Post COP26: does the 1.5°C climate target remain alive?

Andy Wiltshire[1,2], Dan Bernie[1,3], Laila Gohar[1], Jason Lowe[1,4], Camilla Mathison[1,4] and Chris Smith[4,5]

[1]*Met Office Hadley Centre, Exeter, UK*
[2]*Global Systems Institute, University of Exeter, UK*
[3]*Bristol Medical School, University of Bristol, UK*
[4]*Priestley Centre, University of Leeds, UK*
[5]*International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*

Introduction

International climate negotiations agreed in 2015 as part of the Paris Agreement (COP21) to limit the mean global temperature increase in this century to well below 2°C while pursuing efforts to limit the increase even further to 1.5°C relative to the pre-industrial. Achieving this goal likely requires global emissions to first peak and then decline to zero over the coming decades. However, fossil carbon emissions continue to rise and are yet to peak with the remaining total carbon emission envelope – the carbon budget – fast running out (Friedlingstein *et al*., 2022). All in all, this implies we are not yet on a pathway consistent with meeting the 1.5°C ambition. One of the express aims of the 26th annual meeting of the United Nations Framework Convention on Climate Change (UNFCCC), as held in Glasgow, known as COP26, was to keep the 1.5°C goal within reach and move international emissions to a pathway consistent with the target (UK Government, 2021). The arising 'Glasgow Climate Pact' reconfirmed commitment to 1.5°C and emphasised the *'urgent need for Parties to increase their efforts to collectively reduce emissions through accelerated action'* (UNFCCC, 2022) but left open the question of whether commitments made would be enough to keep 1.5°C within reach.

There is no agreed definition of the 1.5°C ambition, but two pathways are commonly assumed; the first involves reaching 1.5°C directly by reducing net emissions to zero staying within an emission envelope in which temperatures do not exceed 1.5°C, the second pathway is by 'overshoot' in which temperatures temporarily exceed 1.5°C but return below this level by 2100. In the latter case, emissions can peak later – temporarily exceeding the carbon budget – but are dependent on net negative emissions later in the century. Either of these pathways can be seen as meeting the target but have very different implications for emission reductions in the coming decades and possible future climate impacts.

Stabilising climate requires all climate active forcers to be controlled. Gases with long atmospheric lifetimes, such as CO_2, need to decrease to zero. Other shorter-lived forcers, such as methane, need to be managed as a minimum requirement. To meet a particular climate target requires net zero CO_2 to be achieved within a carbon budget or emissions envelope. The Intergovernmental Panel on Climate Change (IPCC) assessed this to be 500 $GtCO_2$ (IPCC, 2021) from 2020 to have a 50% chance of meeting 1.5°C. Net zero CO_2 can be achieved through emission reductions and/or carbon dioxide removal (CDR) technologies. Exceeding the emission envelope likely means 'net negative' emissions are required to offset the emissions not within the budget.

The primary mechanism of agreeing emission reductions is through the UNFCCC process of conditional and unconditional nationally determined contributions (NDCs) in which individual countries or blocs make commitments to future emission levels in 2030. COP26 saw an increased level of ambition amongst several countries and a corresponding tightening of 2030 NDCs, amongst additional longer-term pledges including achieving net-zero emissions and global methane reductions. However, the pledges themselves are not binding unless they are incorporated into domestic law, so represent an indication of ambition rather than commitment.

The level of emissions in 2030 is crucial if 1.5°C is to be met with limited or no overshoot. The IPCC Special Report on Global Warming of 1.5°C (SR15; IPCC, 2018) found that half of all scenarios they considered avoiding overshoot required 2030 emissions to be in the range of 25–30 $GtCO_2e$ (IPCC, 2018). Current total greenhouse gas (GHG) emissions reached 51.2 $GtCO_2e$ in 2018 (Crippa *et al*., 2021) implying that emissions need to halve by 2030 to be on track for 1.5°C. Assessments of the COP26 country-level NDC commitments by the Climate Action Tracker (CAT) are for 45–49 $GtCO_2e$ of global emissions in 2030, meaning there is a substantial 'emission gap' between the required emissions and current commitments (UNEP, 2021).

Assessments of the warming implications post COP26 have been made by several international organisations including the International Energy Association (IEA, 2021a,b), Climate Resource (Meinshausen *et al*., 2021), United Nations Environment Programme (UNEP, 2021) and CAT (2021). These 'bottom up' approaches involve the addition of national pledges and policies combined with assumptions over longer term emission implications. The four estimates use differing methods and probability thresholds, but all agree on a likely temperature outcome of 1.8°C in 2100 should NDCs and additional announcements be met. Just considering the 2030 NDC commitments the CAT estimates warming of 2.4°C (1.9–3°C) by 2100. However, a large share of the warming experienced in 2100 is dependent on the emissions that come after the current NDC period. Post 2030 emission pathways are therefore important in determining 2100 temperature outcomes (Rogelj *et al*., 2016). One of the challenges in this 'bottom up' approach of building scenarios from country level emissions upwards is assuming an appropriate level of mitigation post 2030 – whether mitigation actions stalls, continues or accelerates. Common amongst the approaches is to assume a constant level of ambition according to NDCs and other pledges. This is the approach of CAT (Höhne *et al*., 2021), however the assumptions made, and choice of methods are important to determining the climate outcomes (Gütschow *et al*., 2018).

