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Links between emissions pathways and time lags in Earth's climate system

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Headline messages

- Lags of varying timescales exist in the Earth's response to emissions of greenhouse gases – with some aspects of the climate responding almost instantaneously, while others may take decades or more.
- There are also physical and technical limits to how quickly the global economy can reduce emissions. This adds another 'layer' of lag to how rapidly we can tackle climate change.
- As a result, we are locked in to some level of future change for many key climate variables which have widespread human impacts, such as surface temperature warming and sea level rise.
- For surface temperature, it is still possible to limit warming to 1.5ºC (with at least a median probability) this century with collective global action to make rapid and deep cuts to emissions.
- Under a scenario of decreasing emissions (RCP2.6 climate change scenario), surface temperature rises before approximately stabilising during the mid-21st century period.
- For sea level rise, some level of increase is locked-in for the next century and beyond. By reducing emissions, however, we can limit the pace and scale of the rise.
- Rapid and deep cuts to emissions are essential to avoid the most dangerous impacts of change, but it is still necessary to understand and take action to adapt to the impacts we are already locked into.

Introduction

The climate system responds to human influences on a range of different time-scales. Changes in the net amount of the sun's energy absorbed by the Earth, known as the 'radiative forcing', happen quickly in response to emissions of greenhouse gases. For many other climate metrics there is a slower response to a change in radiative forcing, of the order of decades or more for temperature and centuries or more for sea-level rise. Realising the full effect can take more than a thousand years. Therefore, it is prudent to ask:

- When human emissions of greenhouse gases or aerosols lead to a change in radiative forcing, how long will the system continue to experience warming or sea-level rise?
- If we change our emissions, with a resulting change in radiative forcing, how long before the difference in warming response becomes detectable in the real climate system?
- Are time lags the same regardless of whether we are increasing emissions or decreasing them, even to the point of removing more greenhouse gases than we are emitting (known as net negative emissions)?

Because there is a limit on how fast emissions might be reduced, and further there is a time-lag in the response of the climate system to the emission changes, there is also a level of warming we are committed to. Thus, it is also useful to ask:

- How much future warming are we already committed to, given the constraints on future emission scenarios?
- What does this mean for adaptation planning under different mitigation scenarios?

When discussing commitment, the early literature focused on constant concentration (or constant radiative forcing) commitment. This involved looking at warming and other climate changes if stabilisation of atmospheric concentrations of greenhouse gases or aerosols suddenly takes place. Today there is more focus on the commitment if emissions of greenhouse gases or aerosols are suddenly zeroed. This briefing note highlights the changes in climate associated with adjustment of the emissions for both theoretical cases of suddenly zeroing emissions, and the more policy relevant commitment to emission scenarios with potentially feasible emission reductions.

1. Committed global temperature rise and cumulative carbon emissions: Transient Climate Response to Cumulative Carbon Emissions (TCRE) and Zero Emissions Commitment (ZEC)

The Intergovernmental Panel on Climate Change's (IPCC's) Special Report on global warming of 1.5°C (SR1.5)[1] included a discussion of the response time of the climate system when emissions of greenhouse gases or aerosols change. The concentration of greenhouse gases increases instantaneously as emissions of either short-lived or long-lived climate forcing agents enter the atmosphere. Radiative forcing of climate quickly follows, but the response of temperature is much slower, with a component of the response taking decades or more to be realised. The response time is similar for increases in the concentration of short-lived forcers such as atmospheric aerosols (lifetime of a few days in the lower atmosphere) or gases such as methane (lifetime of around a decade in the atmosphere) and increases in long-lived greenhouse gases such as carbon dioxide.

When there is a reduction in emissions the change in atmospheric concentration and radiative forcing can differ between short-lived and long-lived climate forcers. A reduction in emissions of short-lived greenhouse gases may lead to either slower rates of increase in atmospheric concentrations or declines in concentrations, with the decline happening soon after the emission reductions. For instance, a large reduction in the emissions of the short-lived greenhouse gas methane will produce a significant decline in methane concentration over a decade, with further concentration reductions over subsequent years and decades. For carbon dioxide (which is a long-lived greenhouse gas) almost any future emissions will lead to further increases in atmospheric concentration. Zero future emissions will lead to a slow decrease in CO_2 concentrations, although as we see below this may not be enough to reduce temperatures, and carbon dioxide removal causing net negative emissions will lead to a more rapid atmospheric CO_2 concentration reduction.

Figure 1 below shows the potential response for a range of short-lived and long-lived climate forcing agents to large and rapid emission changes, as reported in the IPCC assessment. It considers the hypothetical case of anthropogenic emissions being reduced instantaneously, or over a defined period. Results are shown relative to temperatures in 2020. The result shows that zeroing CO_2 emissions but keeping aerosol and other greenhouse gas emissions constant leads to only a small committed increase in warming over the 21st century (solid blue curve), but with a range that could be positive or negative. If aerosol emissions are also cut at the same time then there is warming over the 21st century of around 0.5ºC (green curve and range), as the net cooling effect of aerosols are removed so that the continued forcing from other greenhouse gases is now sufficiently positive to drive warming increases. However, if other greenhouse gases are also reduced at the same time (orange curve and range) then the initial warming from the removal of short-lived aerosol of around 0.1ºC (occurring within around 5 or so years) is likely to be followed by a cooling over subsequent decades to below the baseline temperature level.

