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Key Points:
- Post-2030 assumptions and methodological choices have significant impact on estimated warming consistent with near-term mitigation targets
- Comparison with scenario databases and directly modeling moderate action scenarios are most useful methods to evaluate continued effort
- Methods and communication techniques can be improved ahead of the next round of mitigation contribution submissions in 2020

Supporting Information:
- Supporting Information S1

Correspondence to:
M. Louise Jeffery,
louise.jeffery@pik-potsdam.de

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Measuring Success: Improving Assessments of Aggregate Greenhouse Gas Emissions Reduction Goals

M. Louise Jeffery[1], Johannes Gütschow[1], Marcia R. Rocha[2], and Robert Gieseke[1]

[1]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany, [2]Climate Analytics gGmbH, Berlin, Germany

Abstract Long-term success of the Paris Agreement will depend on the effectiveness of the instruments that it sets in place. Key among these are the nationally determined contributions (NDCs), which elaborate country-specific goals for mitigating and adapting to climate change. One role of the academic community and civil society in supporting the Paris Agreement is to assess the consistency between the near-term action under NDCs and the agreement's long-term goals, thereby providing insight into the chances of long-term success. Here we assess the strengths and weaknesses of current methods to estimate the effectiveness of the mitigation component of NDCs and identify the scientific and political advances that could be made to improve confidence in evaluating NDCs against the long-term goals. Specifically, we highlight (1) the influence of post-2030 assumptions on estimated 21st century warming, (2) uncertainties arising from the lack of published integrated assessment modeling scenarios with long-term, moderate effort reflecting a continuation of the current political situation, and (3) challenges in using a carbon budget approach. We further identify aspects that can be improved in the coming years: clearer communication regarding the meaning, likelihood, and timeframe of NDC consistent warming estimates; additional modeling of long-term, moderate action scenarios; and the identification of metrics for assessing progress that are not based solely on emissions, such as infrastructure investment, energy demand, or installed power capacity.

Plain Language Summary Under the Paris Agreement, all countries came together to strengthen their commitment to limit warming to well below 2 °C and established an aim toward 1.5 °C. Each country also presented its own climate action plan, including a description of how it intends to reduce its greenhouse gas emissions. A major challenge of the Paris Agreement is ensuring that, when combined, the individual actions of countries are sufficient to achieve the collective long-term goals. In this study, we review the methods used so far to evaluate the sufficiency of the climate action plans and examine how those methods can be improved. A significant difference between current methods is in the assumption of how countries' efforts to reduce emissions will change after the current timeframe of planned action (until 2030)—will it be weaker, stronger, or similar? Some methods are more complex and help to identify opportunities for additional action, while others are better at providing a quick estimate of the warming we can currently expect. We conclude that combining some of the methods we reviewed, modeling of scenarios similar to the current situation, and some clarification in communication would provide a better assessment of collective progress toward the Paris Agreement goals.

1. Mitigation Contributions Toward the Global Goal

At COP21 in Paris, several years of negotiating a unified approach to address the challenges of climate change were concluded in the Paris Agreement (United Nations Framework Convention on Climate Change (UNFCCC), 2015a). Key mitigation components of the Paris Agreement are the establishment of the long-term temperature goal (LTTG) under Article 2 of "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels," and the accompanying operational goals under Article 4 of peaking emissions as soon as possible and to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century," (UNFCCC, 2015a, hereafter referred to as net-zero emissions). These ambitious global goals rely on the collective effort of individual nations, whose actions, under the same agreement, will be nationally determined and "reflecting its common but differentiated responsibilities and respective capabilities." While the Paris Agreement has been hailed as a success of international politics, its long-term legacy will be determined by the extent to which it stimulates action toward meeting the LTTG.

The Paris Agreement and enabling decisions (UNFCCC, 2015a, 2016) established a ratcheting process through which the nationally determined contributions (NDCs) will be evaluated and improved. Key steps in an ongoing process of evaluating the action offered under the NDCs with respect to the needs of the LTTG will be the global stocktakes every 5 years, beginning in 2023, and potentially also the facilitative (Talanoa) dialogue in 2018. Much work remains in determining the full implications of the LTTG, particularly in aiming for below 1.5 °C (Rogelj, Schleussner, & Hare, 2017; Rogelj et al., 2018; Schleussner et al., 2016), but we also need to review our collective ability to assess short-term mitigation efforts in the context of such goals, and improve methods where necessary and possible.

The mitigation components of intended NDCs (INDCs) submitted during 2015 were the focus of multiple assessments attempting to measure the effectiveness of these climate action plans in avoiding dangerous climate change, commonly evaluating success against the 1.5 or 2 °C warming limits (Table 1). Most analyses arrived at the broad conclusion that while the intended NDCs reflect progress, current climate action plans need to be further strengthened to hold warming below the internationally agreed limits. However, disagreement remains on the extent of the progress that remains to be made. Estimated median (50% probability in 2100) warming levels consistent with the initial intended NDCs ranged from 2.6 to 3.5 °C by 2100 (Climate Interactive, 2015; International Energy Agency (IEA), 2015; Jeffery et al., 2015; Rogelj, den Elzen, et al., 2016), a range under which expected impacts vary substantially (Magnan et al., 2016). Understanding the differences between the various assessments is complicated by choices in communication, such as the likelihood with which the reported temperature is exceeded; some use a median warming estimate, while others use a likely (>66%) threshold. However, as we will demonstrate, such temperature estimates also result from markedly different emissions, economic, and energy infrastructure assumptions and scenarios. Substantial work therefore remains to understand and clarify the meaning of the various warming estimates, their implications for climate policy, and any research needs to improve methods for future assessments.

In this paper, we review approaches taken thus far to evaluate the aggregate NDCs in terms of limiting total warming in order to understand how assessment approaches differ, what can be learned, and how future research can robustly support policy making, especially in the context of the Paris Agreement stocktake processes. In addition to being robust, analyses of aggregate NDCs must also be effectively communicated in order to provide useful input to the political discourse. We therefore also review the communication challenges faced, how they have been approached thus far, and how they may be improved.

2. Review of Existing Approaches to Assess the Aggregate Effect of NDCs

If implemented, the unconditional climate action plans put forward in NDCs are expected to lead to emissions in 2030 in the range of 52–56 $GtCO_2e$ (10th to 90th percentiles of studies included in the UNEP Emissions Gap Report; United Nations Environment Programme (UNEP), 2017, and references therein), with most estimates converging around 55 $GtCO_2e$. A more recent study (Benveniste et al., 2018) assessed uncertainty in NDCs due to factors including gross domestic product (GDP) growth and ambition level of NDCs and estimated that the NDCs are consistent with higher emissions of 56.8–66.5 $GtCO_2e$ in 2030 (90% confidence interval), but this quantification does not take into consideration current policy trajectories that suggest lower 2030 emissions than the NDC commitment for some countries, namely, India and China. These two major emitters are also significant contributors to overall uncertainty in aggregate estimates due to uncertainties in their socioeconomic development projections, definition of targets, and consequent impacts on quantification of emissions intensity targets (emissions per unit of GDP; Rogelj, Fricko, et al., 2017). For simplicity, we refer to NDCs throughout but note that we use this term to include INDCs.

