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Extending Near-Term Emissions Scenarios to Assess Warming Implications of Paris Agreement NDCs

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Key Points:

- Several methods to project 2100 temperature rise from countries' climate commitments are introduced and analyzed
- Simple methods can neither reproduce the scenario literature nor assess if emissions reduction pledges are 2°C consistent
- Scenario database-based methods can reproduce literature ranges and be suitable for the assessment of Paris Agreement commitments

Supporting Information:

- Supporting Information S1

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Abstract In the Paris Agreement countries have agreed to act together to hold global warming well below 2°C over preindustrial levels and to pursue efforts to limit warming to 1.5°C. To assess if the world is on track to meet this long-term temperature goal, countries' pledged emissions reductions (Nationally Determined Contributions, NDCs) need to be analyzed for their implied warming. Several research groups and nongovernmental organizations have estimated this warming and arrived at very different results but have invariably concluded that the current pledges are inadequate to hold warming below 2°C, let alone 1.5°C. In this paper we analyze different methods to estimate 2100 global mean temperature rise implied by countries' NDCs, which often only specify commitments until 2030. We present different methods to extend near-term emissions pathways that have been developed by the authors or used by different research groups and nongovernmental organizations to estimate 21st century warming consequences of Paris Agreement commitments. The abilities of these methods to project both low and high warming scenarios in line with the scenario literature is assessed. We find that the simpler methods are not suitable for temperature projections while more complex methods can produce results consistent with the energy and economic scenario literature. We further find that some methods can have a strong high or low temperature bias depending on parameter choices. The choice of methods to evaluate the consistency of aggregated NDC commitments is very important for reviewing progress toward the Paris Agreement's long-term temperature goal.

1. Introduction

The Paris Agreement has been ratified by 176 countries to date (United Nations Framework Convention on Climate Change (UNFCCC), 2017a, 30 April 2018), and 169 countries have submitted their first Nationally Determined Contribution (NDC; UNFCCC, 2017b, 30 April 2018) to indicate their contribution toward meeting the global temperature goal of holding warming well below 2°C and pursuing efforts to limit warming to 1.5°C adopted in Article 2.1 of the Paris Agreement (UNFCCC, 2016a). To assess if the NDCs taken together are sufficient to reach the global temperature goal, their collective global temperature implications need to be determined. Several research groups and nongovernmental organizations (NGOs) have published estimates of the global mean temperature rise by 2100 implied by the NDCs (Climate Interactive, 2017; Gütschow et al., 2015; International Energy Agency (IEA), 2015; Jeffery et al., 2015; Lomborg, 2016; Raftery et al., 2017; Rogelj et al., 2016; United Nations Environment Programme, 2015, 2016). The estimated values range from 2.7°C to 3.5°C of warming by 2100, leading to much debate about the methods and assumptions underlying these projections (Levin & Fransen, 2015; Rogelj et al., 2017; UNFCCC, 2016b; ranges from individual studies are not included in the temperature range presented here). It is important for the negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) to have an estimate of the level of ambition of the targets put forward by countries. The Paris Agreement has a so-called "ratchet mechanism" to encourage strengthening NDCs if they do not collectively line up with the global goal. The first step in this process is the 2018 facilitative dialog which will assess the NDCs in light of the long-term global goal in order to encourage countries to update their NDCs in 2020 (UNFCCC, 2017a, Article 14; Carbonbrief, 2017). United Nations mandated reports, such as the 2016 INDC synthesis report (UNFCCC, 2016b) (INDC: Intended Nationally Determined Contribution), often have a limited mandate and cannot cover all topics relevant for NDC assessment, including whether or not individual countries' or regions' NDCs are consistent with the Paris Agreement long-term temperature goal (LTTG). Negotiators, press, and nonstate actors therefore heavily rely on third-party assessments from NGOs and research groups. It is crucial for the negotiations that the origin of seemingly contradictory results from these studies can be understood as this will assist in establishing a common, quantitative negotiating basis. Several of the published temperature estimates are based on methods that are not peer reviewed. There is also a lack of peer-reviewed literature comparing the different approaches, explaining the differences, and studying their ability to assess the comparability of countries commitments with the Paris LTTG. With this study and Jeffery et al. (2018) we systematically assess the various methods in a quantitative, comparative framework that facilitates a better understanding of the different approaches and provides essential input for ensuring that future assessments are robust.