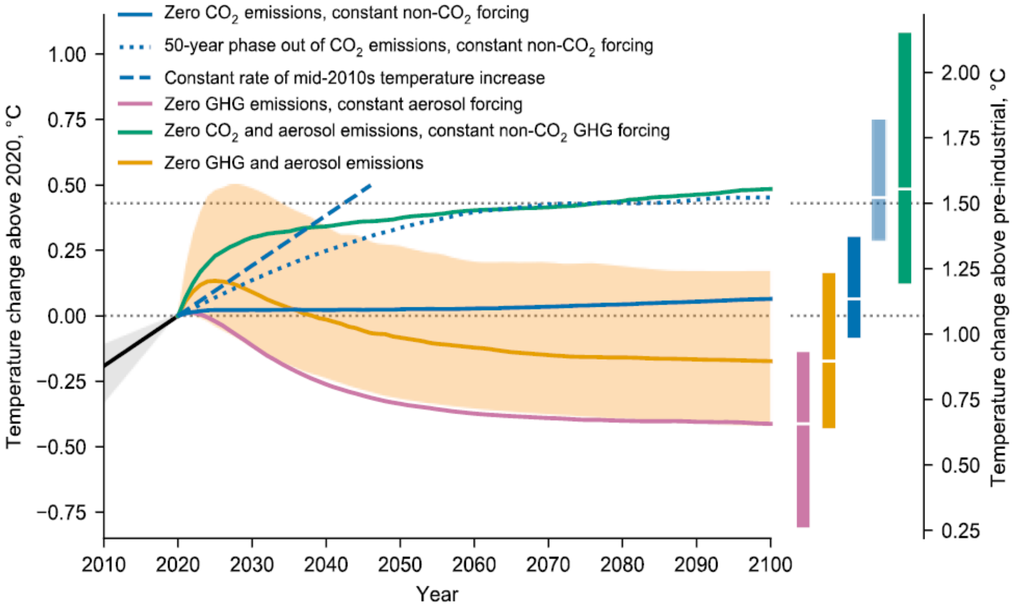

Figure 1. IPCC estimates of response to sudden change in emissions.

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[1] IPCC, 2018: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.

To relate carbon emissions to eventual warming, two measures are defined – Transient Climate Response to Emissions (TCRE) and Zero Emissions Commitment (ZEC). During CO_2 emissions, TCRE (warming created by each additional tonne of cumulative CO_2 emissions) quantifies the warming to the point of emission of a given cumulative amount of CO_2. Thus, an initial warming response to CO_2 emissions is felt immediately.

ZEC refers to the committed changes in global climate if we stop emitting CO_2. The effects on global mean temperature of the long-term continued uptake of carbon and of heat transfer into the ocean tend to offset each other, leading to an approximately constant surface temperature (as seen in the blue line in Figure 1). Deviations from this are the ZEC, and this remains uncertain. It has been shown[2,3,4,5,6] that there is an offset of continued warming following stopping emissions by continued CO_2 removal by natural sinks. The concept of ZEC is being examined further in a new study (ZECMiP) as part of the IPCC 6th assessment cycle.

TCRE and ZEC need to be known to relate carbon emissions to eventual warming and thus to long-term climate targets. Introducing the TCRE concept was a major advance of the IPCC's Fifth Assessment Report[7,8,9,10] (AR5). Since AR5, a considerable literature has developed on constraining the robustness of TCRE[11,12,13,14]. By contrast, there has been relatively less literature on ZEC. Some models continue warming by up to 0.5°C after emissions cease at 2°C of warming[15,16,17] while others simulate little to no additional warming[18]. This led the IPCC's SR1.5 to make the assumption that in the short-to-near term, ZEC was zero[19].

The Met Office are leading a new initiative, called ZECMIP[20] to coordinate multi-model simulations to assess the ZEC for carbon budgets. Preliminary results (Figure 2) from seven models show no clear consensus of ZEC sign but help quantify the uncertainty it introduces. Fuller analysis of the mechanisms and implications of these results is underway and will be submitted for the AR6 WG1 papers deadline in December 2019.

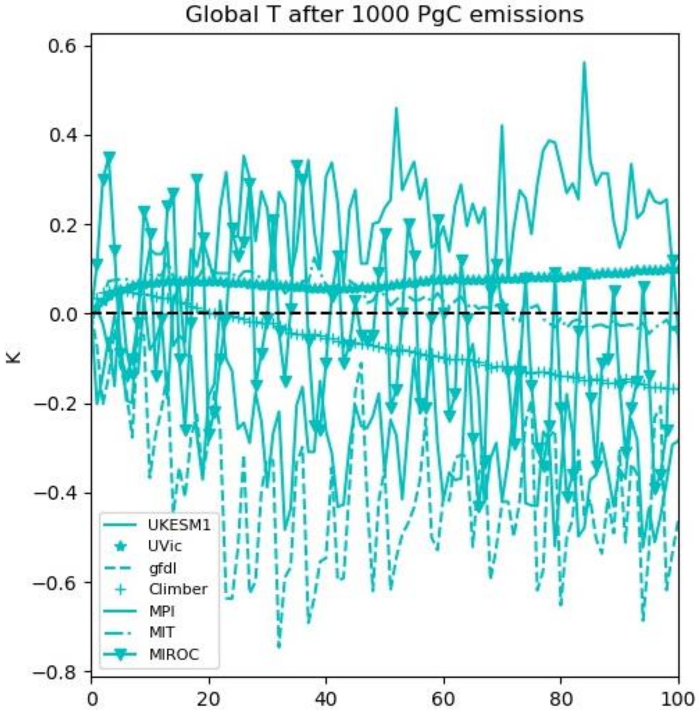

Figure 2. Global mean temperature response following sudden cessation of CO_2 emissions from 7 Earth system models. These models vary in their complexity, with some being Earth system models of intermediate complexity and others being more complex Earth system models.

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[2] Joos et al 2013, Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis.

[3] Matthews and Caldeira 2008, Stabilizing climate requires near-zero emissions.

[4] Solomon et al 2009, Irreversible climate change due to carbon dioxide emissions.