An additional evaluation step is required to relate near-term NDC targets to the longer-term, overarching goals of the Paris Agreement. Some approaches identify criteria that are necessary for limiting warming to 1.5 or 2 °C and perform a binary evaluation of whether the NDCs are consistent with these criteria or not. Other approaches go a step further and try to measure the extent to which the criteria are missed, often by estimating expected warming by 2100 and thereby providing a metric that can be directly compared with the Paris Agreement temperature goal.

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Table 1
Overview of Assessments Comparing Nationally Determined Contributions With the Paris Long-Term Temperature Goal

General Assessment Approach	Examples	Methods	Post-2030 assumptions	Evaluation of warming	Ability to reach LTTG	Dependencies on external modeling
Simple pathway extension on a geometric basis	Climate Interactive (2015) National Plans Scenario	2030 targets continued to 2100; for example, constant emissions; constant % below BAU	No improvement beyond NDC targets post-2030	Median warming estimate for each scenario	No	None
	Climate Interactive (2015) <2.0 °C/1.5 Scenario	2025/2030 emission peak, then constant emissions reductions rates	Constant level of effort throughout century	Median warming estimate for each scenario	Implicit	None
	Lomborg, 2015	Post-2030 exponential return to a BAU pathway	Yes, Only policies needed to meet NDC target are ever implemented.	Temperature deviation from business-as-usual	No	None[a]
Comparing near-term emissions with existing scenarios from integrated assessment models (IAMs)	UNEP Emissions Gap Report (2015)	Comparison of INDC emissions with ranges of 2030 emissions from IAM scenarios	None	Range of likely (>66% probability) warming estimates	Yes	Yes, AR5 scenario database.
	Rogelj, den Elzen, et al. (2016) and UNEP Emissions Gap Report, (2016, 2017)	Comparison of INDC emissions with 2030 emissions in IAM scenarios	Constant level of effort throughout century.	Range of likely (>66% probability) warming estimates	Yes	Yes, AR5 scenario database.
	Climate Action Tracker	Construction and selection of quantiles across IAM pathways.	Constant level of effort throughout century.	Median warming estimate for each scenario	Yes	Yes, AR5 scenario database.
	UNFCCC Synthesis Report	Comparison of emissions levels with pathway sets that meet 2 °C with different mitigation timing and probabilities	None	2 °C consistency assessment only; no warming estimate	Yes	Yes, AR5 scenario database.
Explicitly modeling an NDC scenario in a global economic model	MILES	Simulation of INDCs extended with the REMIND IAM	Moderate increase in carbon pricing, consistent with levels needed to reach INDCs	2 °C consistency assessment only; no warming estimate	Unknown, likely yes[b]	No
	Energy and Climate Outlook (Reilly et al., 2015)	Simulation of INDCs and beyond with MIT Integrated Global Systems Model	No additional policies beyond those required to meet 2030 targets	Central[c] warming estimate	Unknown, likely yes	No
	Fawcett et al. (2015)	Simulation of INDCs and beyond with the GCAM IAM	Decarbonization rate needed to meet INDCs continues to end of century	Single warming estimate expressed as exceedance probability	Yes	No
	Kitous et al. (2017)	Simulation of INDCs extended with POLES-JRC model	GHG intensity of GDP continues to decrease at same rate	Median warming estimate with uncertainty range	Yes	No
Comparing cumulative emissions with a carbon budget	Rogelj, den Elzen, et al. (2016)		None	Budget exceeded or not	Yes	Yes, IAM scenarios used to constrain non-CO_2 budget.

Note. The term INDC is used here where appropriate because many of the assessments were carried out on original INDCs, before ratification of the Paris Agreement. GCAM = Global Change Assessment Model; LTTG = long-term temperature goal; BAU = business-as-usual; NDC = nationally determined contribution; UNEP = United Nations Environment Programme; INDC = intended NDC; UNFCCC = United Nations Framework Convention on Climate Change; MIT = Massachusetts Institute of Technology.
[a]Results are not directly based on IAM scenarios, but establishing the reference information requires IAM scenarios. [b]The REMIND IAM used for the MILES project has successfully simulated 2 °C consistent scenarios for other projects, we therefore consider it likely that the approach could yield a 2 °C consistent result if near-term action were adequate. [c]The *central* warming estimate refers to a simulation with the MIT IGSM-CAM model and a median climate sensitivity.

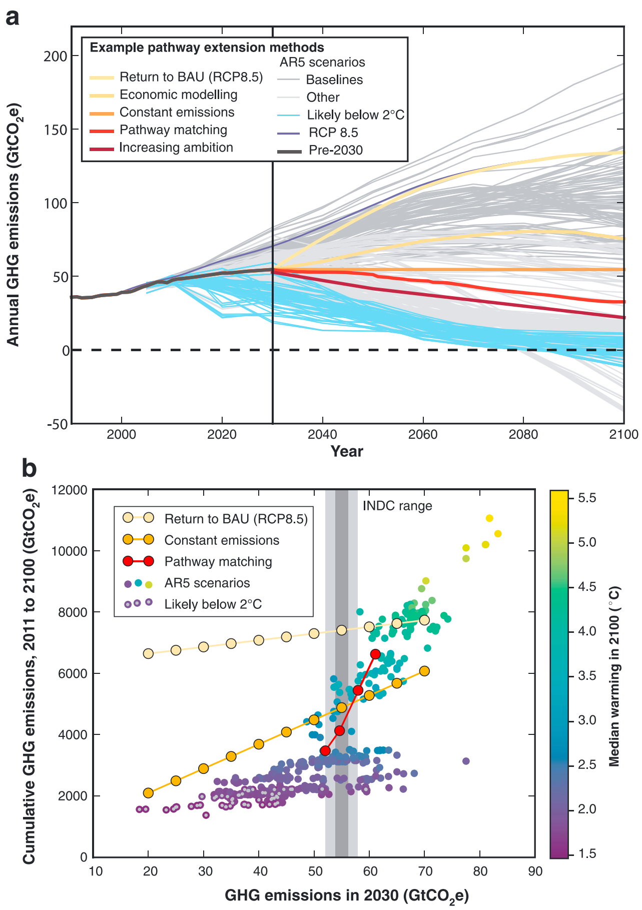

Figure 1. NDC consistent emissions scenarios in the context of the IPCC AR5 scenarios. (a) Example results of different NDC consistent pathway extension methods (orange/red) in the context of scenarios in the IPCC AR5 Database (light gray). Baseline scenarios (dark gray) and scenarios consistent with holding warming below 2 °C with 66% probability (light blue) are highlighted separately. RCP8.5 (dark blue) and historic emissions complemented with a linear projection to 55 $GtCO_2e$ in 2030 indicate an NDC consistent near-term trajectory (black). (b) Cumulative Kyoto GHG emissions from 2011 to 2100 resulting from emissions pathway extension methods for theoretical aggregate NDC emissions in 2030. Comparative cumulative emissions from the IPCC AR5 scenario database color coded according to median warming in 2100. Scenarios that remain below 2 °C with >66% probability are indicated with a gray center circle. BAU = business-as-usual; RCP = Representative Concentration Pathway; GHG = greenhouse gas; NDC = nationally determined contribution; INDC = intended NDC; AR5 = Fifth Assessment Report; IPCC = Intergovernmental Panel on Climate Change