The different methods to assess NDC temperature implications can be grouped into three categories. The first category compares 2030 emissions and other indicators to the scenario literature to assess compatibility with different temperature limits (Hof et al., 2017; Rogelj et al., 2016; Sanderson et al., 2016; UNEP, 2015, 2016; van Soest et al., 2017). The second group uses numerical models to extend the NDC emissions scenario to the end of the century and create an input to simple climate models that can quickly calculate the implied temperature rise (Climate Interactive, 2017; Gütschow et al., 2015; IEA, 2015; Jeffery et al., 2015). The third group uses integrated assessment models (IAMs) to simulate the energy system and economic development consistent with the NDCs and calculate resulting global emissions pathways and global mean temperatures (IEA, 2015; Fawcett et al., 2015; Rogelj et al., 2017; Spencer et al., 2015). The inverse problem—determining an emissions range for a given year consistent with a temperature target—has also been studied using an IAM (Rogelj, McCollum, et al., 2012). Here we focus on the second group because the methods in this group are simple enough to be used for fast response assessments, for example, during a United Nations climate conference, but still generate scientifically rigorous emissions scenarios for the full century. Full century emissions scenarios can be used in simple climate models and provide all necessary input for impact models that require variables in addition to 2100 global mean temperature. IAMs have long simulation times (from a few hours to days) and are thus not suitable for fast response analyses, while the methods in the first group do not provide additional simulation output, such as yearly temperatures and CO_2 concentrations. This additional information permits more precise impact analyses compared to those based on 2100 global mean temperature rise alone (e.g., Frieler et al., 2013, and its implementation on Paris Reality Check; Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths (PRIMAP), 2018).

The differences in the estimates of temperature increase can have several causes. One important source of different estimates is that several NDCs cannot be quantified unambiguously. NDCs or parts of NDCs that are framed in terms of baselines, peaking years, or emissions intensities need additional assumptions to be quantified. In case of a peaking year, it is necessary to assume an emissions level in that year and a rate of decline after the peaking year. In the case of an emissions intensity target, a gross domestic product projection is needed to quantify the emissions level implied by the intensity target. As currently large emitters (e.g., China and India) use these types of targets, the NDC quantification is subject to notable uncertainty. This quantification uncertainty is not the focus of the present study but is contained implicitly in the "high" and "low" NDC estimates. For an in-depth assessment of NDC quantification uncertainties see Rogelj et al. (2017).

In the present study, we analyze the differences in temperature projections arising from projecting emissions past the time frame of the NDCs requiring assumptions on what countries will do after the target year of the NDCs (usually 2030). Climate policy could continue at a similar level of effort (implying some new policies and renewal of old policies), be frozen (only the policies in place are kept), or strengthened. On the pessimistic side, one could assume that once the end of the current NDC period of the Paris Agreement has been reached in 2030, political preferences change drastically leading to a recarbonization of the economy. Ultimately, the warming at the end of this century will be the result of a series of political decisions in the coming decades. However, it is useful and informative to determine the expected warming with which current action is consistent.

This study therefore focuses on a different source of variability in temperature projections: uncertainties and biases due to the chosen methodology and its parameters. The climate policy assumptions described above have to be implemented in a numerical model. When using IAMs at least some of those assumptions can be explicitly modeled, although other uncertainties, such as those related to structural model characteristics, remain difficult to disentangle. For the methods studied here, the assumptions have to be transferred into rather simple numerical models which can lead to very different results for the same policy assumptions. Thus, different methodologies can lead to different results because of the technical implementation of the same political assumptions. However, the method itself can also have uncertainties. We use two groups to describe these uncertainties: scientific uncertainties and expert judgment. Scientific uncertainties come from model parameters that are not explicitly known, such as the inclusion of different models in the result. On the other hand, "expert judgment" uncertainty comes from modelers picking a certain parameter out of a range in the literature. These judgment choices can be made on a scientific basis of what is assumed to be a best estimate but could also be politically motivated to produce an especially high or low temperature estimate.

