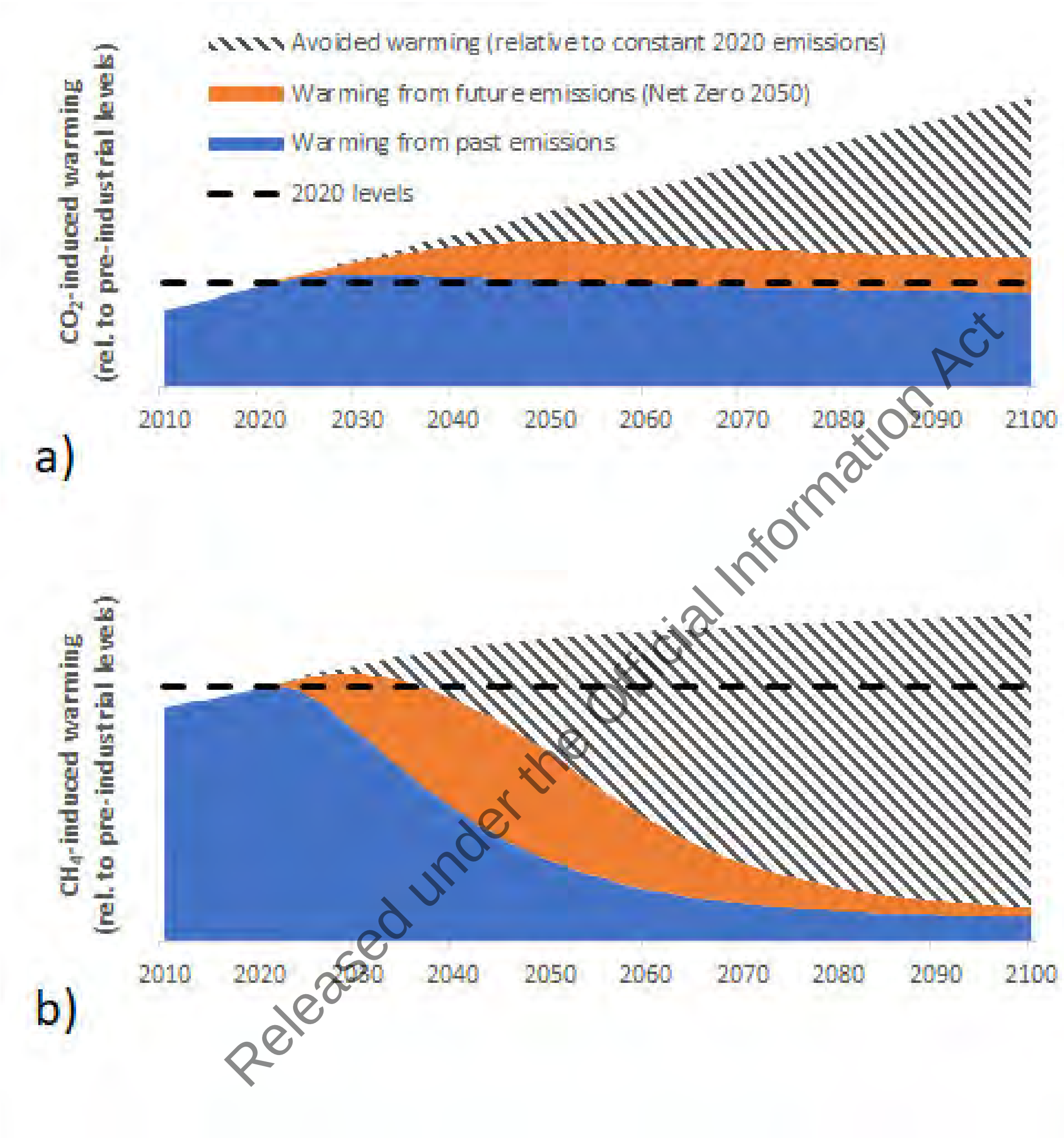

Figure 2: *A stylised illustration of commitment from past emissions to future warming and how much future global temperature is dependent on future and past emissions – for two gases* CO_2 *(top) and* CH_4 *(bottom). The blue area represents a case with an instant drop in emission to zero after 2020, illustrating the commitment from past emissions only on future global temperatures . The orange area shows the warming arising only from future emissions in a scenario in which* CO_2*/*CH_4 *emissions decline linearly from 2020 to (net-) zero emissions in 2050. The hatched area shows the avoided warming wedge between the case with declined emission to zero in 2050 (orange case) and a case with constant future emission at 2020 levels. The dashed lines show levels of global temperature rise above pre-industrial levels from* CO_2*/*CH_4 *emissions in 2020.*

For *Short Lived GHGs* (SLGHG) (CH_4, some F-gases) their global temperature impact depends (as a first order approximation) on the sustained *rate* of emissions. In contrast to the long-lived gases their emissions need only to be gradually reduced and not stopped altogether to prevent further contributions to ever increasing global temperature. An increase in their emission rate, not simply continued emissions will add to future warming. It is important to note that any level of sustained short-lived GHG emissions would still sustain raised global temperature above pre-industrial levels (as does achieving net zero CO_2). Therefore, to reduce their historical contribution to temperature change SLGHG emissions rates need to be reduced whereas net negative emissions of LLGHGs are needed to reduce historical contribution to global temperature from LLGHG emissions. The lower the emissions rate of SLGHGs the lower the contribution of sustained SLGHG emissions to global temperature. Furthermore, emissions of SLGHGs also have longer-term climate impacts through their impact on carbon cycle (e.g., Gasser et al. 2017) and on other climate variables (e.g., sea level rise - Zickfeld et al., 2017), that are not reversed simply by reducing their sustained emissions rates

The different lifetimes of the two gases (CO_2 and CH_4) is fundamental for understanding how past emissions of these gases affect future warming and the role of additional future emissions on top of the committed warming from past emissions. Figure 2 shows in a stylised way the different behavior of these two gases. While for CO_2 the warming from pre-2020 emission remains approximately constant over the century, the warming from past emissions of CH_4 decays over the coming decades (although doesn't disappear entirely). These differences are also important to bear in mind when different metrics are used for comparing effects of emissions (see Section 2.4). In spite of the very different warming profiles, reducing emissions of both gases will significantly contribute to reduced future warming and would help achieve the long-term temperature goal. For CO_2, this abatement comes from avoiding future emissions that add to the committed historical warming from past emissions. For CH_4, this principally comes from emissions reductions that reduce the level of global temperature rise above preindustrial levels that would have been sustained if emissions were kept at current rates.

In summary, both long and short-lived greenhouse gas emissions contribute to keeping global temperatures above pre-industrial levels, but they do so in different ways. For short-lived gases it is via their emission rates. For long-lived gases it is via their cumulative emissions. Abatement from emissions of both short- and long-lived gases benefit the global climate.

1.2.2 Non greenhouse gas emission changes

Changes in emissions that affect aerosol and those that affect ozone concentrations change future temperature and how close we are to temperature targets. Although generally 20-30 years of near-term warming is expected from reducing aerosol pollution following a combination of climate mitigation policies and air quality policies (Smith et al. 2018a; Samset et al. 2018), near term warming can be limited with well-designed policies targeting both short and long-lived pollutants (Shindell and Smith, 2019). Forster et al. (2020) and Weber et al. (2020) examined the climate response to COVID-19 restrictions and showed that some of the short term warming from reduced SO_2 emissions and less aerosol cooling was offset globally by a large near-term reduction in NOx and ozone from reduced transport emissions. This suggests reducing road transport emissions at the same time as SO_2 emissions would lessen any near-term warming.

1.3 Scientific developments

Since the IPCC 5th Assessment Report (AR5), scientific knowledge has developed further with improved understanding of several key processes in the climate system, and longer and improved observation series. The adoption of the Paris Agreement increased the focus on differences between 2°C and 1.5°C in terms of climate responses and impacts, as well as emission pathways compatible with the Paris Agreement ambitions, summarized in the recent IPCC Special Reports. Their assessments also confirm that the fundamental understanding of the climate system has remained largely the same since AR5. From consistency across these reports, there is a robust understanding of what needs to happen to global emissions to meet the temperature goal of the Paris Agreement. This requires reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing (primarily driven by the rate of SLGHG emissions) to halt anthropogenic global warming.

In spite of the fundamental understanding remaining largely unchanged, uncertainties in radiative forcing and climate sensitivity affect the relationship between emissions and surface temperature change, and there have been some relevant developments in these areas which are discussed below.

1.3.1 Climate sensitivity

The latest generation of climate models from the sixth climate model intercomparison exercise (CMIP6) warm more than the previous generation and generally have greater equilibrium climate sensitivities (Forster et al. 2019). However, a five-year assessment of climate sensitivity comparing estimates using paleoclimate evidence, physical process evidence and the evidence from the 1850-2018 period (Sherwood et al., 2020) finds a much more constrained likely range for the equilibrium climate sensitivity that is robustly within 2.3 to 4.5°C. These estimates did not directly rely on the new generation of climate models so provides and independent assessment against which the new generation of complex climate models can be compared. This comparison suggests that the high warming estimates from some of the climate models are unlikely but cannot be ruled out entirely (Forster et al., 2019).

This updated evidence on the climate sensitivity indicates that the likely range of global warming projections due to uncertainty in the climate system response for projections of future climate changes under different global GHG emissions scenarios would have a narrower range than similarly presented ranges in SR1.5 and AR5. As this revised uncertainty in the Earth's climate sensitivity largely affects that tails of the distribution, the central estimates of projected warming for the same emission scenario would likely still remain similar to those shown in SR1.5 and AR5 (see Figure 3). The low estimates of warming have firmed up and are slightly larger than before, whereas the high-end estimate remains somewhat uncertain.

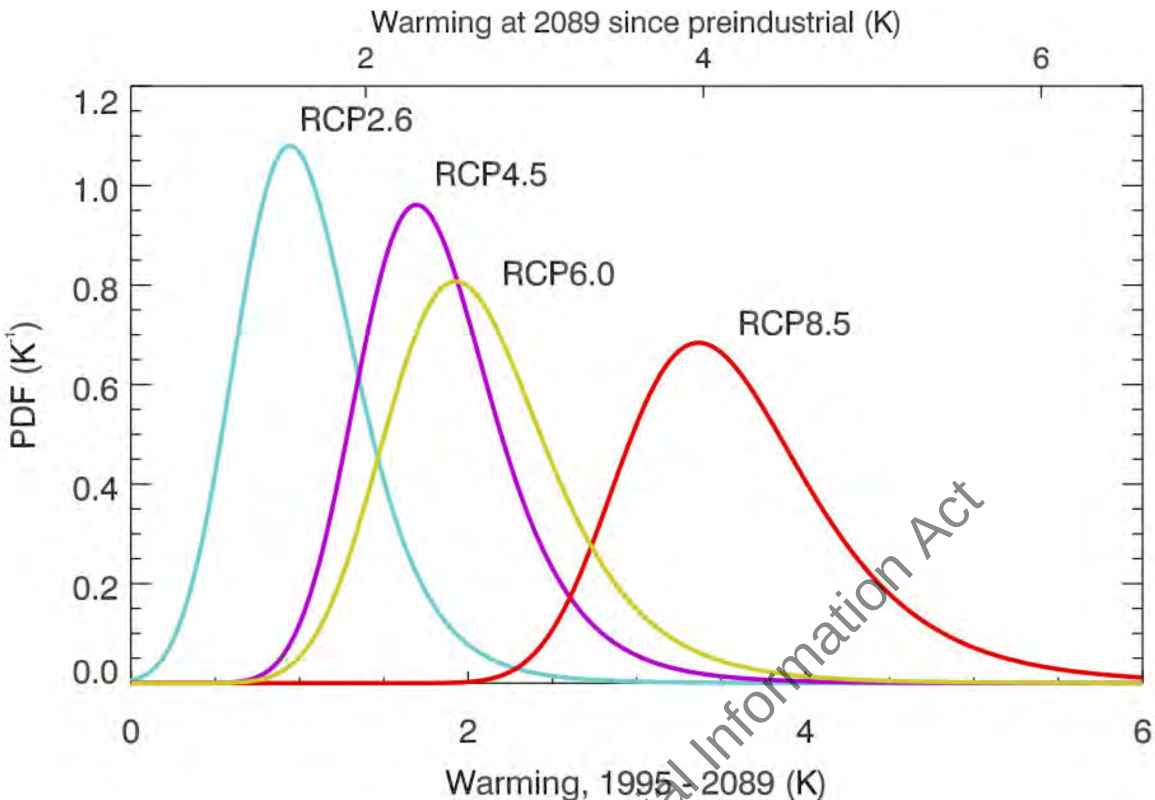

***Figure 3**: Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).*

1.3.2. Radiative Forcing and Global Warming Potentials

The Effective Radiative Forcing (ERF) introduced in IPCC AR5 has now become the accepted way to compare the magnitude of different climate change mechanisms (Richardson et al., 2020). The ERF includes cloud related adjustments to the more traditional stratospherically adjusted radiative forcing, allowing a better comparison of the effect on global surface temperature across forcing agents.

