Net Zero - Technical Annex: Climate Science

Introduction

This annex presents supplementary analysis to the 'Science and international circumstances' chapter (Chapter 2) of the Committee on Climate Change's advice report *Net Zero: The UK's contribution to stopping global warming.* It provides a more detailed look at several aspects touched upon in that chapter.

It is structured in two sections:

1. Emissions of carbon dioxide and aggregated greenhouse gases as a predictor of climate outcomes

2. The contribution of the UK's past and future emissions to global temperature rise

1. Emissions of carbon dioxide and greenhouse gases as a predictor of climate outcomes

Over the last decade climate science has increasingly focused on a cumulative CO_2 emissions 'budget' approach.

Several elements of scientific understanding underpin this:

- Emissions of CO_2 cause very long-lasting increases in atmospheric CO_2 concentrations meaning that CO_2 largely accumulates in the atmosphere. CO_2 emissions therefore lead to almost permanent increases in the global average surface temperature.
- Total emissions over all time are hence more important for determining the warming caused than the emissions of CO_2 into the atmosphere in a particular year.
- This means that to stop warming increasing, emissions of CO_2, net of active removal from the atmosphere, will have to come to near net-zero[1] no matter at what level warming is limited to.

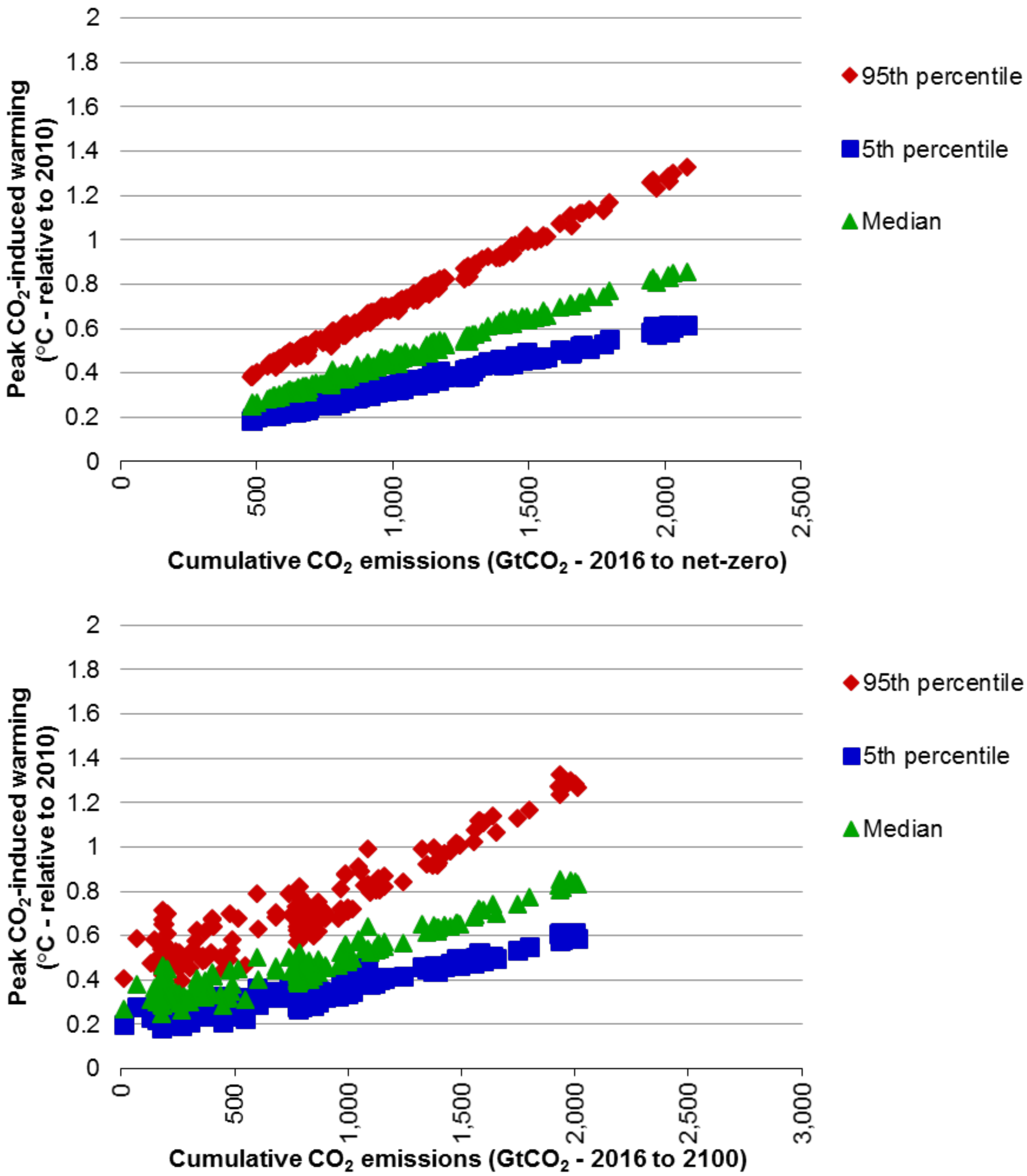
Cumulative CO_2 emissions from now to the point of net-zero are a good indicator of the probability of future CO_2-induced warming exceeding a particular level. However, aspects of these budget estimates needs to be understood for their use in setting mitigation targets:

- The remaining cumulative emissions budgets consistent with limiting future CO_2-induced warming to below a particular level are uncertain, reflecting uncertainty in climate sensitivity and climate feedbacks. Therefore, the total cumulative emissions between now and the time of net-zero offer a relatively tight constraint on keeping future CO_2-induced warming below a given level only *with a particular probability* (Figure 1).
- Cumulative CO_2 emissions to the time of reaching net-zero (Figure 1 - top) is a better constraint on peak future warming than cumulative emissions over the whole century (Figure 1 - bottom). This is because *net* removals of CO_2 from the atmosphere largely do not influence peak warming but instead determine how fast warming falls after it has reached a peak. Instead, cumulative CO_2 between now and 2100 better constrains CO_2-induced warming in 2100 (not shown).

[1] 'Near' net-zero encapsulates that there is some uncertainty in exactly how warming will evolve when CO_2 emissions reach very low levels. If emissions decline rapidly to net-zero it is possible that there could be small amount of induced cooling over the few decades after reaching net-zero, whilst a low level of net-negative emissions may be needed to keep warming constant in the longer term.

- Uncertainty in the amount of future warming due to non-CO_2 emissions can also have a substantial impact on estimates of the remaining cumulative CO_2 emissions budget. The inclusion of non-CO_2 greenhouse gases (GHGs) is considered in the next sub-section.