Our approach, as presented here, differs by taking a 'top-down' view of future emission pathways from the literature that are

RMetS Royal Meteorological Society

compatible with the Paris targets. We take the full database of available scenarios from SR15 (Huppmann *et al*., 2019), consisting of over 400 pathways, and assess the difference in characteristics between scenarios which are consistent or inconsistent with the COP26 2030 NDCs. The SR15 report included an assessment of all existing model-based mitigation pathways that achieved 1.5°C or were close to this target. These pathways were compiled in the SR15 database and represent the range of plausible future scenarios considered by the international scientific community and were available at the time of COP26 when the NDCs were being updated. Our approach is to sample the 2030 level of mitigation consistent with the existing scientific literature on how technology and/or policy may evolve. Alternative pathways remain possible, for instance a significant ratcheting of ambition post 2030, but importantly these pathways would be outside the current literature on the evolution of technology and policy.

Methods

The SR15 report scenarios (Huppmann *et al*., 2019) are used in conjunction with a simple but observationally constrained climate emulator of the full complexity Earth system models (ESMs). This approach, rather than using the computationally very expensive full ESM allows us to explore a much broader range of scenarios in a probabilistic framework. The climate emulator is used to explore the relationship between NDCs (and other characteristics of emission scenarios) and the warming response. The model used is the FaIR climate emulator (finite amplitude impulse response model, Smith *et al*., 2018). FaIR is one of the simple climate models used in the IPCC AR6 WGI report (IPCC, 2021) to help interpret the full complexity models. In AR6, the climate and carbon cycle properties were perturbed within FaIR within uncertain ranges to run many thousands of model versions to produce a range of possible future climates. AR6 constrained the simulated climates using several lines of evidence, including analyses of observations, models, paleoclimate information and understanding of physical, chemical and biological processes and components of the climate system to constrain the ensemble distribution and enable probabilistic projections. This means for a given emission pathway we can simulate the probability of a temperature threshold being exceeded.

In addition to the SR15 scenarios, we include two additional scenarios used by the Committee on Climate Change to inform their advice on the UK's Sixth Carbon Budget Report (CCC, 2020). One scenario represents a pathway to delivering the Paris Agreement (CCC PA), therefore requiring a rapid scaling up of action across the global economy over the next decade. The other, represents 2020 policy and global ambition. This 2020 policy scenario (CCC NDC 2020) meets the previously pledged NDCs for 2030 and decarbonisation then continues but at a much slower rate than the Paris aligned scenario (Gohar *et al*., 2022). The total scenario ensemble of 415 represents a database that can be explored for its consistency with climate policies. In addition to the FaIR simulations, we show the simulations using version 6 of the Model for the Assessment of Greenhouse Gas-Induced Climate Change – MAGICC6 (Meinshausen *et al*., 2021) climate emulator, as included in the database (consisting of 411 available scenarios). The MAGICC6 simulations in the SR15 database and report use an identical setup to AR5 WGIII (Clarke *et al*., 2014), and do not include the latest constraint information from AR6. For a typical scenario MAGICC6 (AR5) derived temperature will differ from FaIR (AR6). This is due to differing model structure and application of constraints.

FaIR requires representation of all climate forcers which are not all available in the databases. The missing gases in the SR15 scenarios are infilled using the method from Bernie and Lowe (2014). The CCC scenarios are infilled using Silicone (Lamboll *et al*., 2020), an open-source Python package, which infers anthropogenic emissions of unmodelled species based on the reported emissions.

FaIR simulated temperatures are taken as anomalies to the 2011–2020 period, with the observed warming from the pre-industrial period then added on. This method is consistent with the AR6 methodology but using a more recent period (AR6 used 1995–2014). For each scenario we find the likelihood of 'peak' and 2100 temperatures exceeding 1.5°C by sampling the cumulative distribution from the 2237 constrained AR6 FaIR ensemble members.

The scenarios are divided into two classes based on their 2030 emissions. A lower emission class, where all the scenarios have 2030 emissions that are below the threshold of 45 $GtCO_2e$ (consisting of 45 scenarios) and a higher emission class (consisting of 174 scenarios) in which all the scenarios are above this 2030 threshold. These two classes represent pathways that are below COP26 emission pledges and those that are consistent with or greater than those pledges. The thresholds are based on the global NDC assessment from the CAT reports which include a summation of country-level NDCs, any missing countries (<20% of global emissions) to form global totals and further additions from international aviation, shipping and land-use change.[1]

