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LETTER

Guidance on emissions metrics for nationally determined contributions under the Paris Agreement

Steve Denison[1], **Piers M Forster** and **Christopher J Smith**

School of Earth and Environment, The University of Leeds, Leeds LS2 9JT, United Kingdom

[1] Author to whom correspondence should be addressed.

E-mail: ee16s2d@leeds.ac.uk

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Abstract

Many nationally determined contributions (NDCs) under the Paris Agreement follow the established practice of specifying emissions levels in tonnes of CO_2 equivalent emissions. The Global Warming Potential (GWP) is the emissions metric used most often to aggregate contributions from different greenhouse gases (GHGs). However, the climate impact of pathways expressed in this way is known to be ambiguous. For this reason, alternatives have been proposed but the ambiguity has not been quantified in the context of the Paris Agreement. Here we assess the variation in temperature using pathways consistent with the ambition of limiting temperature increases to well below 2 °C. These are taken from the IPCC Special Report on Global Warming of 1.5 °C (SR15). The CO_2 emission levels are adjusted so that the pathways all have the same total CO_2 equivalent emissions for a given emissions metric but have different proportions of short-lived and long-lived pollutants. We show that this difference affects projections by up to 0.17 °C when GWP_{100} is used. Options of reducing this ambiguity include using a different emissions metric or adding supplementary information in NDCs about the emissions levels of individual GHGs. We suggest the latter on the grounds of simplicity and because it does not require agreement on the use of a different emissions metric.

1. Introduction

Country-level contributions to the Paris Agreement are in the form of nationally determined contributions (NDCs) that typically contain quantified emission reduction commitments. An emissions metric is used to calculate total levels of combined GHG emissions in units of tonnes of carbon dioxide equivalent ($GtCO_2$-eq) emissions, rather than specifying reduction targets for individual GHGs. Various metrics (for example GWP and the global temperature change potential (GTP) (Shine *et al* 2005)) have been devised to measure this 'equivalence' in order to either quantify the total impact of an emissions pathway comprising different greenhouse gases or to compare the impact of different gases on climate (Myhre *et al* 2013a). Emissions of different greenhouse gases have different atmospheric lifetimes and climate impacts. All metrics necessarily consider only a limited set of impacts for specific time periods, as this is the only way that different greenhouse gases can be quantitatively compared (Plattner *et al* 2009, Tol *et al* 2012).

Metrics based on physical impacts are most commonly used in climate policy and an important example is found in the Kyoto Protocol. Participants' obligations to limit aggregate emissions of six key pollutants are quantified using a specified metric, Global Warming Potential measured over 100 years (GWP_{100}). Alongside its long history of use in successive IPCC assessments, its central role in the Kyoto Protocol has contributed to GWP_{100} becoming a de facto standard in the policy arena (Plattner *et al* 2009). However, there is extensive literature covering the limitations of metrics (Fuglestvedt *et al* 2003, Forster *et al* 2007, Shine *et al* 2007, Jenkins *et al* 2018) and GWP in particular (Shine *et al* 2005, Ocko *et al* 2017, Allen *et al* 2018). This motivates the question as to whether the use of metrics, especially GWP_{100}, serves the purpose of the

Table 1. Key features of NDCs of the six largest emitters of greenhouse gases (excluding land-use change emissions).

Country	Type of NDC	Scope	Metric[a]
China	Intensity target	Carbon dioxide	None
USA	Absolute target	Kyoto gases[b]	GWP_{100}
EU28	Absolute target	Kyoto gases	GWP_{100}
India	Intensity target	Not specified	Not specified
Russian Federation	Absolute target	Kyoto gases	GWP_{100}
Japan	Absolute target	Kyoto gases[c]	GWP_{100}

[a] In all cases where GWP_{100} is specified, reference is made to the IPCC Fourth Assessment Report (AR4).

[b] The gases included here under the heading of 'Kyoto gases' are carbon dioxide, methane, nitrous oxide, HFCs, PFCs, sulphur hexafluoride, and nitrogen trifluoride.

[c] The NDC for Japan also includes supplementary information with individual targets for reductions of carbon dioxide, methane, nitrous oxide and for fluorinated gases as a group comprising HFCs, PFCs, sulphur hexafluoride and nitrogen trifluoride.