The establishment of ERF as the standard measure of forcing can help improve the estimates of GHG metrics (such as the GWP), including for methane. A number of other factors studied in recent publications may also influence the GWP value for methane:

- Moving to ERF increases CO_2 radiative forcing but leads to a decrease in methane radiative forcing from cloud adjustments (Smith et al. 2018).
- Etminan et al. (2016) include the shortwave forcing from methane and updates to the water vapour continuum and account for the overlaps between carbon dioxide and nitrous oxide.
- Thornhill et al. (2020) quantify the indirect effect of methane on ozone radiative forcing based on several models and strengthen the knowledge basis about indirect effects of methane.

- The results of Wang and Huang (2020) show that due to high cloud changes the stratospheric water contribution to methane GWP-100 which was 15% in AR5 might be closer to zero in the ERF framework. This change would be additional to the adjustments outlined in Smith et al. (2018b) and in of itself it would *decrease* the GWP.
- Gasser et al. (2017) and Sterner and Johansson (2017) give descriptions of how to account for climate carbon cycle feedbacks in emission metrics. AR5 Working Group I included this feedback for non-CO_2 gases, which up to then was only included for the reference gas CO_2, and imply an underestimation of GWP values for non-CO_2 gases. Due to lack of sufficient literature at the time of writing AR5, the inclusion of this feedback effect was presented as tentative.

Studies have not yet applied these results or combined these analyses for an overall estimate of methane GWP. At this stage it is difficult to be more quantitative regarding the net result, but the IPCC Sixth Assessment Report will attempt to assess these and other studies, bringing different lines of evidence together to form a new comprehensive assessment.

For CH_4, the GWP value also depends on whether the carbon is of biogenic or fossil origin. When oxidised, fossil methane will introduce additional CO_2 to the atmosphere. The metric value for fossil methane will therefore be slightly higher than for biogenic methane. Thus, AR5 Working Group I gave two values for the methane GWP-100; i.e., 28 for biogenic and 30 for fossil methane. It was pointed out that “In applications of these values, inclusion of the CO_2 effect of fossil methane must be done with caution to avoid any double-counting because CO_2 emissions numbers are often based on total carbon content. Methane values without the CO_2 effect from fossil methane are thus appropriate for fossil methane sources for which the carbon has been accounted for elsewhere, or for biospheric methane sources for which there is a balance between CO_2 taken up by the biosphere and CO_2 produced from CH_4 oxidization.”

Other updates are also available in the literature, e.g., Hodnebrog et al. (2020) gives an update of radiative efficiency and GWP and GTP values for halocarbons. New radiative efficiencies calculations are presented for more than 400 compounds in addition to the previously assessed compounds, and GWP calculations are given for around 250 compounds. Present-day radiative forcing due to halocarbons and other weak absorbers was estimated to be 0.38 [0.33–0.43] W m^{-2}, compared to 0.36 [0.32–0.40] W m^{-2} in IPCC AR5 (Myhre et al., 2013), which is about 18% of the current CO_2 forcing.

1.3.3 Surface temperature projection estimates

Climate model emulators such as FaIR and MAGICC (employed in SR1.5) are often used to estimate global warming futures across multiple scenarios. Such reduced complexity climate models can either be set up to mimic the behaviour of global-mean surface temperature change from more complex models or can be set up in probabilistic form to match the assessed range of climate sensitivity and effective radiative forcing from other assessments or lines of evidence. Due to the prominent role of such models in projecting net zero scenarios in SR1.5, an intercomparison is currently underway (**https://www.rcmip.org/)** between a variety of these reduced complexity models. Preliminary results from this show that such models generally work well for projections of global surface temperature (Nicholls et al. 2020). Such models based on updated estimates of ERF and climate sensitivity can provide the basis for calculating national emissions contributions to global temperature changes and could also be used to understand the direct global temperature impacts of New Zealand's emissions (see Section 3.1).

2. Trade-offs in global emissions pathways to keep warming to 1.5°C

At a global level, different combinations of future long-lived and shorter-lived GHG emissions trajectories can be consistent with achieving the long-term temperature goal of the Paris Agreement. This section looks at the understanding of possible combinations of cumulative long-lived GHG emissions and sustained emissions rates of shorter-lived GHGs that could be consistent with an overall global temperature trajectory consistent with the Paris Agreement.

2.1 Understanding GHG trade-offs determining the level of peak warming reached

Physically, warming could be kept to 'well-below' 2°C or below 1.5°C with a range of possible combinations of global future cumulative LLGHG emissions and global SLGHG emissions rates.

Fundamentally, there are three key contributions from future emissions to the level of peak warming reached:

1. The level of global temperature increase above pre-industrial levels arising from future cumulative LLGHG emissions between now and the timing of reaching net zero. This warming is additional to that caused by past-emissions of LLGHGs.[6]
2. The level of global temperature increase sustained by the rate of SLGHG emissions over the couple of decades prior to peak warming. Depending on whether the global emissions rates are higher or lower than values over the recent past, the level of global temperature rise above pre-industrial levels sustained by global SLGHG emissions could be greater, the same, or lower than the level of global temperature rise above pre-industrial levels sustained by these emissions today.
3. Changes in the levels of global temperature decrease below pre-industrial levels that are sustained by global human emissions of aerosols (which have a net cooling effect on the climate). These emissions are also shorter-lived meaning that the contribution from these emissions to peak warming largely depends on the emissions rate of the aerosols. Some aerosols emissions are often co-emitted with GHG emissions, so efforts to reduce emissions in the future and improve air quality mean that global emissions of aerosols are expected to be reduced in the future, meaning that they are expected to suppress less the GHG induced warming at the time of peak warming than they do today.

[6] Nitrous oxide emissions have a perturbation lifetime of ~100 years in the atmosphere, meaning that, unlike carbon dioxide, some of the warming caused by past nitrous oxide emissions early in the historical record will have decayed away. For the purposes of future nitrous oxide emissions over the next several decades, nitrous oxide can be treated largely analogous to CO_2 when converted through the GWP-100 metric to CO_2-equivalent emissions.

Variations in any one of these three factors has implications for the combinations of the other two that would be consistent with a given climate outcome. Emissions of aerosols are not formally regulated under climate policy frameworks (such as the Paris Agreement) so changes in aerosol emissions are often considered as exogenous to climate policy considerations on the balance of GHG emissions, despite not being entirely independent.

Overall, the higher the global rates of SLGHG emissions the lower the cumulative total of LLGHG emissions that would be consistent with keeping expected peak warming to any level and vice versa the lower the global rate of SLGHG emissions the greater the cumulative total of LLGHG emissions. These physically-based trade-offs have been illustrated in the literature through the use of simple climate models (e.g. Leahy et al. 2020) and summarised by the IPCC in Figure SPM1 of the Special Report on Global Warming of 1.5°C.

Alongside the use of simple climate models, the relationship between different futures for global cumulative long-lived GHG emissions and reductions/increases in the rate of global short-lived GHG emissions for can be explored for a wide range of situations using new emission metrics (see Section 2.4); e.g., proposed metrics that more directly measure the 'warming-equivalence' between long-lived and short-lived GHG emissions (Allen et al., 2016, Allen et al., 2018, Collins et al., 2018, Cain et al., 2019, Collins et al., 2020).[7] An application of these metrics to approximate trade-offs between global methane emission futures and futures of long-lived GHGs are shown in Figure 4.

Table 1 provides conversion factors to approximate the amount of cumulative carbon dioxide emissions that would create the same warming as a sustained change in the emissions rate of a shorter-lived GHG such as methane. Whilst there is some variation across time horizons for these factors, the fractional variation is significantly reduced relative to conventional metrics (e.g., global warming potential - Section 2.4), suggesting that comparing pulses of LLGHGs and sustained emissions rates of SLGHGs provides the most robust approximation for the effects on global temperature across a range of timescales, and could be used to explore a wide range of scenarios.

[7] Collins et al. (2018), applied a process-based approach to assess the importance of methane reductions for the 1.5°C target. Their modelling approach included indirect effects of methane on tropospheric ozone, stratospheric water vapour and the carbon cycle. They find a robust relationship between decreased CH_4 concentration at the end of the century and increased amount of cumulative CO_2 emissions up to 2100. This relationship is independent of climate sensitivity and temperature pathway. In terms of relation between end of the century emission changes in CH_4 and CO_2, their results achieve similar results as those obtained by Allen et al., 2016 in a GWP* context. Collins et al., 2018, also point out that the non-climate benefits of mitigating CH_4 can be significantly larger than indicated by IAM studies.

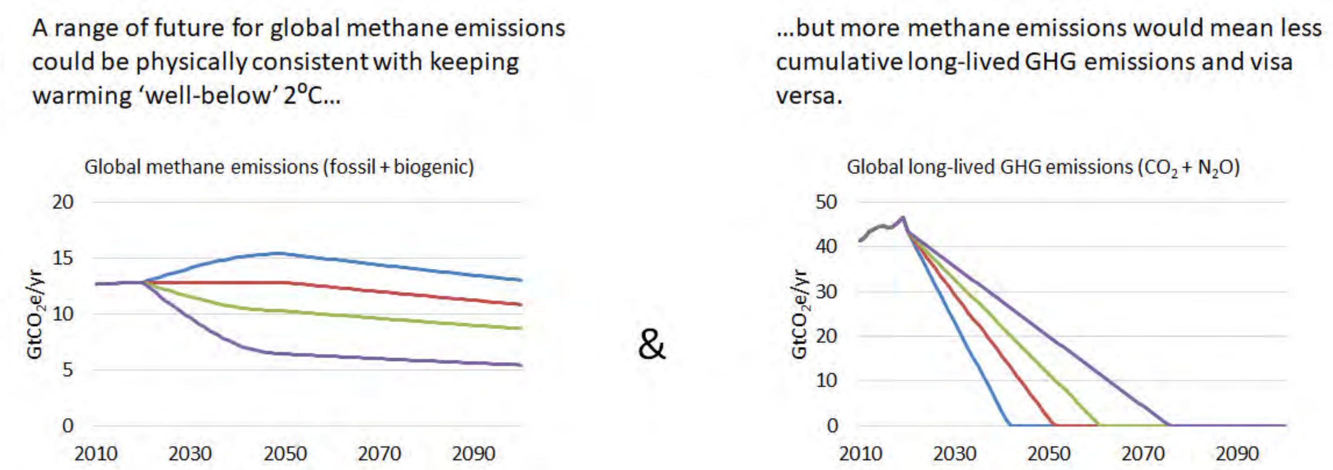

Figure 4: *Stylised trajectories that illustrate the trade-off between global trajectories for anthropogenic methane emissions (fossil and biogenic sources) and long-lived GHG emissions using the framework of Cain et al. (2019). Trajectories are constructed to keep expected peak warming to approximately 1.75°C above pre-industrial levels.*[8]

Table 1: Equivalence between CO_2 and CH_4 emissions under the combined global temperature potential (CGTP) metric of Collins et al. (2020).