[1]https://climateactiontracker.org/methodology/global-pathways/

Results

The SR15 scenarios from MAGICC6 and new simulations using AR6 FaIR are shown in Figure 1 which relates 2030 emissions to temperature outcomes. Of all the scenarios, 134 with FaIR and 100 with MAGICC are not compatible with a 1.5°C target as they have a high certainty of exceeding 1.5°C. The COP26 emission pledges are approximately in the middle of the range of 2030 emissions considered in the SR15 database and are lower than the pre COP26 Stated Policies Scenario (STEPS) for 2030 from IEA (53 $GtCO_2e$, IEA, 2021c). COP26 pledges are below current policy and, should the pledge become policy, implies an increase in level of ambition. Figure 1 clearly shows a greater likelihood of avoiding overshooting 1.5°C if emissions are reduced rapidly over the next few years. An important conclusion from this analysis is that COP26 NDCs do not go far enough in terms of lowering emissions. We are more likely to limit warming to the level specified in the Paris agreement with 2030 emissions that are lower than the NDCs. However, if we consider overshooting scenarios the relationship between 2030 emissions and the chances of meeting 1.5°C in 2100 is weaker as there is a greater dependency on post 2030 levels of mitigation action. A less rigorous definition of the climate target therefore opens more pathways to its fulfilment.

Using the database of probabilistic temperature simulations classified by 2030 emission, we further select the simulations with at least 50% likelihood of meeting 1.5°C. Of the available scenarios (415 for FaIR and 411 for MAGICC), just 18 scenarios (less than 5%) in the FaIR simulations (Figure 1, red) and 9 (2%) in the MAGICC simulations (Figure 1, blue) have a greater than 50% likelihood of peak warming remaining below 1.5°C during the twenty-first century (Figure 1a). All of these require much lower emissions in 2030 than those in the COP26 pledges. However, there are many more scenarios which overshoot 1.5°C and come back below this threshold by 2100 with a greater than 50% likelihood (117, 28% FaIR, 90, 22% MAGICC) (Figure 1b). One such scenario is the CCC PA which has a likelihood of peak warming exceeding 1.5°C of 56%; however, this is a lower likelihood than other SR15 scenarios with similar 2030 emissions. The CCC NDC 2020 scenario has 2030 emissions above both the COP26 NDCs and IEA current policy (Figure 1, grey shaded region and cyan line respectively), which gives a 100% likelihood of exceeding 1.5°C both in terms of peak temperature during the twenty-first century or by 2100. Figure 2 shows emissions (a) and temperature (b) time series for the FaIR simulations, dividing the pathways into the high and low emission categories. Of those FaIR pathways that overshoot, 96

