He Pou a Rangi
Climate Change Commission

Official Information request reference: 2021-013

23 March 2021

Email: Roger.Lincoln@dairynz.co.nz

Dear Roger

Thank you for your request under the Official Information Act 1982 (the Act) of 23 February 2021 requesting:

"…all correspondence between the Commission and the report writing team." [referring to Piers Forster, Richard Millar and Jan Fuglestvedt – the authors of *Climate science considerations of global mitigation pathways and implications for New Zealand mitigation pathways*]

On 24 February, you clarified that you are requesting correspondence on the "scope and content of the report and the CCC's feedback on the draft" not the contractual negotiations. Accordingly, we have interpreted this request as covering all correspondence with the report writing team excluding correspondence solely about the contract for its delivery.

In response to your query, please find enclosed the following documents:

Number	Document Name
1	Forster Fuglestvedt Millar NetZero-NZ-report-DRAFT_V1-MRA_comments_emailed from MJS 18 November 2020
2	Forster Fuglestvedt Millar NetZero-NZ-report-DRAFT_V1-REVISION_AR_emailed from MJS 19 October 2020
3	NetZero-NZ-report-DRAFT_V1_emailed 26 September 2020
4	NetZero-NZ-report-DRAFT_V1-REVISION_emailed 12 October2020
5	NewZealand_revised12Jan_MJS proofs_PF_emailed from PF 12 Jan 2021
6	NewZealand_revised12Jan_MJS proofs_PF_refJF_emailed 14 Jan 2021
7	NewZealand_revised18Dec_RM_JF_PF_emailed 9 Jan2021
8	Science advice commissioning - 20200706_emailed to Jan F 7 August 2020
9	Science advice commissioning_emailed to PF 2 July 2020
10	Commission feedback on the draft report
11	Correspondence Piers Forster 1
12	Correspondence with authors 1

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Number	Document Name
13	Correspondence with authors 2
14	Correspondence with authors 3
15	Email from Piers Forster 7 Jan 2021
16	Jan F 23 September 2020
17	Jan F arranging meetings
18	Jan F introduction
19	Jan F introductory meeting
20	Piers Forster introduction
21	Provision of external review AR

Documents 1 – 9 were attachments to email correspondence between the Commission and the authors. The date of the correspondence is appended to the document titles so you can match attachments to emails. Documents 10 – 21 are email chains or individual emails between Commission staff and the authors. The Commission's feedback on the draft report is contained in document 10.

Documents 1 and 2 were provided to you in your request of 9 February 2021. They are included here for completeness.

Email addresses and other contact information for people in the correspondence threads have been redacted in accordance with section 9(s)(a) of the Official Information Act which allows withholding such information "to protect the privacy" of persons.

I hope this answers your queries.

Please note that the Commission has a policy of proactive release of OIA responses to help others have access to more information so this letter will be published on the website with your name and contact details redacted to protect your privacy.

Kind regards

J E Hendy

Jo Hendy
Chief Executive
He Pou a Rangi – Climate Change Commission

Climate Science Considerations of Net-Zero for New Zealand

Piers Forster (1), Richard Millar (2) and Jan Fuglestvedt (3)

1. **Priestley International Centre for Climate, University of Leeds, UK**
2. **UK Committee on Climate Change, UK**
3. **CICERO, Norway**

11 October 2020

Introduction

This report gives a brief overview of the current scientific understanding of emissions reductions needed to achieve the temperature ambitions of the Paris Agreement. It builds on the findings in the IPCC special Report on global warming of 1.5 °C and Special Report on Climate change and Land, as well as recent updates in the scientific literature. It focuses on the main characteristics of the emission pathways and what choices exist between mitigation of different greenhouse gases. We also discuss how different choices affect the prospects of meeting the Paris temperature goals.

1. Climate response to emissions of different GHGs

This first section examines how much warming greenhouse gas increases have committed us to and how well we understand the climate response to future emissions.

1.1 Committed warming

Future global warming largely depends on future global emissions of greenhouse gases (GHGs), but also from changes in other air pollutants. The concept 'committed warming' - or 'warming in pipeline' due to past emissions received increased attention in the context of the Paris Agreement aiming at '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'.

Based on the literature and knowledge available at the time, the 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? There is new science emerging on the committed warming if CO_2 emissions fall to zero, the zero emission commitment (ZEC). There have also been additional warm years since 2018 and a revision of historic temperature records. The amount of warming for future GHG emissions before targets are passed also depends on emission changes in non-greenhouse gas pollutants. The sections below detail how understanding of each of these has progressed since the 2018 IPCC Special Report on global warming of 1.5 °C.

1.1.1 Historic warming estimates

Before we discuss future warming, in light of the Paris temperature target it is worth considering historic warming estimates. SR1.5 estimated that the human-induced warming had reached around 1°C (with a 0.8°C to 1.2°C range) by the end of 2017 above pre-industrial levels. This was based on averaging the first four datasets in Table 1.1 of that report. Since then these historic temperature datasets are in the process of being revised. We expect these revisions to lead to a slight increase in the warming to date overall (e.g. Kennedy et al. 2019, Kadow et al. 2020) and the years since 2017 have continued to be among the hottest in the instrumental record. The discussion of how we define globally average surface temperature was addressed in Chapter 2 of SR1.5 for the calculation of the remaining carbon budget. 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 combined the observations with model data to estimate the near surface air temperature trend everywhere. The latter choice was there estimated to lead to 10% higher levels of present day warming and therefore a reduced remaining carbon budget. This 10% uplift was a model calculation and more recent work suggests that it 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).

Commented [MA1]: Need to explain that this arises from a downward revision of he estimated temperature in 1850-1900 due to new (and possibly improved) statistical methods and some additional data: hence it does NOT mean climate change today (in terms of current impacts) is "worse than we thought"

IPCC SR1.5 used the average of 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 of the choice of 1750 or 1850-1900 for the pre-industrial baseline. Using 1750 as a pre-industrial baseline could add around 0.05°C more warming to date 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 historic surface temperature change since preindustrial times and these would have knock on effects for remaining carbon budget analyses. Note that by altering the historic temperature we are implicitly altering the applied relationship between global temperature and 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 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.

Commented [MA2]: Ah, you got here. Maybe just add the point about where the revision comes from in response to previous comment. Many people will think we have revised up estimate of warming to date because we've had some hot years recently. This is not the case: recent years have been pretty much on-trend.

1.1.2 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 from 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) examined the climate response to COVID-19 restrictions and showed that some of the short term warming from reduced SO2 emissions and

Commented [MC3]: There is also a recent paper, Weber et al, which reinforces this result using UKCA modelling https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL090326 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 SO2 emissions would lessen any near-term warming.

1.1.3 The zero emission commitment (ZEC)

MacDougall et al. (2020) conclude that the most likely value of the ZEC 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 either sign but is always less than +0.5°C across models, with a best estimate, based on current evidence of close to zero.

Commented [MA4]: If you add the plus sign, it makes it clear you aren't talking about he absolute value.

Commented [MC5]: The PLASIM-GENIE line has a greater than 0.5C devia ion. Unless I'm misunderstanding here.