Figure 1. CO_2-induced future peak warming as a function of cumulative future CO_2 emissions to date of net-zero (top) and 2100 (bottom)



Source: Huppmann, D. et al. (2018) A new scenario resource for integrated 1.5°C research. *Nature Climate Change*, 8 (12), 1027.
Notes: CO_2-induced and total future warming is projected by the FaIR model, also used in IPCC-SR1.5. This is different to the projected warming shown in Chapter 2 of the Committee's Net Zero report which used the MAGICC model. The colours show different parts of the model's assumed distribution of climate response uncertainty, with each dot indicating a different global mitigation pathway.

Annual CO_2 emissions rates as a predictor of future CO_2-induced warming

A particular cumulative CO_2 emissions budget could be spent in a number of different ways whilst causing the same total amount of CO_2-induced warming:

- For instance, the 420 $GtCO_2$ global budget consistent with limiting warming to below 1.5°C with 66% probability[2] would be consistent with global CO_2 emissions declining in a straight line from now until net-zero in around 20 years.
- Alternatively if CO_2 emissions remain around 40 $GtCO_2$/yr to 2030, approximately consistent with current Nationally Determined Contributions (NDCs), emissions would then have to decline to net-zero practically instantaneously (which would be impossible when considering inertia in the global economy) to keep total emissions within the same budget.

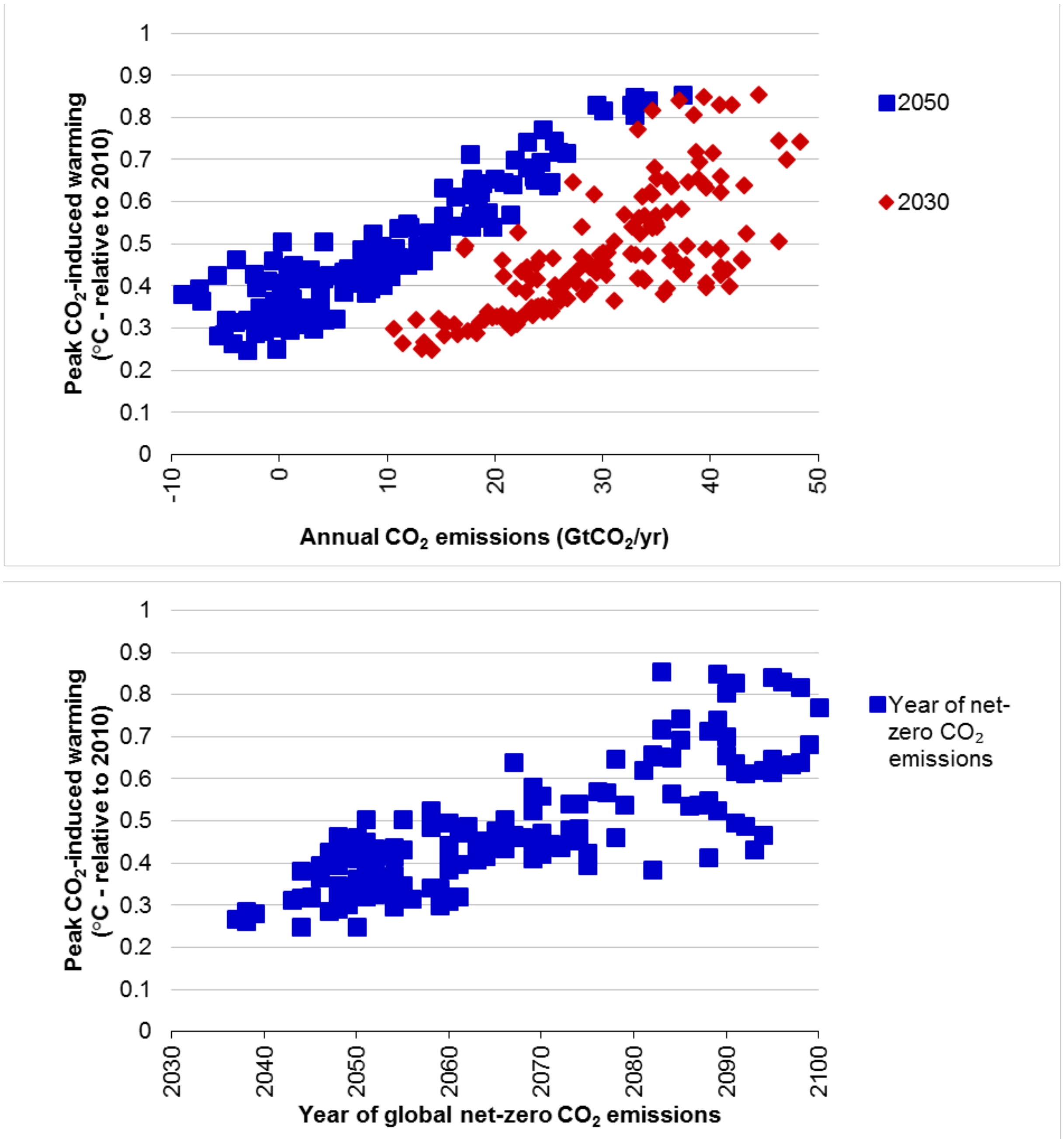
This means that a range of annual emissions rates in any specific year in theory could be consistent with the same cumulative CO_2 emissions and CO_2-induced warming depending on the shape of the emissions pathway. In practice, the tight overall budgets for 1.5°C and well below 2°C, along with limits on the realistic pace of global change, imply that these ranges for annual emissions are unlikely to be large.

Scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) do not consider all possible pathways to meet a particular carbon budget, but only those produced by cost-minimising models of the global economy that reduce emissions where and when they are cheapest to do so (see Box 3.1 of the Committee's *Net Zero* report for a discussion of some of the limitations of such models).

- In these scenarios CO_2 emissions in 2030, 2050 or the date of net-zero CO_2 emissions do not constrain expected future CO_2-induced warming as tightly as the cumulative CO_2 emissions (Figure 2).
- However, as most 'cost-optimal' emissions reduction pathways reduce emissions immediately, rapidly and monotonically towards net-zero, they do provide a proxy predictor for the global cumulative CO_2 emissions to the time of net-zero emissions.
- Therefore annual emissions rates or the date of net-zero CO_2 emissions do provide a (weaker) constraint on the median level of peak CO_2-induced warming reached due to common characteristics of the shape of these global emissions reductions pathways (in turn reflecting some common characteristics in the underlying models and assumptions).

[2] IPCC (2018), *Special Report on Global Warming of 1.5°C. This cumulative emissions budget depends on reductions in non-CO_2 GHG emissions, including methane and nitrous oxide.*

Figure 2. CO_2 emissions (top) in 2030 and 2050, and date of net-zero CO_2 emissions (bottom), as a predictor of peak CO_2-induced warming



Source: Huppmann, D. et al. (2018) A new scenario resource for integrated 1.5°C research. *Nature Climate Change*, 8 (12), 1027.