[5] Ricke and Caldeira 2015, Maximum warming occurs about one decade after a carbon dioxide emission

[6] Lowe et al 2009, How difficult is it to recover from dangerous levels of global warming?

[7] IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[8] Allen et al 2009, *Warming caused by cumulative carbon emissions towards the trillionth tonne*.

[9] Matthews et al 2009, *The proportionality of global warming to cumulative carbon emissions*.

[10] Meinshausen et al 2009, *Greenhouse-gas emission targets for limiting global warming to 2 °C*.

[11] Goodwin et al 2015, Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake.

[12] MacDougall et al 2016, Enhancement of non-CO_2 radiative forcing via intensified carbon cycle feedbacks.

[13] Millar and Friedlingstein 2018, The utility of the historical record for assessing the transient climate response to cumulative emissions.

[14] Tachiiri et al 2015, Increase of uncertainty in transient climate response to cumulative carbon emissions after stabilization of atmospheric CO_2 concentration.

[15] Frolicher et al 2014, Extending the relationship between global warming and cumulative carbon emissions to multi-millennial timescales.

[16] Paynter and Frolicher 2015, Sensitivity of radiative forcing, ocean heat uptake, and climate feedback to changes in anthropogenic greenhouse gases and aerosols

[17] Williams et al 2017, Drivers of Continued Surface Warming After Cessation of Carbon Emissions.

[18] Nohara et al 2015, Examination of a climate stabilization pathway via zero-emissions using Earth system models.

[19] Rogelj et al 2018, Scenarios towards limiting global mean temperature increase below 1.5 °C

[20] Jones et al 2019, The Zero Emission Commitment Model Intercomparison Project (ZECMIP) contribution to CMIP6: Quantifying committed climate changes following zero carbon emissions

Whilst the link between increasing CO_2 emissions and warming is approximately linear, the relationship between cumulative carbon emissions and surface temperature change has been investigated since AR5 and found to be nonlinear during periods of negative emissions owing to the lagged response of the deep ocean to previously increasing CO_2 concentrations[21]. Schwinger et al 2018[22] quantified the response due to previously stored ocean carbon versus newly taken up ocean carbon. Again, multi-model results will become available during 2019, under the CDRMIP project[23], and results will be analysed for the AR6 WGI papers deadline in December.

In summary, this section highlights that even very rapid reductions in CO_2 emissions may not lead to rapid reductions in atmospheric concentrations of CO_2. Even when reductions in CO_2 concentration occur, the global temperature response will still take decades or more to fully respond.

2. Precipitation changes in response to changing radiative forcing and temperatures

Greenhouse gases (GHGs) and anthropogenic aerosols influence precipitation through both direct heating of the atmosphere, resulting in changes with little time lag (of perhaps about a month), and via the slower process of warming or cooling the oceans[24]. Therefore, the rate of change in global or regional precipitation does not coincide precisely with either the rate of increase in GHGs or aerosol concentrations or the rate of surface warming, but is influenced by both, and therefore responds on multiple timescales.

In emissions scenarios where GHG emissions stabilise (or decline), but surface temperatures continue to rise (or stabilise), this can change the balance between the warming and emissions-driven influences on precipitation change. This means that precipitation change during stabilisation or reduction of GHG emissions may not be the same as during the phase of increasing emissions[25]. On a global scale, precipitation anomalies per degree of warming are larger when greenhouse gas concentrations are constant or declining, compared to when they are increasing. On regional scales the impact of surface warming on precipitation change is less certain and varies by region[26,27,28].

Another way that lags in the climate system can affect precipitation change is through the pattern of surface warming in the oceans. Due to mixing between the surface and sub-surface ocean, different parts of the ocean warm at different rates in response to GHG or aerosol forcing[29]. As the sub-surface ocean warms over time, the efficiency of ocean mixing for surface cooling is reduced, and the pattern of surface warming changes. Climate sensitivity[30] and regional precipitation change[23] are both sensitive to the pattern of ocean warming, and so these both change over time as the sub-surface ocean warms up. These lags occur on timescales from decades to centuries[31] depending on which part of the ocean circulation is involved.

3. Estimates in lag of warming and precipitation change in response to a radiative forcing change over the UK

In this section we focus on the lags associated with a step increase in radiative forcing, specifically showing the potential response for the UK using the latest Met Office climate model. This provides a local demonstration of the actual magnitudes involved. The results show that the same type of lag behaviour anticipated earlier in the document for global warming response also occurs for the UK (Figure 3), with several decades being needed following a forcing increase before the warming reaches above 80% of its long-term warming amount. For precipitation over the UK there is also a lag before the long-term situation is reached and, further, the pathway towards the long-term change is complex and may even affect the sign of change in the initial decades after a forcing increase.

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[21] Zickfield et al 2016, The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change

[22] Schwinger et al 2018, Ocean Carbon Cycle Feedbacks Under Negative Emissions

[23] Keller et al 2017, The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6

[24] Allen and Ingram 2002, Constraints on future changes in climate and the hydrologic cycle

[25] Wu et al 2012, Temporary acceleration of the hydrological cycle in response to a CO_2 rampdown

[26] Bony et al, Robust direct effect of carbon dioxide on tropical circulation and regional precipitation

[27] Chadwick et al, Spatial Patterns of Precipitation Change in CMIP5: Why the Rich Do Not Get Richer in the Tropics

[28] Voigt and Shaw 2015, Circulation response to warming shaped by radiative changes of clouds and water vapour

[29] Clement et al 1996, An Ocean Dynamical Thermostat

[30] Andrews et al 2015, The Dependence of Radiative Forcing and Feedback on Evolving Patterns of Surface Temperature Change in Climate Models

[31] Held et al 2010, Probing the Fast and Slow Components of Global Warming by Returning Abruptly to Preindustrial Forcing