Paris Agreement well enough. For example, using GWP_{100} to calculate cumulative CO_2-equivalent emissions does not lead to an accurate estimate of peak warming (Allen *et al* 2018, Fuglestvedt *et al* 2018). This is a problem given a specific goal of the Paris Agreement is to limit the temperature increase caused by anthropogenic emissions.

The Paris Agreement differs from the Kyoto Protocol in several important respects. In place of binding (though not always achieved) emission reductions there is a global target for limiting warming to be achieved through voluntary NDCs made by individual countries. It anticipates that the initial NDCs, which imply greater reductions in emissions than those mandated in the Kyoto protocol, will not be sufficient to limit warming to 2 °C (Rogelj *et al* 2016, Vrontisi *et al* 2018). Therefore, a five yearly cycle of global stocktakes and provision of enhanced NDCs is included to create a ratchet mechanism through which national efforts are increased. Despite this fundamental difference in approach, the Paris Agreement requires countries to take account of established practices. This is reflected in many NDCs by the presentation of reductions in terms of combined emissions, the use of GWP_{100} and the list of GHGs covered.

NDCs vary in form and content leading to uncertainty in estimates of their aggregated impact. NDCs can be categorised by absolute targets, emission intensity targets, reductions from business as usual and policy measures (Conte Grand 2016, UNFCC 2016). Some also include targets for adaptation. Coverage of pollutants is incomplete, with varying levels of clarity as to what is included. Few specifically mention aerosols. Where a metric is specified it is usually GWP_{100} from a single, but not necessarily the latest, IPCC assessment report. Table 1 summarises the key features of the NDCs submitted by the six largest emitters of GHGs excluding land-use change emissions.

Under the NDCs, global emissions in 2030 are estimated to be between 52.0 and 59.3 Gt CO_2-eq (UNFCC 2016) compared to 53.5 Gt CO_2-eq in 2017 (UNEP 2018). Assuming the conditional elements (for example, reductions dependent on the provision of financial aid) are implemented and that the annual rate of decarbonisation after 2030 equals that during 2020–2030, the global mean temperature in 2100 is expected to be 2.6 °C (2.4 °C–3.1 °C) above pre-industrial levels (Vrontisi *et al* 2018). Furthermore, until emissions of long-lived GHGs are reduced to zero, temperatures will continue to rise (Cain *et al* 2019). The uncertainty in the estimate of the level of 2030 emissions arises from a number of sources other than the use of emissions metrics (Rogelj *et al* 2017). The main factor is socio-economic assumptions particularly where NDCs are formulated in terms of emission intensity improvements. Other factors include variation in historical emission baselines, inclusion of ranges, alternative energy accounting rules and different attribution of non-commercial biomass.

Therefore, if NDCs contain a commitment to an absolute level of abatement, it is expressed as a total for all GHGs combined using an emissions metric. $GWP_{100,}$ the metric often used in the policy arena, fails to take full account of the differences in impacts at different points in time between pollutants, leading to uncertainty in calculations of the aggregated impact. However, it is not the only source of ambiguity. Questions therefore include whether the uncertainty introduced by the use of GWP_{100} is significant in the context of achieving the target of the Paris Agreement and, if it is, how it could be addressed.

2. Methods

A pragmatic approach is used to quantify this uncertainty. The starting point is a set of emission pathways compatible with the temperature target of the Paris Agreement. These have different mixes of short-lived and long-lived pollutants. The levels of CO_2 emissions are adjusted to make the total emissions calculated using an emissions metric the same for all pathways and the global temperature changes arising from each pathway are calculated. The variation in temperatures arising from the adjusted pathways is used as an estimate of the uncertainty arising solely due to the use of metrics.