Weather – Month 9999, Vol. 99, No. 99

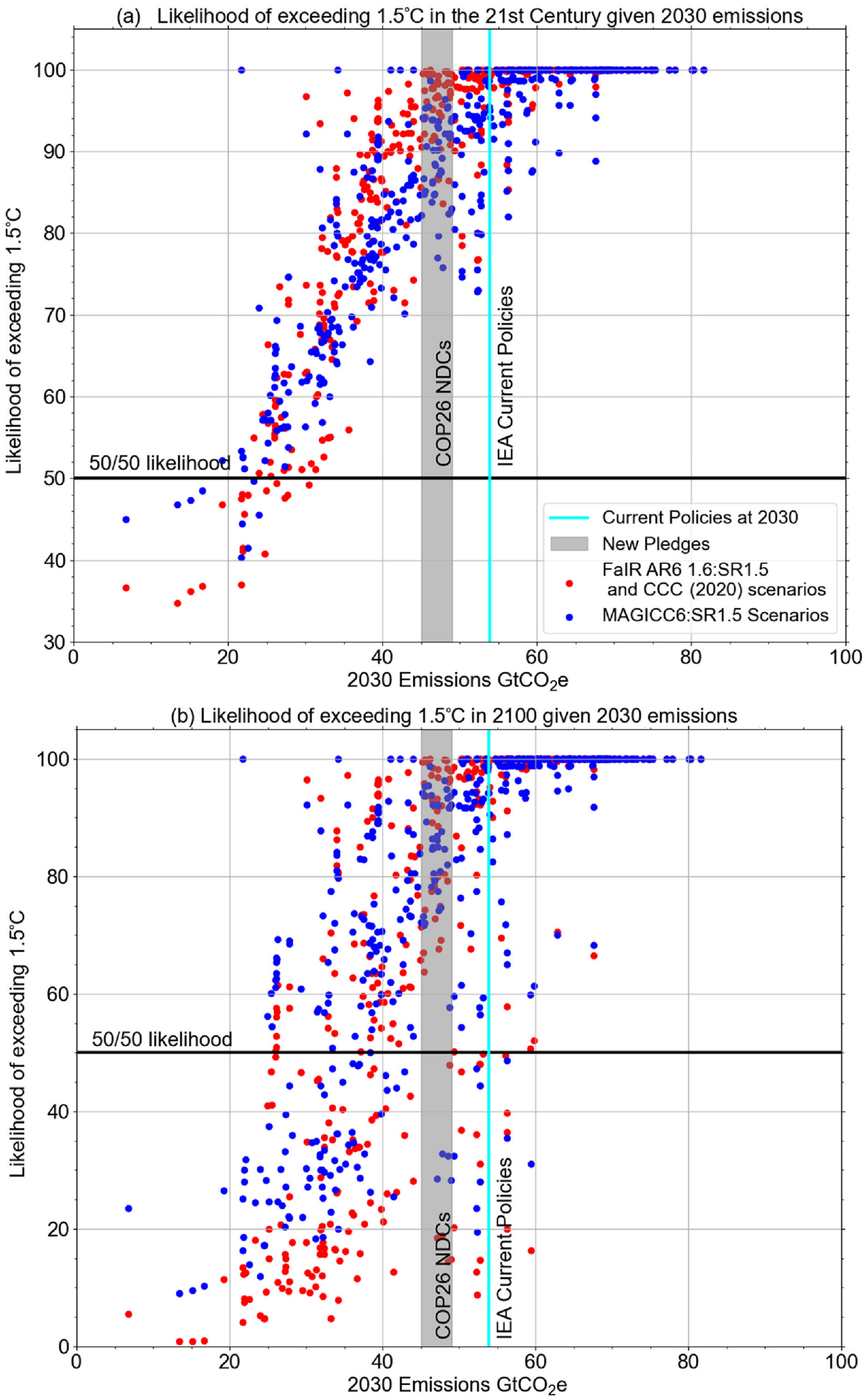

Figure 1. Likelihood of (a) peak or (b) 2100 temperature exceeding 1.5°C versus 2030 emissions. We show MAGICC6 simulations (blue dots) and FaIR AR6 simulations (red dots) using the period 2011–2020 to define the observed warming since the pre-industrial period. Scenarios are from the SR15 database complemented with additional runs from the Committee on Climate Change. Highlighted is the Climate Action Tracker assessment of 2030 nationally determined contribution emissions and the current 2030 emissions from International Energy Association (IEA) given pre-COP26 stated policies. There are 134 scenarios when run with FaIR and 100 for MAGICC with a 100% likelihood of exceeding 1.5°C in this database for both (a) peak warming and (b) 2100 temperatures.

temperature pathways fall into the lower emission category (grey plume) and 21 in the consistent with or higher than COP26 NDCs (red plume, Figure 2). This goes to show the level of challenge and the very limited pathway options available to policy makers to avoid an overshoot.

Pathways with higher 2030 emissions tend to require more rapid emission cuts post 2030 than those in scenarios with early emission reductions, and on average require net negative emissions to be achieved earlier in the century. This combines with higher temperature outcomes and an overall greater likelihood of being warmer by the end of the century.

This is shown graphically in Figure 3. In both models the higher emission category is associated with a greater magnitude and duration of overshoot in some cases reaching near 2°C and remaining in excess of 1.5°C for multiple decades. There are clear differences between the two models with MAGICC (Figure 3b) having several scenarios with a peak warming below 1.5°C, where there are none for FaIR (Figure 3a). Most of the scenarios have peak warming in MAGICC of between 1.5 and 1.7°C (Figure 3b) but in FaIR there are more scenarios above this range even with 2030 emissions below the current pledges. Sustained overshoot of the 1.5°C target is associated with a greater level of climate impact and higher risk of exceeding climate thresholds (Schleussner *et al.*, 2016). Furthermore, the year-on-year emission reductions required are on average 50% higher, implying that delayed mitigation requires more rapid decarbonisation and offsetting of greenhouse gases than would be the case with earlier action.

Discussion

The analyses presented here consider year 2030 emission pledges in the context of available global emission pathways from the SR15 database. Our assessment suggests that the COP26 2030 NDCs are likely to lead to an exceedance of the 1.5°C climate target with at least a 75% likelihood. Remaining below 1.5°C with a greater than 50% likelihood requires that emissions approximately halve relative to present levels by 2030. This is consistent with the SR15 analyses and UN Emissions Gap Report (UNEP, 2021). The COP26 emissions therefore imply we are more likely to be on an 'overshoot' pathway. Achieving 1.5°C in 2100 is comparatively more likely to be achieved and therefore more feasible than a non-overshoot pathway. The increased feasibility arises from a greater pathway flexibility offered by a later achievement date and a shifted dependence from near-term emission reductions to longer term emission removals. Delayed emission reductions imply an increasing reliance on deeper and more rapid emission cuts post 2030 (Figure 2). In turn, this implies a greater reliance on negative emission technology than is the case with earlier action. Delayed mitigation and greater exceedance of the temperature target is associated with increased transition risks in global energy systems through decarbonisation, reduced demand, offsetting and removal (Akimoto *et al.*, 2018); and greater climate hazards and impacts associated with temporary exceedance of a climate target (SR15).