Time horizon	50 years	75 years	100 years
Size of pulse of CO_2 emissions ($GtCO_2$) with equivalent warming effect to a sustained 1 $MtCH_4$/yr change in CH_4 emissions rates depending on time horizon	3.3	3.7	4.0

2.2 Tradeoffs between GHGs after peak warming

Section 2.1 summarized how the trajectories of SLGHGs and LLGHGs relate to each other prior to peak warming for efforts to keep warming to below a particular level. After reaching peak warming the evolution of both long-lived and short-lived GHGs will also be important for whether temperatures remain constant or fall from their peak.

[8] These trajectories assume a present-day (2020) warming of around 1.2°C, consistent with the definition of present-day warming (GSAT) used for carbon-budget calculations in IPCC-SR1.5, and a TCRE of 0.45°C/$TtCO_2$ consistent with IPCC SR1.5 Ch2. A contribution to future warming from aerosols is approximated through a 0.4Wm^{-2} increase in net aerosol forcing between 2020 and mid-century consistent with typical modelled global emissions pathways that keep warming to 1.5°C with no or low overshoot. Methane emissions trajectories are specified to fall at approximately the rate required to not add to further warming after 2050. Emissions are expressed as CO_2-equivalent values using the Global Warming Potential metrics (time horizon of 100 years) from the IPCC 5th Assessment Report (including carbon-climate feedbacks).

Reductions in global temperature after peak warming could occur due to either net anthropogenic removals of long-lived GHG emissions from the atmosphere (e.g., direct air capture of carbon and storage) or through permanent falls in the annual rate of short-lived GHG emissions after the time at which peak temperature is reached whilst long-lived GHG emissions remain at net-zero. Table 1 provides a way to estimate the magnitude in the reduction of the annual global CH_4 emissions rate below the levels at the timing of peak warming that would be required to achieve a given level of cooling over a specific period. Based on mid-range estimate of the transient climate response to cumulative emissions (TCRE) of 0.45°C/TtCO_2 a cooling of around 0.2°C over 50 years after temperature peaked would require a cumulative net active removal of CO_2 from the atmosphere of around 445 GtCO_2 over this 50 year period[9]. Table 1 indicates that this same cooling effect could also be created by a permanent reduction in the rate of global methane emissions by around 135 MtCH_4/yr below the levels over the couple of decades prior to the timing of peak warming.

2.3 Modelled economic least-cost global pathways

Global GHG emissions trajectories consistent with the Paris Agreement are often studied using Integrated Assessment Models (IAMs). These models of the energy and land-use systems allocate emissions reductions across sectors, countries, and gases to keep the overall 'net present cost' of the emissions reduction pathway as low as possible whilst constraining global emissions to pathways expected to be consistent with a specified global temperature goal.[10] These modelled pathways, regularly summarised and applied in the IPCC assessment reports and intergovernmental documents such as the 'Emissions Gap' reports from UN Environment, can be useful indicators of what an idealised 'cost-effective' global emissions pathways might look like across sectors, gases and regions, but do not explicitly incorporate additional considerations of fairness, political will or institutional capability which will all be important additional determinants of how reductions are shared across sectors, gases and regions in the real world.

The balance of effort between reductions in different GHGs across the full range of pathways produced by international modelling groups used in the IPCC Special Report on Global Warming of 1.5°C is summarised in Table 2, with trajectories for LLGHGs (CO_2 and N_2O) and biogenic CH_4 from these simulations shown in Figure 5.[11] As now relatively widely known, these pathways require significant deviations in the historical trends of global emissions. Whilst technological progress (including the falling costs of renewable power generation) has helped shift projected future emissions trajectories away from the highest emissions futures, expected emissions at the global level out to 2030 remain far from these trajectories (UNEP, 2020).

This scenario set is not a statistically well-defined set of simulations and should not be treated as such. It includes simulations where particular technologies are explicitly excluded as contributing

[9] Assuming a perfectly symmetric global temperature response to positive and negative CO_2 emissions.
[10] In many IAMs this is achieved using a 'shadow value of carbon' for all emissions. This is typically applied to non-CO_2 GHG emissions using the global warming potential (GWP) metric for a 100-year time horizon.
[11] Methane emissions from the energy sector are not included within these plots but are an important source of emissions at the global level.

to the emissions reductions (e.g., nuclear) and come from a wide set of models with varying levels of detail regarding the representation of energy system technologies, varying assumptions regarding their relative costs, and varying assumptions about global developments (e.g., population, economic growth and development) in the absence of climate policies or impacts. Some scenarios also impose specific behavioural change (e.g., diet preferences) future exogenous to the modelling framework (van Vuuren et al., 2018). Differences in the evolution of the global energy systems can be larger between different models as it can between different levels of climate ambition within the same model. Although the differing assumptions and outcomes in the land and agriculture sector have been studied (Popp et al., 2017), it is difficult to clearly identify the drivers of differences between the high-level global emissions outcomes without additional targeted experiments, and the fundamental drivers of different balances between reductions in biogenic methane and LLGHGs within these modelling frameworks in pursuit of ambitious climate objectives remain poorly understood.

Table 2. *Summary statistics of global cost-optimal pathways (median is given, with max and min in parentheses - long-lived GHG emissions include only CO_2 and N_2O aggregated using GWP-100 value of 298). 'Biogenic' methane is here approximated as all non-energy sources including both agricultural and waste sources. Globally biogenic methane emissions rates were estimated to be around 220 $MtCH_4$/yr in 2015 from observationally-based datasets (Hoesly et al., 2018).*

Scenario grouping	Cumulative LLGHG emissions from 2020 to 2050 - $GtCO_2e$	Cumulative LLGHG emissions from 2020 to peak warming - $GtCO_2e$	Rate of LLGHG emissions at 2030 - $GtCO_2e$/yr	Rate of LLGHG emissions at 2050 - $GtCO_2e$/yr	Rates of biogenic CH_4 emission at 2030 - $MtCH_4$/yr	Rates of biogenic CH_4 emission at 2050 $MtCH_4$/yr	Rates of biogenic CH_4 emission over 20 years prior to peak warming $MtCH_4$/yr
1.5ºC (~50% probability)	545 (325 - 705)	535 (360 - 810)	23 (14 - 28)	2.3 (-8.3 - 12)	180 (110 - 230)	140 (60 - 200)	175 (100 - 240)
<2ºC (~66% probability)	790 (580 - 1060)	930 (625 - 1430)	30 (20 - 46)	12 (1.9 - 20)	190 (160 - 300)	155 (115 - 205)	155 (100 - 245)

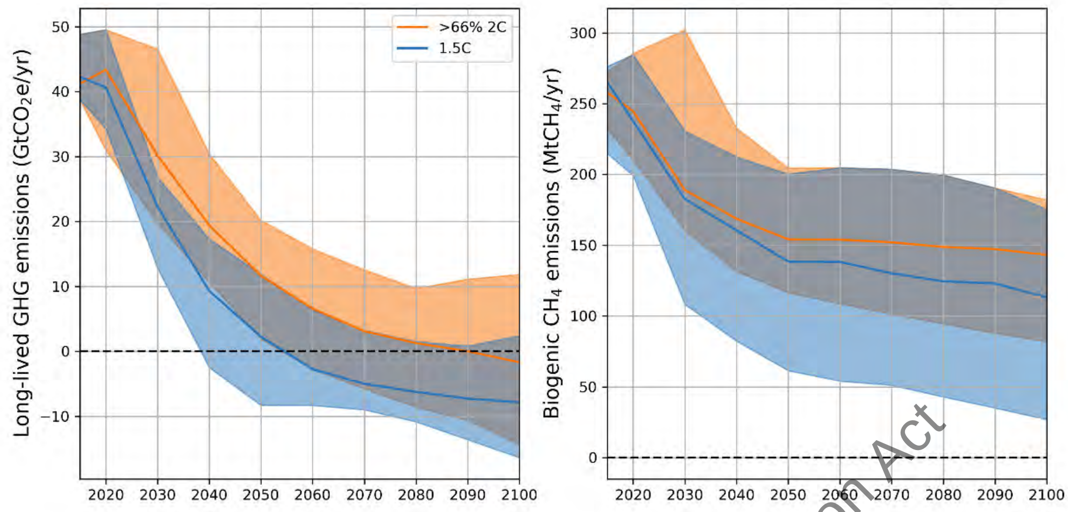

Figure 5: *The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for Long-lived GHGs (CO_2 and N_2O) and biogenic CH_4. Solid lines denote the median of the scenario set.*

Figure 5 illustrates the different roles the gases CO_2 CH_4 and N_2O can play in future model-based emissions pathways that are compatible with the temperature ambitions of the Paris Agreement. The global emissions of CO_2 have to go to net zero around the middle or second half of the century, depending on level of temperature ambition. Large reductions in CH_4 and N_2O are also generally found in these modelled pathways but there is more variation. The model studies found that strong reductions in methane are simulated in all pathways, but zero CH_4 is not achieved in any pathway. This non-zero global residual CH_4 emission is due to the assumed cost of reducing the remaining CH_4 emissions not because of its physical properties (Harmsen et al. 2019). For N_2O, the pathways show smaller reductions or even modest increases depending on the degree of future fertilizer use. N_2O emission pathways also do not reach net-zero. The large spread in possible pathways for emissions of CH_4 and N_2O are worth noting, reflecting different assumptions about abatement costs including potential for demand-side changes. However, in the vast majority of these modelled least economic cost global pathways, biogenic CH_4 emissions are seen to decline strongly by mid-century. This reduces the level of global average CH_4-induced warming relative to the warming these emissions are causing at present.

Peak warming generally occurs around 2050 in scenarios that keep warming to 1.5°C with ~50% probability - approximately corresponding with the date of global net-zero CO_2 emissions (Figure 2.6 in UK CCC, 2019). Although net long-lived GHG emissions remain positive at the time of peak warming (due to some residual N_2O emissions in all scenarios), the effect of falling methane emissions over the decades prior to 2050 (which reduces CH_4-induced levels of global

temperature rise) temporarily acts to offsets some of the temperature implications of these residual long-lived GHG emissions, sufficient to bring global temperature to a peak.[12]

Many of these scenarios continue to reduce CO_2 emissions further so that global CO_2 (and long-lived GHG) emissions go net-negative. This has the effect of reducing temperatures after peak warming has been reached, but doesn't significantly contribute to the level of peak warming achieved. In many scenarios that peak warming at around 1.5°C (or less than 0.1°C of overshoot) by 2050 the net-negative CO_2 emissions largely contribute to temperatures declining from their peak to around 1.3°C by 2100. Alternative pathways exist that would avoid these net-negative emissions - for example Rogelj et al. (2019) shows that pathways which reach net-zero CO_2 emissions around 2040 and then maintain this level still achieve a peak temperature around 1.5°C with warming remaining around this level out to 2100, in part due to the continued reduction of global methane emissions after warming peaks acting to offset any increases in the level of global temperature due to non-zero residual (non-CO_2) long-lived GHG emissions. In the long-term (centennial timescales) it may be necessary to have a certain amount of net negative global CO_2 emissions even to sustain global temperature at a constant level. This is to counter any slow Earth System feedbacks such as permafrost thawing which would add to atmospheric concentrations (and therefore warming) over long-timescales (see Section 1).