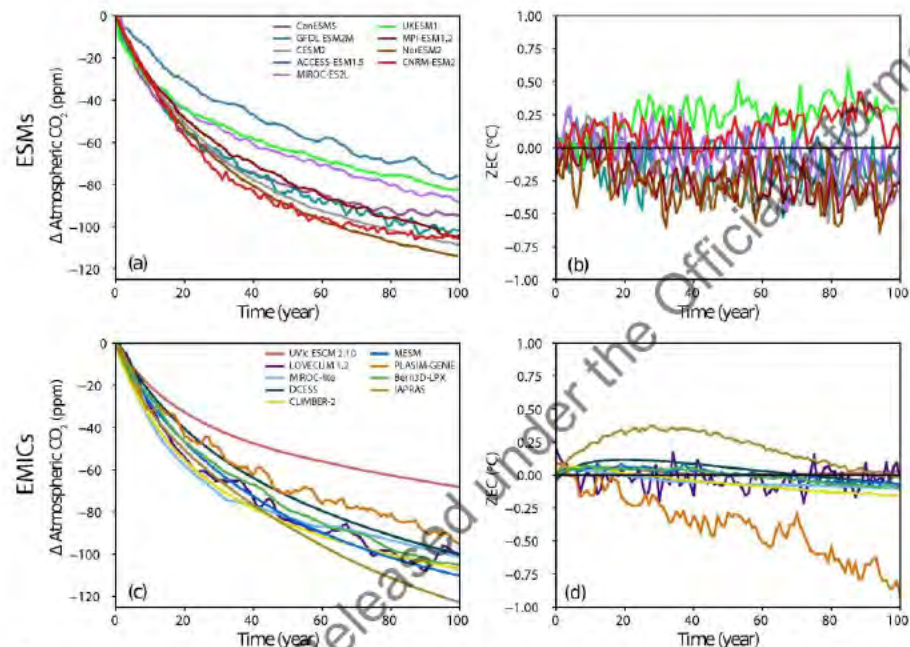


Figure 1. *Atmospheric* CO_2 *concentration anomaly and (b, d) Zero Emissions Commitment following the cessation of emissions during the experiment wherein 1000 PgC was emitted following the 1 % experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation.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

Commented [MC6]: ESM and EMIC aren't defined

The current common view is still that we are not expecting significant warming in the pipeline due to past GHG emissions. However, the uncertainties are large particularly on 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). Future GHG emissions from the global economy will be significantly more important for the amount of climate change experienced this century than feedbacks from Earth system processes. Nevertheless, such climate feedbacks cannot be ruled out and it might be prudent to factor these into remaining carbon budget estimates: Chapter 2 of SR1.5 allowed for the poss bility of an extra 100 $GtCO_2$ on century timescales from such feedbacks (Table 2.2) and such an approach seems prudent, 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 and warming peaked to keep to the temperature level of the Paris Agreement long-term temperature goal (around 2050-2070) (see SR1.5 Chapter 2, Rogelj et al., 2019a and Rogelj et al., 2019b).

Commented [MA7]: The possibility of Ear h System Feedbacks is, however, highly relevant to an ambitious goal for achieving net zero that potentially relies heavily on offsetting ongoing fossil fuel emissions (from aviation, for example) through afforestation or other nature-based climate solu ions. Estimates of the rate of CO2 release from ESFs for he second half of this century (e g. Lowe and Bernie, 2018) are similar to maximal estimates of global CO2 uptake rates through NbCS (e.g. Griscom et al, 2017). Note that these feedbacks were not considered in the "P1-P4" scenarios of SR1.5. Hence it does not make sense for an ambitious net zero strategy to rely on biological offsetting of continued fossil fuel use past 2050 if it is to be consistent with global 1.5C pathways and our understanding of earth system feedbacks.

Since this is an option that might be considered for New Zealand, this is a very important point here.

1.2 Greenhouse gas response

For future emissions of *long-lived GHGs* (LLGHG) (CO_2, N_2O, some F-gases) 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 CO_2 (using GWP100; see section 2) when thinking about impacts for this century. As shown in SR1.5 and the scientific literature, these emissions need to come down to close to net zero (aggregate GWP100) to stop their warming contr butions. As some level of N_2O emissions are expected to be unavoidable, this would require net negative emissions of CO_2.

On the other hand, 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. These emissions need to be stabilized (and then gradually reduced) to stop their further contr butions to ever increasing global warming, but would not need to be reduced to zero. 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 would net zero emissions of CO2: the only way to compensate for the impact of historical CO2 emissions is active removal of a comparable cumulative amount). The lower the emissions rate the lower the contribution of sustained SLGHG emissions to global temperature. Thus, these emissions represent an opportunity for reducing the current anthropogenically enhanced global temperature. Furthermore, 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).

Since 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. The IPCC Special Reports published since AR5 largely focus on low emissions pathways. 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.

Commented [MA8]: Perhaps quote the SR1.5 report here: "Reaching and sustaining net-zero global anthropogenic CO2 emissions AND declining net non-CO2 radiative forcing (primarily driven by the on-going rate of SLGHG emissions) would halt anthropogenic global warming"

And you could add that Cain et al (2019) provide a quantification of the necessary rate of decline: approximately 0.3% per year for typical values of he equilibrium climate sensitivity, transient climate response and deep ocean thermal adjustment time.

So greenhouse-gas induced warming from a sector, country or world, over any time-interval of a few years to a few decades is given by this expression

$$\Delta T_{GHG} = \kappa \sum_{t=t_0}^{t_1} (E_{LLCP}(t) + 4 \times E_{SLCP}(t) - 3.75 \times E_{SLCP}(t-20)),$$

Where kappa is the TCRE. There have been rather specious claims that this formula can "only" be applied to global emissions, so it might be helpful for you to give it, and point out it applies equally to any emission source, from a cow to a planet.

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, discussed below.

1.2.1 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; Tebaldi et al., 2020). 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 equil brium 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 (see Section 1.2.3) 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 2).

Commented [MA9]: And I would expect on physical grounds (but hopefully there is a reference here) that the fact hat the upper bound is largely unchanged, with most of the tightening being the lower bound, hat this does not change previous conclusions regarding the ZEC. The most obvious way you get a large ZEC is if you have a very low realized warming commitment (low TCR/ECS ratio). So the fact that the upper bound is not strongly revised is crucial.