To create the test pathways, 222 scenarios from Integrated Assessment Models described in SR15 (Rogelj *et al* 2018, Huppmann *et al* 2018a, 2018b) have been used. We use the same definitions to classify scenarios by temperature pathways as table 2.1 of SR15: Below 1.5 °C, 1.5 °C low overshoot (OS), 1.5 °C high OS, Lower 2 °C and Higher 2 °C. Scenarios are classified by the probabilities of staying within 1.5 °C or 2 °C above pre-industrial in the MAGICC climate model (Meinshausen *et al* 2011), and in the cases of the 1.5 °C-consistent pathways, whether and by how much they exceed 1.5 °C before returning below this threshold. Scenarios which are more likely than not (>50% probability) to exceed 2 °C before 2100 ('Above 2 °C' in SR15 terminology) are not analysed. For each of the five scenario classes, the mean level of CO_2-eq emissions has been calculated using the following GWP and GTP metrics: GWP_{20}, GWP_{100}, GTP_{20}, GTP_{50} and GTP_{100} using the indices in the IPCC's Fifth Assessment Report AR5 (Myhre *et al* 2013a). Only the Kyoto gases are included in the calculation of combined emissions, reflecting the typical scope of current NDCs. The levels of CFC, aerosol and fossil fuel and industry CO_2 emissions are modified for each pathway and levels of all other GHG emissions are unchanged. Levels of CFC emissions follow those from representative concentration pathway 2.6 values and levels of aerosol emissions are set to the mean of all scenarios in that class. Fossil fuel and industry CO_2 emissions are adjusted for each scenario to make the level of CO_2-eq emissions equal to the class mean. This numerical adjustment imposes an identical CO_2-eq emissions trajectory for each scenario in each class under a given metric. It is recognised that some aerosol emissions have the same source as CO_2 (Rogelj *et al* 2014) and it could be argued that the adjustments to CO_2 levels should be accompanied by a corresponding change to aerosol levels. This has been estimated using the tool developed by Rogelj *et al* (2014) and is found to be too small to have a material impact on the projections of global temperatures.

The temperatures arising from the 222 modified pathways have been calculated using the FaIR climate model (version 1.3.4) (Millar *et al* 2017, Smith *et al* 2018). FaIR temperature projections are somewhat lower than these class names imply due to updated assumptions pertaining to radiative forcing, historical temperature constraint and prior distributions for climate sensitivity, and structural differences between the models (Forster *et al* 2018). However, we maintain the MAGICC-based scenario classifications here for consistency with SR1.5. Using FaIR projections rather than MAGICC would increase the probability of remaining under 1.5 °C or 2 °C. FaIR uses a four-box representation of the airborne fraction of CO_2 where the time constant of each box is scaled in order to replicate the decline in efficiency in carbon uptake by the land and ocean with both increasing temperature and increasing cumulative carbon emissions. Emissions of 30 non-CO_2 gases are described with a one-box decay model in which the radiative efficiencies and atmospheric lifetimes of each gas are as reported in (AR5). The sole exception is for methane, in which an atmospheric burden lifetime of 9.3 years is used (Smith *et al* 2018). Further detail on the treatment of methane in FaIR is contained in the supplementary information which is available online at stacks.iop.org/ERL/14/124002/mmedia. Aerosol and tropospheric ozone forcing is calculated from emissions of short lived climate pollutants, which includes a negative temperature feedback on ozone forcing (Stevenson *et al* 2013), direct aerosol effects informed by Aerocom multi-model studies (Myhre *et al*, 2013b) and cloud-albedo effects based on the simplified global models of Ghan *et al* (2013) and Stevens (2015).

Temperature results are presented for the period 2000–2100. The projected temperature increase for each pathway is calculated as the median of the retained members of a 1000-member perturbed-parameter ensemble. The perturbed parameters represent plausible geophysical responses. Radiative forcing from well-mixed GHGs, ozone, aerosols and land-use change are perturbed based on their AR5 uncertainty ranges. Equilibrium climate sensitivity, transient climate response, carbon cycle and global mean temperature response ranges are based on evidence from Coupled Model Intercomparison Phase 5 (CMIP5) climate models (Forster *et al* 2013, Geoffroy *et al* 2013, Millar *et al* 2017) and the efficiency of land and ocean carbon uptake with respect to increasing temperature and cumulative carbon emissions is taken from CMIP5 and other carbon cycle models (Friedlingstein *et al* 2006). Ensemble members are retained if the resulting temperatures from 1880 to 2016 fall within the range of uncertainty from the historical in-filled Cowtan and Way (2014) dataset of 0.95 °C ± 0.17 °C, using the regression-based method of Thompson *et al* (2015) that factors in natural variability and uncertainty in observations. For the purposes of comparing ensemble members to the historical period, solar and volcanic forcing have been included, but excluded for future projections, consistent with the treatment in SR1.5 (Rogelj *et al* 2018). Temperatures are reported using a pre-industrial baseline of 1850–1900.