However, maximum warming depends largely on cumulative emissions until the end of the century, or beyond (Allen et al., 2009; Matthews & Caldeira, 2008; Meinshausen et al., 2009; Zickfeld et al., 2009). Evaluating warming levels consistent with the NDCs therefore requires assumptions about the trajectory of emissions beyond 2030, which can lead to significantly different long-term emissions pathways and therefore cumulative emissions. Rogelj, Fricko, et al. (2017) distinguish between assumptions of stalling, continuing, and accelerated action, which can each lead to very different long-term emissions pathways. Under each of these assumptions, the particular methodology implemented can also have a significant impact (Gütschow et al., 2018).

In Figure 1a, we illustrate how those assumptions can determine long-term cumulative emissions with scenarios that all begin at the same emissions level in 2030 but are extended to the end of the century with different methods and assumptions. These methods are either simple, for example, *return to business-as-usual (BAU)* or *constant emissions* or are representative of more complex approaches, such as the *modeling* or *increasing ambition* scenarios (see the supporting information for more details on the creation of scenarios). By 2100, these extended scenarios span a large portion of the Fifth Assessment Report (AR5) scenario space, from baseline to moderate mitigation scenarios. The associated cumulative emissions, and therefore expected warming estimate, span a correspondingly large range.

To further explore and understand this range, we group existing methodological approaches to assess the effectiveness of NDCs into four broad categories: (1) simple pathway extension on a geometric basis, for example, constant rate of emissions; (2) comparing near-term emissions with existing scenarios from integrated assessment models (IAMs); (3) explicitly modeling an NDC scenario in a global economic model; and (4) comparing cumulative emissions with a carbon budget (Table 1). Within each of these four general approaches, different results can be obtained according to the specific implementation methods selected and assumptions made. Here we discuss the strengths and weaknesses of each approach and highlight potential aspects for improvement.

2.1. Simple, Geometric Emissions Pathway Construction

One option to deal with uncertainty in post-2030 emissions trajectories is to minimize the assumptions made or to make those assumptions as clear and simple to follow as possible. Advantages to this approach include transparency and clarity, ease of pathway calculation, and ability to isolate the direct impact of the NDC pledges.

On a technical level, one method is to assume that post-2030 emissions return to a BAU trajectory (*Return to BAU*, Figure 1a). A second methodological option is to assume that the emissions reduction target remains constant post-2030. In implementation terms, a reduction below emissions in a fixed reference year yields constant emissions at that absolute level post-2030, or for a percent reduction below BAU, emissions remain at the same percent below the same BAU for the remainder of the century (Climate Interactive, 2015). These methodological approaches are independent of any structural and economic implications of meeting the NDCs in the near term.

Any method that assesses whether current action is sufficient to be consistent with a warming limit must be able to evaluate success and failure at meeting the long-term goals, depending on the near-term emissions trajectories. In Figure 1b we show how cumulative emissions over the 21st century correspond to 2030 emissions levels under three of the different emissions pathway construction approaches illustrated in Figure 1a.

When using a return to BAU assumption for extending 2030 emissions, cumulative emissions have a low sensitivity to 2030 emissions (Figure 1b) and are strongly dependent on the reference BAU scenario. Clearly, it is not possible to find a 2 °C compatible 2030 target if it is assumed that the emissions trajectory returns to a BAU pathway, regardless of the expected 2030 emissions under NDCs. Under an assumption of constant emissions, cumulative 21st century emissions are more sensitive to the level of aggregate 2030 emissions (Figure 1b) but only approach 2 °C consistent levels for 2030 emissions close to 20 $GtCO_2e$, whereas scenarios in the AR5 database indicate 2 °C consistent scenarios for much higher 2030 emissions levels (up to ~45 $GtCO_2e$, excluding *delay 2030* scenarios).

The current timeframe of the NDC process, with mitigation plans only until 2030 for most countries, cannot alone guarantee that emissions will be sufficiently limited to meet the 2 °C warming limit (Climate Interactive, 2015). Under return to BAU or constant emissions assumptions, the conclusion that NDCs are not sufficient to limit warming to 2 °C is therefore a critique of the time scale of the NDC process rather than of the NDC targets themselves. As yet, no one has proposed a simple pathway construction approach that does not rely on external modeling but can capture the long-term impacts of near-term (until 2030) mitigation efforts in a similar manner. These approaches are therefore not appropriate for answering the question of how effective the NDCs are in limiting warming below 1.5 or 2 °C.

2.2. Comparison With IAM Scenarios

To capture the longer-term inertia of short-term action, many NDC assessment approaches rely on suites of scenarios (Intergovernmental Panel on Climate Change (IPCC), 2015) produced by the integrated assessment modeling community (Table 1). A common feature of this assessment approach is to identify which long-term emissions trajectory the NDCs are consistent with, if the NDCs are fully implemented and efforts to reduce emissions continue. These methods are capable of indicating a successful political process toward the 2 °C limit if 2030 aggregate NDC emissions were sufficiently low (e.g., pathway matching, Figure 1b). To represent a continued level of effort, these approaches either implicitly or explicitly assume that the stringency of the global carbon price required to achieve the 2030 NDC targets would be continued throughout the remainder of the century.

Here we describe some modeling comparison approaches in detail, explore their limitations, and identify possible improvements. When most of these assessments were performed, the most comprehensive, publicly available set of reference scenarios was that of the IPCC's AR5 (IPCC, 2015, hereafter referred to as the AR5 scenario database). Our assessment therefore also focuses on this scenario suite. Although additional scenarios are now being explored in major modeling projects, for example, ADVANCE or CD-LINKS, few of these scenarios are currently publicly available. An exception is the shared socioeconomic pathway (SSP) scenario database (International Institute for Applied Systems Analysis (IIASA), 2016; Riahi et al., 2017), which we do examine in more detail below.

The Climate Action Tracker (CAT) explicitly describes the basis for their extensions as identifying emissions pathway development assuming that the *level of mitigation effort* (Gütschow et al., 2018; Jeffery et al., 2015) remains constant throughout the rest of the century. The CAT uses a *Constant Quantile Extension* method to implement this continued effort assumption. A pathway distribution is calculated based on a scenario database, and the near-term NDC pathway is compared to that distribution. The relative position of the NDC pathway within the overall pathway distribution is calculated and expressed as a quantile. The resulting emissions pathway is then the one that follows that same quantile through the scenario database, from the NDC target year to the end of the century. For more details on the CAT methods, please see Climate Action Tracker (2015) and Gütschow et al. (2018).