After the completion of SR1.5, new scenarios have been developed by various scenario groups. These may give more insight to cost optimal emissions pathways for these gases and provide a stronger knowledge basis for options to reach the temperature goals.

2.4 Emission metrics

The Global Warming Potential (GWP) is defined as the time-integrated radiative forcing (RF) due to a pulse emission of a non-CO_2 gas, relative to a pulse emission of an equal mass of CO_2. It is used for expressing the effects of different emissions on a common scale; so-called 'CO_2 equivalent emissions'. The GWP was presented in the First IPCC Assessment, where it was stated that "It must be stressed that there is no universally accepted methodology for combining all the relevant factors into a single global warming potential for greenhouse gas emissions. A simple approach has been adopted here to illustrate the difficulties inherent in the concept, …".

Since then, the GWP has become a widely used metric for aggregation of different gases to 'CO_2 equivalent emissions' in the context of reporting emissions as well as in designing and assessing climate policies. The GWP for a time horizon of 100 years was adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol.

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[12] This compensatory effect of falling methane emissions could only temporarily offset the additional warming from continued positive emissions of long-lived GHGs, as falling methane emissions could not be maintained forever, ultimately keeping warming constant would require net-zero long-lived GHG emissions to be reached, necessitating net-negative emissions of CO_2 and some level of residual positive agricultural N_2O emissions are expected to be unavoidable.

The numerical values for GWP have been updated in the successive IPCC reports, as a consequence of updated science but also due to the changes occurring in the atmosphere; in particular the CO_2 concentration to which the radiative forcing has a non-linear relation.

Since its introduction, the concept has been evaluated and tested for use in design of mitigation policies. IPCC AR4 stated that “Although it has several known shortcomings, a multi-gas strategy using GWPs is very likely to have advantages over a CO_2-only strategy (O’Neill, 2003). Thus, GWPs remain the recommended metric to compare future climate impacts of emissions of long-lived climate gases.” In IPCC AR5, the assessment concluded that “The choice of metric and time horizon depends on the particular application and which aspects of climate change are considered relevant in a given context. Metrics do not define policies or goals but facilitate evaluation and implementation of multi-component policies to meet particular goals. All choices of metric contain implicit value-related judgements such as type of effect considered and weighting of effects over time.”

The Paris Agreement text does not explicitly specify any emission metric for aggregation of GHGs, but under the Paris rulebook adopted at COP 24 in Katowice [Decision 18/CMA.1, annex, paragraph 37], parties have agreed to use GWP-100 values from the IPCC AR5 or GWP-100 values from a subsequent IPCC assessment to report aggregate emissions and removals of GHGs and for accounting under NDCs. In addition, it is also stated that parties may use other metrics to report supplemental information on aggregate emissions and removals of greenhouse gases.

After IPCC AR5, new metric concepts have been published; some of them building on the similarity in behaviour of a sustained change in SLGHG and pulse of CO_2 (Allen et al., 2016), similar to the approach explored earlier by Lauder et al. (2013).

This new approach for comparing emissions, denoted GWP*, uses the same GWP values, but apply rate of change in emissions of the short-lived gas, e.g., methane. Cain et al. (2019) refined the concept to better represent the relationship between cumulative CO_2-warming-equivalent emissions and modelled warming in diverse CH_4 mitigation scenarios by taking into account the delayed warming impact of past methane emission increases. Lynch et al. (2020) demonstrated this for idealized cases. Collins et al. (2020) take an analytical approach and derive the combined global temperature change potential (CGTP) metric for calculating an equivalence between a sustained step-change in SLGHG emissions and a CO_2 emissions pulse. Collectively, these metrics that represent SLGHG emissions with a rate of emissions of CO_2 that would have the same impact on global temperatures are known as “warming-equivalent”.

These mixed step-pulse metrics can be used to aggregate SLGHG together with CO_2 and approximate the development of temperature relative to a reference year. In this way, the mixed step-pulse metrics allow for inclusion of SLGHG into the relation between cumulative CO_2-equivalent emissions and temperature change.

It is important to note that the two metric concepts GWP* and GWP measure different things. GWP measures the warming effect from emissions of a gas (e.g., CH_4) relative to the absence of that emission, whereas GWP* measures the warming effect from that emission relative to the warming from a reference emissions level. Thus, the physical quantity that is being compared for SLGHGs emissions relative to the warming from CO_2 is different for the two metrics. The differences are shown in the stylised example in Figure 2. For both LLGHGs and SLGHGs their past emissions contribute to global temperatures remaining above preindustrial levels in the future. For LLGHGs the contribution from past emissions persists at current levels for centuries. For SLGHGs their past contribution to temperature change above preindustrial decays over the next few decades (compare blue segments in Figure 2a and 2b). Therefore, the global temperature change contributed by post-2020 CH_4 emissions is quite different to the change in the global temperature level, comparing the 2020 reference level to the level at a future date, unlike for CO_2. This is because the contribution of CH_4 to warming from past emissions will decay over time (Figure 2b).

The fundamental science underlying these metrics is well established and much of the ongoing debate is about the framing and applications of metrics for various questions and contexts.

Metrics can also be used for assessing the concept "GHG balance" as used in Article 4 in the Paris Agreement. Fuglestvedt et al. (2018) tested metrics for calculation of temperature response to various composition of GHGs and found that balance determined using GWP* imply approximately constant temperatures once the balance has been achieved, whereas a balance based on GWP implies slowly declining temperatures when the mix of GHGs contains a significant positive contribution from SLGHGs[13]. This raises issues related to consistency between Article 4 and Article 2 in the Paris Agreement and what the ultimate temperature goal of the agreement is (Fuglestvedt et al. 2018; Schleussner et al., 2019). Tanaka and O'Neill (2018) find that net zero GHG emissions (in terms of GWP-100) are not necessarily required to remain below 1.5°C or 2°C, assuming either target can be achieved without temporarily overshooting these warming levels.

It is useful to consider how trading emissions under GWP-100 affects surface temperature change. Different combinations of LLGHGs and SLGHGs can give the same overall CO_2 equivalent emission trajectory (when aggregated using GWP-100 values) (e.g., Fuglestvedt et a., 2000, Fuglestvedt et al., 2003; Myhre et al., 2013; Allen et al., 2016; Allen et al., 2018). Globally the ambiguity generated for realistic strong mitigation pathways has been found to be important at the 10% level (or 0.17°C) (Denison et al., 2020). However, larger ambiguities could exist at sector and country level; e.g., in countries where methane emissions represent a larger fraction of total greenhouse gas emissions.

Figure 6 illustrates the temperature responses for different and purely hypothetical scenarios for New Zealand. The blue and green lines (or the purple and red) are contributions from pathways with the same total CO_2 equivalent emission trajectory (based on GWP-100) but different trajectories of CO_2 and biogenic CH_4 emissions comprising it. The green pathway has 47% biogenic CH_4 reductions by 2050 but at the expense of extra CO_2 emissions (to match the CO_2-equivalent emissions of the blue line) and does not reach net zero CO_2 emissions by 2050, which

[13] Balance based on GWP could theoretically lead to a warming effect if SLGHG removal is used to balance ongoing CO_2 emissions on a large scale.

happens in the blue pathway. Over this century the extra biogenic CH_4 reduction under the GWP-100 CO_2 equivalent assumption (green line) leads to lower contributions to global temperature than scenarios with identical aggregated GWP-100 emissions but lower cumulative CO_2 emissions. However, after 2100, the long-term warming effect of the extra CO_2 emissions dominate (substituted for CH_4) and give a continuing warming trend due to not achieving net-zero CO_2 emissions. Similarly, the purple line includes extra CO_2 emission reduction on top of the 24% CH_4 reduction scenario to match the GWP-100 trend in the 47% scenario. This scenario results in a continued long-term reduction in the contribution to global temperature due to the sustained net-negative CO_2 emissions. Generally, these results show that if New Zealand were to specify a single CO_2-equivalent emission reduction target based on GWP-100, there could be significant difference in the resulting global warming trajectory over century timescales. This is illustrated by the pairs of curves (green and blue, purple and red) in Figure 6 where differences give the scale of the ambiguity introduced and show how these change through time. Put simply, if you mitigate CO_2 as a substitute for CH_4 emissions you get long term benefits (a lower long-term temperature level), and if you mitigate CH_4 and a substitute for CO_2 emissions you get cooling for several decades (at the expense of longer term benefits).

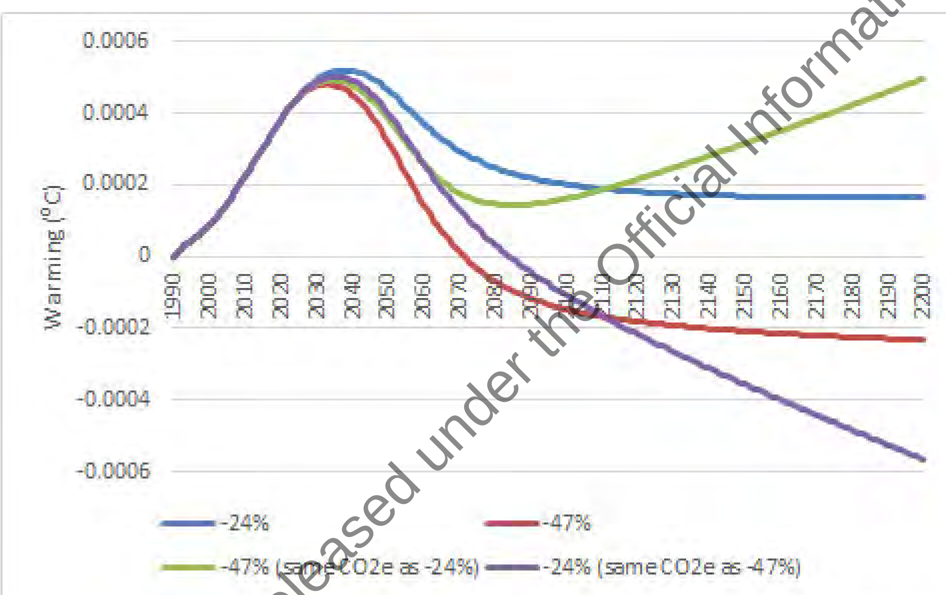


Figure 6: *An illustration of New Zealand's contribution to global warming (relative to the level of its contribution in 1990). The blue and red pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel CH_4, and have either 24% (blue) or 47% (red) reductions in biogenic CH_4 from 2017 levels to 2050. The green line has 47% biogenic CH_4 reduction but additional emissions of CO_2 to match the CO_2e emissions of the blue line based on IPCC AR4 GWP-100 values. The purple line has 24% CH_4 reduction but has extra CO_2 emission reduction to match the CO_2-equivalent emission within the 47% scenario. Emissions from 2050 do not alter. See Section 3.1 for the methodology.*

3. Considerations for national pathways consistent with keeping warming to 1.5°C

Section 2 considered the tradeoffs between mitigation of different greenhouse gases. This section discusses other considerations that could be taken into account in national pathways. There is no fundamental physical reason why a national pathway should follow either the global temperature or the global emissions trajectory, given different national circumstances and different mix of sectors with different long-lived and short-lived greenhouse gases.

3.1 National contribution to global warming.

New Zealand's historic contribution to global warming is estimated to be above 0.01 °C, from large-scale deforestation prior to 1840 (Reisinger and Leahy, 2019). The warming is estimated to be around 0.003 °C from biogenic methane emissions, nitrous oxide and fossil fuel CO_2 (Figure 7). There are also small contributions from F-gases and fossil fuel methane, which are not included in the Figure.