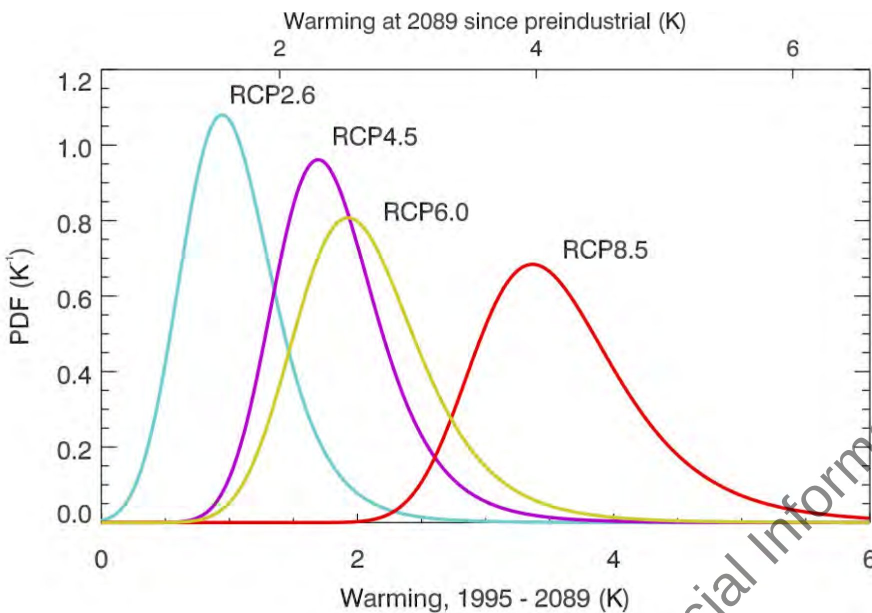


***Figure 2**: Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).*

1.2.2 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 has helped improve the estimates of GHG metrics (such as the GWP), including for methane. A number of other factors studied in recent publications will 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. 2018b). In of itself this would *decrease* the GWP100 by ~20%.
- 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. In of itself this would *increase* the GWP100 by 25%.
- Thornill et al. (2020) quantify the indirect effect of methane on ozone radiative forcing and based on several models they find a significantly lower value than what was used in AR5 for GWP and GTP calculations. This could decrease the GWP100 by 25%.

- The results of Wang and Huang (2020) show that due to high cloud changes the stratospheric water contribution to methane GWP100 which was 15% in AR5 might be closer to zero in the ERF framework, in of itself *decreasing* the GWP by up to 15%.
- Gasser et al. gives a better description of how to account for climate carbon cycle feedbacks in emission metrics. AR5 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.

Commented [MA10]: See footnote in http://www.dailymail.co.uk/news/article-2331057/Why-I-think-wasting-billions-global-warming-British-climate-scientist.html

Studies have not yet tested 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 next year.

Hodnebrog et al. (2020) gives an update of radiative efficiency and GWP and GTP values for halocarbons. New radiative efficiencies (RE) 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 is 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.

1.2.3 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

The previous section described how both long-lived and short-lived GHG emissions affect the climate system. 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 evidence for trade-offs between these two dimensions at a global level, considering both pathways arising from cost-optimising economic models and from more idealised pathways.

2.1 Emission metrics

The Global Warming Potential (GWP) is defined as the time-integrated radiative forcing 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 (Houghton et al., 1990), 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.

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 GWP100 values from the IPCC AR5 or GWP100 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. Using CO2-e under GWP100 for reporting does not preclude the use of other metrics for policy, since CO2-equivalent values under different metrics are related by very simple formulae. CO2-e emissions of SLGHGs under GWP20 are typically about three times their value under GWP100, while CO2-warming-equivalent emissions under GWP* are four times the current value of CO2-e under GWP100 minus 3.75 time the value 20 years previously.

After IPCC AR5, new 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*, use the same GWP values, but apply rate of change in emissions of the short-lived gas, e.g. methane. Cain et al refined the concept to better represent the relationship between cumulative CO2-warming-equivalent emissions and modelled warming in diverse CH4 mitigation scenarios by taking into account the delayed warming impact of past methane emission increases. Lynch et al demonstrated this for idealized cases. Collins et al. (2019) take an analytical approach and derive the combined global temperature change potential (CGTP) metric for calculating an equivalence between a sustained step-change in SLCF emissions and a CO_2 emissions pulse. Collectively, these metrics that represent SLCF emissions with a rate of emissions of CO2 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-equivalents and temperature change.

The GWP* concept and its potential applications has received criticism for only reflecting the additional warming effect of emissions relative to a chosen date and not the historical respons bility already caused due to past emissions (Rogelj and Schleussner, 2019). Cain et al (2020) observe, however, that this is not an intrinsic property of the metric, but how it is applied, since a pre-industrial baseline could be used to reveal historical responsibility, as in Allen et al (2018).

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 constant temperatures once the balance has been achieved, whereas a balance based on GWP implies slowly declining temperatures if (and only if) the mix of GHGs contains a significant positive contr bution from SLGHGs. Balance based on GWP could imply indefinite warming if SLGHG removal is used to balance ongoing CO2 emissions. 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 GWP100) are not necessarily required to remain below 1.5°C or 2°C, assuming either target can be achieved without overshoot.

Commented [MC12]: This sentence is a bit awkward to understand. Perhaps: Cain et al refined the concept to better represent the relationship between cumulative CO2-warming-equivalent emissions and modelled warming in diverse CH4 mitigation scenarios. Lynch et al demonstrated this for idealized cases.

Commented [MA13]: Since he statement is demonstrably wrong (no hing in definition of GWP* precludes a pre-industrial baseline, do you want to cite it at all?

Commented [MC14]: By choosing a preindustrial baseline, GWP*-based equivalent emissions would reveal the historical responsibility though.

Commented [MA15]: This is getting closer: De Richter, R., T. Ming, P. Davies et al., Removal of non-CO2 greenhouse gases by large-scale atmospheric solar photocatalysis, *Prog. Energy and Combustion Sci*, **60**, 68-96, 2017.

2.1 Global cost-optimal 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 poss ble whilst achieving a specified global emissions goal.[1] 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 determiners of reductions in the real world.[2]

The balance of effort across the range of global cost-optimal pathways produced by international modelling groups of the 2018 IPCC Special Report on Global Warming of 1.5°C is summarised in Table 1 and Table 2, with trajectories for long-lived GHGs (CO_2 and N_2O) and biogenic CH_4 from these simulations shown in Figure 3.[3] 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.

Table 1: 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 a using GWP100 value of 298)

Scenario grouping	Cumulative LLGHG emissions from 2020 to 2050 [to peak warming] - $GtCO_2e$	Rates of biogenic CH_4 emission at 2050 [over 20 years prior to peak warming] - $MtCH_4$/yr
1.5C (~50% probability)	545 (325 - 705) [To peak: 535 (360 - 810)]	140 (60 - 200) [Prior to peak: 175 (100 - 240)]
<2C (~66% probability)	790 (580 - 1060) [To peak: 930 (625 - 1430)]	155 (115 - 205) [Prior to peak: 155 (100 - 245)]

[1] In many IAMs this is achieved using a 'shadow value of carbon' for residual emissions. This is typically applied to non-CO_2 GHG emissions using the global warming potential (GWP) metric for a 100 year time horizon.
[2] 'Cost-effectiveness' is a principle for global action that was established in the UNFCCC, together with 'common-but-differentiated responsibilities and respective capabilities' suggesting that developed nations do more than developing nations to combat climate change.
[3] Methane emissions from the energy sector are not included within these plots but are an important source of emissions at the global level.

Commented [MA16]: Is the definition of "cost-effectiveness" really a principle of action? I thought it was used here more as a technical term to refer to cost-minimizing pathways wi hout specific constraints on technology deployment under some discount rate. Which doesn't map onto the kind of thing the UNFCCC would consider a principle of action at all.