The UNEP EGR (e.g., UNEP, 2016) currently also uses a methodology based on the AR5 scenario database that was first presented in Rogelj, den Elzen, et al. (2016). To estimate warming at the end of the century that is consistent with NDCs, it is first assumed that climate action will continue, but not accelerate. This assumption is implemented by comparing the median warming at the end of the century with 2030 total greenhouse gas (GHG) emissions for scenarios in the AR5 database. Only scenarios that have a constant policy assumption from 2010 onward are used (*Baseline* and *Immediate Action* policy scenarios in Figure 2a). A smoothing spline fit to this relationship is then used to interpolate the mean warming in 2100 from an NDC consistent emissions level in 2030. A range in 2030 emissions of 52–58 $GtCO_2e$ yields 2.6–3.1 °C median warming (2.9–3.4 °C *likely below*, or $>$ 66% probability) in 2100 (Rogelj, den Elzen, et al., 2016).

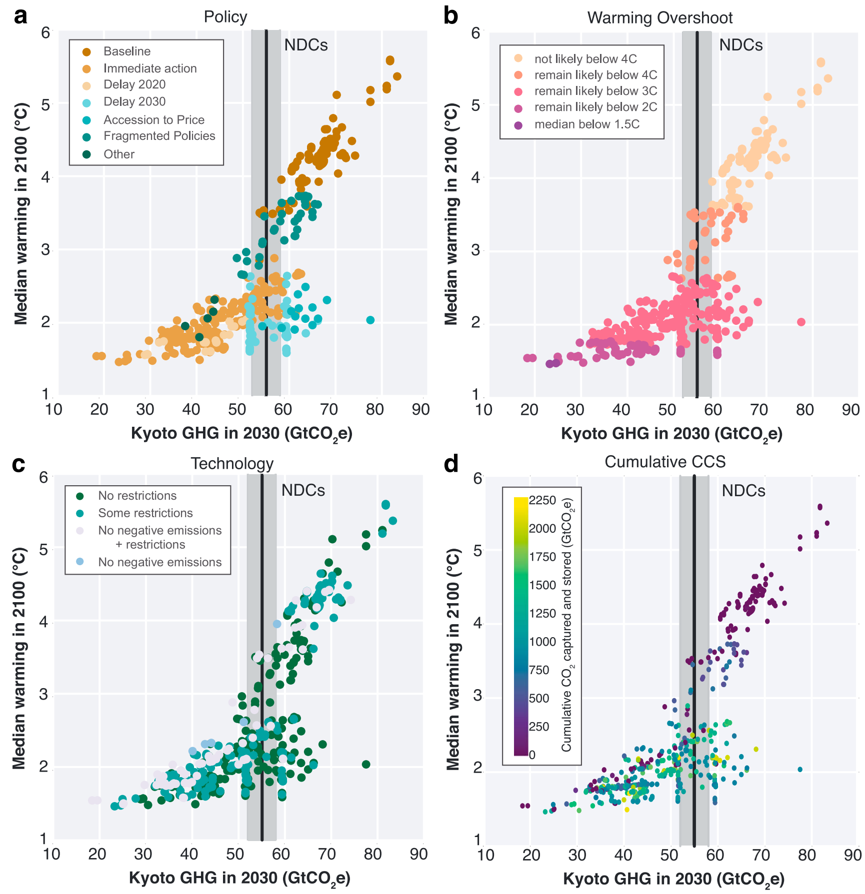

Figure 2. Characteristics of scenarios in the AR5 scenario database. Although several scenarios in the AR5 scenario database lie within the region of current aggregate NDC emissions targets in 2030 (gray area with central estimate in black), those scenarios differ significantly in terms of the underlying policy assumptions (a), whether or not temperatures overshoot the warming limits before 2100 (b), the technology options available (c), and the extent of CCS required (d). Categories for (a)–(c) are defined in the Intergovernmental Panel on Climate Change AR5 WGIII report (Krey et al., 2014), and cumulative CCS is calculated from interpolated scenario data. Further description and variables can be found in the supporting information. AR5 = Fifth Assessment Report; NDC = nationally determined contribution; GHG = greenhouse gas; CCS = carbon capture and storage.

By using scenarios that incorporate information about energy infrastructure and the time scales and magnitudes of responses to policies and economic circumstances, IAM comparison-based assessments can provide estimates and scenarios that contain more information about current emissions trajectories. However, a robust result relies on having a useful set of IAM scenarios on which to base the analysis. The AR5 scenario database contains 492 emissions scenarios for which associated temperatures are provided (IPCC, 2015). Of these, 60 (12%) lie within the 10th to 90th percentile range (52–58 $GtCO_2e$) of emissions estimates in 2030 under NDCs (Rogelj, den Elzen, et al., 2016; UNEP, 2016) and have a median warming in 2100 from 1.74 to 3.55 °C. Given solely this information, the combined uncertainties of NDC aggregation and scenario projections result in a range of possibilities that is extremely large. However, additional information from the scenarios can further constrain the likely pathways and help to infer policy implications.

Both of the above approaches (CAT and UNEP; Rogelj, den Elzen, et al., 2016) assume that there is some relationship between total emissions in 2030 and warming by the end of the century. In the AR5 scenario database, higher emissions in 2030 are consistent with higher warming levels, but how much warming depends significantly on the policy, socioeconomic, and technology characteristics of the scenario. In Figure 2, the relationship between 2030 emissions and total warming over the century in the AR5 scenarios is color coded according to the policy (Figure 2a), maximum warming (Figure 2b), technology restrictions, (Figure 2c), and the cumulative CO_2 sequestered through carbon capture and storage (CCS), used in the scenarios. Further description and definitions of the categories can be found in the supporting information and Annex II of the Working Group 3 report of the IPCC's AR5 (Krey et al., 2014).

For a given 2030 emissions level, scenarios developed under a fragmented policy regime lead to higher temperatures than scenarios with concerted policy action (Figure 2a). The current bottom-up nature of NDCs indicates that the real world is better reflected by a fragmented policy regime. Achieving lower temperatures in 2100 from emissions between 50 and 60 $GtCO_2e$ in 2030 relies on a combination of increased action post-2030 (Figure 2a), overshooting temperature limits before 2100 (Figure 2b), availability of a full suite of technology options (Figure 2c), and substantial CO_2 sequestration (Figure 2d). Both the CAT (Jeffery et al., 2015; Rocha et al., 2014) and UNEP EGR (UNEP, 2015) exclude delayed action scenarios (delay 2030 and accession to price, Figure 2a) from their comparative analysis because, by definition, these scenarios rely on delayed action and a higher burden on future generations and therefore are not consistent with the assumption that the level of effort required to achieve the NDC targets will be continued.