Notes: CO_2-induced warming is projected by the FaIR model, used to project the climate consequences of emissions scenarios in IPCC-SR1.5. Scenarios are restricted to show all those that reach net-zero CO_2 emissions at or before 2100. Peak CO_2-induced warming is shown at the 50th (median) percentile for all cases.

Aggregated greenhouse gas emissions as a predictor of future warming

When the emissions of additional non-CO_2 gases (methane, nitrous oxide and F-gases) are included, using the conventional aggregation with GWP_{100}, the link between cumulative emissions and peak warming becomes less direct due to the differences between how these gases affect the climate compared to CO_2.

The overall effect of future emissions of these gases (along with the cooling effect from emissions of aerosols) is expected to add to future warming above that created by CO_2 emissions:

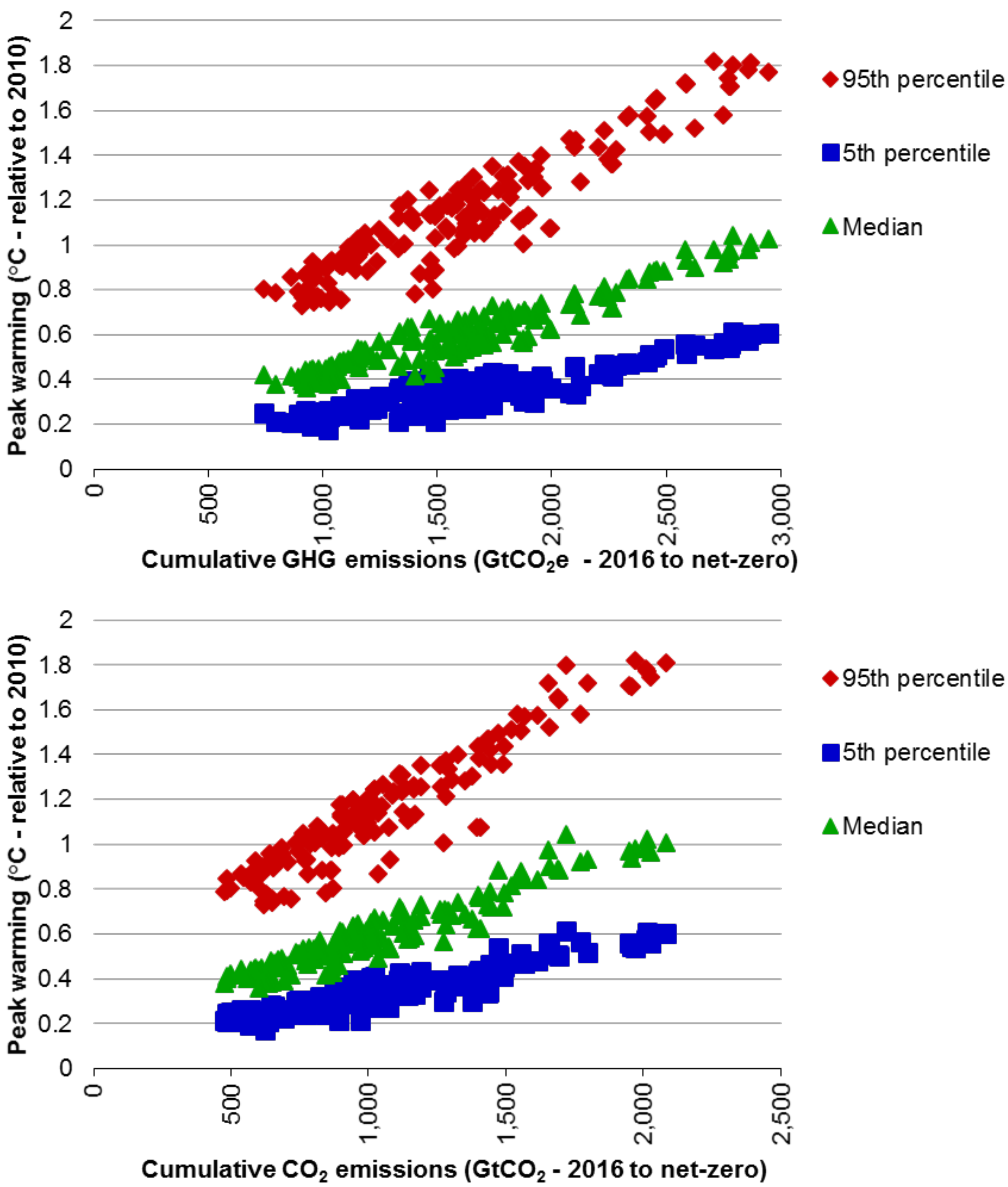
- Gases that have a relatively short residence time in the atmosphere (such as methane) affect the climate system in a quantitatively different way to CO_2 (see Box 2.3 of the Committee's Net Zero advice report) but can be potent greenhouse gases, particularly over the near term.
- Aerosols are also short-lived in the atmosphere but have a cooling effect on the climate system both by directly reflecting sunlight away from the planet and also by their effects on the properties of clouds. Aerosols are not currently included within the basket of emissions regulated by climate treaties, but are expected to decline significantly in future under nearly all of the emissions scenarios, in part due to efforts to avoid their negative effects on air quality.

When aggregating all GHGs as CO_2-equivalent, there is a somewhat weaker link between cumulative emissions and total future warming (Figure 3 - bottom) than between cumulative CO_2 emissions and CO_2-induced warming. Future cumulative CO_2 emissions are the largest contributor to future warming and make up the bulk of cumulative future GHG emissions. Additional spread around the straight-line relationship is introduced in particular by short-lived GHGs. For example, the warming induced by methane is more connected to the current rate of emission than the cumulative total to that time.

Cumulative future GHG emissions therefore do also provide a proxy predictor for peak future total warming, but one that is less tightly constrained than for cumulative CO_2 emissions. A similar picture emerges for annual metrics of GHG emissions as for CO_2 due to the shape of the emissions pathways (Figure 4).