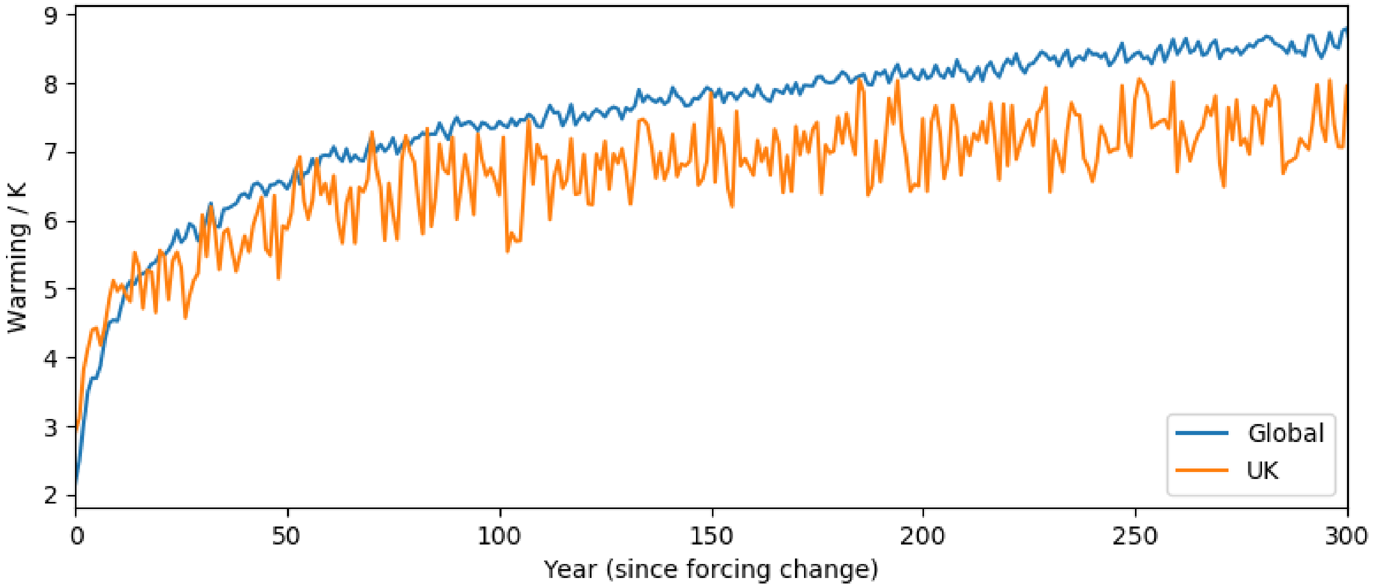

Figure 3: Changes in surface air temperature (blue: global mean; orange: UK mean) as a function of time, following an abrupt quadrupling of CO_2 concentration.

Experiments were performed with UKESM1 (which is based on the physical model HadGEM3-GC-3.1) in which the radiative forcing, resulting from a sudden increase in greenhouse gas concentrations, were tracked over time. In this experiment atmospheric CO_2 is abruptly quadrupled, then held constant. This represents a forcing of around 7.4 W/m2 - close to that reached by the RCP8.5 scenario near the end of the century. Model responses, expressed with respect to the fixed-forcings pre-industrial control, reveal different timescales of response to a change in forcing. Such a sudden change in forcing is not meant to represent a policy relevant scenario but instead to illustrate the large-time lags that follow a forcing change.

Figure 4 shows the response of temperature rise over the UK, as a fraction of the long-term temperature rise (taken as the average from 200-300 years after the initial forcing). The results show the fraction of eventual warming response to the changing forcing at various times in the future. A decade after the change in forcing around 60-70% of the temperature response has been experienced. This rises to 80% or more by 50 years after the forcing and is approaching 90% by a century. The spatial pattern is likely to be influenced in this region by changes in the warming response of the Atlantic Ocean. These results are consistent with the recent global study by Lickley et al (2019)[32] using CMIP3 and CMIP5 model results, with a focus on warming.

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[32] Lickley et al 2019, Time of Steady Climate Change