Commented [MA17]: Is this correct? The cap ion to Figure 3 of the SR1.5 SPM just says "interquartile range across pathways" (not necessarily restricted to cost-optimal ones). I'm pretty sure the P1 scenario, which is not cost-optimal because some technologies are excluded and includes measures that are not costed, is included in hat ensemble, for example. Also, is this an interquartile or full range? Or have you recalculated ranges from only the cost-optimal, all-technologies subsample directly from he IIASA database? If so, great, but please say so.

Table 2: Emissions rates of gases in 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 a using GWP100 value of 298)

Scenario grouping	2030		2050	
	Biogenic CH_4 - $MtCH_4/yr$	LLGHG - GtCO2e/yr	Biogenic CH_4 - $MtCH_4/yr$	LLGHG - $GtCO_2e/yr$
1.5C (~50% probability)	180 (110 - 230)	23 (14 - 28)	140 (60 - 200)	2.3 (-8.3 - 12)
<2C (~66% probability)	190 (160 - 300)	30 (20 - 46)	155 (115 - 205)	12 (1.9 - 20)

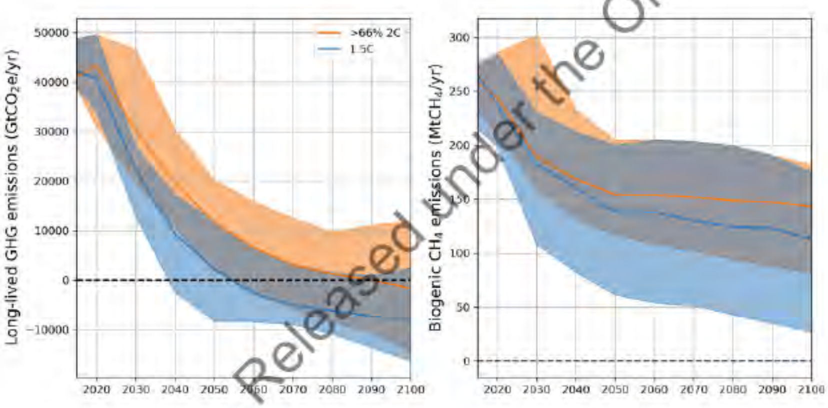


Figure 3: *The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for Long-lived GHGs (CO_2 and N_2O) and biogenic CH_4. Solid lines denote the median of the scenario set.*

Commented [MA18]: All pa hways, or only the cost-optimal, all technologies pathways? The latter makes sense, the former doesn't, because they include effectively normative pathways in which investigators have imposed specific outcomes, like global behaviour changes, that do not emerge from a cost-optimisation process.

Figure 3 illustrates the different roles the two 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 to be needed but there is more variation. The model studies found that strong reductions in methane are needed in all pathways, but that net-zero CH_4 is not achieved in any pathway. 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. However, in the vast majority of these cost-effective pathways emissions, CH_4 emissions are seen to decline by strongly mid-century. This reduces the level of global average CH_4-induced warming and allows for more warming from cumulative emissions of long-lived GHGs on the pathway to net zero emissions.

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 of detail regarding the representation of energy system technologies, varying assumptions regarding their relative costs, and varying assumptions about global development (e.g. population, economic growth and development) in the absence of climate policies or impacts. 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 long-lived GHGs remain poorly understood.

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.

2.2 Understanding trade-offs between shares of effort across gases in global mitigation pathways

The scenarios described in the previous section for global emissions share the effort between sectors and gases solely based on minimizing overall cost within the modelling framework. Other splits between reductions in different GHGs could be possible whilst achieving the same global temperature outcome, and may be more desirable when incorporating additional constraints regarding fairness, just transition, and societal preferences.

Commented [MA19]: Needed, or observed? This is a consequence of the marginal abatement cost curves for me hane implicit in hese models, which contain many assumptions.

Commented [MA20]: It would be very helpful to note how much, and how many tCO2 these reductions in methane emissions are "worth"

Commented [MA21]: Thanks for the clarification: you should quote van Vuuren et al (2018): these scenarios include cases in which behavior changes such as global diet change are imposed by the modelling groups (e.g. van Vuuren et al, 2018; Grubler et al, 2018). "Since it is nearly impossible to put a price tag on most of these measures, none of the scenarios [with these additional measures] has been evaluated in terms of costs." van Vuuren et al (2018). Or, better still, you can replot restricting attention to global, all-technologies scenarios. This would be really interesting.

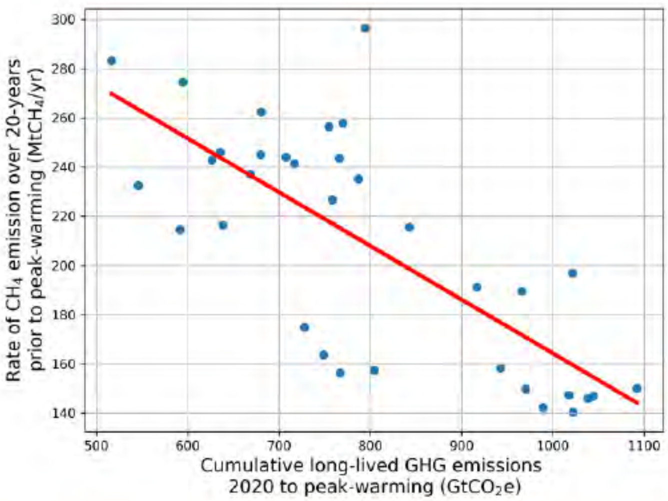


Figure 4: *Relation between CH_4 emissions 20 years prior to peak warming and the cumulative CO2-equivalent emissions ($CO_2 + N_2O$) based on GWP100 for scenarios that keep peak warming to 1.6-1.7C. This temperature range was chosen to give a large number of modelled scenarios that peak warming within this relatively narrow range.*

Emergent relationships between properties of this scenario ensemble can be used to explore alternative pathways not included in this scenario set. Figure 4 illustrates an alternative to the use of traditional metrics for comparing and trading across gases. It shows the relation between methane emissions prior to peak warming (y axis) and magnitude of allowed cumulative CO_2 and N_2O emissions aggregated at CO_2 equivalents based on GWP100 (x-axis) for scenarios with a very similar (within 0.1°C) peak warming outcome. This approximately linear derived relation reflects that the higher CH_4 emissions the more constrained the cumulative GHG/CO_2 budget we have. And the more the world reduces CH_4, the higher cumulative LLGHGs will be compatible with the peak temperatures (in this case 1.6-1.7°C). This relationship indicates that a 10 $MtCH_4$/yr reduction in the average rate of CH_4 emission over the two decades prior to the time of peak warming could allow for around an additional 45 $GtCO_2$-equivalents of long-lived GHG such as CO_2 and N_2O. Whilst this value will be somewhat sensitive to the specifics of the simple climate model emulator used to project the climate outcomes consistent with these emissions scenarios, and the effects of systematic variations in changes of aerosol forcing that may correlate with one of the axes, it offers a simple way to explore the trade-offs between these two dimensions.