3. Results

Figure 1 illustrates this approach, using GWP_{100} as the metric. Panels (a) and (b) show the levels of CO_2 and CH_4 emissions, these being the most significant long-lived and short-lived pollutants. Panel (c) shows the adjustment made to CO_2 emissions to make levels of total CO_2-eq emissions equal to the class mean and (d) the temperature anomalies arising from the test pathways in FaIR. The shaded areas are of particular interest as they show the range of temperatures arising

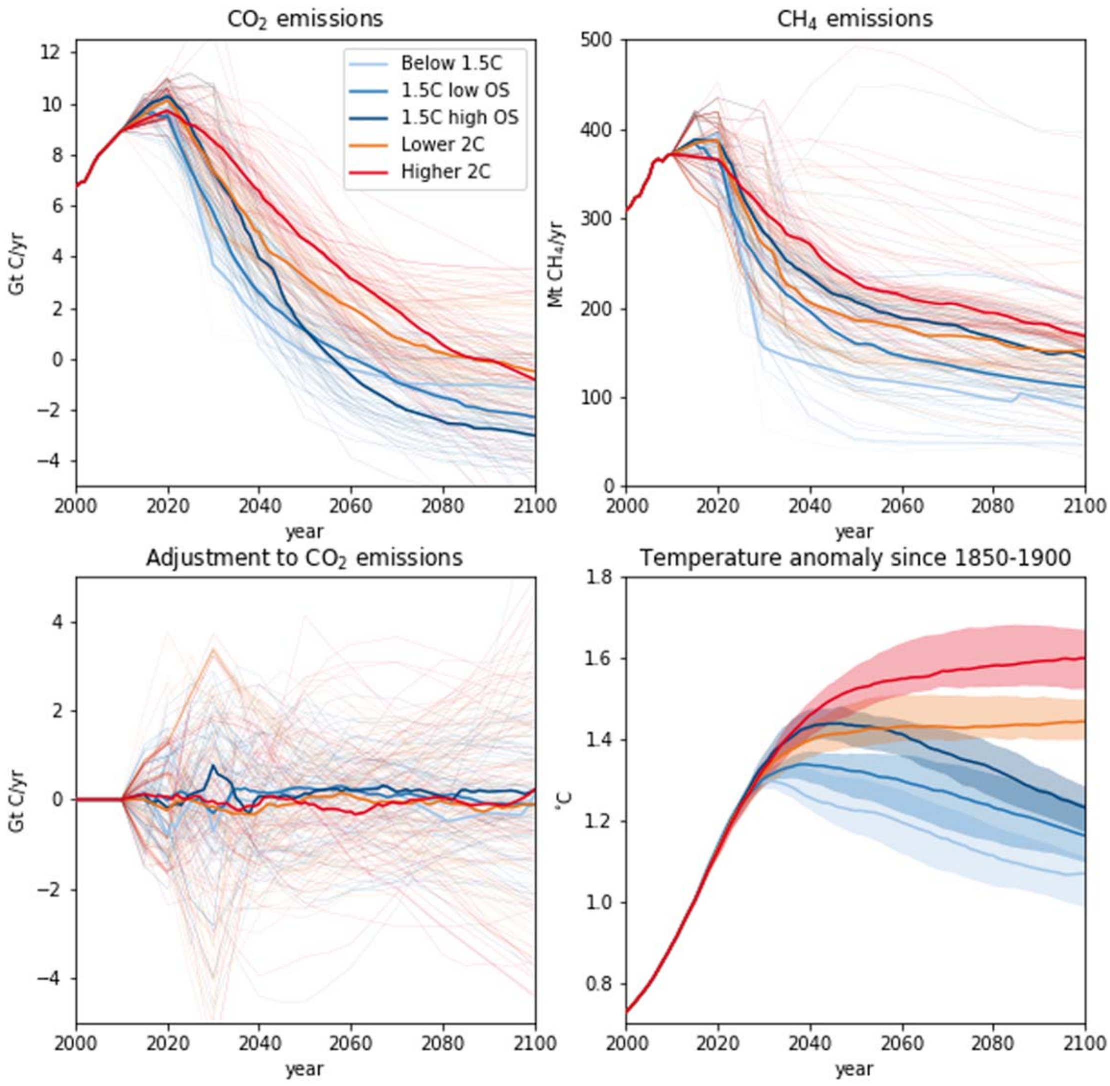

Figure 1. (a) CO$_2$ fossil and industrial emissions pathways in the 1.5 °C and 2 °C consistent SR15 scenarios. (b) CH$_4$ pathways in the same scenarios. (c) Adjustment to CO$_2$ emissions in each pathway to ensure that each pathway has identical CO$_2$-eq emissions to the class mean as measured by GWP$_{100}$. (d) Temperature anomaly since 1850–1900 for the adjusted pathways (ensemble medians in FaIR). (a)–(c): thin lines are individual scenarios and thick lines represent the median of all scenarios in each class. (d): class median (lines) and 5th to 95th percentile range across scenarios (shaded regions) for scenarios with identical GWP$_{100}$ emissions. Classes are as defined in SR15: Below-1.5 °C, 1.5 °C return with low overshoot, 1.5 °C return with high overshoot, Lower 2 °C and Higher 2 °C, respectively.

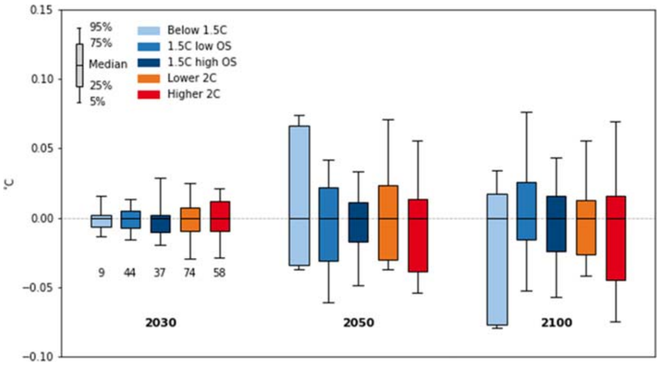