Although our analyses imply a likelihood of overshoot, alternative pathways not

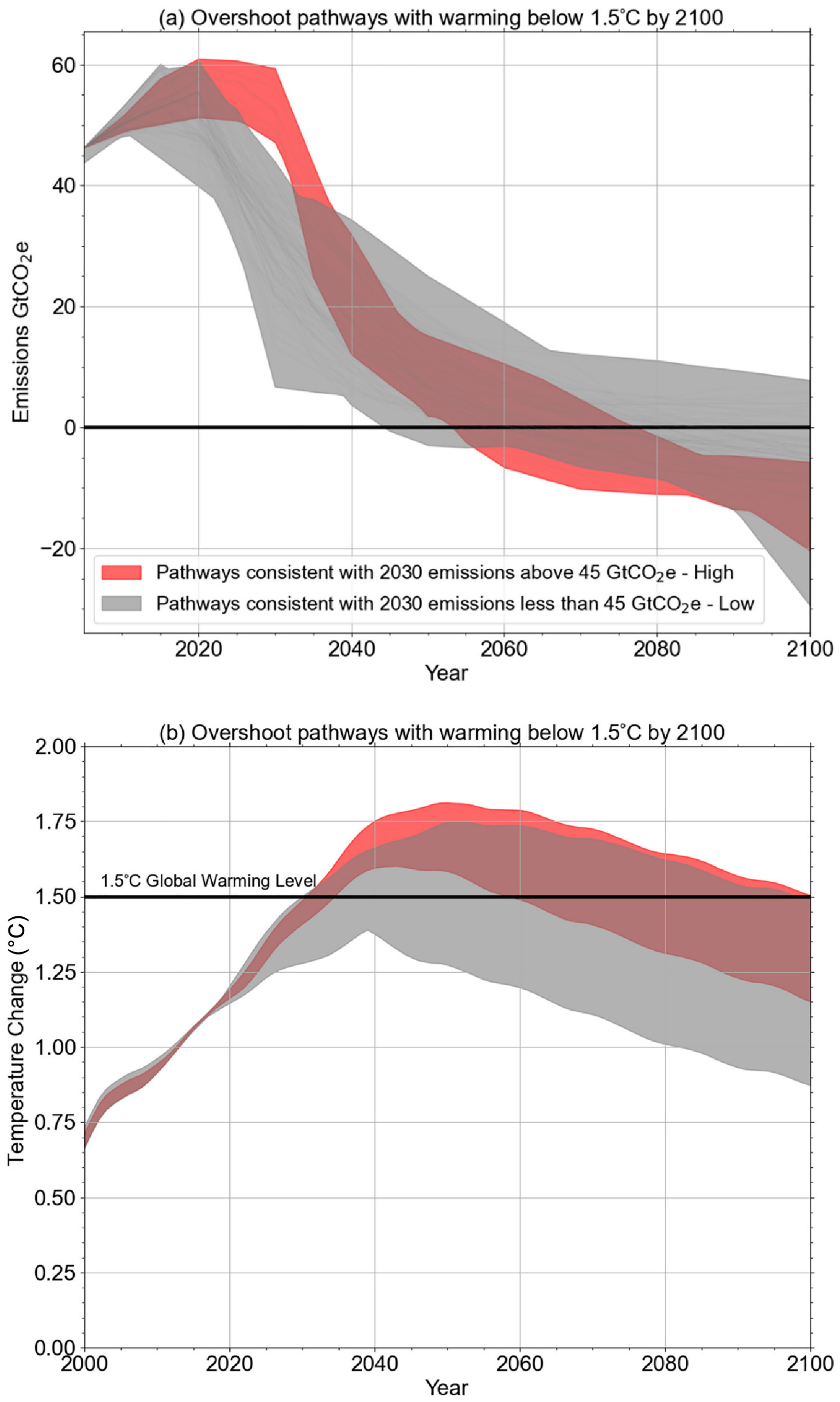

Figure 2. (a) Emission pathways and (b) temperature outcomes for scenarios with 2030 emissions less than 2030 nationally determined contributions (NDCs) (grey) and equal or greater than the assessed NDCs (red) for FaIR simulations.

considered by the international community may be possible. This is because the COP26 pledges likely mean the carbon budget will not be exceeded by 2030. A recent assessment by the Global Carbon Budget found a remaining carbon budget of 420 $GtCO_2$ from 2022 with a 2020 emission rate of 38.0 $GtCO_2$. Should CO_2 emission stabilise or peak and slowly decline (as implied by the COP26 commitments) then a very small carbon budget remains in 2030. This suggests a pathway avoiding overshoot exists that is dependent on extremely deep and rapid emission reductions. However, such a pathway is outside the scope of current scenario-based assessments of the future evolution of technology and policy.