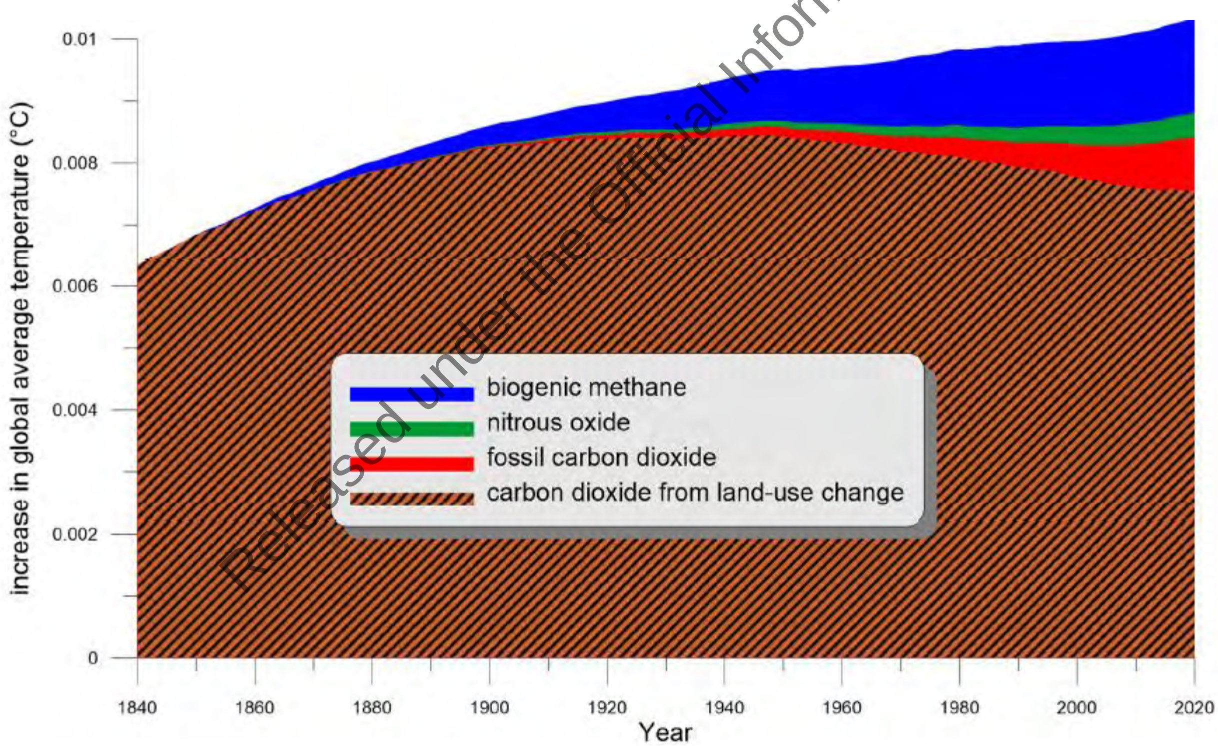


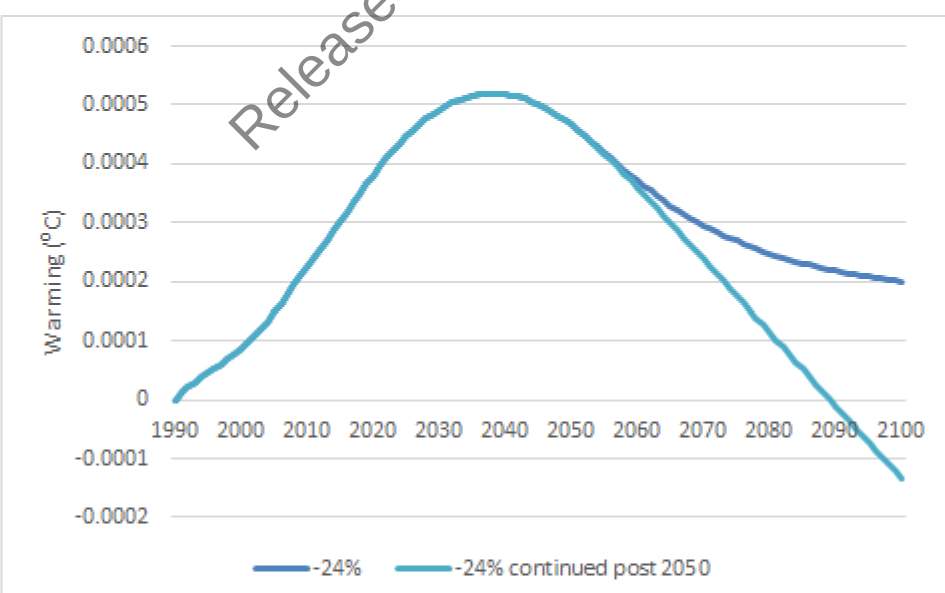
Figure 7: *Estimate of New Zealand's contribution to global warming from emissions until the end of 2019. Figure is taken from Reisinger and Leahy (2019).*

Figure 8 focuses on estimates of New Zealand's future contribution to global warming from emissions since 1990. New Zealand emissions from 1990-2018 are taken from New Zealand's greenhouse gas inventory and before that are taken from Reisinger and Leahy (2019) using Ausseil et al. (2013). They combine fossil fuel emissions, land-use change and biogenic emissions. The estimates of temperature change use the impulse response functions provided in the IPCC 5th Assessment Report for calculating GHG metrics as a simple climate model. Non-GHG contributions to warming (e.g. aerosol emissions) are not part of these scenarios.

The blue and red curves in Figure 8 approximate the range of New Zealand's possible future contributions to global warming under current policies, with a range of idealised assumptions after 2050. Under both 24% and 47% biogenic CH_4 reduction policies, New Zealand is beginning to reverse its contribution to global warming by around 2040. Under 24% reduction policies, the 2050 contribution to the level of global warming from New Zealand's emission since 1990 matches today's level of New Zealand's contribution to the level of global warming. Under 47% biogenic CH_4 reduction policies, the 2050 level of global warming from New Zealand's emissions approximately matches that from 2015.

Contributions to global temperature rise are sensitive to the shape of the emissions reduction profile as well as the end point reached in 2050 or any other year when mitigation approaches might change. This is particularly so for LLGHG pollutants, but less so for SLGHGs. Early reductions in LLGHGs have lower cumulative LLGHG emissions and overall less climate impact in the longer term (see Section 2.3). However, the most relevant factor for New Zealand's contribution to global temperatures rise above pre-industrial levels over most of this century will be the level of reduction of SLGHGs.

What happens to emissions after 2050 is important for the longer term contribution to global temperatures (see Sections 2.3 and 4.2). This is theoretically explored in Figure 8, which keeps net-zero CO_2 emissions at zero after 2050 and compares options for stable or continued biogenic methane emission reductions. These results illustrate that although the choices of biogenic emission pathway up until 2040 do influence New Zealand's contribution to global warming, the benefits of choosing 47% biogenic CH_4 abatement become more visible after 2040, when pathways are reversing New Zealand's historical contribution to global warming.



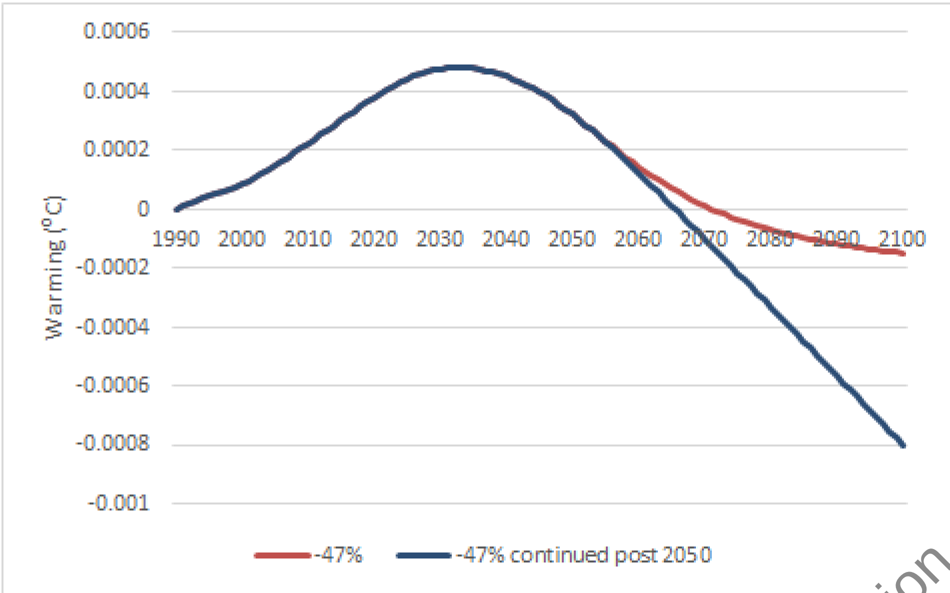


Figure 8: *As Figure 6, except emissions reductions continue beyond 2050. 24% biogenic CH_4 reduction by 2050, shown in the top panel and 47% reduction in the bottom panel. The panels have two scenarios: emissions unchanged after 2050, matching Figure 6, and the biogenic methane reduction rate continuing after 2050.*

Figure 9 explores a scenario where the 47% biogenic CH_4 reduction pathway is planned but biogenic CH_4 abatement does not prove possible, so CO_2 abatement is substituted assuming GWP-100 based equivalence. This pathway would give some more warming in the short term but eventually lead to less warming overall. Continued biogenic CH_4 reductions (as shown in Figure 8) and/or net negative CO_2 emissions (as shown in Figure 9) have a large effect on how much New Zealand's warming contribution is reversed.

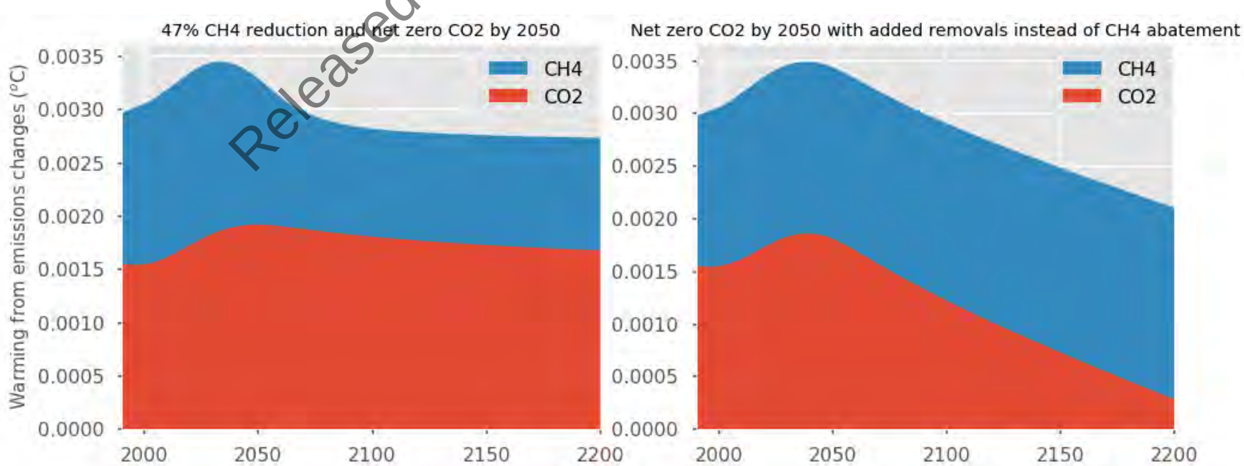


Figure 9: *Changes to warming contributions (above pre-industrial levels excluding emissions from historical land-use change) from different abatement strategies. The left plot shows the 47% biogenic CH_4 reduction scenario until 2050 reaching net zero CO_2 emissions at the same time.*

The right plot shows a scenario where additional CO_2 abatement is substituted for the CH_4 reduction assuming GWP-100 equivalence.

3.2 Fairness and equity

When determining either net zero targets dates or proportioning the remaining carbon budget into national quotas, choices have to be made regarding fairness, equity and burden sharing. These are obviously not straightforward and can have a large effect on levels of ambition for mitigation reduction (see Figure 3.9 from the UK CCC, 2019). It is not possible to include methane emissions scaled by GWP-100 within carbon budget estimates. However, similar equity principles could be applied to CH_4 emissions rates and cumulative CO_2 emissions.