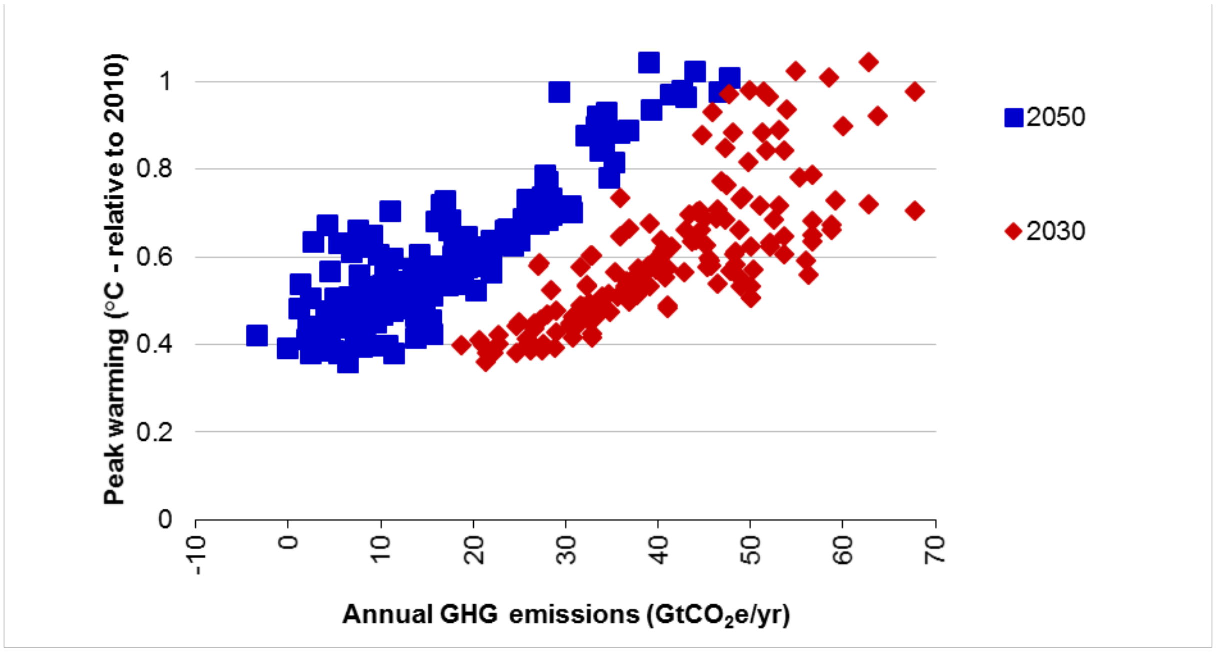
Uncertainty over climate response can also be expressed in terms of the probability of exceeding a particular level of warming. Figure 5 shows that reaching net-zero CO_2 or GHG emissions in any given year still permits a range of probabilities for exceeding a given temperature threshold, as for other annual metrics. However, scenarios that reach net-zero emissions earlier generally have higher probabilities of keeping warming beneath 1.5°C or 2°C.

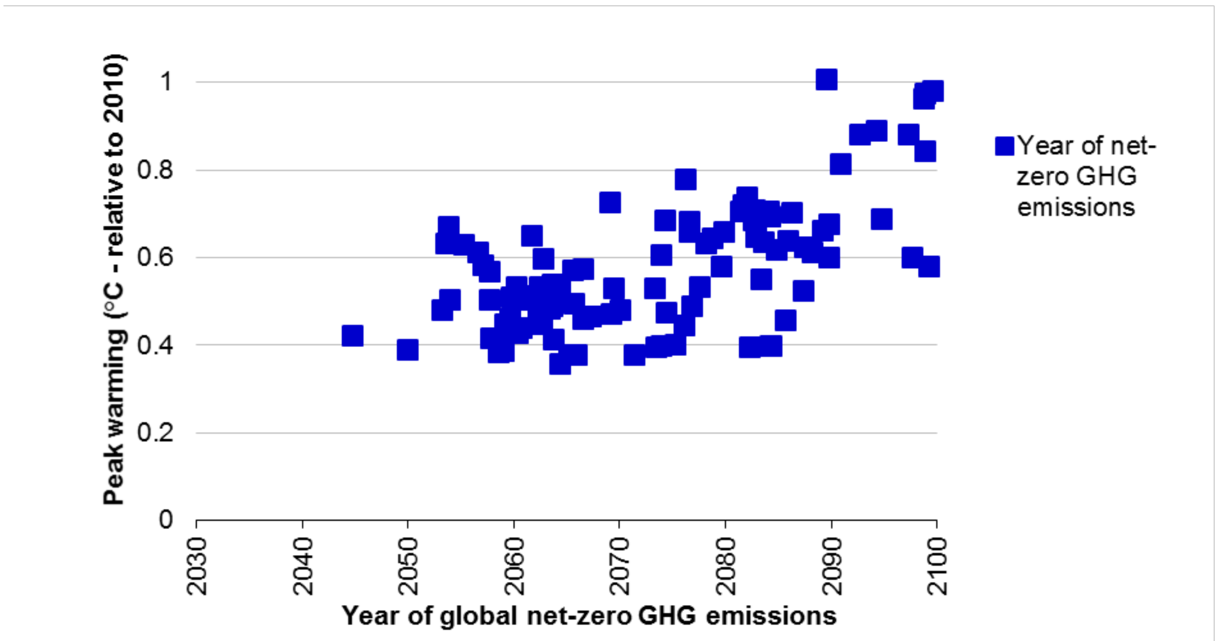
Figure 3. Cumulative future CO_2 emissions (top) and GHG emissions (bottom) and expected peak future warming



Source: Huppmann, D. et al. (2018) A new scenario resource for integrated 1.5°C research. *Nature Climate Change*, 8 (12), 1027.
Notes: In the bottom panel GHG emissions are aggregated using the GWP_{100} values from the IPCC 4th Assessment Report.

Figure 4. Annual GHG emissions (top) in 2030, 2050, and date of net-zero GHG emissions (bottom), as a predictor of overall peak warming