A major challenge with using the AR5 scenario database is a lack of scenarios that explore the current NDC trajectory range for emissions in 2030 (see supporting information Figures S1 and S2). The IPCC AR5 scenarios explored here contain only 25 scenarios consistent with 2.5–3 °C median warming, and 20 scenarios consistent with 3–3.5 °C median warming in 2100, compared with 192 that reach below 2 °C, 66 of which remain likely below 2 °C throughout the 21st century. Comparatively few scenarios therefore explore the *limited action* policy space between baselines and strong mitigation scenarios. In addition to the concerted effort in mapping the scenario space needed to achieve the 1.5 °C target initiated by the request for a special IPCC report, the policy assessment community would also benefit from additional research into the implications of limited action and fragmented or bottom-up policies (see also Peters, 2016; van Ruijven, 2016). Furthermore, a deeper understanding of the policy and infrastructure differences between a 3 and 2 °C world could help to identify key areas of focus for enhanced policies and an identification of potential dangers in missed opportunities or adverse long-term impacts of current policies. An enhanced scenario suite would also facilitate opportunities for differential and comparative analyses and the identification of metrics that can help to differentiate ambitious NDCs and policies.

The SSP scenario database (Figure 3; Riahi et al., 2017) complements the AR5 scenario database in filling some of this space. In particular, those scenarios targeting radiative forcing consistent with Representative Concentration Pathway (RCP) 4.5 have 2030 emissions comparable to those of current NDCs (Figure 3b), although all RCP and baseline categories have some scenarios that fall in this range. Median warming for RCP4.5 is in the range of 2.52 to 2.75 °C for scenarios with 2030 emissions ranging from 45 to 67 $GtCO_2e$. Our discussion here focuses on the AR5 scenario database because the SSPs were not available in 2015, when most of the assessments reviewed in this manuscript were performed. However, incorporation of the SSP scenarios into future analyses may help to give a more informed assessment of effort (e.g., Gütschow et al., 2018), particularly when combined with the underlying SSP storylines (Figure 3a) and different model realizations (Figure 3c). Other modeling studies, such as ADVANCE or CD-LINKS, may also yield useful scenarios for the policy community, but many studies focus on how to reach the LTTG from weak initial action, consistent with the current NDCs, and do not explore the longer-term implications of continuing moderate efforts over multiple decades.

Finally, the scenarios in the AR5 database usually provide *first* best scenarios, by assuming a *uniform* global carbon price and cooperation across countries. Therefore, those scenarios are not consistent with the current policy framework, limiting their usefulness for assessing real-world mitigation progress. Comparison with IAMs predominantly uses information about aggregate emissions at either the regional or global (UNEP, 2015; UNFCCC, 2015b) level. Such comparisons are not currently capable of ensuring full consistency between the emissions trajectories that meet the NDCs and the emissions trajectories contained within the model in terms of changes to energy infrastructure, implementation of carbon prices, or sectoral and gas splits in mitigation efforts. Comparing carefully selected key indicators, such as installed power capacity, infrastructure investment, and research and development of key technologies, could provide additional measures of the extent to which NDCs, or policies, are consistent with IAM scenarios (Iyer et al., 2017).

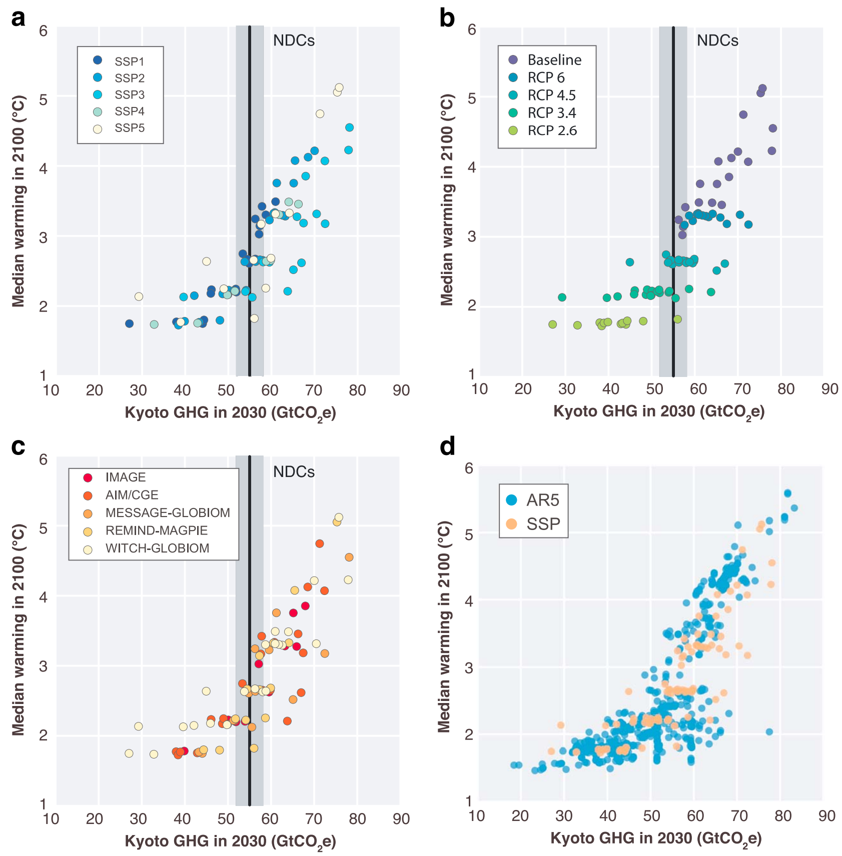

Figure 3. The role of emissions scenarios in the SSP database (Riahi et al., 2017) in supplementing the reference scenarios for NDC assessment. Scenarios in the SSP database vary along multiple dimensions, including the SSP storyline represented (a), the RCP that constrains the allowed emissions (b), and the model used to simulate the scenario (c). These scenarios, particularly RCP4.5, complement the distribution of scenarios in the AR5 scenario database for assessing the long-term trajectory of 2030 emissions (d). In this figure, SSP scenarios from the Global Change Assessment Model are not included because the full Kyoto-GHG emissions scenarios are not provided in the online database. SSP = shared socioeconomic pathway; NDC = nationally determined contribution; RCP = Representative Concentration Pathway; GHG = greenhouse gas; AR5 = Fifth Assessment Report.

2.3. Modeling NDC Scenarios in a Global Economic Model

One approach to addressing the lack of appropriate reference scenarios is to run economic modeling analyses for NDC scenarios directly. A model can be tailored to the actual commitments made in the NDCs and to the surrounding political and economic framework. For example, the nonfossil energy targets of China's NDC were explicitly incorporated in the modeling assessment of the MILES project (Spencer et al., 2015). We recognize three main ways in which an IAM may be used for assessing the NDCs: (1) estimating the long-term warming if the NDC scenario were to be continued, (2) examining the structural differences between an NDC scenario and a (cost-optimal) 2 °C scenario, and (3) exploring how the Paris LTTG may be met from the current NDCs. In this study, we focus on (1) but also highlight the insights from approaches (2) and (3) that help to assess overall progress reflected in mitigation targets.