Figure 2. Variation in global temperature for each class of scenario in 2030, 2050 and 2100 for scenarios with CO$_2$ emissions varied to match the class mean as measured under GWP$_{100}$. Variation of ensemble median for each scenario expressed relative to the median temperature projections of each class. The number of scenarios in each class is shown under the 2030 results.

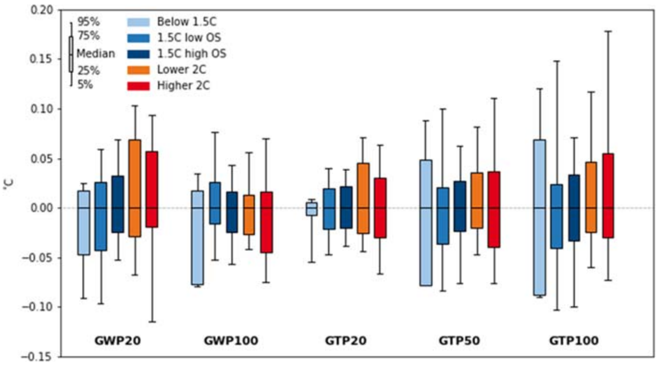

Figure 3. Variation in global temperature for each class of scenario in 2100 for scenarios with CO_2 emissions varied to match the class mean as measured under GWP_{20}, GWP_{100}, GTP_{20}, GTP_{50} and GTP_{100}. Variation of ensemble median for each scenario expressed relative to the median temperature projections of each class .

from the scenarios in each class and are analysed further in figure 2.

Figure 2 shows the variation in temperature for each class in 2030, 2050 and 2100 as whisker plots relative to the class median, again using GWP_{100} to calculate levels of combined emissions. The maximum variation in temperature between the 5th and 95th percentile of scenarios in each class is used as an indication of by how much temperatures could realistically vary for a pathway expressed as combined emissions and consistent with the Paris Agreement target. With GWP_{100} it does not exceed 0.17 °C for any class. For each class the time of the maximum variation does not necessarily coincide with that of peak warming.