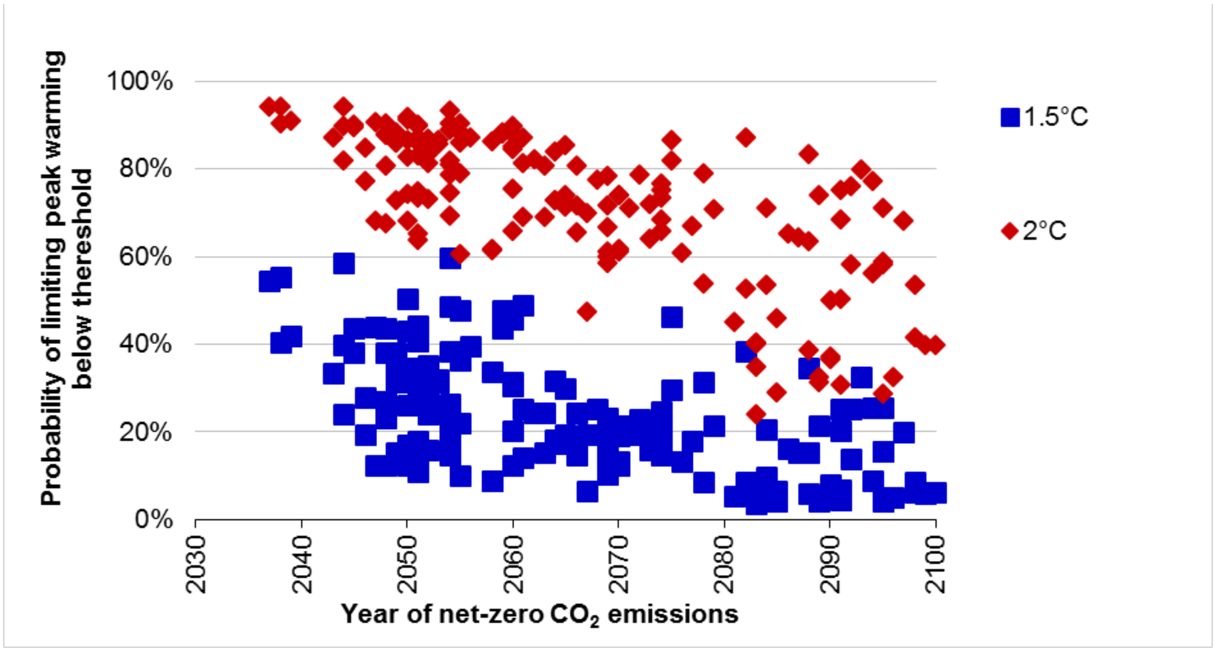


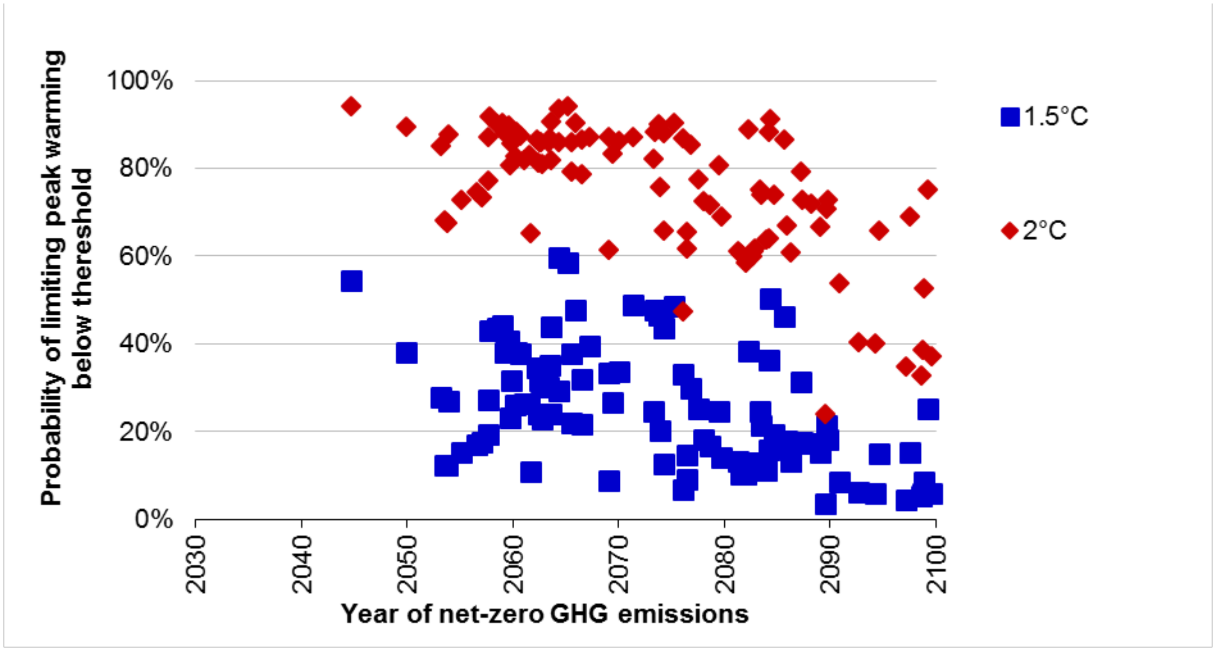


Source: Huppmann, D. et al. (2018) A new scenario resource for integrated 1.5°C research. *Nature Climate Change*, 8 (12), 1027.

Notes: Warming is projected by the FaIR model, used to project the climate consequences of emissions scenarios in IPCC-SR1.5. Scenarios are restricted to show all those that reach net-zero GHG emissions at or before 2100. GHG emissions are aggregated using the GWP_{100} values from the IPCC 4th Assessment Report. Peak warming is shown at the 50th (median) percentile.

Figure 5. Probability of warming exceeding 1.5°C and 2°C levels against year of global net-zero CO_2 emissions (top) and GHG emissions (bottom)





Source: Huppmann, D. et al. (2018) A new scenario resource for integrated 1.5°C research. *Nature Climate Change*, 8 (12), 1027.

Notes: Probability of keeping warming below a threshold of warming taken from the MAGICC climate model. GHGs are aggregated using the GWP_{100} values from the IPCC 4th Assessment Report. The '1.5°C' points consider this threshold specifically and don't allow for the small overshoot used in the main classification of scenarios for SR1.5.

All individual predictors (cumulative emissions, net-zero date and 2050 emissions) less clearly distinguish between scenarios at the lowest end of future peak warming (such as keeping future warming to around 0.64°C above 2010 levels, approximately consistent with 1.5°C to 2°C above pre-industrial levels[3]), than across the full range of scenarios. This is due to the very small permissible amount of future warming meaning that all uncertainties have large relative effects.

Predictors of the UK contribution to warming

As for the globe as a whole, the UK's contribution to future warming is not fully constrained by the level of emissions reached in 2050 or the date of net-zero emissions, but more by the cumulative emissions of long-lived GHGs between now and the date of net-zero and the emissions rate of short-lived GHG emissions.

However, a number of factors indicate that the level of the UK's long-term emissions target will be an effective proxy on the UK's contribution to warming between now and the time of reaching net-zero long-lived GHG emissions:

- The Climate Change Act, which requires interim allowable levels of UK GHG emissions (carbon budgets) to be set on the cost-effective path to achieving the long-term temperature goal, means that the long-term target will largely determine UK cumulative GHG emissions between now the 2050.
  - These aggregated GHG emissions budgets could be met with various make-ups of long- and short-lived GHGs so do not completely constrain the cumulative emissions of long-lived gases.
  - However, rapid reductions in both long-lived and short-lived GHGs will be required along the whole pathway to meet the interim budgets and the long-term target.
- Emissions of greenhouse gases per person are currently close to the global average in the UK, but are declining, unlike for the world as a whole. This indicates that UK emissions pathways under the Climate Change Act to reach net-zero in a particular year are likely to have equal or lower future cumulative emissions per person as the global average reaching a similar net-zero date. Reaching net-zero GHG ahead of the world would therefore be likely to lead to a lower per person contribution to future warming than the average for the world as a whole.