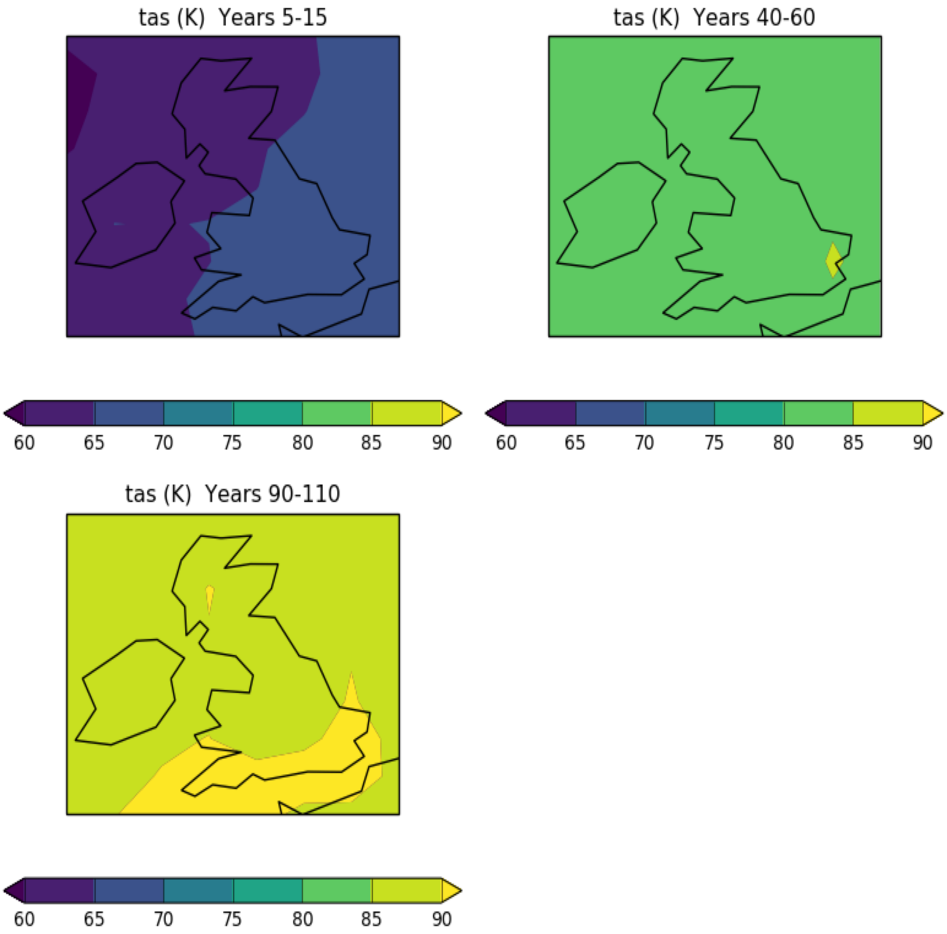

Figure 4: Response of near surface temperature over the UK for a step increase in radiative forcing in the UKESM1 model expressed as a % of the long-term change (taken as 200-300 years after the forcing change).

Using the same experiment, we go beyond the Lickley et al. results by also looking at the response of precipitation, which is more complex (as section 2 highlights).

Precipitation (Figure 5) is altered by the direct response to forcing, as well as surface warming, so exhibits both fast and slow responses. The fast-direct response to forcing change adds complexity, requiring a different approach. In the figure each cross represents a single location in the UK. It is evident that in the first decade after the forcing increase the precipitation over the UK actually shows a reduction for most locations in this example (the crosses lie below the horizontal dotted line). By the second decade there are a mix of locations with positive and negative changes, but most are still a considerable amount below the long-term precipitation responses. It is more than a century after the step forcing increase that the precipitation changes approach their long-term values.

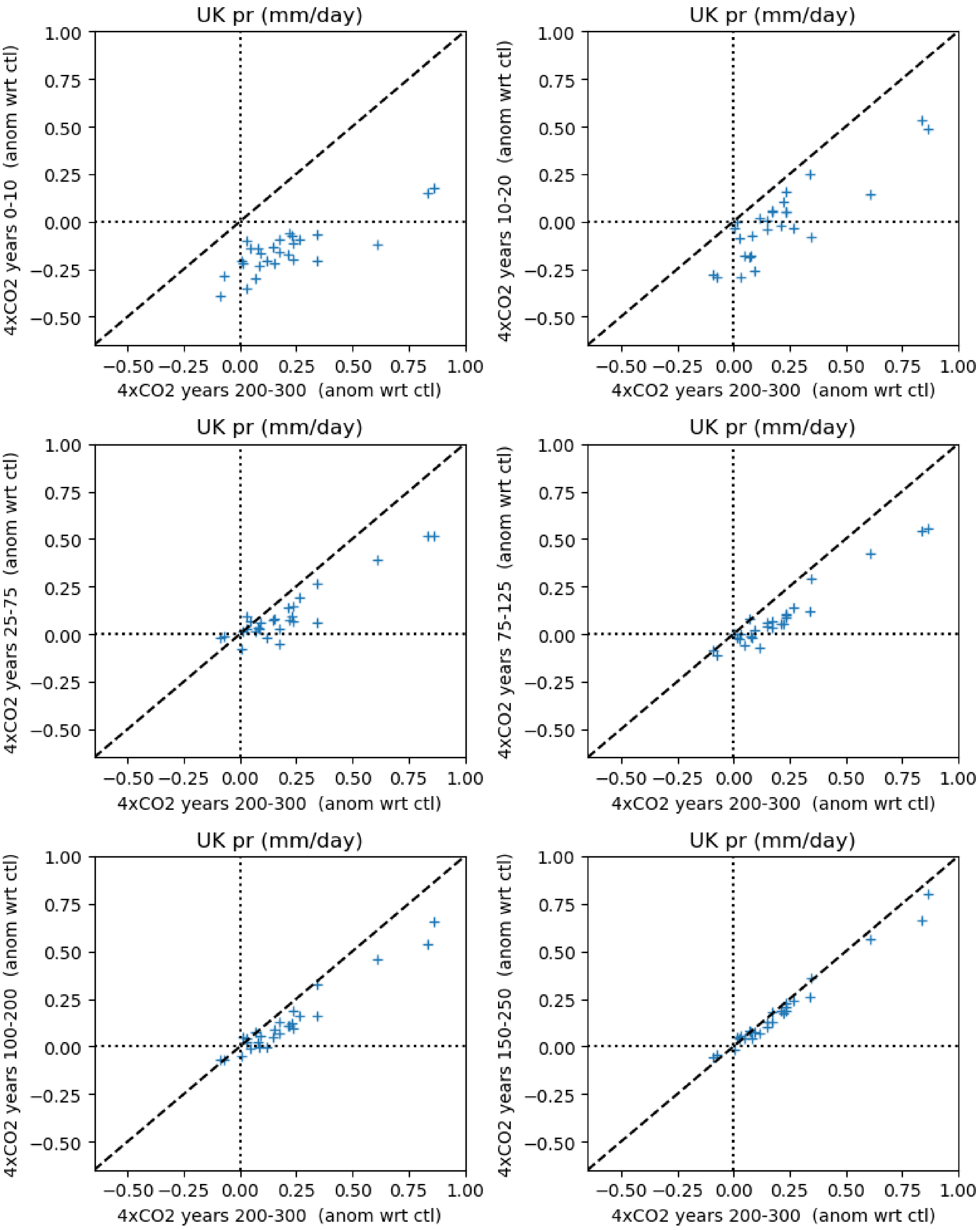

Figure 5: Response of UK grid points to a step change in radiative forcing in the UKESM1 model.