In both SR15 and AR6, the pathways that overshoot the 1.5°C target largely rely on CDR technologies, which must exceed residual CO_2 emissions later in the century to bring the temperatures below 1.5°C again by 2100. The larger the overshoot, the greater the reliance on CDR. These technologies have not yet been deployed at large scales and there is considerable uncertainty regarding their impacts if this is the action taken. There is high confidence that the current methods of CDR, such as bioenergy with carbon capture and storage (BECCS) and afforestation, could have large impacts on land, energy, water or nutrients if deployed at large scale (IPCC, 2018, 2021). Direct air capture and storage has less environmental impacts than BECCS but is currently more expensive (Fuss *et al*., 2018). A diverse portfolio of CDR technologies could mitigate the environmental impacts and reduce the economic costs of CDR (Napp *et al*., 2019). This requires a large amount of investment in research and development and the need for robust and comprehensive national policies (Napp *et al*., 2019; Strefler *et al*., 2021; van der Wijst *et al*., 2021).

Climate impacts, including climate extremes have already caused widespread adverse impacts beyond natural variability (IPCC, 2022). At 1.5°C these impacts are substantially reduced compared to higher warming levels, but they cannot be eliminated entirely. The risks and severity of these climate impacts have been found to be greater at 2°C of global warming and above than at 1.5°C (Schleussner *et al*., 2016). Already even with the current levels of observed warming, there has been a widespread deterioration of land and ocean ecosystems that has been driven by extremes in temperature. This has led to species migration and loss (IPCC, 2022). In some cases, on return to a lower temperature some of these effects may not fully reverse. The higher the warming level, the length and magnitude of overshoot, the greater the risk of reaching a point of unexpected and abrupt change. These abrupt and irreversible changes are forms of tipping point in the Earth system. For example, permafrost thaw in the Arctic and the retreat of glaciers in mountain ecosystems are possibly irreversible on the decadal timescale. Palter *et al*. (2018) found that geographic patterns of sea level rise are shown to be sensitive to the pathway to 1.5°C, with overshoot leading to long-lasting additional sea-level rise (Tokarska and Zickfeld, 2015). Furthermore, Pattyn *et al*. (2018) found that the risk of abrupt collapse of the Greenland and West Antarctic ice sheets increases with temperature, this is linked to significant global impact through sea level rise. At millennial timescales, a tipping point in ice sheet stability likely exists around the 1.5–2°C threshold highlighting the need to both limit warming and minimise any overshoot to minimise the worst effects of climate change.

Other pathways to 1.5°C outside of those considered here remain possible but are highly likely to be dependent on net negative emissions to some extent and/or immediate and rapid termination of emissions in 2030. The analyses presented here

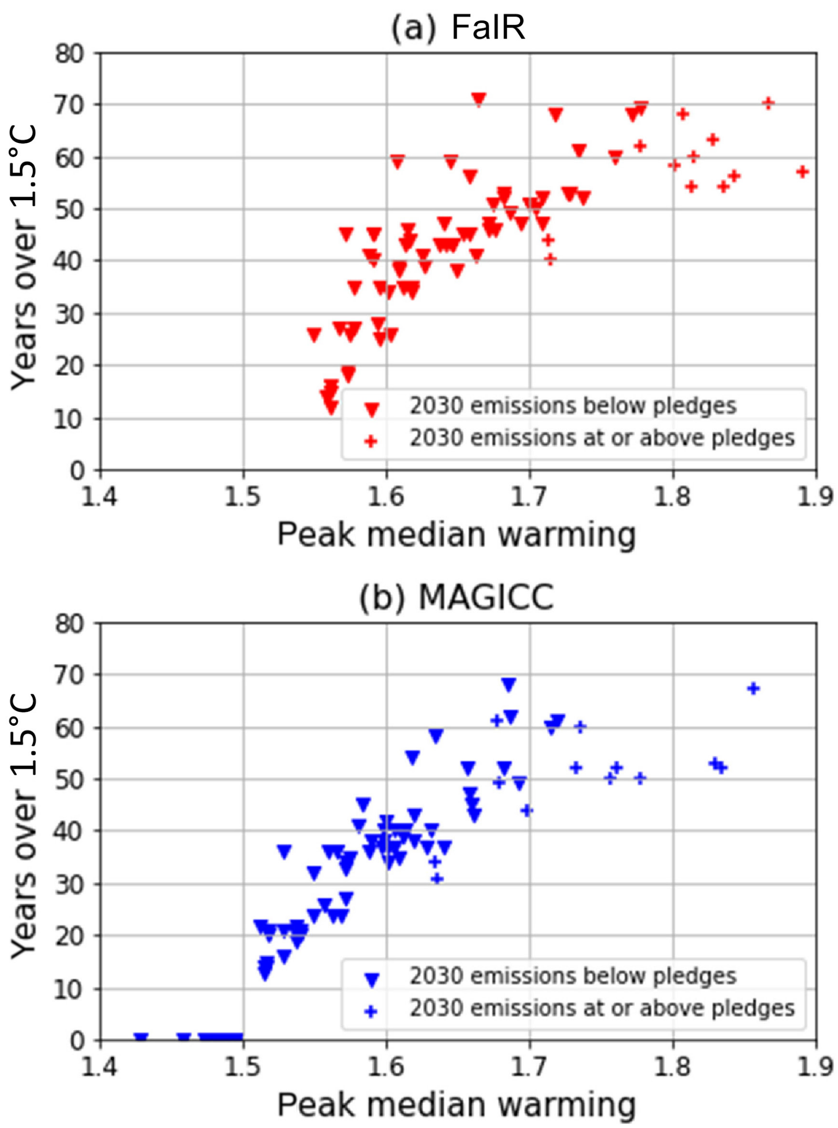

Figure 3. The number of years exceeding 1.5°C against the peak median warming for (a) FaIR and (b) MAGICC. Scenarios with 2030 emissions less than the 2030 nationally determined contributions (NDCs) are highlighted using filled triangles and those that are equal to or greater than the assessed NDCs are shown by plus signs.