In the *Net Zero* report we do not assess a full pathway of the UK's GHG emissions between now and net-zero, but solely the net-zero date and compatible level of GHG emissions in 2050. The level of the fourth and fifth carbon budgets (covering 2023-2027 and 2028-2032), and any tightening of the path required for the sixth carbon budget (2033-2037, which will be the first budget set on the path to net-zero emissions in 2050) will also determine the UK's contribution to future global warming along with the level of the long-term target and the make-up of residual emissions and removals to achieve it.

[3] As simulated by the FaIR model.

2. The contribution of the UK's past and future emissions to global temperature rise

This section looks at the warming associated with past and future UK greenhouse gas emissions separately.

UK contribution to warming from past greenhouse gas emissions

Greenhouse gases rapidly mix relatively uniformly across the planet's surface. This means that warming from greenhouse emissions can be partitioned into contributions from different national jurisdictions. Although the relative national contributions to historical CO_2-induced warming can be estimated from cumulative historical CO_2 emissions, a simple climate model is needed to include the effects of other greenhouse gases in order to build a full picture of a country's overall climate impact over time.

To investigate the effect of past UK emissions[4] on global temperature change we use a dataset of reconstructed UK GHG emissions and a simple climate model:

- Emissions of GHGs (CO_2, CH_4, N_2O and F-gases) since 1990 are taken from the UK's greenhouse gas inventory.
- Prior to 1990 emissions are taken from the PRIMAP-hist dataset.[5] This relies on extending national emissions inventories with datasets published by international research organisations back as far as possible. Emissions time series are extended back to 1850 using the shape of the estimated global average emissions time series.
  - This dataset provides a best-estimate of historical UK emissions, however uncertainties are large, particularly for non-CO_2 emissions, and increase further back in time.
  - We do not include the effects of UK emissions of other pollutants that aren't regulated under international climate treaties. These are dominated by pollutants that have a cooling effect on the climate, but are generally short-lived.
- These emissions time series are then input into a simple climate model, FaIR,[6] which was used in the IPCC Special Report on Global Warming of 1.5°C to map the temperature consequences of future emissions pathways. The UK share of total GHG-induced warming is estimated using a 'counterfactual' approach[7] to assess how much lower GHG-induced warming would be if emissions from the UK had not occurred.

As the UK was the birthplace of the industrial revolution it has a relatively large legacy of historical emissions. The methodology described above suggests that historical UK greenhouse gases have contributed 2 - 3% of the total GHG-induced warming.[8]

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[4] Based on 'territorial' emissions. The contribution from UK demand for goods and services produced abroad (UK 'consumption' emissions) are not considered in this analysis.

[5] Gütschow, J. et al. (2016) The PRIMAP-hist national historical emissions time series. *Earth System Science Data*, 8(2), pp.571-603.

[6] Smith, C.J. et al. (2018) FAIR v1. 3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development*, 11(6), pp.2273-2297.

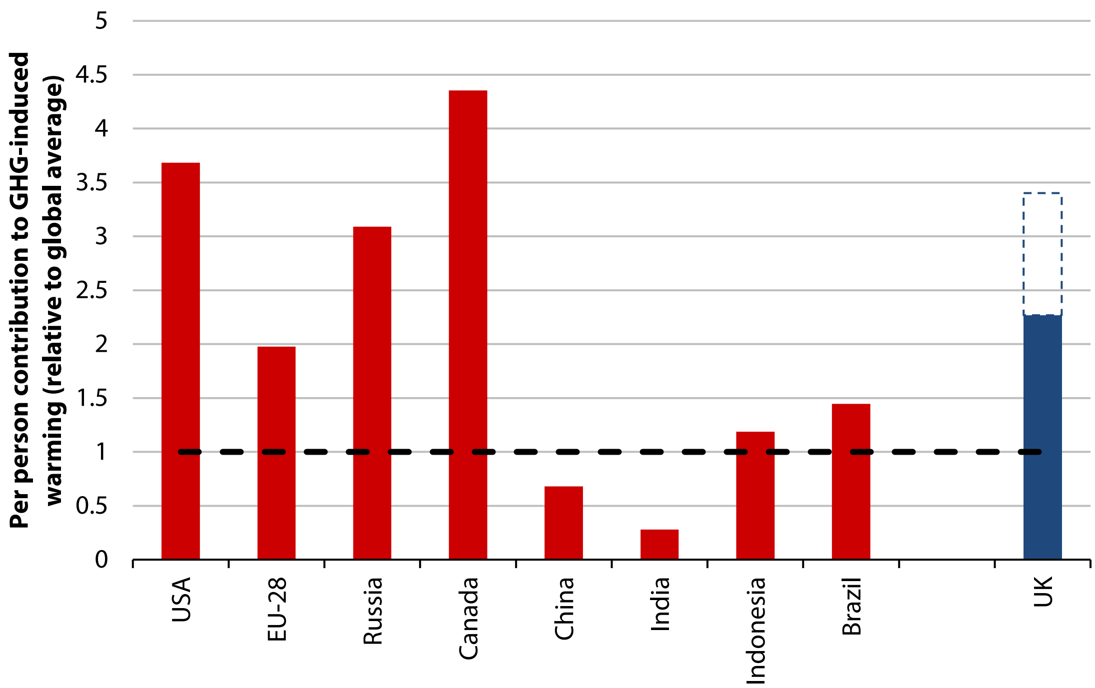
[7] Skeie, R.B. et al. (2017) Perspective has a strong effect on the calculation of historical contributions to global warming. *Environmental Research Letters*, 12(2), p.024022.

[8] 2 - 3% represents an expanded uncertainty range encompassing our central modelling result (2.7%) and another estimate derived from recently published methods (2.4%). This uncertainty range reflects uncertainties across models, methodologies, evaluation date and pre-industrial periods. The UK's contribution is expressed as a percentage as the absolute level is uncertain due to the broad range of possible global GHG-induced warming and partial compensation by cooling aerosols resulting in the better-constrained total global human-induced warming of around 1°C.

- The *fractional* UK contribution has declined over recent decades while the UK's absolute contribution to human-induced warming has continued to increase.[9] This is due to the fact that other emitters have rapidly increased their greenhouse gas emissions over recent decades whilst the UK's have been going down.
- This estimate is broadly consistent with updated analysis from Skeie et al. (2017) who identified a dependence on the start and evaluation date and which emissions are included. Updated to a 2016 evaluation year, methods from Skeie et al. (2017) indicate that UK historical emissions were responsible for 2.4% of the global GHG-induced warming.

On a per-person basis (using in-year population), this puts the UK as one of the largest contributors to climate change to date (with per-person contributions around three times the global per-person average) due to the large historical emissions and relatively small present-day population (Figure 6).