Figure 3 shows the variation in temperature in the year 2100 for each class using a range of metrics to calculate the total emissions. GWP_{100} and GTP_{20} lead to the lowest variation.

4. Discussion

The reason for the variation in temperature projections between different scenarios in the same class is principally due to differing proportions of CO_2 and CH_4 and the limitations of the metrics used. These are designed to equate the impacts of different GHGs over a specified time period and cannot be accurate over other periods. The range of CH_4 emission levels has a direct bearing on the temperature variation. For a given temperature target, the range is constrained as shown in figure 1(b) by socio-economic factors incorporated in the integrated assessment models used to calculate the emission scenarios. This, in turn, constrains the range of temperatures resulting from the scenarios.

The maximum variation of 0.17 °C under GWP_{100} is materially less than the amount by which the well below 2 °C target will be exceeded based on full implementation of the current NDCs (0.4 °C–1.1 °C). It is also significantly less than the range of class median temperatures at 2100. It is, however, significant in the context of SR15 which describes the differences in impacts between warming of 1.5 °C and 2 °C. Also, as future NDCs are enhanced and other causes of uncertainty are reduced, temperature differences of the order of 0.1 °C may become material in the future, particularly as the cost of abatement increases under severe mitigation.

Emerging metrics, for example GWP* (Allen *et al* 2018), have potential to reduce uncertainty in temperature projections. An alternative solution is to recognise the fundamental difference between the Kyoto Protocol where reductions in total emissions were specified for each participant and the Paris Agreement with its emphasis on NDCs. In the former case, the mandating of combined emissions levels, rather than levels of all included GHGs individually, gave participants flexibility to design the most cost-effective approach. Under the Paris Agreement, emission reductions are not mandated and countries already have the freedom to determine their abatement strategies and targets for individual GHGs. Using a combined total to report GHG emission levels in NDCs leads to uncertainty. The problem could be removed by parties including information about reductions of individual GHG emissions in NDCs.

Changes to improve the quality of NDCs could be introduced over a period of time as the ambition of NDCs increases. An initial step could be for information on levels of carbon dioxide and methane to be included as non-binding supplementary information by more significant emitters of both gases, following the example of Japan. With 45% of methane emissions originating from 5 countries (World Bank 2018) a substantial reduction in this ambiguity is possible.

It should be noted that more sophisticated emission metrics which better reflect the temperature implications of a given emissions pathway could play a significant role in other areas where it is important to make a meaningful comparison of the impacts of reductions of different GHGs. Also, the magnitude of the uncertainty introduced by the use of metrics will change and should be kept under review as the content of NDCs improves (for example to include aerosol emissions) and better information about emission levels is provided by global stocktakes.

5. Conclusion

We have used the scenarios contained in SR15 to represent the range of emission pathways compatible with the Paris Agreement and estimated the uncertainty in projections of global temperatures arising from the use of emissions metrics. With the de facto standard metric, GWP_{100}, the maximum difference is 0.17 °C, less than the amount by which the well below 2 °C target will be exceeded with the current NDCs. Addressing this 'metric uncertainty' is less urgent than fully meeting current NDCs and increasing the ambition of future NDCs, making their emissions reductions more explicit. A proportionate approach could be to include non-binding supplementary information in future NDCs. This would not limit the freedom of individual countries to determine their commitments or the means by which they are achieved, and would increase transparency. In this way the quality of NDCs can be improved incrementally without need to reach agreement on the use of a different metric.

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Data availability statement

The SR15 scenarios used in this study are openly available at DOI: 10.5281/zenodo.3363345 (Huppmann *et al* 2018b). The FaIR source code (v1.3.4) is available from DOI: 10.5281/zenodo.1403266 and the data used to support the findings of this study is available at DOI: 10.5281/zenodo.3490452.

Author contributions

SD and PMF conceived the study. CJS performed model simulations. All authors contributed to analysis, interpretation and writing of the paper.

Additional information

Correspondence and requests for materials should be addressed to SD.

Competing financial interests

The authors declare no competing financial interest.

ORCID iDs

Steve Denison https://orcid.org/0000-0002-3201-1375

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