This relationship illustrated in Figure 4 can provide a simple, but relatively accurate, way of estimating the implications of a the difference between a 47% and 24% cut in global biogenic methane emissions relative to 2017 levels by 2050 (the range of reductions in biogenic CH_4 emissions reductions within the New Zealand Zero Carbon Act) in terms of the equivalent effort

Commented [MA22]: This is a very confusing figure, because it may well muddle variations in temperature outcome with trade-offs between methane and LLGHG emissions, given the total methane-induced contribu ion to peak warming is of order 0.1C in these scenarios. I suggest you colour the dots by temperature outcome and do a 2-way regression to identify the outcome-independent relationship between methane emission rates and cumulative LLGHGs, which is very close to what Michelle did in her 2019 paper (so I think I can guess the result), or just use her coefficients.

Commented [MA23]: The principle of comparing methane reductions wi h cumulative CO2 emissions is good, but here is some hing wrong here. Under GWP*, a 10 MtCH4/yr reduction in methane emissions is, after 20 years, equivalent to cumulative CO2-we emissions of 10x4x20x28=22.4 GtCO2-we. Even under GWP20, 10 MtCH4/year for 20 years = 0.2GtCH4 = 16.8 GtCO2-e. I suspect about half he slope you see in figure 4 arises from the fact that there is still a spread of peak warming across this ensemble. Warming-equivalent emissions whether from GWP* or CGWP give a straightforward way of rela ing methane emission rates with cumulative CO2 emissions, so I'd suggest you use those formulae, rather than this empirical relationship which seems to be out be a factor of at least 2.

Commented [MC24]: How does this compare to the Collins et al 2018 calculation comparing extra methane with additional carbon budget? Myles: my guess is that it compares poorly…

Commented [MC25]: Up until now we heard nothing about NZ so this comes in rather suddenly. The earlier part of the paper/report is all global so worth introducing here why we are suddenly talking about NZ.

in cumulative long-lived GHG emissions savings. Approximately 56% of global methane emissions are from biogenic origin (Hoesley et al., 2018). This means that the difference in the 2050 CH_4 emissions rate between a global reduction of 24% and a reduction of 47% (relative to 2017 levels) is approximately 47 $MtCH_4$/yr in absolute terms. Based on the relationship approximated from Figure 4 this would mean that around 200 $GtCO_2$-equivalents of additional cumulative long-lived GHG (CO_2 + N_2O) mitigation would be required if the world as a whole reduced its biogenic CH_4 emissions by only 24% by 2050 compared to one in which they are reduced by 47% whilst achieving the same peak temperature outcome. This is approximately 35% of the cumulative long-lived GHG emissions over 2020-2050 in the median IPCC SR1.5 keeping warming to below 1.5°C with no or low overshoot (Table 1).

As an alternative to the TCRE approach for calculation of remaining carbon budgets, 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.

2.3 Implications of post-2050 net-negative emissions

Section 1 summarised how emissions of long-lived GHG need to fall to net-zero to stop contr buting to rising global temperature. Peak warming generally occurs around 2050 in scenarios that keep warming to 1.5C 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 net-zero CO_2 emissions (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 warming) offsets this.

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 contr bute 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 Roge j et al (2019b) 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. For scenarios that do significantly overshoot a 1.5°C target level in the middle of the century, significant amounts of global net negative CO_2 emissions would be necessary to return warming to 1.5°C by 2100. For example, temperatures peaking around 1.7 °C, would require around 200 $GtCO_2$ of negative emissions over the 21st century to return temperatures to 1.5C, but if temperatures peaked at 1.85 °C around 400 $GtCO_2$ of negative emissions would be required (Roge j et al. 2019b). In the long-term (centennial

Commented [MC26]: Worth including he absolute value here, and an explanation of where this figure comes from, as I didn't find this figure in he paper referenced (although the paper is 40 pages long and I spent about 1 minute looking). Should define what is meant by biogenic here as I assume the NZ target means anthropogenically emitted biogenic methane. A bit of a contradiction in terms, but I assume NZ don't mean to reduce natural sources of biogenic methane!

Commented [MA27]: Why not just compare cumula ive methane warming-equivalent emissions? Very straightforward to do. Triangular wedge increasing to 47-24=23% 250MtCH4/year = DeltaE of 57.5 MtCH4/yr and Ebar of 28.75 MtCH4/yr. Cumulative E* = 75xDeltaE + 0.25xEbarxDeltat = 75x57.5+28.75x30 = 145GtCO2e. So, your 200 GtCO2 is an over-es imate, because some of the relationship you see in figure 4 is due to different levels of peak warming.

Commented [MC28]: Please give us the relevant info here in the text so that we can work this out ourselves. Do you mean reduction in anthropogenic biogenic emissions? The value of 47MtCH4/yr looks plausible (a quick check shows the equivalent value in Saunois et al 2020 is about 57MtCH4/y)

Commented [MA29]: Correct number is 25% (see previous comment)

Commented [MA30]: So I hink you are safe using the Cain et al GWP* formulae. CGWP would give similar numbers.

Commented [MC31]: Offsets the temperature implications of this

Commented [MA32]: "some of this warming" – good to quantify how much to keep this in perspec ive. 50% reduction in biogenic methane = 315 GtCO2-we = 0.14°C = 7 years of current CO2-induced warming.

Commented [MA33]: Implies a TCRE of 0.35/0.4=0.875 °C/GtCO2 = 3.2°C/TtC, which is high even for Joeri…

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 1.1).

The relationship across the scenarios between cumulative long-lived GHG emissions and the rate of CH_4 emissions identified in Section 2.2 also helps elucidate the tradeoffs between further reductions in trajectories of biogenic methane emissions post-2050 and net-negative CO_2 emissions after reaching net-zero.

Commented [MA34]: Or just published expressions for CO2-we emissions.

These results again make the case for early action to reduce emissions of LLGHGs. As such actions can both reduce peak temperatures and the level of negative emissions technology needed to achieve a 2100 temperature goal. This is relevant for several reasons. *Firstly*, there are implications of allowing overshoot on the global energy system. In a world that is trying to reduce global temperatures after 2050 there might be a greater need for energy generation associated with the removal of CO_2 from the atmosphere (such as through bioenergy with carbon capture and storage - BECCS) than in a world that is not trying to decline temperatures after 2050. This might therefore change the make-up of a desirable electricity generation mix in the decades prior to 2050. In such pathways you also need to worry about competing interests for land-use (see IPCC Special Report on Climate Change and Land). *Secondly*, any sustained post 2050 methane abatement could also help reduce temperatures and reduce the dependence on long-term net negative CO_2 emissions, indicating an interdependence of the post-2050 trajectories between the gases in a world of declining temperature (see also Figure 6). *Thirdly*, even if temperature targets are reached, some long-term net negative GHG emissions might need to be sustained.

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.

3.1 National contribution to global warming

The research outlined in Sections 1 and 2 and much previous research shows that methane emission changes have a different time evolving climate impact than a CO_2 emission change. This means that a national emission pathway that specifies the change in aggregated greenhouse gas emissions will not necessarily follow the same global warming, as different combinations of long-lived GHGs and shorter-lived GHGs can give the same overall CO_2 equivalent emission trajectory (when aggregated using GWP100 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 such as New Zealand where methane emissions represent a larger fraction of total greenhouse gas emissions. To illustrate this, the blue and green lines (or the purple and red) in Figure 5 illustrate global warming contributions from two pathways with the same GWP100

Commented [MA35]: Realis ic with the technologies allowed in current IAMs, which all completely exclude active methane removal, which is energetically favourable relative to DAC of CO2 at GWP100.

based total CO_2 equivalent emission trajectory but different CO_2 and biogenic CH_4 trends. 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. Initially the extra biogenic CH_4 reduction under the GWP100 CO_2 equivalent assumption (green line) gives more cooling. However, after 2100, the long-term warming effect of the extra CO_2 emissions would be expected to dominate and give more warming eventually. If New Zealand were to specify a single CO_2-equivalent emission reduction target based on GWP100, the up to 20% difference in resulting global warming trajectory illustrated by the pairs or curves in Figure 5, gives the scale of the ambiguity introduced.