Figure 6. Contribution to 2016 GHG-induced warming for selected big emitters



Source: Skeie et al. (2017) Perspective has a strong effect on the calculation of historical contributions to global warming. *Environmental Research Letters*, 12(2), p.024022; CCC analysis.
Notes: Relative contributions to Kyoto-basket GHG-induced warming are evaluated in 2016, with 2016 population data used to normalise across countries (expressed as a multiple of the warming contribution of the global average person). The UK bar is estimated from the FaIR model as described in the text and is therefore marked differently to the other bars, which use data updated from Skeie et al (2017). The dashed bar in the UK column shows the uncertainty across a 2 - 3% UK contribution to global average GHG-induced warming. The start date for contributions to warming used is 1900. The dashed black line indicates the global average (normalised to one).

[9] The per-person UK contribution to warming has continued to grow as UK per-person GHG emissions have been above the global average.

UK contribution to warming from future greenhouse gas emissions

The UK's future contribution to warming under legislated emissions targets will depend on the long-term target, the pathway to the target and the make-up of residual greenhouse gas emissions and removals.

Figure 2.3 of Chapter 2 of the main advice report used the impulse-response functions for the calculation of global temperature potentials in the IPCC 5th Assessment Report (IPCC-AR5) to assess the contribution of the UK's future emissions to future global average warming:[10]

- These track the increase in atmospheric concentration following a pulse-emission of a gas, accounting for the natural removal of the gas from the atmosphere.
- Radiative efficacy factors (from IPCC-AR5) are then used to link these increases in atmospheric concentration with an increase in 'radiative forcing' (a measure of the heat-trapping potential of human impacts on the climate system).
- From this increase in radiative forcing, contributions to global average warming is calculated using a two-box simple representation of the climate system response.

Although the response of the climate system to pulse-emissions of greenhouse gases has been shown to evolve over time and depends on the size of the emissions pulse,[11] UK emissions are a small fraction of the global total and therefore using impulse-response functions calibrated to the present-day is expected to give a good first-order approximation of the warming response to UK emissions over the next 30 years.[12] In reality there will be a dependence on the emissions trajectory the rest of the world takes over this period.

Alternative methods can also be used to estimate the contribution of UK emissions to future warming:

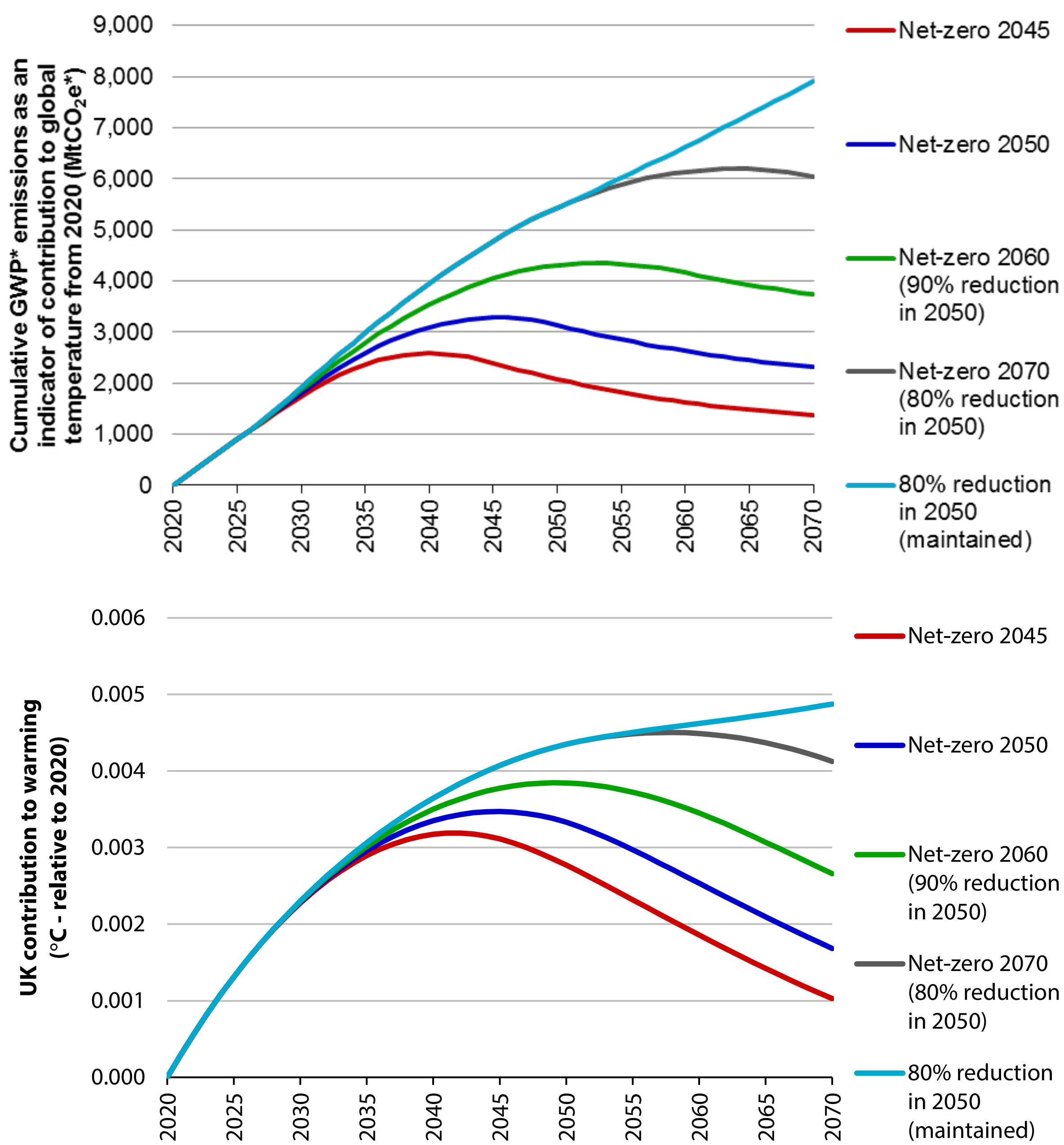
- A recently proposed new metric for aggregating greenhouse gases suggested a way to account for the different effects that short-lived and long-lived greenhouse gases have on global average temperature. Under this metric, known as GWP*, cumulative aggregated CO_2-equivalent GHG emissions is a good proxy for the impact of emissions on temperature.[13] A peak in these 'temperature-tracking' cumulative emissions have been shown to correspond well to the timing of a peak in induced warming.
- For the hypothetical future UK emissions pathways considered in Chapter 2, these temperature-tracking emissions would indicate a peak in the UK contribution to warming prior to the date of net-zero GHG emissions (Figure 7) and a cooling effect on global temperature under sustained net-zero GHG emissions achieved with net-negative emissions of long-lived gases. This is broadly similar shape to the temperature responses as calculated using the IPCC-AR5 impulse-response functions (Figure 7 - bottom).