4. Global sea level response to a change in emissions

Under a scenario of decreasing emissions (RCP2.6 climate change scenario), surface temperature rises before approximately stabilising during the mid-21st century. The precise magnitude of this warming has a range of uncertainty depending on the climate model but is of the order of 1.5°C to 2ºC. However, sea level is much slower to respond to reductions in greenhouse gas (GHG) emissions and global sea level is expected to continue to rise until at least 2300[33,34,35,36]. This continued rise is sometimes referred to as "sea level commitment" and is associated with the long lifetime of GHG (particularly CO_2) in the atmosphere and the effect this has on radiative forcing of the climate system. It is important to realise that even for lower emission scenarios, like RCP2.6, the sea-level continues to rise in the 21st century and beyond. Reductions in emissions reduce the rate of sea-level rise but do not halt it, and the emissions reductions may be viewed as simply buying more time for adaptation to sea-level rise.

Essentially, global sea level continues to rise while radiative forcing remains positive (the ocean gains heat and expands) and the surface temperature remains elevated (promoting addition of land-based ice to the ocean), relative to preindustrial. Typically, the sea level commitment has both a thermal expansion component and an ice melt component. The behaviour of the ice melt component is strongly dependent on whether deglaciation irreversibility thresholds are passed for the ice sheets[37]. Of particular concern for global sea level rise is the possibility of "tipping points" associated with the ice sheets in Greenland and Antarctica, which could result in committed sea level rise of many metres, albeit over many centuries or millennia[38,39].The scientific evidence suggests that efforts to reduce GHG emissions will have a dramatic effect on the magnitude of the long-term committed sea-level rise and the maximum rate of future rise over the coming centuries and beyond but will not halt it in the near future[30,34]. It is also important to recognise that when considering both the potential "tipping points" and rates of sea-level rise there is considerable uncertainty. This is particularly large for the land ice contribution and results from limited understanding of, and ability to model, a range of ice sheet processes – such as marine ice cliff instability.

Mengel et al (2018)[40] have assessed the committed sea-level rise under a variety of future scenarios that meet the Paris Agreement targets of temperature stabilisation at 2ºC and 1.5ºC relative to preindustrial through achieving net zero GHG emissions during the 21st century. They find that temperature stabilization below 2ºC is insufficient to limit sea-level rise at 2300 below 1.5m (compared to levels in 2000) and emphasises the importance of early action to prevent the sea-level rise commitment becoming much larger. Exploratory projections developed for UKCP18 suggest a range of 0.6-2.2m (relative to the 1981-2000 average) for global sea level rise at 2300 under the RCP2.6, low emissions scenario.

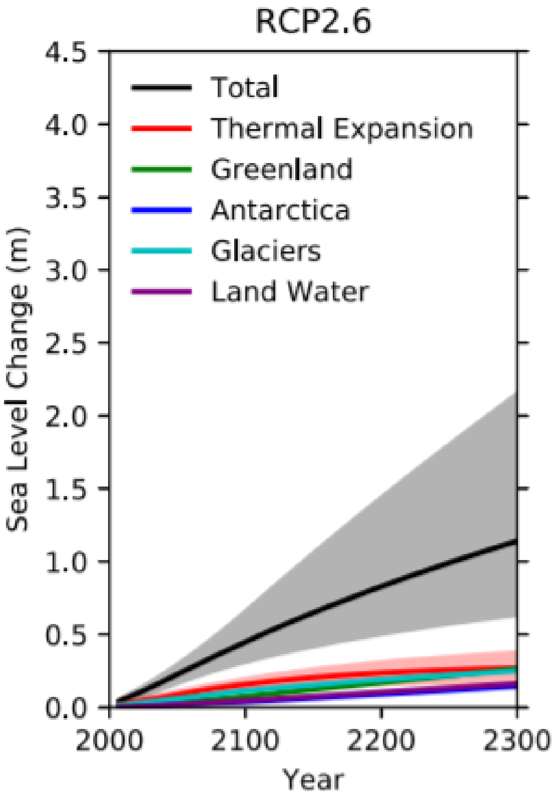

Figure 6: Long-term sea-level rise for the RCP2.6 scenario, when forcings held constant at the end of the 21st century. The warming response in this scenario peaks in the 21st century before decline to well below 2ºC by 2300. From UKCP18 Marine Report, November 2018 (Figure 4.2.1)[1]

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[33] Nicholls et al 2006, Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century

[34] Nauels et al 2017, Synthesizing long-term sea level rise projections – the MAGICC sea level model v2.0

[35] Palmer et al 2018, Extending CMIP5 projections of global mean temperature change and sea level rise due to thermal expansion using a physically-based emulator

[36] Edwards et al 2019, Revisiting Antarctic ice loss due to marine ice-cliff instability

[37] Ridley et al 2005, Elimination of the Greenland Ice Sheet in a High CO_2 Climate

[38] DeConto and Pollard 2016, Contribution of Antarctica to past and future sea-level rise

[39] Clark et al 2016, Consequences of twenty-first-century policy for multi-millennial climate and sea-level change

[40] Mengel et al 2018, Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action

5. SR1.5 Scenario Commitment and Nationally Determined Contributions (NDCs)

Whilst theoretical concepts such as zero emission commitment (section 1) or an understanding of how much warming, precipitation change or sea-level rise (sections 2, 3, 4) follows a step change in radiative forcing provide an illustration of how the real climate system might respond in future, it is instructive to also look at the projected response to a range of policy relevant emission scenarios.