The blue and red curves in Figure 5 approximate the range of New Zealand's possible future contr butions to global warming since 1990 under current policies, assuming that emissions do not change after 2050. Under both 24% and 47% biogenic CH_4 reduction policies, New Zealand is beginning to reduce its contribution to global warming by 2050. Under 24% reduction policies, the 2050 contribution to global warming from New Zealand's matches today's level of New Zealand's contribution to global warming. Under 47% biogenic CH_4 reduction policies, the 2050 contr bution to warming level approximately matches that from 2015.

Commented [MA36]: I'm fine with plot ing everything rela ive to 1990, but you might want to add in the captions how much warming NZ had caused prior to 1990, to keep some of your readers happy…

Commented [MA37]: Suggest you avoid this phrasing, or clarify. UK CCC and UK Govt use "contribution to global warming" to refer to contribution to warming rate, not contribution to warming level (otherwise "ending our contribu ion to global warming" would entail removing all UK's historical CO2 emissions). How about "reverse its contribution…"

Commented [MA38]: Looks more like 2040 to me.

Commented [MA39]: This is unambiguous to me, but I'm not sure how many people will appreciate he importance of he word "level". Strongly suggest you unpack this whole paragraph to make clear the difference between warming rate and warming level (perhaps by avoiding he use of the pesky word "warming" entirely).

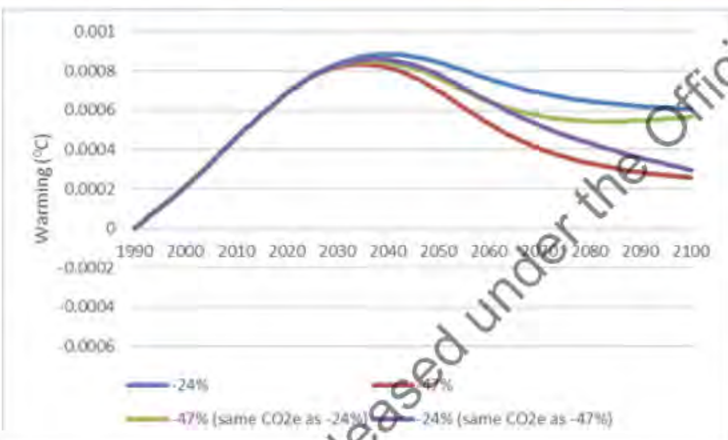
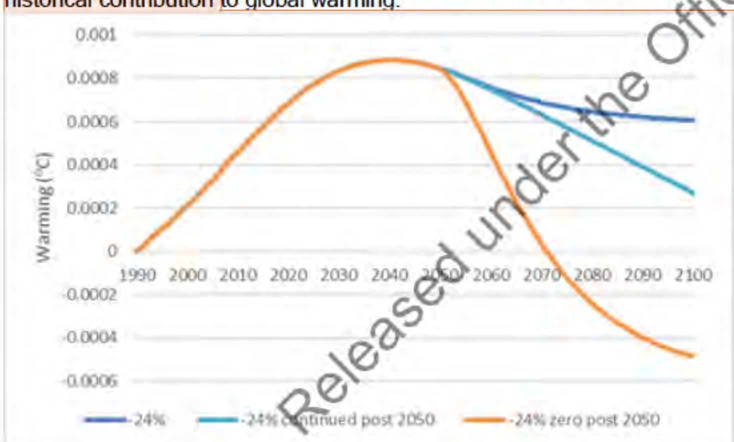


Figure 5: *An illustration of New Zealand's contribution to global warming since 1990. The blue and red pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel CH_4, and have either 24% (blue) or 47% (red) reductions in biogenic CH_4 from 2017 levels to 2050. The green line has 47% biogenic CH_4 reduction but additional emissions of CO_2 to match the CO_2e emissions of the blue line based on IPCC AR4 GWP100 values. Emissions from 2050 do not alter. New Zealand emissions from 1990-2018 are taken from https://www.mfe.govt.nz/climate-change/state-of-our-atmosphere-and-climate/new-zealands-greenhouse-gas-inventory. The estimate using the impulse response functions provided in the IPCC 5th Assessment Report for calculating GHG metrics as a simple climate model to assess the temperature implications of a*

national emissions pathway. Non-GHG contributions to warming (e.g. aerosol emissions) are not part these scenarios.

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 and emission changes might stop. This is particularly so for LLGHG pollutants, but less so for short-lived pollutants. Early reductions in LLGHGs have lower cumulative LLGHG emissions and overall less climate impact in the longer term (also see Section 2.3). In the near-term front loaded trajectories might lead to a rise in temperature from reductions in co-emitted pollutants resulting in less aerosol cooling (see Section 1.1.2), the near-term rise and peak temperatures can also be reduced by early action on SLGHGs.

What happens to emissions after 2050 is important for the longer term response (see Sections 2.3 and 4.2). This is theoretically explored in Figure 6, which keeps net-zero CO_2 emissions at zero after 2050 but varies methane emission reductions across a range of options from the highest temperature response (no change in emissions) to the largest cooling (biogenic emissions drop to zero after 2050). These results illustrate that although the choices of biogenic emission pathway up until 2050 do influence New Zealand's contribution to global warming, either choice should begin to reverse the country level contribution to further warming after 2040. However, the figure also shows that it is the choices after 2050 that really matter in the longer term, where continued decline of biogenic CH_4 would be needed after this date to begin to reverse New Zealand's historical contribution to global warming.



Commented [MA40]: This is better wording – see comments above.

Commented [MA41]: For context, it would be good to know what this is.

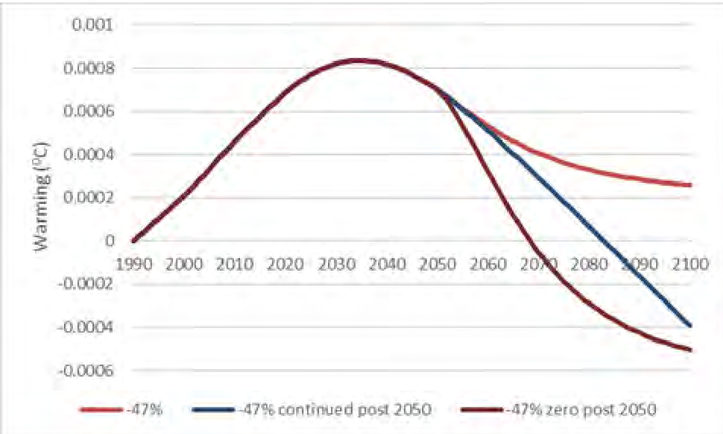


Figure 6: *As Figure 5, except emissions reductions continue beyond 2050. 24% biogenic CH_4 reduction by 2050, shown in the top panel and 47% reduction in the bottom panel. The panels have three scenarios: emissions unchanged after 2050, matching Figure 5; the biogenic methane reduction rate continuing after 2050; or biogenic methane emissions suddenly decline to zero after 2050.*

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 7 and Figure 3.9 from the UK CCC, 2019).