As with other methodological approaches, modeling of NDC scenarios to estimate the long-term warming also requires post-2030 assumptions to be made (Table 1). In the Energy and Climate Outlook (Reilly et al., 2015) it is assumed that no policies beyond those required to achieve the NDCs are put in place. The MILES project implemented the REMIND model with the assumption of a "continuation of a steady but moderate increase of ambition level in both the pricing and technology policies" (Spencer et al., 2015). Simulations presented in Fawcett et al. (2015) were run assuming a continued, constant, rate of decarbonization post-2030, and the International Energy Agency continue their model to 2050 and extend the scenario further with a pathway between that of RCP6 and RCP4.5 (IEA, 2015). Vandyck et al. (2016) continue the annual rate of reduction in GHG intensity that is needed to meet the NDCs through to 2050 by implementing carbon prices that converge according to income.

An alternative approach to assessing the effectiveness of NDCs is to compare a continued NDC scenario as part of a larger suite of scenarios and thereby explore potential post-2030 options. Rose et al. (2017) include a scenario constrained by post-2030 emissions held constant at 2030 levels. Rather than keeping emissions constant, van Soest et al. (2017) keep the carbon tax constant at 2030 values until the end of the century. Finally, Kitous et al. (2017) examine an NDC scenario in which the GHG intensity of GDP continues to decrease at the same rate as in the 2020–2030 period, as constrained by the NDCs.

Where calculated, these studies report estimates of median warming associated with the NDCs spanning a range of 2.7 to 3.5 °C in 2100, reflecting the methods and assumed level of effort post-2030. The more complex modeling approaches do not, therefore, yield additional certainty in terms of expected warming than the pathway construction or comparison approaches.

IAM analyses collectively offer an insight into why different warming levels may be reached from the same aggregate 2030 emissions levels. The difference between a 2.7 and 3.5 °C scenario can be investigated in terms of the different economic, policy, and structural developments in each scenario, offering insight into the most crucial issues to address. Such information could help to ensure that the lower end of the warming estimate range is met and that potential pitfalls leading to higher warming could be avoided. Modeling assessments can also examine the efforts required to reach the LTTG if stronger mitigation efforts are delayed until 2030 (Riahi et al., 2015; van Soest et al., 2017). Such studies provide insights into the additional costs and challenges (Luderer et al., 2016) associated with delayed action. Finally, multiple studies combine these different types of assessment and compare the different scenarios, outlining the consequences of different pre- and post-2030 political, technical, and socioeconomic options (Riahi et al., 2015; Rogelj, Fricko, et al., 2017; Rose et al., 2017).

A single model has inherent assumptions and parameterizations regarding available technologies and the responsiveness of the energy and economic system to policies. Some of the parameterization can be modified and the implications understood with appropriate sensitivity tests, yet some fundamental differences between models remain. Robust and detailed comparisons between models therefore offer a deeper understanding of the breadth of policy choices available and sensitivity to inherent uncertainties in socioeconomic development. Multimodel comparison exercises such as LIMITS and ADVANCE address these issues and could further aid NDC assessment if similar multimodel assessments were performed for NDC scenarios on a regular basis. Running such scenarios every 2.5 years, in-line with the NDC submissions and Global Stocktake cycles would be constructive.

Such multimodel assessments are limited in that they are not able to provide quick-response assessments to new NDCs as they are submitted. As the pathway comparison methods described above can respond more quickly to changing mitigation contributions and incorporate information from multiple models, they are better suited to some tasks. However, as argued above, robust and reliable assessments require a wide range of reference scenarios, including for the midrange (~3 °C) scenario space. IAMs provide a crucial role in establishing this reference base and can provide further, in-depth insights through well-timed, comprehensive assessment exercises and an exploration of if-then scenarios structured around the current, and possible future, NDC targets.

2.4. Carbon Budgets

Although not extensively used for assessing aggregate NDC emissions levels, the carbon budget approach (IEA, 2015; Rogelj, den Elzen, et al., 2016; UNEP, 2016) provides an alternative metric for measuring progress. In principle, the carbon budget approach is simple; total warming is proportional to cumulative CO_2 emissions (Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009), and there is therefore a fixed amount of CO_2 that can be emitted to remain below a certain warming limit, and emissions will either exceed that cumulative amount or not. However, the actual implementation of the approach is more complex. Defining the budget is complicated by whether the budget is calculated according to a threshold exceedance or threshold avoidance approach and by how reference and current temperatures are defined (Peters, 2016, 2018; Rogelj, Schaeffer, et al., 2016). To assess the compatibility of the NDCs with a carbon budget, the contribution of warming by non-CO_2 GHGs must also be estimated and accounted for (Meinshausen et al., 2009).

This could be done by either calculating a *GHG budget* against which to measure or estimating the CO_2 component of emissions under NDCs. The former is somewhat easier to calculate for moderate mitigation pathways generated by IAMs as the CO_2 and total GHG budgets are highly correlated (Gütschow et al., 2018), although budgets for more stringent mitigation targets are more sensitive to non-CO_2 emissions (Rogelj et al., 2018; Rogelj, Schaeffer, et al., 2016). IAMs are often used to define the non-CO_2 portion of the budget because they provide economically consistent pathways for CO_2 and non-CO_2 species. The carbon budget approach is therefore not independent of the pathway matching or modeling approaches described above that depend on the same scenarios.

Scenarios developed using IAMs often include negative emissions, or carbon dioxide removal (CDR), as part of the suite of options for limiting global temperature increase. In many scenarios that are consistent with the Paris Agreement's LTTG, the use of CDR results in net-negative global GHG emissions in the latter half of this century (Rogelj et al., 2018; Schleussner et al., 2016). Taking these negative emissions into account leads to technical and communication challenges in measuring progress against a carbon budget. Carbon or GHG budgets calculated using a threshold avoidance approach (Rogelj, Schaeffer, et al., 2016) over a fixed time period (e.g., 2011–2100) may be consistent with scenarios that have peak cumulative emissions higher than the calculated budget. If emissions were to follow these scenarios, actual emissions would exceed the budget midcentury but, if CDR technologies were employed as envisioned, the temperature limit could still be met, consistent with the scenarios underlying the calculation of the budget. For example, in IPCC AR5 scenarios (IPCC, 2015) that remain likely below 2 °C, a GHG budget of 2000 $GtCO_2e$ from 2011 is exceeded as early as 2055 but later net-negative emissions decrease the cumulative emissions over the century and under these scenarios the 2 °C warming limit is still met. Communicating that an allowed emissions budget has been exceeded, but that the temperature target is still possible under certain conditions, is not easy and directly communicating progress with the use of the scenarios themselves may be clearer.