We analyze five different methods and investigate their ability to project global mean temperature rise in line with the scenario literature for different 2030 emissions levels. We furthermore analyze their robustness against parameter choices and possible biases, for example, toward high or low temperatures both from the method itself as well as from parameter choices. As this study provides in-depth analysis and comparison of methods, we focus on methods from one group such that they can be compared using the same tools and benchmarks for all methods. A broader analysis of the conceptual frameworks to assess the effectiveness of NDCs, including an analysis of the available reference scenarios and the communication of results, is presented in Jeffery et al. (2018).

The paper also provides the first peer-reviewed description of the pathway selection and constant quantile extension methods which have been developed by the authors.

2. Modeling Approaches Considered

We study four methods that have been used in different NDC analyses and additionally include the growth rate extension as a simple numerical model. The first two methods were developed by the authors of this study and are first described in peer-reviewed literature here. Detailed descriptions are available in the methods (section 7) and the supporting information.

Constant quantile extension. The constant quantile extension (CQE) has been used by the Climate Action Tracker (CAT) since 2015 (Climate Action Tracker, 2015; Gütschow et al., 2015; Jeffery et al., 2015). It is based on a database of emissions scenarios created by IAMs. The idea of this method is that the relative ambition of climate policy is kept constant after the end of the NDC pathway. The relative position, or mathematically speaking "the quantile," of the pathway in the scenario database is used as a proxy for relative ambition. To achieve this, a pathway distribution is calculated from the scenario database. The NDC pathway is compared to this distribution, and the relative position of the NDC pathway in the database is determined and expressed as a quantile. If the NDC emissions level corresponds to the x% quantile, this means that x% of scenarios have lower and $100 - x$% of scenarios have higher emissions than the NDC emissions level. This quantile is kept constant for the rest of the century to create an extension pathway from the database. During the calculation of the quantiles, scenarios can be binned according to different parameters, such as the underlying IAM or technological assumptions, to moderate the influence of large sets of pathways that use similar assumptions and models. The scenario database can also be filtered to remove scenarios that match certain criteria, for example, delayed action scenarios. All scenarios in the database are harmonized to the same historical emissions before the quantile calculation.

Pathway selection. The pathway selection (PWS) method was used by the CAT in 2014 (Hare et al., 2014). Similar to the CQE method, it is also based on a database of IAM generated scenarios. The idea behind this method is to select a future scenario consistent with the NDC pathway. For a defined period of overlap with the NDC pathway, the scenarios with the least distance to the NDC pathway are determined. An extension pathway is then constructed from the selected scenarios. Scenarios can be weighted to weaken the influence of large sets of pathways that use similar assumptions and models. Filtering scenarios is also possible. As for the CQE method, the scenario database is harmonized to historical data before the calculation.

Constant emissions. In the constant emissions (CE) approach, it is assumed that emissions reduction targets beyond the NDC period neither improve nor degrade, consistent with the no backsliding principle. The assumption is implemented by keeping emissions constant after the end of the NDC pathway. This method is used in the Climate Scoreboard (Climate Interactive, 2017) for countries with an absolute emissions level NDC and countries with an "emissions peak in year X" NDC.

Growth rate extension. In the growth rate extension (GRE) approach, it is assumed that the decarbonization of the economy continues after the end of the NDC period at a similar pace which slows down to eventually reach constant emissions. To implement this numerically, the average growth rate of the last years of the NDC pathway is calculated. The pathway is extended using a growth path starting with this growth rate and converging linearly to 1 in a given year, implying a convergence to constant emissions in that year.