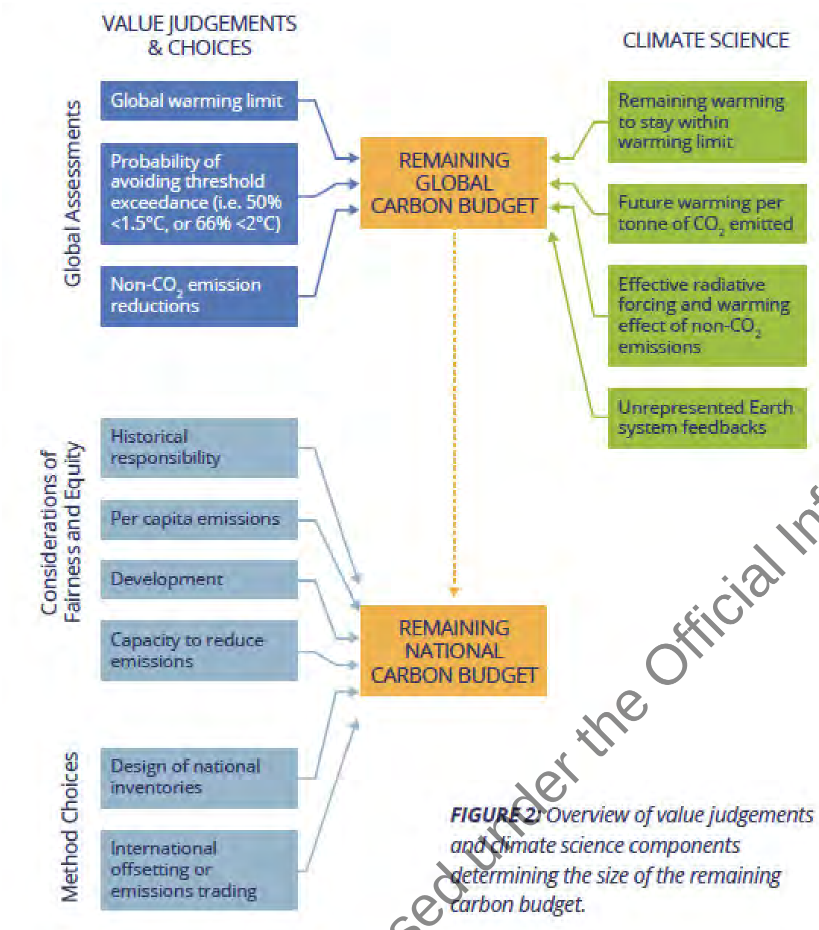


Figure 7: *Methodological, fairness and equity choices when creating national carbon budgets from the global remaining carbon budget. Figure 2 from the 2019 CONSTRAIN report https://constrain-eu.org/. See also Rogelj et al. (2019a).*

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.

Commented [MA42]: This is very important for New Zealand, and should be discussed more in he conclusions. Is a balance between fossil aviation fuel and carbon uptake by afforestation considered equivalent to net zero? It isn't indefinitely sustainable at a global level (particularly given earth system feedbacks men ioned above), but for New Zealand might be sustained for quite a long time. But is this a "fair" level of reliance on biological offsetting when the opportunity arises because of New Zealand's circumstances, and there is no way the world could offset continued fossil fuel emissions in this way. You should refer to Simon Upton's report https://www pce.parliament.nz/publications/farms-forests-and-fossil-fuels-the-next-great-landscape-transformation

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.

Commented [MA43]: Not sure what it adds to cumulative CO2-warming-equivalent emissions.

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).

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Climate Science Considerations of Net-Zero for New Zealand

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Introduction

This report gives a brief overview of the current scientific understanding of emissions reductions needed to achieve the temperature ambitions of the Paris Agreement. It builds on the findings in the IPCC special Report on global warming of 1.5 °C and Special Report on Climate change and Land, as well as recent updates in the scientific literature. It focuses on the main characteristics of the emission pathways and what choices exist between mitigation of different greenhouse gases. We also discuss how different choices affect meeting the Paris temperature goals.

1. Climate response to emissions of different GHGs

This first section examines how much warming greenhouse gas increases have committed us to and how well we understand the climate response to future emissions.

1.1 Committed warming

Future global warming largely depends on future global emissions of greenhouse gases (GHGs), but also from changes in other air pollutants. The concept 'committed warming' - or 'warming in pipeline' due to past emissions received increased attention in the context of the Paris Agreement aiming at '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'.

Based on the literature and knowledge available at the time the 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? There is new science emerging on the committed warming if CO_2 emissions fall to zero, the zero emission commitment (ZEC). There have also been additional warm years since 2018 and a revision of historic temperature records. The amount of warming for future GHG emissions before targets are passed also depends on emission changes in non-greenhouse gas pollutants. The sections below detail how understanding of each of these has progressed since the 2018 IPCC Special Report on global warming of 1.5 °C.

Commented [AR1]: I find the title problematic, since it implies something different to what was asked for in the brief and even different to what the report actually covers. Suggest the itle is changed so that it matches the brief and content of the report.

Commented [AR2]: The section has one major flaw in that it conflates historic warming (i.e. warming up to now) with committed warming (i.e. the level of future warming that emissions up to now commit us to).

Section 1.1.3 presents only results for CO2 zero emissions commitment, but provides no complementary presentation on a CH4 zero emissions commitment. This needs to be added.

There should then be a section 1.1.4 that brings the previous sec ions together and answers clearly to what extent past emissions of CO2 and CH4 commit us to future warming.

The reason why I see this as important is that a lot of public confusion arises from the fact that people treat the warming caused to date from CH4 in the same way as warming to date from CO2, i.e. as historical commitment that we either universally dismiss or include equally in future targets for all gases. A simple analysis of the extent to which past emissions of different gases commit us to future warming would help disentangle this confusion.

It would also be useful (though perhaps less critical) for section 1.1.1 or 1.1.2 to separate out how much of the total currently observed warming is due to CH4 emissions. Reisinger & Clark 2017 (10.1111/gcb.13975) did this for global livestock emissions but not for all methane emissions. Piers is doing some hing like that for IPCC (WGIII chapter 2) right now. This would be useful to give a sense of scale (how important are me hane emissions in warming to date), noting that CH4 concentration/RF is not a sufficient proxy to answer this question because CH4 emissions also cause indirect warming that CH4 concentrations alone do not capture (see e.g. Figure 8.17 in the AR5 WGI report).