When comparing national emission pathways, it is important to consider different national starting points. The same '1.5°C consistent' mitigation actions measured by cost or other measure of effort could result in different rates of emissions reductions in different regions depending on national circumstances and their respective capabilities to cut emissions. This includes the share of hard-to-abate emissions within a country profile today. For example, if the energy sector is already mostly decarbonised, the national emissions might not fall as quickly as the global average, whose rapid decline over the 2020s in 1.5°C scenarios is associated primarily with the rapid removal of coal from the electricity generation mix. Assessing whether a nation is taking the '1.5°C consistent' actions with its planned emissions reduction pathway may need to be more nuanced than a simple comparison with the global average reductions. It may also consider additional effort, outside of the domestic emissions account that a country might be undertaking to support the global transition (e.g. climate finance provision, purchase of credits through international markets, technology transfer etc.) to form a holistic picture of whether planned action to 2030 is 1.5°C-aligned.

3.3 Net Zero in the context of New Zealand

New Zealand currently plan to reach net zero GHG emissions by 2050 excluding biogenic methane for which a range of reductions in emissions rate by 2050 is being considered. Whether net zero GHG is reached is dependent on the emission metric choice in the way that net zero GHG is defined. As discussed in Fuglestvedt et al. (2018), it can be defined as a balance between anthropogenic emissions and removals, aggregated across gases by a chosen emission metric. The UK and the EU have set net-zero GHG targets based on GWP-100 which would be expected to lead to steadily declining temperatures if achieved globally. The New Zealand goal would not reach net zero GHGs under GWP-100 but would still lead to declining temperatures. Using the GWP* emission metric to assess if national pathways achieve net zero, both the UK and New Zealand goals would be seen as achieving net-negative GHG emissions.

Summary and conclusions

Section 1 presented a brief update of the science on past and future warming from greenhouse gases. Section 2 illustrated global trade-off considerations in strong mitigation emission pathways and Section 3 considered implications for deriving national strategies.

In the further development of policy towards New Zealand's contribution to the global effort of achieving the Paris temperature goals, our report has highlighted several issues and choices that would benefit from consideration. These are outlined below:

4.1 Evolving science

As knowledge is being developed and assessment reports are being published, it is important to be clear and transparent about what is used as the basis for the policy design; i.e. which parameter values and which definitions are adopted and used and how they might be revised as science understanding evolves.

4.2 Abatement choices

Choices of approach not only need to consider the physical science uncertainty but also need to consider the overall objectives of the climate policy and the practicalities of usage and communication. As illustrated in Section 3.1, the selection of greenhouse gases and as well as the emission metric used will have a significant effect on timing and efforts to achieve net zero and on the resulting global warming. The UK legislated for a net zero target in terms of GWP-100 emissions. One of the reasons given was that such a target would actively decrease its future warming commitment over time (see Section 2.1 and 3.1). For New Zealand to continue to decrease its future warming commitment after 2050, additional CH_4 reductions and/or negative emissions of CO_2 would be needed (Section 3.1).

New Zealand, by employing a two-target approach, one for biogenic methane and one for other greenhouse gases, largely avoids complications to do with emission metrics discussed in Section 2.4. However, if at a future date biogenic CH_4 and CO_2 abatements were traded as illustrated in Figure 9, the way of doing this trading would need to be considered. Using a GWP-100 metric would lead to long term additional cooling effect but shorter term additional warming when using carbon dioxide removal as a substitute for methane abatement (see Figure 9). However, other metric choices for trading between the gases could be considered. More generally, Sections 2.2 and 3.1, showed how it is possible to reverse the global warming trend and/or a nation's contribution to it by either a net removal of cumulative CO_2 emissions or by a permanent reduction in the rate of methane emissions below the levels at the time of peak warming. Where 445 $GtCO_2$ removal would have the same cooling effect as a permanent reduction in the rate of global methane emissions by around 135 $MtCH_4$/yr.

The Paris Agreement aims for a net-zero type target on a global basis. In the development of mitigation strategies for a single country it is important to consider how the plans for net zero might be achieved internationally and how a nation's plan fits into the international effort (i.e., which countries might achieve net negative, net zero or net positive emissions, and how international trading is used).

4.3 Pathways after net-zero

As shown in the pathways in SR1.5, achieving net zero CO_2 is just one part of the challenge in limiting future warming. Plans for the further path of emissions of the individual gases after net zero target is achieved also need to be addressed and communicated, particularly how greenhouse gas removal can be sustained given finite and competing interest for land resources (see Section 3.1).

4.4 Defining national high-ambition pathways

Which fairness and equity principles that are applied as rationale for New Zealand's efforts are important to communicate as a part of a mitigation strategy. As New Zealand's starting position in terms of sectoral emissions is different from other nations, a high ambition emission reduction trajectory might look quite different to a high ambition pathway from another country. In particular, many countries are expected to rapidly decarbonise their power sector out to 2030, leading to large national emission reductions in the 2020s. Countries such as New Zealand (and the UK) where the power sector is already mostly decarbonised, urgent actions are needed on other sectors such as agriculture, buildings and transport for mitigation compatible with Paris Agreement ambitions. Policy actions in these areas might take longer to manifest themselves in emissions trends. Such a pathway was presented for the UK 6th carbon budget (UK CCC, 2020), where actions over 2020-2025 only produced modest emission reduction by laying the groundwork for march larger emission reductions at the end of the 2020s.

New Zealand, by getting to net zero CO_2 as soon as possible with concerted action to substantially reduce biogenic CH_4 emissions as much as possible, can limit the contribution it makes to global warming which is expected to peak around 2040 and then begin to reverse. If actions continue to 2050 and beyond, New Zealand could substantially reduce its historic contribution to global warming from fossil fuel emissions, nitrous oxide and biogenic methane by the end of the century.

References

Allen M.R. et al. 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change,* **6,** 773-776, doi: 10.1038/nclimate2998

Allen, M. R., K. P. Shine, J. S. Fuglestvedt, R. J. Millar, M. Cain, D. J. Frame, and A. H. Macey, 2018 : A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Nature npj Climate and Atmospheric Science*, **1(2018-16)**, , doi: 10.1038/s41612-018-0026-8.

Ausseil A-GE, Kirschbaum MUF, Andrew RM, McNeill S, Dymond JR, Carswell F, Mason NWH 2013 Climate regulation in New Zealand: contribution of natural and managed ecosystems. In Dymond JR ed. Ecosystem services in New Zealand – conditions and trends. Manaaki Whenua Press, Lincoln, New Zealand.

Cain, M., Lynch, J., Allen, M. R., Fuglestvedt, J. S., Frame, D. J., and Macey, A. H. (2019). Improved calculation of warming-equivalent emissions for short-lived climate pollutants. NPJ Clim. Atmos. Sci. 2, 1–7. doi:10.1038/s41612-019-0086-4.

Collins, W.J.,C.P. Webber, P.M. Cox, C. Huntingford, J. Lowe, S. Sitch, S.E. Chadburn, E. Comyn-Platt, A.B. Harper, G. Hayman and T. Powell, 2018: Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters*, **13(5)**, doi:10.1088/1748-9326/aab89c.

Collins, W. J. , Frame, D. J., Fuglestvedt, J., and Shine, K. P. (2020). Stable climate metrics for emissions of short and long-lived species – combining steps and pulses. Environ. Res. Lett. doi:10.1088/1748-55 9326/ab6039.

UK Climate Change Committee, 2020, Sixth CArbon Budget Report, https://www.theccc.org.uk/publication/sixth-carbon-budget/

Denison S., Forster P.M., Smith C.J., 2019: Guidance on emissions metrics for nationally determined contributions under the Paris Agreement. *Environmental Research Letters*, **10** (7-10), doi:10.1038/s41558-019-0660-0.

Etminan, M., Myhre, G., Highwood, E. J., and Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophys. Res. Lett. 43, 12,614-12,623. doi:10.1002/2016GL071930.

Forster P.M., A.C. Maycock, C.M. McKenna and C.J. Smith, 2020: Latest climate models confirm need for urgent mitigation. *Nature Climate Change*, 1–14, doi:10.1007/s11027-017-9762-z.

Forster, P. M., Forster, H. I., Evans, M. J., Gidden, M. J., Jones, C. D., Keller, C. A., et al. (2020a). Current and future global climate impacts resulting from COVID-19. *Nature Climate Change*. oi:10.1038/s41558-020-0883-0.

Fuglestvedt J.S., Rogelj, R. J. Millar, M. Allen, O. Boucher, M. Cain, P. M. Forster, E. Kriegler and D. Shindell., 2018: Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philosophical Transaction of the Royal Society A*, **376(2119)**, doi:10.1098/rsta.2016.0445.

Fuglestvedt J.S., Berntsen T.K. and Skodvin T., 2000: Climate implications of GWP-based reductions in greenhouse gas emissions. *Geophysical Research Letters*, **27(3)**, 409–412, doi:10.1029/1999GL010939.

Fuglestvedt J.S., Berntsen T.K., Godal O., Sausen R., Shine K.P. and Skovin T., 2003 Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. *Climatic Change*, **58**, 267-331, doi:10.1023/A:1023905326842 .

Gasser T. et al., 2016: Accounting for the climate–carbon feedback in emission metrics. *Earth System Dynamics*, **8**, 235-253, doi: 10.5194/esd-8-235-2017.

Grubler A. et al., 2018: A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, **3**, 515-527, doi:10.1038/s41560-018-0172-6 .

Hawkins E. et al., 2017: Estimating Changes in Global Temperature since the Preindustrial Period. *American Meteorological Society*, **98(9)**, 1841-1856, doi:10.1175/BAMS-D-16-0007.1.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J.-I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geosci. Model Dev., 11, 369–408, https://doi.org/10.5194/gmd-11-369-2018, 2018

Hodnebrog Ø. Et.al., 2020: Updated Global Warming Potentials and Radiative Efficiencies of Halocarbons and Other Weak Atmospheric Absorbers. *Reviews of Geophysics*, **58(3)**, doi:10.1029/2019RG000691.

Jackson, R.B., Solomon, E.I., Canadell, J.G. *et al.* Methane removal and atmospheric restoration. *Nat Sustain* **2,** 436–438 (2019). https://doi.org/10.1038/s41893-019-0299-x

Kadow, C., Hall, D. M., and Ulbrich, U. (2020). Artificial intelligence reconstructs missing climate information. *Nat. Geosci*. 13, 408–413. doi:10.1038/s41561-020-0582-5.

Kennedy J.J. et al.,, 2019: An Ensemble Data Set of Sea Surface Temperature Change From 1850: The Met Office Hadley Centre HadSST.4.0.0.0 Data Set. *JGR Atmospheres*, 124(14), 7719-7763, doi:10.1029/2018JD029867.

Lauder, A. R., I. G. Enting, J. O. Carter, N. Clisby, A. L. Cowie, B. K. Henry, and M. R. Raupach, 2013:

Offsetting methane emissions—An alternative to emission equivalence metrics. *Int. J. Greenh. Gas Control*, 12, 419–429.

Leahy, S. C., H. Clark, and A. Reisinger, 2020: Challenges and prospects for agricultural greenhouse gas mitigation pathways consistent with the Paris Agreement. *Front. Sustain. Food Syst*., 1–15, https://doi.org/10.3389/fsufs.2020.00069.

Lynch J. et al., 2020: Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environmental Research Letters*, **15(4)**, doi:10.1088/1748-9326/ab6d7e .

Myhre G.. et al., 2013: Radiative forcing [Stocker, T.F. et al. (eds.)]. Cambridge University Press, pp. 659-740.