The future emission pathway for the world is not yet known but given the long-term UNFCCC goal of limiting warming to 1.5ºC (or at least well below 2ºC) we can examine the pathways of emissions provided in the recent IPCC 1.5SR, produced using integrated assessment models. We can also examine the warming response to the UNFCCC emission pledges (NDCs), which at present levels may lead to a range of warming that reaches up to much greater than 1.5ºC. Indeed Kriegler et al (2018)[41] highlight that following an NDC trajectory until 2030 would imply larger mitigation challenges in terms of the need for even faster and deeper emissions reductions after 2030 in order to meet the lowest warming targets.

In the latest IPCC special report on global warming of 1.5°C (SR1.5) estimates of global greenhouse gas emissions by 2030, compatible with the current NDCs submitted under the Paris Agreement, range between 52-58 $GtCO_2eq$ yr-1 (*medium confidence*)[42]. We present results using scenarios from the IPCC 1.5SR report database, including those that pass through the NDC range, to examine the scenario commitment to warming. The warming levels were estimated using a simple climate model. We present the median warming response for the scenarios considered. Alternative choices of climate model parameters can lead to either a greater or lesser warming.

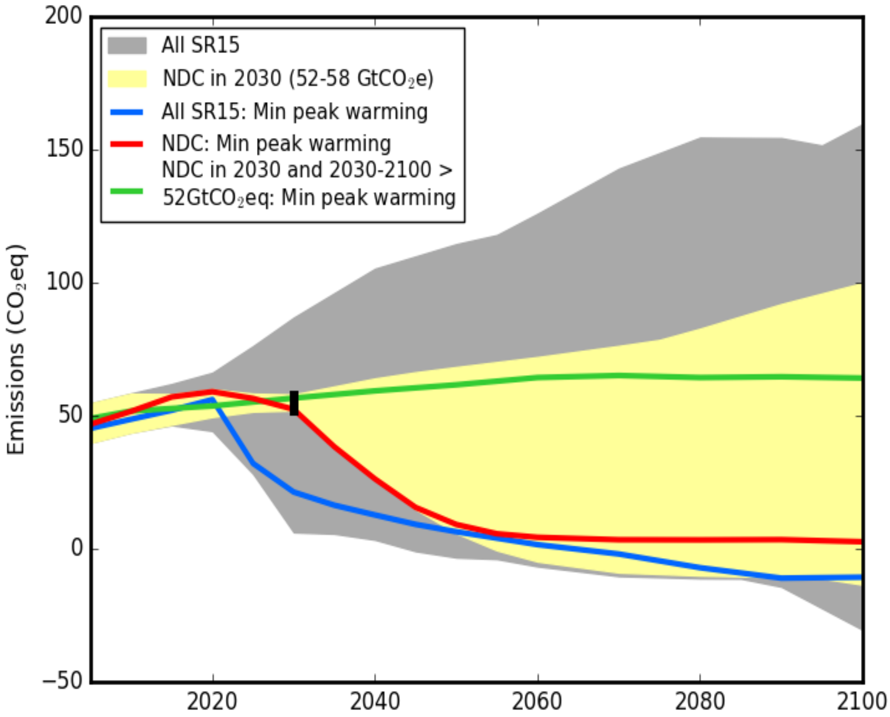

Figure 7: shows the CO_2 equivalent emissions to 2100 for the scenarios in SR1.5. All 411 scenarios used in the IPCC SR1.5 report are shown in grey, with the scenarios consistent with NDC emissions in 2030 in yellow. Many of the SR1.5 scenarios have emissions in 2030 either above the NDCs or below them (note there is grey both above and below the yellow plume and only the yellow plume shows scenarios that meet the NDC range). The blue line shows the scenarios in SR1.5 set which leads to the lowest peak temperature, with the red line showing the SR1.5 scenario with the lowest peak temperature which also has 2030 emissions within the NDC range. The scenario in green is the scenario with the lowest peak temperature this century and which is consistent with the NDCs in 2030 but which then has no further emission reductions that would take them below the NDC level at any point between 2030 and 2100 (i.e. the emissions for the Green curve pass through the NDCs but then never drop below 52 $GtCO_2e$ after 2030). This is as close to an NDC “commitment” scenario that exists in the SR1.5 scenario set.

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[41] Kriegler et al 218, Pathways limiting warming to 1.5°C. A tale of turning around in no time?

[42] Greenhouse gas emissions are here expressed in units of CO_2-equivalence computed with 100-year global warming potentials (GWPs) reported in IPCC SAR (as per UNFCCC decision 9/CP.2). Using IPCC AR4 instead of SAR GWP values is estimated to result in a 2–3% increase in estimated 1.5°C and 2°C emissions levels in 2030 (SR15).