1.1.1 Historic warming estimates

Before we discuss future warming, in light of the Paris temperature target it is worth considering historic warming estimates. SR1.5 estimated that the human-induced warming had reached around 1°C (with a 0.8°C to 1.2°C range) by the end of 2017 above pre-industrial levels. This was based on averaging the first four datasets in Table 1.1 of that report. Since then these historic temperature datasets are in the process of being revised. We expect these revisions to lead to a slight increase in the warming to date overall (e.g. Kennedy et al. 2019, Kadow et al. 2020) and the years since 2017 have continued to be among the hottest in the instrumental record. The discussion of how we define globally average surface temperature was addressed in Chapter 2 of SR1.5 for the calculation of the remaining carbon budget. 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 combined the observations with model data to estimate the near surface air temperature trend everywhere. The latter choice was there estimated to lead to 10% higher levels of present day warming and therefore a reduced remaining carbon budget. This 10% uplift was a model calculation and more recent work suggests that it 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 of 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 of the choice of 1750 or 1850-1900 for the pre-industrial baseline. Using 1750 as a pre-industrial baseline could add around 0.05°C more warming to date 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 historic surface temperature change since preindustrial times and these would have knock on effects for remaining carbon budget analyses. Note that by altering the historic temperature we are implicitly altering the applied relationship between global temperature and 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 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.

1.1.2 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 from 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) examined the climate response to COVID-19 restrictions and showed that some of the short term warming from reduced SO2 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 SO2 emissions would lessen any near-term warming.

1.1.3 The zero emission commitment (ZEC)

Commented [AR3]: As per previous comment, major flaw is that this is for CO2 only, which lends itself to a misleading interpretation hat this applies to all gases.

What this section should demonstrate is to what extent zero future emissions from specific gases (chiefly CO2 and CH4) commit us to future warming, and hence what amount of future warming (by 2050 to reflect peak warming under 1.5°C scenarios) is a historical liability and what amount is the result of future emissions that are still under our control.

This is essential to then have a more ra ional discussion about a focus on "additional warming above the current temperature level" is an appropriate lens for making policy choices about how much to reduce future emissions of individual gases.

I'm confidentially including a figure that will likely appear in he WGIII assessment on metrics, but I wouldn't be too worried if a figure of this type appeared in this report, too. I'm happy for this figure to be shared with the authors of this report (Jan has seen it already anyway).

MacDougall et al. (2020) conclude that the most likely value of the ZEC 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 either sign but is always less than 0.5°C across models, with a best estimate, based on current evidence of close to zero.

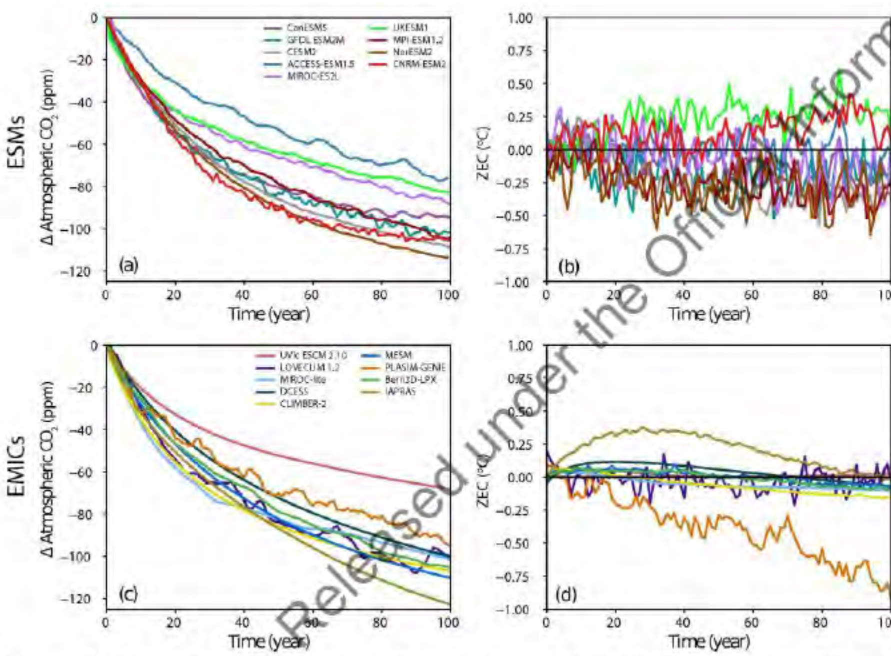
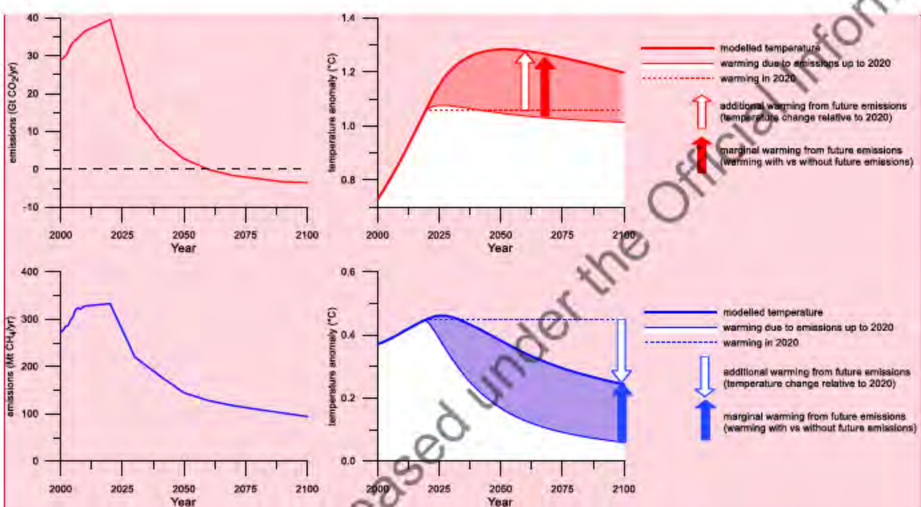


Figure 1. *Atmospheric* CO_2 *concentration anomaly and (b, d) Zero Emissions Commitment following the cessation of emissions during the experiment wherein 1000 PgC was emitted following the 1 % experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation.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

The current common view is still that we are not expecting significant warming in the pipeline due to past GHG emissions. However, the uncertainties are large particularly on 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). Future GHG emissions from the global economy will be significantly more important for the amount of climate change experienced this century than feedbacks from Earth system processes. Nevertheless, such climate feedbacks cannot be ruled out and it might be prudent to factor these into remaining carbon budget estimates: Chapter 2 of SR1.5 allowed for the poss bility of an extra 100 $GtCO_2$ on century timescales from such feedbacks (Table 2.2) and such an approach seems prudent, 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 and warming peaked to keep to the temperature level of the Paris Agreement long-term temperature goal (around 2050-2070) (see SR1.5 Chapter 2, Rogelj et al., 2019a and Rogelj et al., 2019b).



Commented [AR4]: As per above comment, a figure like this would help illustrate to what extent past emissions of different gases commit us to future warming, and how much future warming is due to future emissions and hence additional to the warming from past emissions (rather than additional to the warming right now).

1.2 Greenhouse gas response

For future emissions of *long-lived GHGs* (LLGHG) (CO_2, N_2O, some F-gases) 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 CO_2 (using GWP100; see section 2) when thinking about impacts for this century. As shown in SR1.5 and the scientific literature, these emissions need to come down to close to net zero to stop their warming contr butions. As some level of N_2O emissions are expected to be unavoidable, this would require net negative emissions of CO_2.