MacDougall A.H. et al., 2020 Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2.*Biogeoscience*, 17(11)**,** doi: 10.5194/bg-17-2987-2020.

Morice C.P., J. J. Kennedy N. A. Rayner J. P. Winn E. Hogan R. E. Killick R. J. H. Dunn T. J. Osborn P. D. Jones I. R. Simpson. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. JGR Atmospheres. 15 December 2020. https://doi.org/10.1029/2019JD032361

Nicholls Z.R.J. et al., 2020: Reduced complexity model intercomparison project phase 1: Protocol, results and initial observations. *Geoscientific Model Development*, doi: 10.5194/gmd-2019-375.

O'Neill, B., 2003: Economics, natural science, and the costs of global warming potentials. *Clim. Change,* 58, 251–260.

Popp et al., 2017: Land-use futures in the shared socio-economic pathways*. Global Environmental Change,* Volume 42, January 2017, Pages 331-345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Reisinger, A. and Leahy, S., 2019: Scientific aspects of New Zealand's 2050 emission targets, New Zealand Agricultural and Greenhouse Research Centre Technical Report, available at https://www.nzagrc.org.nz/user/file/1941/Scientific%20aspects%20of%202050%20methane%20targets.pdf

Renaud de_Richter, Tingzhen Ming, Philip Davies, Wei Liu, Sylvain Caillol, Removal of non-CO2 greenhouse gases by large-scale atmospheric solar photocatalysis, Progress in Energy and Combustion Science, Volume 60, 2017, Pages 68-96, ISSN 0360-1285, https://doi.org/10.1016/j.pecs.2017.01.001.

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, M. V. Vilariño, 2018a, Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

Rogelj J. et al., 2018b: Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, **571**, 335-342, doi:10.1038/s41586-019-1368-z

Rogelj J. et al., 2019: A new scenario logic for the Paris Agreement long-term temperature goal. *Nature*, **573**, 357-363, doi:10.1038/s41586-019-1541-4 .

Richardson T.B. et al., 2019: Efficacy of Climate Forcings in PDRMIP Models. *JGR Atmospheres*, 124(23), 12824-12844, doi:10.1029/2019JD030581 .

Schleussner, C.-F., Nauels, A. , Schaeffer, M., Hare, W. and Rogelj, J.: 2019: Inconsistencies when applying novel metrics for emissions accounting to the Paris agreement. *Environ. Res. Lett*. 14 (2019) 124055 https://doi.org/10.1088/1748-9326/ab56e7

Sherwood S.C. et al., 2020: An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*, **58(4)**, e2019RG000678, doi:10.1029/2019RG000678 .

Samset B.H. et al, 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical Research Letters*, **45**, 40**8-**411, doi:10.1002/2017GL076079 .

Shindell D. and Smith J., 2019: Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature*, **573(sup1)**, 408-411, doi: 10.1038/s41586-019-1554-z

Smith C.J.. et al., 2019: Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming. *Nature Communications*, **10(101)**, doi: 10.1038/s41467-018-07999-w.

Smith C.J. et al., 2018: Understanding Rapid Adjustments to Diverse Forcing Agents *Geophysical Research Letters*,**16(21)**,12023-12031, doi: 10.1029/2018GL079826

Steffen W. et al., 2018: Trajectories of the Earth System in the Anthropocene. *PNAS*, **115(33)**, 8252,8259, doi:10.1073/pnas.1810141115.

Sterner, E. and Johansson D., 2017: The effect of climate–carbon cycle feedbacks on emission Metrics. *Environ. Res. Lett*. 12 034019

Tanaka K. and O'Neil B.C., 2018: The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets. *Nature Climate Change*, **8**, 319-324, doi:10.1038/s41558-018-0097-x.

Thornhill G. et al., 2019: Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models *Atmospheric Chemistry and Physics*, doi: 0.5194/acp-2019-1207.

Turetsky M.R. et al., 2020: Carbon release through abrupt permafrost thaw. *Nature Geoscience*, **13**, 138-143, doi:10.1038/s41561-019-0526-0.

UNEP 2020 Emissions Gap Report, https://www.unenvironment.org/emissions-gap-report-2020.

UK Committee on Climate Change: Net Zero – The UK's contribution to stopping global warming, https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

van Vuuren D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8**, 391-397, doi:10.1038/s41558-018-0119-8.

Weber, J., Shin , Y.M, Staunton Sykes, J., Archer-Nicholls, S., Abraham, N. L., Archibald, A.,: 2020: Minimal Climate Impacts From Short-Lived Climate Forcers Following Emission Reductions Related to the COVID-19 Pandemic. *Geophys. Res. Let.,* 13 October 2020. https://doi.org/10.1029/2020GL090326

Wang Y and Huang Y., 2020: The Surface Warming Attributable to Stratospheric Water Vapor in CO_2-Caused Global Warming. *JGR Atmospheres*, **125(17)**, e2020JD032752, doi: 10.1029/2020JD032752.

Zickfeld K. et al., 2017: Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. *PNAS*, doi: 10.1073/pnas.1612066114.

Science piece

Ask

The Climate Change Commission (the CCC) is seeking to commission a report on climate science on keeping global warming to less than 1.5 degrees Celsius above pre-industrial levels. This report is to assist with the CCC's response to the Minister of Climate Change's request for advice under s5K of the Climate Change Response Act 2002 and in advising the government on proposed emission budgets for 2022-2035.

Background

The Paris agreement and the Special Report on 1.5 degrees

In 2015, New Zealand lodged its first commitment under the Paris agreement (its Nationally Determined Contribution or NDC) to reduce emissions to 30 per cent below 2005 levels by 2030, using a carbon budget approach over 2021 to 2030.[1]

The Paris agreement article 2 states that one of its goals is to hold warming to well below 2 degrees above pre-industrial levels, and to pursue efforts to limit warming to 1.5 degrees[2]:

Article 2

1. This Agreement in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

a) *Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;*
b) *Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and*
c) *Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.*

2. This Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

The addition of text reflecting the goal of keeping warming below 1.5 degrees marked a shift away from the main temperature goal being to keep warming below 2 degrees, although 2 degrees remained the primary temperature objective. To support this new goal, at the 21st Conference of the Parties to the UNFCCC that adopted the Paris agreement, parties also agreed to invite the IPCC to provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways.

[1] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/New%20Zealand%20First/New%20Zealand%20first%20NDC.pdf
[2] https://unfccc.int/sites/default/files/english_paris_agreement.pdf

The IPCC delivered and approved its final version of its report in October 2018 titled *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development* (the Special Report on 1.5 degrees, or SR1.5).

The SR1.5 outlined the impacts of keeping warming to 1.5 degrees, as well as a range of modelled scenarios that illustrated how the world could do so. In particular, these scenarios illustrated that long-lived gases needed to go to net zero emissions around the middle of the century, while emissions of methane needed to be cut significantly, but not to zero.

New Zealand's Zero Carbon Act

The SR1.5 informed work that New Zealand was doing in establishing new targets for long-term mitigation. In 2018 and 2019, the New Zealand government was developing a new framework for climate change targets and policies referred to as the Zero Carbon Act (the Act).[3] The Zero Carbon Act established new climate change targets for New Zealand:

- A split gas target for 2050 to:
    - Reduce emissions of biogenic methane to between 24 and 47 per cent below 2017 levels
    - Reduce all other emissions to net zero.
- A target for biogenic methane to be reduced by 10 per cent below 2017 levels by 2030.

These targets are in addition to the existing commitment enshrined in New Zealand's NDC.

The Zero Carbon Act also established the Climate Change Commission (the Commission) to provide independent advice to government on emission budgets and policies to meet these targets. Emission budgets will be for five years and be set 10 years before they begin. The Commission will be advising on the level of the first three emissions budgets covering the period 2022-2035 in early 2021.

Under the Act, the Commission is required to consider a range of specific matters in its work and specifically consider the state of scientific advice. Section 5M states:

> *In performing its functions and duties and exercising its powers under this Act, the Commission must consider, where relevant,—*
>
> *(a) current available scientific knowledge*

The Commission is also required to specifically consider scientific advice in advising on emissions budgets. Section 5ZC states:

> *The Commission and the Minister must—*
>
> *(b) have regard to the following matters:*
>
> *(ii) a broad range of domestic and international scientific advice.*

The report will assist the Commission in meeting these requirements, as it advises on the first three emission budgets.

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[3] The reforms referred to as the Zero Carbon Act were passed however by amending an existing piece of legislation so it was technically the Climate Change Response (Zero Carbon) Amendment Act 2019. http://www.legislation.govt.nz/act/public/2019/0061/latest/LMS183736.html

Reviews

In addition to the requirements to advise on emission budgets, the Minister for Climate Change, Hon. James Shaw, in 2019 requested that the Commission provide him with advice on two matters[4]:

1. The potential reductions in biogenic methane emissions which might eventually be required by New Zealand as part of a global effort under the Paris Agreement to limit the global average temperature increase to 1.5 degrees Celsius above pre-industrial levels;
2. Whether New Zealand's NDC is compatible with a global effort to keep warming to 1.5 degrees above pre-industrial levels, and any recommended changes to ensure it is compatible with a global effort to keep warming to 1.5 degrees above pre-industrial levels.

The report we are seeking to have completed will assist the Commission in articulating what issues and questions are raised by "compatible with a global effort to keep warming to 1.5 degrees."

Detail

The purpose of the report is to concisely summarise the state of scientific understanding of what actions are needed to keep warming below 1.5 degrees, and to outline the policy and political choices that exist that are compatible with that goal. It will articulate the choices and assumptions that underly particular pathways for different greenhouse gases, so that the CCC can be clear about its recommendations on New Zealand's NDC, and on the long-term cuts to methane that may be required of NZ.

The report needs to:

1. Summarise the state of scientific understanding of:
   - the different warming effect of different gases
   - different global pathways that are consistent with keeping warming to 1.5 degrees
   - what levels the world needs to reduce emissions of different gases to, particularly methane, to by 2030 and by 2050 in order to keep warming below 1.5 degrees.
2. Articulate the main choices and trade-offs that are available to New Zealand while still being consistent with a global effort to keep warming below 1.5 degrees. These will draw on modelled pathways and make underlying assumptions choices within those pathways clear so that the required choices can be associated with different pathways. These could include but are not limited to:
   - The speed of reaching net zero emissions of long-lived gases vs the level of ongoing methane emissions
   - The extent to which carbon capture and storage is developed
   - The extent to which develop countries do more and reduce emissions faster than the global average, or developing countries take more time to reduce emissions to reflect their national circumstances
3. Articulate the implications that are not optional for keeping warming below 1.5 degrees.

The report should *not* attempt to address what settings New Zealand should make within these choices, but only articulate what the choices are, and should not discuss policies needed to achieve particular types of reductions.

The report should be based on relevant scientific studies, although it will be heavily informed by the IPCC SR1.5 and the draft Sixth Assessment Report.

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[4] As empowered under s5K of the Climate Change Response Act 2002.

Review process

The Commission will nominate a group of relevant scientists to provide technical review. The Commission will organise review comments first from technical reviewers, and secondly from wider group of sector reviewers.

Indicative timeframe

Timing	Phase of work
By 13 July	Contracting
12 August	First draft
20 August	Review comments back to author
31 August	Final report

Science piece

Ask

The Climate Change Commission (the CCC) is seeking to commission a report on climate science on keeping global warming to less than 1.5 degrees Celsius above pre-industrial levels. This report is to assist with the CCC's response to the Minister of Climate Change's request for advice under s5K of the Climate Change Response Act 2002 and in advising the government on proposed emission budgets for 2022-2035.