Both these methodologies provide central estimates of the consequence of future UK emissions for future changes in global average surface temperature, but the precise amount of warming is

[10] IPCC (2013) *Chapter 8 - Anthropogenic and Natural Radiative Forcing*, Working Group 1 - 5th Assessment Report.
[11] Joos, F. et al. (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics*, 13(5), pp.2793-2825.
[12] In Figure 2.3 of the main advice report we integrate UK emissions starting from 1990 onwards, sufficiently long to approximately equilibrate the transient warming created by recent emissions of short-lived climate pollutants like methane.
[13] Allen, M.R. et al. (2018) A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science*, 1(1), p.16.

affected by the uncertainty in the climate response. As such, the absolute magnitude of the UK's contribution to future warming is uncertain over a broad range, but the shape of the response is expected to be relatively robust across this uncertainty.

Figure 7. Temperature-tracking (GWP*) cumulative emissions under hypothetical future UK emissions scenarios (top) as an indicator of UK contribution to global warming (bottom)



Source: CCC analysis; Allen, M.R. et al. (2018) A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science*, 1(1), p.16.
Notes: A peaking in the curve of cumulative GWP* emissions approximately corresponds to a peaking of contribution to global temperature rise, with declining cumulative emissions (net-negative GWP* emissions) corresponding to an overall cooling contribution to global temperature. Emissions of carbon dioxide, methane and nitrous oxide are aggregated using the GWP* metric, which equates a sustained rate of change of methane emissions with a one-off emission of CO_2. Cumulative emissions are expressed from the start of 2020. The bottom figure reproduces Figure 2.3 of the Committee's *Net Zero* report.

Alternative net-zero emissions compositions

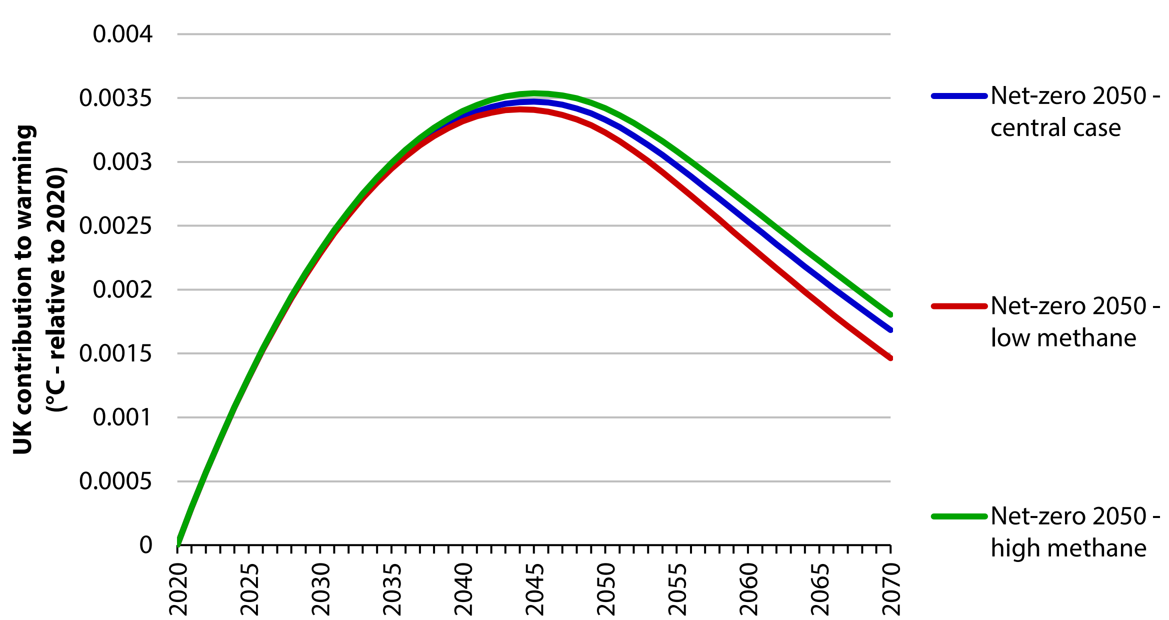
A UK or global net-zero GHG target could be achieved using different make-ups of residual non-CO_2 emissions and net removals of CO_2 from the atmosphere. The precise temperature consequence of achieving net-zero GHG emissions will be sensitive to the make-up of gases that aggregate to the net-zero total (using the GWP_{100} metric).

In Chapter 2 of the Committee's *Net Zero* report, we estimated the temperature consequences of achieving net-zero emissions with additional CO_2 removals beyond the 'Further Ambition' scenario in Chapter 5. As a sensitivity here we consider an alternative hypothetical scenario in which methane emissions continue as under the 'Existing Policies' projection for methane emissions from the Energy and Emissions Projections 2018.[14]

- This scenario considers the effect of policies currently in place but not any new or planned polices. As such, it represents a projected 'business-as-usual' world for UK methane emissions, capturing a projected decline in emissions from waste, but with relatively constant agricultural methane emissions.
- In this scenario the methane emissions across the economy decline between now and 2050 but far less rapidly than in our 'Further Ambition' scenario.

We also consider a scenario in which methane emissions fall further below the level in our 'Further Ambition' scenario, representative of a future in which additional methane mitigation is used to make up the gap to net-zero GHG emissions.

Figure 8. Alternative compositions of a net-zero 2050 GHG scenario



Source: CCC analysis

[14] BEIS (2019) *Energy and Emissions Projections*.

Both of these scenarios show that while the precise UK contribution to warming will depend on the make-up of a net-zero target, these differences are expected to be relatively small over the period to 2050 and in the decades following (Figure 8).

In the longer term, the consequence for global temperature of maintaining a net-zero GHG target will also depend on exactly how that net-zero target is maintained.

- If net-zero GHG was maintained by allowing short-lived GHG emissions to continue to rise while being compensated by increasing removals of CO_2 this would lead an increasing contribution to warming over this period.
- However, stable or decreasing short-lived emissions compensated by stable or decreasing CO_2 removals respectively would imply a cooling contribution to global temperature over this period.

Hypothetically, net-zero GHG could be achieved without net-negative long-lived GHG emissions if ways to remove atmospheric methane from the air could be created and deployed at sufficient scale to achieve net removals of methane (gross methane removals would have to be in excess of residual positive sources of methane emissions, such as from agriculture). If net removals of methane was used to compensate for residual net positive emissions of long-lived gases, this could lead to a rising UK contribution to warming in the long-term if maintained. While such methane removal technologies are theoretically possible,[15] no clear technology proposals exist and it is far less developed as a technology than proposals to remove CO_2 from the atmosphere at scale.

[15] Boucher, O. & Folberth, G.A. (2010) New directions: atmospheric methane removal as a way to mitigate climate change? *Atmospheric Research*, 44, pp.3343-3345.