A useful metric for assessing the aggregate impact of NDCs is not only capable of assessing success or failure to meet the LTTG but also to measure progress toward meeting the goal. The metric should therefore be responsive to changes in NDCs so that progress, or regress, can be identified and communicated. The carbon budget is commonly used to assess the effectiveness of climate action in three ways: (1) the fraction of the budget used by the target year, (2) the year in which the budget will be exceeded, assuming an extended NDC scenario (e.g., Neslen & Mathiesen, 2015), and (3) the years remaining at a given level of emissions until the budget is used (e.g., Friedlingstein et al., 2014; Pearce, 2017).

Assessing the NDCs using the fraction of the budget used in 2030 does not add a significant amount of information to the total aggregate emissions estimate for 2030 because the two are highly correlated for a range of scenarios (Figure 4b). Using the AR5 scenario database as a reference, median warming in 2100 can vary over a wide range for a given fraction of the budget used in 2030 (Figure 4a). The expected percent of the remaining budget used in a given year can be a useful communication tool in terms of the urgency of the problem but is not so useful for tracking progress toward the 1.5 and 2 °C warming limits.

The year in which the budget will be exhausted, assuming a continued NDC scenario, can respond to policy changes and provide a continuous measure of progress with a metric (years) that is readily comprehensible (Neslen & Mathiesen, 2015). There are two problems with this particular metric. First, the construction of an extended scenario requires assumptions to be made about how to extend the scenario, similar to other methods described above. Although for a carbon budget assessment, the scenario may not need to be extended as far as 2100. Second, the year of exceedance responds little to a wide range of scenarios with warming exceeding 2.5 °C but is highly sensitive for scenarios that approach success in limiting warming to 2 °C (Figure 4c). For higher emissions trajectories, the year of exceedance may also be more sensitive to the selected reference budget than to the actual cumulative emissions in the scenario being assessed. For example, the year of exceedance differs by a decade for high emissions pathways and by several decades for stringent mitigation pathways, depending on whether the upper (1400 $GtCO_2$) or lower (750 $GtCO_2$) limits of the carbon budget proposed by Rogelj, Schaeffer, et al. (2016) are used. The metric is therefore not very useful for measuring progress at target levels that are similar to the current NDCs and is very sensitive to parameterization and assumptions (see also Peters, 2016, 2018).

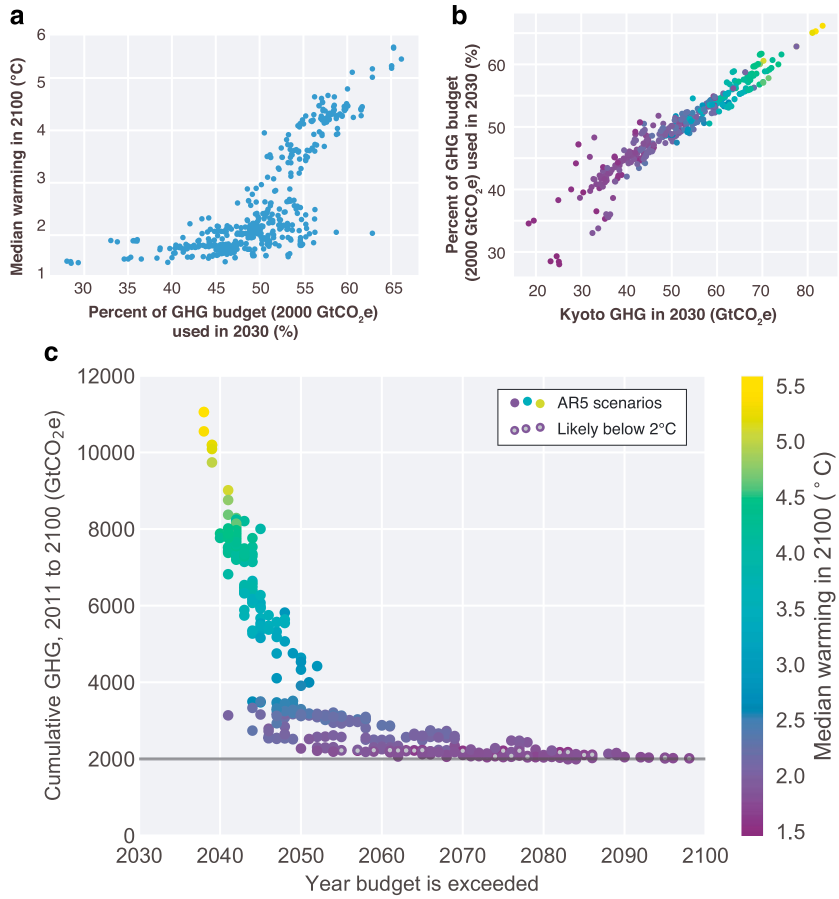

Figure 4. The use of carbon budget-based metrics to measure the adequacy of 2030 emissions reduction targets, based on Intergovernmental Panel on Climate Change AR5 scenarios. The fraction of the Kyoto-GHG budget used by 2030 is highly correlated with 2030 emissions (b), which means that the inference of probable warming by the end of the century is not clearer than with 2030 emissions alone (a). The year in which a given Kyoto-GHG budget (here 2000 $GtCO_2e$) is exceeded is not sensitive to high emission pathways but very sensitive to lower emission pathways (c). GHG = greenhouse gas; AR5 = Fifth Assessment Report.

3. Communicating Results

In addition to the technical challenges of NDC assessment, clear communication of the results and their meaning can also be challenging. The most common metric used for communication is the total warming by the end of the century. As it is directly comparable with international targets of limiting warming to 1.5 or 2 °C, it appears an easy communication tool. Further reflection, however, uncovers some critical caveats, particularly since the adoption of the net-zero emissions and 1.5 °C goals under the Paris Agreement. Future efforts to assess aggregate effort will need to better address these challenges.

One reason that the warming estimates of different groups differ is that some report the *median* warming estimate, while others report the *likely below* warming, the temperature that warming will be limited to with at least 66% probability. Most studies use a probability range evaluated using the same historically constrained probabilistic mode of the simple climate model MAGICC (Meinshausen et al., 2009, 2011), for which *likely* warming is approximately 1.1 times that of the median warming (Gütschow et al., 2018, supporting information Text S2) when the equal quantile walk method is used to determine individual gas contributions (Meinshausen et al., 2006). A median warming of 2.7 °C is therefore equivalent to a likely warming of just below 3 °C, which narrows, for example, the difference between the warming estimates of CAT (Jeffery et al., 2015) and UNEP EGR (UNEP, 2015). Rather than specifying a warming estimate, Fawcett et al. (2015) presented their modeling results as the change in probability of warming being limited to 2 °C. This approach both incorporates a measure of changing risks and addresses the difficulties of median versus likely warming but may be more difficult to communicate.