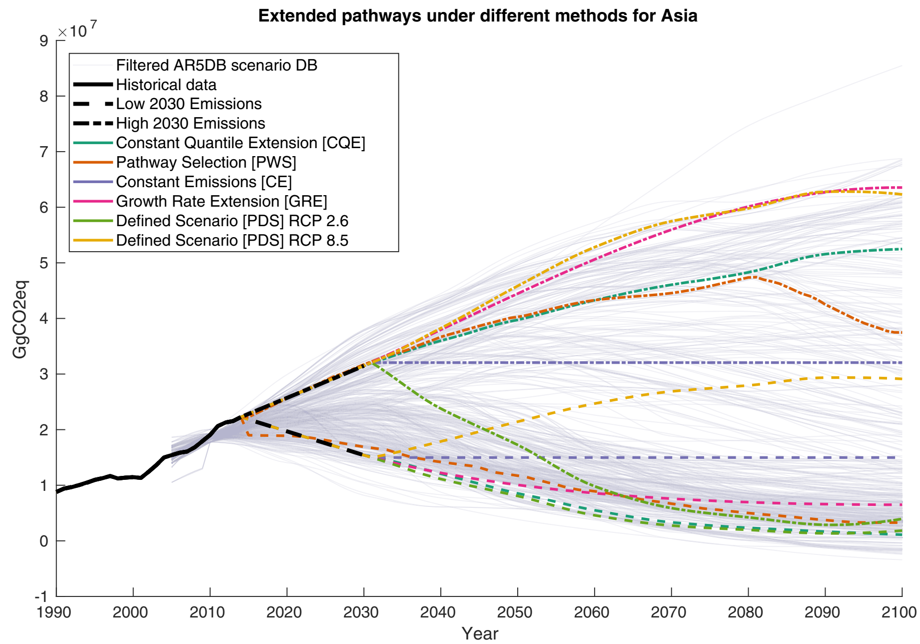

Figure 1. Extended 2030 pathways for a high and a low 2030 emissions case. The constant emissions extension clearly does not present a continuation of emissions trends but rather a drastic change. The predefined scenario (PDS) method is presented with two different extension scenarios: Representative Concentration Pathway (RCP) 8.5 is a good continuation for the high 2030 emissions case but represents a reversal in trends for the low emissions case. For RCP 2.6 it is the other way around. The remaining three methods, constant quantile extension (CQE), pathway selection (PWS), and growth rate extension (GRE), all show a form of continuation of trends from the 2030 scenario in line with developments in the underlying scenario database. For the GRE method, however, this is pure coincidence. A midrange 2030 emissions case would show almost constant emissions, while the scenario database shows decreasing emissions for scenarios in that range (supporting information, Figures S5–S10). The 2030 scenarios here are of purely theoretical nature and selected to show a high and low 2030 emission case. They have no connection to the actual Nationally Determined Contributions.

Predefined scenario. The NDC pathway is extended with the growth rates of a selected scenario which does not depend on the NDC pathway. This method was used by the CAT prior to 2014 and by the IEA for the post-2050 development (IEA, 2015). Climate Interactive also uses this method in the Climate Scoreboard for countries which have a "relative to baseline" NDC (Climate Interactive, 2017).

All of these approaches can be applied on different regional resolutions that are only limited by the available scenario databases used in some of the methods. We use the "Region Categorization 5" (RC5) regions employed by the Intergovernmental Panel on Climate Change (IPCC) for the Fifth Assessment Report (AR5) for all methods. The RC5 regions divide the world into five geographical and economical regions: Asia (R5ASIA), Latin America and the Caribbean (R5LAM), the Organisation for Economic Co-operation and Development (OECD; R5OECD), Middle East and Africa (R5MAF), and the Reforming Economies region consisting of countries of the former USSR (R5REF). A detailed region description is available in Intergovernmental Panel on Climate Change (IPCC; 2014, page 1287).