show that 2030 emission levels are important as they imply both a path dependency on future emissions and an inertia in global energy systems (Eom *et al*., 2015). This does not mean to say exceeding 1.5°C is inevitable, the possibility remains for discovery of novel energy sources or a major shift in our consumption of energy outside the assumptions of current scientific thinking. However, the COP26 NDCs likely play an important role in committing emissions beyond 2030. As part of the Paris Agreement all participants agreed to monitor progress towards the collective goals and report on their progress through the 5-yearly peer reviewed process called the Global Stocktake. COP26 specifically calls for increased ambition prior to 2030, following the requirement for successive NDCs to be a progression on those having gone before and using the Global Stocktake, to ratchet the level of ambition. The stocktake to be completed at COP28 in 2023 provides an opportunity to close the emission gap. However, the results presented here are consistent with those from CAT, IEA, UNEP and CR which are that 2030's NDC emissions at the time of COP26 are not consistent with a high likelihood of limiting warming to below a 1.5°C target.

Conclusions

The 1.5°C climate target remains alive post COP26 under the broader definition of achievement in which temperatures temporarily exceed 1.5°C between now and 2100 but return to or below 1.5°C by 2100. Keeping under 1.5°C likely requires urgent, rapid and immediate emission reductions that are below the COP26 NDCs. Not only does meeting the COP26 NDCs in year 2030 likely put us on an overshoot pathway but getting back to 1.5°C will require deeper and rapid reductions in the 2030s than would be the case if earlier action was taken. The current Global Stocktake provides an opportunity to ratchet the level of ambition.

Although the 1.5°C target remains alive, the delayed action seen in the COP26 NDCs is associated with increased risks from climate impacts linked to the temporary exceedance of the 1.5°C target and increased transition risk from a requirement for more rapid and deeper emission reductions through decarbonisation, offsetting and reduced demand. Multi-decadal temperature outcomes are strongly dependent on post 2030 emissions, but available scenarios imply a close link and pathway dependency on 2030 emissions partly through inertia in energy systems. Early action therefore implies a broader range of pathway options remain open and provides a reduced risk and technological reliance. Meeting the 1.5°C goal in 2100 post overshoot given the pledges remains feasible but urgent action is required to ensure the year 2030 pledges are met and policies are in place for the very deep and rapid emission reductions that are required post 2030.

References

Akimoto K, **Sano F**, **Tomoda T**. 2018. GHG emission pathways until 2300 for the 1.5°C temperature rise target 14 and the mitigation costs achieving the pathways. *Mitig. Adapt. Strateg. Glob. Chang.* **23**(6): 839–852.

Bernie D, **Lowe JA**. 2014. Future temperature responses based on IPCC and other existing emissions scenarios. AVOID 2 WPA.1 Report 1. http://www.avoid.uk.net/2014/07/analysis-of-climate-projections-from-the-ipcc-working-group-3-scenario-database

Clarke L, **Jiang K**, **Akimoto K *et al***. 2014. Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Edenhofer O, Pichs-Madruga R ***et al***. (eds). Cambridge University Press: Cambridge, UK and New York, NY, pp. 413–510.

Climate Action Tracker (CAT). 2021. *Warming Projections Global Update Climate Action Tracker*. https://climateactiontracker.org/documents/997/CAT_2021-11-09_Briefing_Global-Update_Glasgow2030CredibilityGap.pdf

Committee on Climate Change (CCC). 2020. The Sixth Carbon Budget. The UK's path to Net Zero report. https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf.

Crippa M, **Guizzardi D**, **Solazzo E *et al***. 2021. *GHG Emissions of All World Countries – 2021 Report, EUR 30831 EN*. Publications Office of the European Union: Luxembourg. https://doi.org/10.2760/173513, JRC126363.

Eom J, **Edmonds J**, **Krey V *et al***. 2015. The impact of near-term climate policy choices on technology and emission transition pathways. *Technol. Forecast. Soc. Change* **90**: 73–88.

Friedlingstein P, **Jones MW**, **O'Sullivan M *et al***. 2022. Global carbon budget 2021. *Earth Syst. Sci. Data* **14**: 1917–2005.

Fuss S, **Lamb WF**, **Callaghan MW *et al***. 2018. Negative emissions – part 2: costs, potentials and side effects. *Environ. Res. Lett.* **13**: 063002.