Warming may also either be reported as that expected in 2100 or the maximum over the course of the 21st century. Emissions pathways consistent with the current NDCs generally still have significant net-positive emissions in 2100, and the *maximum 21st century warming* and *warming in 2100* are therefore commonly the same. In these cases, using a timeframe of 2100 places an artificial upper limit on total warming because temperatures would continue to rise beyond those stated in the headline results for 2100. Estimating the maximum total warming beyond 2100 is, however, difficult as it would require assumptions regarding emissions trajectories into the 22nd century, for which few scenarios exist, and speculation would be high. One solution would be to place a lower bound on total committed warming by evaluating temperature trajectories if emissions were to stop in 2100.

If projected 2030 emissions are lowered, and substantial progress made with CDR technologies, maximum projected warming could occur prior to 2100 and may become a more relevant metric. Future analyses may need to look at both peak and stabilization warming for direct comparison with the globally agreed warming limits.

Warming results may be presented as a range of possible temperatures or a single value. At present, only climate-carbon model uncertainty is included in the probability estimates, and therefore, political uncertainty and the implications of post-2030 assumptions are not included in the uncertainty. In addition to reflecting uncertainty from climate and carbon cycle modeling, a range of estimated warming can be used to reflect the political uncertainties of post-2030 emissions trajectories and present a range of possible futures consistent with near-term action. The full uncertainty range in the pathway continuation methods used by the CAT in 2014 (Gütschow et al., 2018; Rocha et al., 2014) represents this possibility space by including most IAM scenarios consistent with the near-term emissions trajectory. A more nuanced approach would reflect the political choices that span that possibility space. From a given 2030 emissions level, different temperatures may be achieved depending on a range of political, technical, and socioeconomic developments (Figures 2 and 3). Under a clear if-then framework, trade-offs between various policy decisions should be elucidated.

4. Increasing Confidence in Projected Warming Estimates

Significant disagreement remains as to the emissions trajectory that is consistent with the current NDCs. Regardless of general methodology applied, those that assume some level of continued action lead to lower projected warming than those that assume no additional policies, efforts, or longer-term reduction targets. The timeframe of the NDCs themselves makes long-term warming projections challenging. NDCs can only provide a step toward significant global emissions reductions and alone cannot be sufficient to limit warming to less than 2 °C, even if ambitious and fully implemented. Seen as a step only, their evaluation should therefore be based on whether that step is sufficient to put global emissions on a trajectory that allows the LTTG to be met with minimal additional burden on future generations. In this context, several political and scientific steps can be made in the coming years to enable more robust assessments for the facilitative dialogue in 2018 and on completion of the next NDC submission phase in 2020.

On a policy level, additional, national targets for later years would allow analysts to better constrain long-term emissions trajectories. Countries have been invited to "formulate and communicate long-term low-GHG emission development strategies" by 2020 (UNFCCC, 2015a, 2016) with Benin, Canada, France, Germany, Mexico, and the United States having done so by 1 October 2017 (UNFCCC, 2017). Development of, and commitment to, quantifiable 2050 targets would provide a strong quantitative constraint on the long-term emissions trajectory and help to reduce the number and influence of post-2030 assumptions made by analysts. National policies and commitments that would help to further constrain long-term emissions trajectories include clear and ambitious targets for nonfossil energy production, progression toward absolute emissions reductions targets, and commitments to peaking emissions, a key step on the road to net-zero emissions. Such commitments are key to constraining emissions levels under NDCs (Rogelj, Fricko, et al., 2017). Moreover, strong, long-term, domestic mitigation plans give clear signals of intent, potentially increasing the likelihood of compliance.

Scientific analyses that can support better policy assessment include the following: (1) further development of midrange emissions scenarios that encompass actions consistent with the current NDCs, (2) improved understanding of the LTTG (Rogelj, Schleussner, & Hare, 2017; Schleussner et al., 2016), (3) reflection on and improvement of current assessment methods, and (4) clear and consistent communication of results. Establishing a stronger link between actions and policies under the NDCs and related emissions trajectories could help to strengthen confidence in trajectories. However, as emissions projections are lowered, uncertainties regarding the rates of technological deployment and availability of negative emissions technologies will increasingly influence the results. The operational goals of the Paris Agreement pose potentially more difficult evaluation challenges than the LTTG; How can a global emissions peak be anticipated? Under what conditions will we be able to say that we are on track to reach net-zero emissions?

5. Conclusions

In assessing the long-term impact of mitigation action under the NDCs, post-2030 assumptions are critical to the warming estimate. Three post-2030 assumptions can be considered; first, assuming weakened action post-2030 highlights the dangers of discontinued effort but may fail to capture any economic and institutional inertia generated by implementing the NDCs. Second, assuming continued action at a similar level and translating this into longer-term trends provides a measure of the current level of effort in the framing of long-term goals, such as total warming. Finally, assuming accelerated or enhanced action provides insights into the possibility space remaining and the social, technical, and economic challenges that may be faced when delaying more stringent climate policy.

We have reviewed four groups of methods (see section 2 and Table 1) that primarily implement the first two of the above assumptions: weakened or continued action. In doing so, we show that simple, geometric pathway construction approaches are not a useful tool for evaluating the sufficiency of NDCs because they do not account for structural system changes and are not able to identify 2 °C consistent scenarios if the near-term action is sufficient. This is partly due to the fact that these approaches are either implicitly or explicitly based on an assumption of stalled climate action—it is therefore no surprise when they conclude the NDCs to be far from sufficient.

Comparing aggregate NDC emissions with a suite of IAM scenarios provides a useful, quick analysis that could be further improved by additional reference scenarios that have fragmented climate policy over the course of the century. Such scenarios would better reflect a continuation of the current situation, and not stalling or accelerating action. Deliberate modeling of NDC scenarios that incorporate the specifics of NDC targets, with a global economic model under similar continued action assumptions, can provide additional, sectoral, and economic insights and perspectives. Finally, a carbon budget analysis appears simple but in practice is complicated by technical challenges concerning non-CO_2 emissions and communication challenges concerning negative emissions.

We suggest that a combination of the latter three groups of these approaches—comparing aggregate NDC emissions with IAM scenarios, modeling NDC scenarios directly, and carbon budget analyses—can together provide the necessary information required for policy makers and that the most appropriate tool depends on the desired knowledge. With a clear timetable of review and resubmission set out under the Paris Agreement, the analytic community should be prepared to respond to new NDCs with an expectation of how plausible NDCs will affect their results. More explicitly, the sensitivity of results to a range of plausible policy scenarios could be tested before the next round of NDC submissions in 2020 (e.g., Gütschow et al., 2018). For example, what if other countries were to follow the United States and state their intent to withdraw from the Paris Agreement? What if China and India were to announce more stringent emissions intensity targets?

Finally, the way in which the results are communicated should be considered ahead of time to account for lessons learned from previous work. In particular, what are the assumptions that go alongside the emissions scenarios, and how can they be clearly communicated in the meaning of results? What do reported uncertainties mean; are they political or scientific? How can these be made clear? By addressing these issues, the scientific and analytic community can provide a sound basis for decision making, during the next NDC submission cycle and the 2023 Global Stocktake.

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