Figure 1 illustrates the pathways created under different extension methods for high and low 2030 emissions for the Asia region. Similar figures for the other regions are available in the supporting information, Figures S1–S4.

3. Analytical Approach

A method suitable for a scientifically rigorous estimate of the likely global mean temperature rise from current climate commitments has to fulfill several conditions. First of all, it has to be in line with the scientific literature. This means that for a given 2030 emissions level the projected temperatures should be in line with the literature range for similar assumptions of post NDC climate policy. The simple models analyzed here should reproduce the results of the more complex IAMs. The most important benchmarks are the "likely below 2°C" and 1.5°C Paris limits, but the question of where current NDCs and current policy trends lead us are also of great importance. As there is substantial uncertainty in the temperatures consistent with a given 2030 emissions level, we will assess if the method produces results in the uncertainty range in the literature and if those are near the central estimate or rather outliers. A key facet of a method is its sensitivity to changes in the shorter-term emissions scenario, that is, how cumulative emissions over the century (used here as a proxy for warming) change with changing short-term emissions scenarios. The sensitivity governs both whether different temperature values are reached for 2030 emission levels in line with the literature and the resolution of the method in terms of 2030 emission differentials that give a clear (and same sign) temperature difference. If the cumulative emissions do not depend on the 2030 emissions in a monotonically increasing manner, the effectively usable sensitivity will be low; that is, large changes in the NDC emissions level are needed to make a reliable statement about the change in projected warming. For policy makers and the public this is not sufficient as no statement can be made about improvements in the targets of individual countries. While the uncertainty in warming projections is substantial and justifies fluctuations, a good method should provide a central estimate that is smooth and monotonic, even for small changes.

To analyze the different methods, we create a set of short-term pathways (until 2030) for each of the RC5 regions. The pathways cover the range of regional 2030 emissions from the harmonized and filtered (see section 7.2) scenario database of the 5th IPCC Assessment Report (AR5; International Institute for Applied Systems Analysis (IIASA), 2014), where we use the 2.5% to 97.5% range to limit the influence of outlier scenarios. Each of the regional short-term pathways is extended with all methods for each region individually, and cumulative emissions from 2011 to 2100 are calculated. For details, see methods section 7.3. We use cumulative emissions for two reasons. First, we need the cumulative emissions to indicate sensitivity for regions. Second, we also use the cumulative emissions as a proxy for the temperature response. In section 7 we demonstrate that when using the Equal Quantile Walk (EQW; Meinshausen et al., 2006) to derive the multigas input needed for the simple climate model Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) (Meinshausen et al., 2011), there is an almost linear relationship between cumulative emissions and median warming (Figure 5 and section 7). This linear relationship allows us to use the cumulative emissions directly to estimate the implied temperature response without running a climate model for each case.

The 2030 emissions to 2100 temperature relation derived from the regional scenarios is analyzed for its correspondence to literature values for 2030 emissions consistent with different warming levels, especially the 1.5°C and 2°C limits. Our main benchmarks are the AR5 database and Shared Socioeconomic Pathways (SSP) scenario database (IIASA, 2016) which we complement with ranges from other studies. The analysis also allows us to investigate if methods are monotonic. We also examine the uncertainty and special biases of the individual methods. Additionally, we investigate if the method can be fine-tuned to match the scenario literature or biased (purposefully or not) through parameter and input data choices. Finally, we assess the current NDCs and current policy trends to complement the sensitivity analysis with real world examples.

Throughout this study emissions scenarios include emissions from land use and international aviation and marine transportation (bunkers). Land use is included because several NDCs include land use in their emissions reduction target. Furthermore, we would have to select a land use pathway which is kept constant over the whole NDC scenario range, thus introducing elements of the predefined scenario (PDS) method into all methods and potentially biasing the results depending on the chosen pathway. Also, the AR5 scenarios consist of consistent land use and fossil and industrial emissions pathways. By using a fixed land use pathway, this consistency would be lost. However, we distinguish between land use and fossil and industrial emissions during the harmonization step. Land use emissions are not harmonized to historical data as the variability in historical data used by the IAMs that generated the AR5 scenarios is large. The same region can have positive emissions for one model and negative emissions for another model.