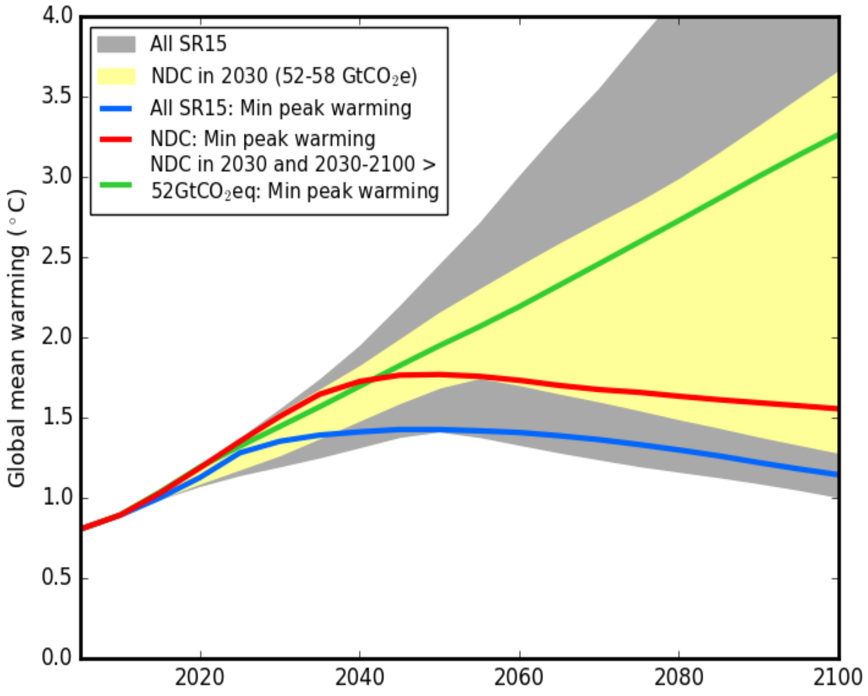

Figure 8: The median temperatures for the SR1.5 scenarios in figure 1. As before the scenario with the lowest peak temperature which is compatiable with the NDCs in 2030 is shown in red, which reaches 1.77°C before slowly reducing towards 1.5°C late in the century. The lowest peak warming in the SR1.5 set is 1.43°C (blue). For scenarios with emissions over 52 GtCO$_2$eq yr^{-1} from 2030 to 2100, none will peak and start to decline by the end of the century. The lowest "peak" temperature in this case is 3.26°C in 2100, shown in the green. The warming responses for the IPCC 1.5SR scenarios summarised in the figures is the global mean change. A UK response could be estimated using pattern-scaling.

Based on this analysis the SR1.5 scenarios imply that:

- Without reducing emissions after 2030 to below those of the NDCs, temperatures will not peak by the end of the century and may exceed 3.2°C.
- Scenarios with 2030 emissions lower than the NDCs exist which limit peak warming to less than 1.5°C
- The NDCs in 2030 followed by no further emission reductions after 2030 are not sufficient to limit peak warming to 1.5°C, although there are pathways that pass through the NDCs in 2030 and for which subsequent emission reductions bring the 2100 temperature very close to 1.5°C.
- Peaking warming ultimately requires net CO$_2$ emissions to approach zero, with further reductions in non-CO$_2$ gases.

It is also instructive to report on recent work by Smith et al (2019)[43], who examine the committed warming from present-day fossil fuel assets. This study shows that if carbon-intensive infrastructure is phased out at the end of its design lifetime, starting from the end of 2018, then there is a 64% chance that peak global mean temperature rise will remain below 1.5C. As fossil fuel combustion emits short-lived climate forcers alongside CO$_2$, and both are gradually reduced in an infrastructure phase-out scenario, there is no sudden increase in warming from reducing emissions gradually.

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[43] Smith et al 2019, Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming

6. When we will detect deviations from a high emission pathway?

A key question when considering lags in the climate system is when will they become detectable in the temperature record? Until recently it was generally thought that benefits of mitigation are hidden by internal climate variability until later in the century. Ciavarella et al. (2017)[44] show that if the likelihood of extremely hot seasons is considered, the benefits of mitigation emerge more quickly than previously thought. It takes less than 20 years of emissions reductions in many regions for the likelihood of extreme seasonal warmth to reduce by more than half, following initiation of mitigation. In some parts of the world, this happens even sooner – in under 15 years. This means positive impacts could be seen well before 2050.

Lewis et al (2019)[45] also shows that the future frequency, severity and duration of temperature extremes depend on the emissions decisions made by the major emitters. By implementing stronger climate pledges, major emitters can reduce the frequency of future extremes and their own calculated contributions to these temperature extremes.

7. Conclusion

This briefing note highlights a number of important aspects associated with the lagged response and committed change of the climate system to changes in greenhouse gas and aerosol emissions.

- The atmospheric concentration of radiative active species increases almost instantaneously following an increase in emissions.
- When emissions are reduced the response of radiative active species in the atmosphere is more complex. In terms of short lived greenhouse gases, the concentrations and radiative forcing can quickly decrease. For example; methane - following a large reduction in emissions, significant concentration reductions would be expected to occur within a decade. For long-lived carbon dioxide, any emissions (even if significant reductions on today's levels) will still lead to an increase in concentrations in the atmosphere *but* greenhouse gas removal leading to net negative emissions could rapidly reduce concentrations.
- The climate response to a change in the concentration of radiative active species in the atmosphere will lag the forcing. Temperature has a rapid initial response component of a few years, and a longer-term slow response of several decades or centuries. Precipitation changes have a more complex response to changes in the climate system as they depend on both radiative forcing and warming. Over the UK, several decades or more would be needed before the long-term response is approached. Sea-level rise lags behind radiative forcing and surface temperature change. It starts to respond quickly after a change in radiative forcing but continues for centuries or more long after temperature rise has slowed.

The evidence implies:

- Even for the most stringent global emission reduction scenarios there is likely to be some further increase in temperature and a continued long-term increase in sea level. In order to avoid damages, both adaptation and mitigation will be needed, with further consideration of potential climate changes and impacts across future decades and centuries. In many cases, this might mean beginning a process of flexible adaptation measures.
- When trying to observe the effect of a deviation from a high emission scenario to a low emission scenario on climate metrics, such as temperature, any change will initially be obscured in the real climate by natural variability but will become apparent over a small number of decades, depending on location.

The magnitude of large-scale climate response remains uncertain, and the local changes are even more uncertain. Further work is required to quantify the local changes so that adaptive measures can be best targeted.

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[44] Ciavarella et al 2017, Early benefits of mitigation in risk of regional climate extremes

[45] Lewis et al 2019, Assessing Contributions of Major Emitters' Paris-Era Decisions to Future Temperature Extremes