Gohar L, **Bernie D**, **Millar R *et al***. 2022. Quantifying the impact of alternate climate response uncertainty distributions under the global mitigation scenarios in the UK's Committee on Climate Change Sixth Carbon budget. *Climatic Change* (in review). https://doi.org/10.21203/rs.3.rs-1812163/v1

Gütschow J, **Jeffery ML**, **Schaeffer M *et al***. 2018. Extending near-term emissions scenarios to assess warming implications of Paris Agreement NDCs. *Earth's Futures* **6**(9): 1242–1259.

Höhne N, **Gidden MJ**, **den Elzen M *et al***. 2021. Wave of net zero emission targets opens window to meeting the Paris Agreement. *Nat. Clim. Change* **11**: 820–822.

Huppmann D, **Kriegler E**, **Krey V *et al***. 2019. *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA*. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis. https://doi.org/10.5281/zenodo.3363345

International Energy Agency (IEA). 2021a. *World Energy Outlook 2021*. OECD Publishing: Paris. https://doi.org/10.1787/14fcb638-en.

International Energy Agency (IEA). 2021b. *COP26 climate pledges could help limit global warming to 1.8 °C, but implementing them will be the key*. https://www.iea.org/commentaries/COP26-climate-pledges-could-help-limit-global-warming-to-1-8-c-but-implementing-them-will-be-the-key

International Energy Agency (IEA). 2021c. *World Energy Model Documentation October 2021*. https://iea.blob.core.windows.net/assets/932ea201-0972-4231-8d81-356300e9fc43/WEM_Documentation_WEO2021.pdf

IPCC. 2018. Summary for policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Masson-Delmotte V, Zhai P, Pörtner H-O *et al*. (eds). Cambridge University Press: Cambridge, UK and NewYork, NY, pp 3–24.

IPCC. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte V, Zhai P, Pirani A *et al*. (eds) . Cambridge University Press: Cambridge, UK and New York, NY.

IPCC. 2022. Summary for policymakers. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner H-O, Roberts DC, Tignor M ***et al***. (eds) . Cambridge University Press: Cambridge, UK and New York, NY, pp. 3–33.

Lamboll RD, **Nicholls ZRJ**, **Kikstra JS *et al***. 2020. Silicone v1.0.0: an open-source Python package for inferring missing emissions data for climate change research. *Geosci. Model Dev.* **13**: 5259–5275.

Meinshausen M, **Lewis J**, **Nicholls Z *et al***. 2021. COP26 Briefing paper: updated warming projections for NDCs, long-term targets and the methane pledge. Making sense of 1.8°C, 1.9°C and 2.7°C. https://data.climateresource.com.au/ndc/20211109-ClimateResource-1-9C_to2-7C.pdf

Napp TA, **Few S**, **Sood A *et al***. 2019. The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets. *Appl. Energy* **238**: 351–367.

Palter JB, **Frölicher TL**, **Paynter D *et al***. 2018. Climate, ocean circulation, and sea level changes under 21 stabilization and overshoot pathways to 1.5 K warming. *Earth Syst. Dyn.* **9**(2): 817–828.

Pattyn F, **Ritz C**, **Hanna E *et al***. 2018. The Greenland and Antarctic ice sheets under 1.5 °C global warming. *Nature Clim. Change* **8**: 1053–1061.

Rogelj J, **den Elzen M**, **Höhne N *et al***. 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **534**: 631–639.

Schleussner C-F, **Lissner TK**, **Fischer EM *et al***. 2016. Differential climate impacts for policy-relevant limits to global warming: the case of 1.5°C and 2°C. *Earth Syst. Dyn.* **7**(2): 327–351.

Smith CJ, **Forster PM**, **Allen M *et al***. 2018. FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* **11**: 2273–2297.

Strefler J, **Bauer N**, **Humpenöder F *et al***. 2021. Carbon dioxide removal technologies are not born equal. *Environ. Res. Lett.* **16**: 074021.

Tokarska KB, **Zickfeld K**. 2015. The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environ. Res. Lett.* **10**(9): 094013.

UK Government. 2021. *COP26 Explained*. https://ukcop26.org/wp-content/uploads/2021/07/COP26-Explained.pdf

UNFCCC. 2022. *Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its third session, held in Glasgow from 31 October to 13 November 2021*. FCCC/PA/CMA/2021/10/Add.1. https://unfccc.int/documents/460950

United Nations Environment Programme (UNEP). 2021. *Emissions Gap Report 2021 Addendum*. A preliminary assessment of the impact of new or updated nationally determined contributions, other 2030 pledges and net-zero emissions pledges announced or submitted since the cut-off dates of the Emissions Gap Report 2021. https://wedocs.unep.org/bitstream/handle/20.500.11822/37350/AddEGR21.pdf

van der Wijst K, **Hof AF**, **van Vuuren DP**. 2021. Costs of avoiding net negative emissions under a carbon budget. *Environ. Res. Lett.* **16**: 064071.

Correspondence to: A. Wiltshire

andy.wiltshire@metoffice.gov.uk

doi: 10.1002/wea.4331