Background

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Article 2

1. This Agreement in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

- *a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;*
- *b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and*
- *c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.*

2. This Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

The addition of text reflecting the goal of keeping warming below 1.5 degrees marked a shift away from the main temperature goal being to keep warming below 2 degrees, although 2 degrees remained the primary temperature objective. To support this new goal, at the 21st Conference of the Parties to the UNFCCC that adopted the Paris agreement, parties also agreed to invite the IPCC to provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways.

[1] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/New%20Zealand%20First/New%20Zealand%20first%20NDC.pdf
[2] https://unfccc.int/sites/default/files/english_paris_agreement.pdf

The IPCC delivered and approved its final version of its report in October 2018 titled *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development* (the Special Report on 1.5 degrees, or SR1.5).

The SR1.5 outlined the impacts of keeping warming to 1.5 degrees, as well as a range of modelled scenarios that illustrated how the world could do so. In particular, these scenarios illustrated that long-lived gases needed to go to net zero emissions around the middle of the century, while emissions of methane needed to be cut significantly, but not to zero.

New Zealand's Zero Carbon Act

The SR1.5 informed work that New Zealand was doing in establishing new targets for long-term mitigation. In 2018 and 2019, the New Zealand government was developing a new framework for climate change targets and policies referred to as the Zero Carbon Act (the Act).[3] The Zero Carbon Act established new climate change targets for New Zealand:

- A split gas target for 2050 to:
    - Reduce emissions of biogenic methane to between 24 and 47 per cent below 2017 levels
    - Reduce all other emissions to net zero.
- A target for biogenic methane to be reduced by 10 per cent below 2017 levels by 2030.

These targets are in addition to the existing commitment enshrined in New Zealand's NDC.

The Zero Carbon Act also established the Climate Change Commission (the Commission) to provide independent advice to government on emission budgets and policies to meet these targets. Emission budgets will be for five years and be set 10 years before they begin. The Commission will be advising on the level of the first three emissions budgets covering the period 2022-2035 in early 2021.

Under the Act, the Commission is required to consider a range of specific matters in its work and specifically consider the state of scientific advice. Section 5M states:

> *In performing its functions and duties and exercising its powers under this Act, the Commission must consider, where relevant,—*
>
> *(a) current available scientific knowledge*

The Commission is also required to specifically consider scientific advice in advising on emissions budgets. Section 5ZC states:

> *The Commission and the Minister must—*
>
> *(b) have regard to the following matters:*
>
> *(ii) a broad range of domestic and international scientific advice.*

The report will assist the Commission in meeting these requirements, as it advises on the first three emission budgets.

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[3] The reforms referred to as the Zero Carbon Act were passed however by amending an existing piece of legislation so it was technically the Climate Change Response (Zero Carbon) Amendment Act 2019. http://www.legislation.govt.nz/act/public/2019/0061/latest/LMS183736.html

Reviews

In addition to the requirements to advise on emission budgets, the Minister for Climate Change, Hon. James Shaw, in 2019 requested that the Commission provide him with advice on two matters[4]:

1. The potential reductions in biogenic methane emissions which might eventually be required by New Zealand as part of a global effort under the Paris Agreement to limit the global average temperature increase to 1.5 degrees Celsius above pre-industrial levels;
2. Whether New Zealand's NDC is compatible with a global effort to keep warming to 1.5 degrees above pre-industrial levels, and any recommended changes to ensure it is compatible with a global effort to keep warming to 1.5 degrees above pre-industrial levels.

The report we are seeking to have completed will assist the Commission in articulating what issues and questions are raised by "compatible with a global effort to keep warming to 1.5 degrees."

Detail

The purpose of the report is to concisely summarise the state of scientific understanding of what actions are needed to keep warming below 1.5 degrees, and to outline the policy and political choices that exist that are compatible with that goal. It will articulate the choices and assumptions that underly particular pathways for different greenhouse gases, so that the CCC can be clear about its recommendations on New Zealand's NDC, and on the long-term cuts to methane that may be required of NZ.

The report needs to:

1. Summarise the state of scientific understanding of:
   - the different warming effect of different gases
   - different global pathways that are consistent with keeping warming to 1.5 degrees
   - what levels the world needs to reduce emissions of different gases to, particularly methane, to by 2030 and by 2050 in order to keep warming below 1.5 degrees.
2. Articulate the main choices and trade-offs that are available to New Zealand while still being consistent with a global effort to keep warming below 1.5 degrees. These will draw on modelled pathways and make underlying assumptions choices within those pathways clear so that the required choices can be associated with different pathways. These could include but are not limited to:
   - The speed of reaching net zero emissions of long-lived gases vs the level of ongoing methane emissions
   - The extent to which carbon capture and storage is developed
   - The extent to which develop countries do more and reduce emissions faster than the global average, or developing countries take more time to reduce emissions to reflect their national circumstances
3. Articulate the implications that are not optional for keeping warming below 1.5 degrees.

The report should *not* attempt to address what settings New Zealand should make within these choices, but only articulate what the choices are, and should not discuss policies needed to achieve particular types of reductions.

The report should be based on relevant scientific studies, although it will be heavily informed by the IPCC SR1.5 and the draft Sixth Assessment Report.

[4] As empowered under s5K of the Climate Change Response Act 2002.

Review process

The Commission will nominate a group of relevant scientists to provide technical review. The Commission will organise review comments first from technical reviewers, and secondly from wider group of sector reviewers.

Indicative timeframe

Timing	Phase of work
By 13 July	Contracting
12 August	First draft
20 August	Review comments back to author
31 August	Final report

[redacted]

From: Piers Forster <[redacted]>
Sent: Wednesday, 30 September 2020 8:39 pm
To: [redacted]; Jan Sigurd Fuglestvedt
Cc: Millar, Richard
Subject: Re: [UNCLASSIFIED] RE: Draft outline

Hi [redacted]
We are all well. It was Jan's crash and gave him a couple of days hassle when we were due to submit. Richard also choose to move house the same week. I have no excuses!

Thanks for this very comprehensive feedback. It makes a lot of sense. We mentioned GWP* by name in an earlier draft on section 2 and can put this back.

We also didn't really cover the long term stuff so can add more.

We'll discuss amongst ourselves and get cracking with the edits
Piers

From: [redacted]
Sent: Wednesday, September 30, 2020 2:29 am
To: Piers Forster; Jan Sigurd Fuglestvedt
Cc: Millar, Richard
Subject: RE: [UNCLASSIFIED] RE: Draft outline

[UNCLASSIFIED]

Hi Piers, Jan, Richard

Sorry I only just noticed – car crashes? Who crashed? Are you/they ok? I hope you all are alright.

Thanks for the opportunity to review – it was good to dig into the draft and think about the questions we are trying to answer. Apologies it took a bit longer than I thought it would. There was a lot in the draft that we really liked. For example, the diagram in section 3.2 of the value judgements vs climate science was one of them many parts we thought was particularly useful. There are a few things we'd comment on to make them more useful/relevant to our task – mostly around methane and trading between gases. Some of the suggestions are to help us with our analysis, and some are to help us bring people with us in how they think about issues.

I really liked the way you drew a relationship between cumulative long-lived emissions and the rate of methane emissions in section 2.2. I think that's very helpful. We discussed it a bit here and the question that arose is that isn't that linear relationship the underpinning of GWP*? I know we'd said that GWP* is contentious in NZ given our political circumstances – where it's being pushed by some to be used in domestic policy – but the comparison between cumulative LLGHGs and the rate of methane emissions seems like a very appropriate use for it and we wouldn't want to avoid talking about GWP* but discuss its approach in all but name. If you think it makes sense to use GWP* in that section, or to reference or include it alongside for comparison then don't hold back.

One of the questions we are trying to answer is the long-term (beyond 2050) cuts to biogenic methane required to keep temperature increase below 1.5 degrees. I know the question as framed is more than a little speculative and not entirely answerable – but there's a little content you might add and a bit in how you frame it that could make a big difference in helping us to address the question. On the content, the modelling for the IPCC SR1.5 scenarios had range of emissions cuts to agricultural methane out to 2100 – one thing that would be useful is a bit of description of the kinds of features of scenarios/technology assumptions associated with the low end the range of methane cuts in 2100 and the high end of the range in 2100. Being able to describe the common elements in the story that is being told in those models and the differences in the top and bottom end of the range of projected methane cuts would be a useful way we can address the question. Figure 5 shows that the scenarios with higher cumulative LLGHGs emissions generally reduce methane emissions more and vice-versa – is there a bit you can add in to say at a high level what drives those results? Are some scenarios assuming diet changes or making different assumptions about the cost-effectiveness of renewable energy technology? Any insight you can provide there would be helpful. In that same vein, if you're able to extract what the models generally assumes about how agricultural methane emissions are reduced in the models would be useful too. It doesn't need to be detailed, just clear about what options are assumed. You quite rightly make the point that the IPCC model results are cost optimal pathways and some clarity on those assumptions helps us to inform the public debate around what we do on methane if we succeed in developing a methane inhibitor/vaccine.

Then in how it's framed, it'd be helpful to add a para bringing some of the different pieces relevant to the question of long-term cuts to methane together in one place. You've quite sensibly started from the point of keeping temperatures to 1.5 degrees and what that means for overshoot and cumulative emissions and other risks around definition. I wonder if it's possible to add a paragraph or two at the end of section 2 bringing together the different pieces relevant to the question of long-term methane cuts at a global level? It wouldn't answer it obviously but just laying out that the long term cuts to methane necessary to keep warming below 1.5 degree will depend on 1) cumulative long lived emissions which sets how much overshoot you need to manage; 2) how much emission removal tech you can use and flagging any known uncertainty about its feasibility. 3) Any further developments in our ability to cost-effectively reduce agricultural methane emissions (if it becomes cheap through a vaccine/inhibitor, we might do more on methane and use less BECCS) – if you think those are the relevant factors to the question of how much the world would need to reduce agricultural methane emissions to keep to 1.5 degrees.

Some more minor feedback – for NZ, our methane targets are strictly "biogenic methane" which is defined as methane from the agriculture and waste sectors of the GHG inventory. To the extent you can, focusing on agricultural methane rather than all methane in the modelling pathways is useful – as fossil methane is not as relevant for NZ (e.g. the middle graph in figure 4).

You asked for some feedback on the conclusions – one of the conclusions we drew from the graphs in figure 4 was that emissions reductions need to be much more rapid between now and 2030 than they are between 2030 and 2050. The rationale for rapid immediate cuts to LLGHGs and SLGHGs are similar but not the same, and perhaps that could be drawn out in your conclusions. The paper makes the point at the end of section 2 that the risk of overshoot and reliance on BECCs makes the case for early action to reduce LLGHGs. The modelling results in figure 4 that show rapid reductions also in methane would indicate that rapid reductions in methane are also cost-optimal for keeping warming below 1.5 degrees. Is it fair to conclude then that given how close the world is to 1.5 degrees of warming, the reductions in methane can either be later to help *mitigate* overshoot, or earlier to help *avoid* overshoot? And the timing of reductions while leading you to the same place temperature-wise in the long-term, sets a different trajectory to get there? That's obviously a value-judgement – but if that framing is correct, it's a helpful way for us to consider and decide on recommendations for methane emissions reductions.

I think that it's it from us

Let us know if that doesn't make sense or if you have other questions!

Kind regards

[redacted]

From: Piers Forster <[redacted]>
Sent: Saturday, 26 September 2020 7:37 am
To: [redacted] Jan Sigurd Fuglestvedt <[redacted]>
Cc: Millar, Richard <[redacted]>
Subject: Re: [UNCLASSIFIED] RE: Draft outline

Dear [redacted],

Sorry we are overdue on our homework and especially so considering time zones. Please find our first draft attached. We are still a little ashamed of it, hence they made me first author. Life got in the way this week with house moving and car crashes... We want to make sure it meets your needs though, so we wondered if a quick internal review was worthwhile before going for the external review? This way we could do any extra analysis you may want and get it reviewed as well..

Thanks in advance and best wishes

Piers