The situation for bunkers is more complex: NDCs do not include international transport as mitigation in this sector is in the responsibility of the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO). However, the AR5 scenarios include, but do not explicitly specify, emissions from international transport. Isolating bunker emissions from the AR5 scenarios is not possible without guesswork and might influence the results, as growth rates in transport scenarios can be substantial. We thus perform the analysis including bunkers emissions and consequently add them to historical data before

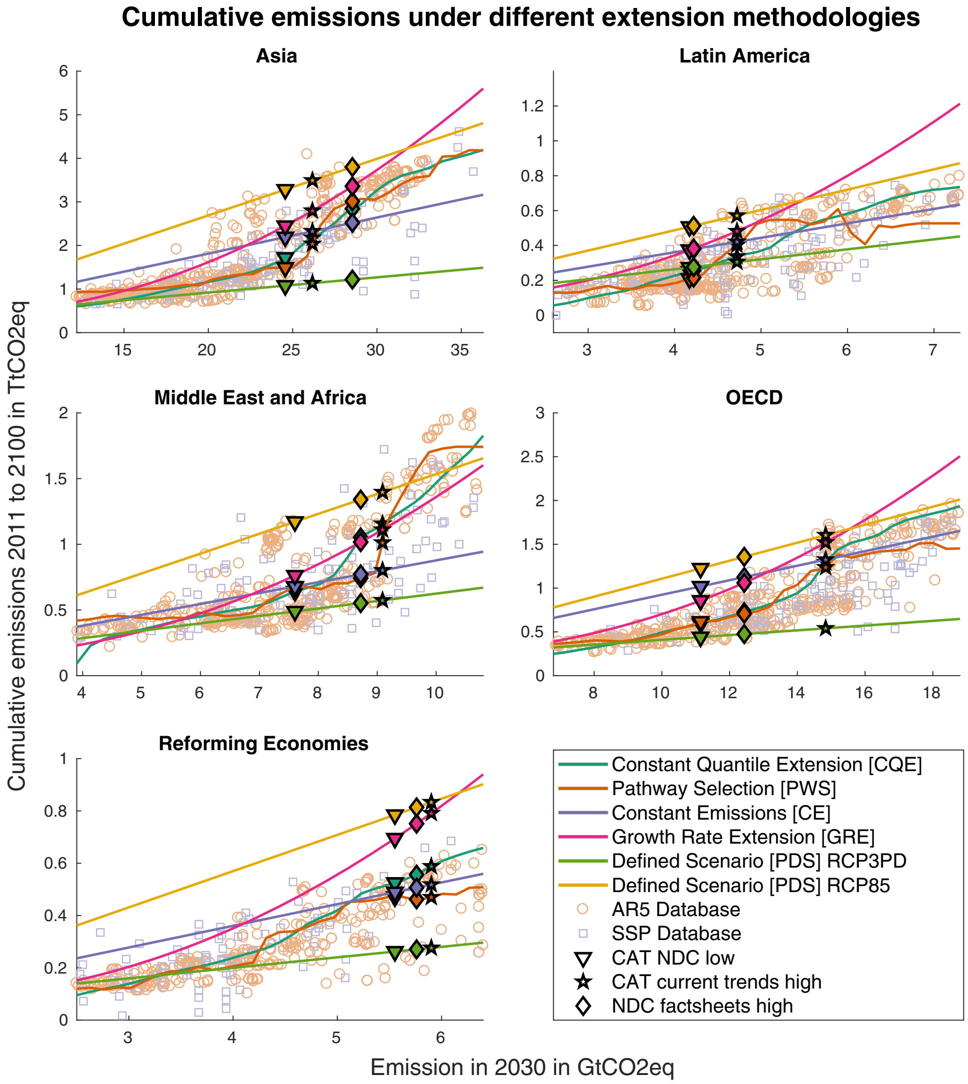

Figure 2. Comparison of methods for the Region Categorization 5 regions. The regional values show that the predefined scenario method creates a linear dependency of cumulative emissions on 2030 emissions, similar to the constant emissions method just with a different slope. The growth rate extension (GRE) method overestimates cumulative emissions for high 2030 emissions but somewhat resembles the shape of the scenario databases. The constant quantile extension (CQE) and Pathway Selection (PWS) methods are based on the 5th IPCC Assessment Report (AR5) Database scenarios and can actually model the scenario database more closely. It is apparent that the PWS method is not monotonic and therefore problematic. For clarity only some of the Nationally Determined Contributions (NDC) and current trend values are shown. See Figures S11–S15 in the supporting information for all values.

harmonization and creation of the 2030 pathways. Historical data for national emissions is taken from PRIMAP-hist v1.1 (Gütschow et al., 2016, 2017), and international transport CO_2 data are taken from CDIAC 2017 (Boden et al., 2017).

4. Results

Figure 2 shows the regional analysis of all studied methods. Figure 3 shows the temperature response to global 2030 emissions under the studied methods.

The underlying scenario database limits the range of 2030 emissions to roughly 28–80 Gt CO_2 eq in 2030. The range could be extended a little by using the full 2030 range instead of the 2.5% to 97.5% range, however, that would give single outlier scenarios a strong influence on the results on the borders of the range

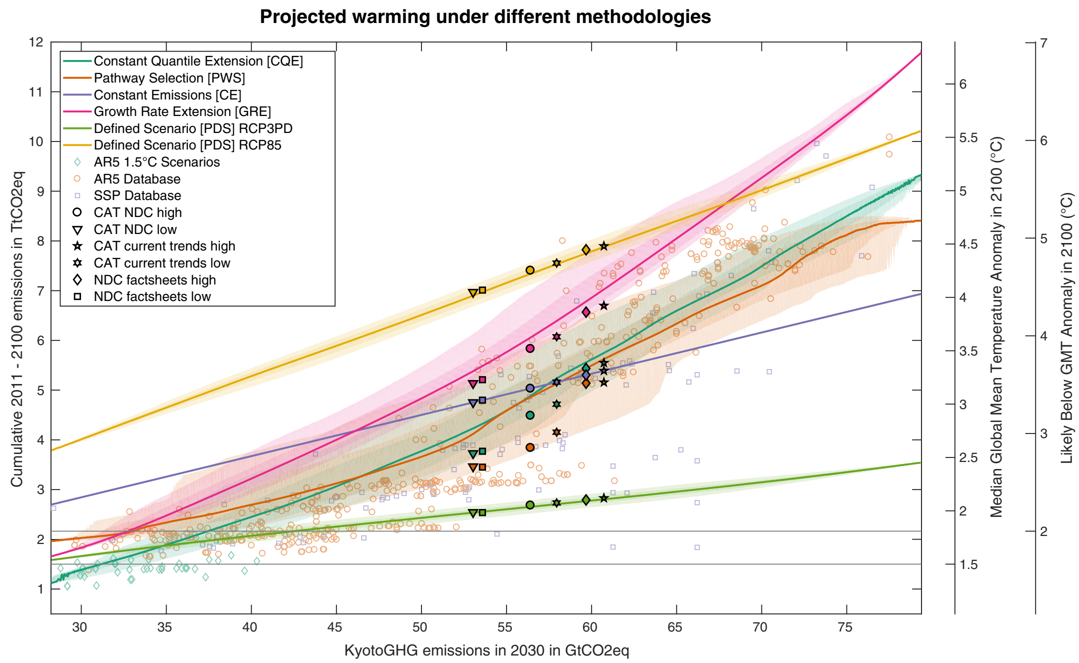

Figure 3. Comparison of methods for global aggregates. The shaded areas define the 98% and 67% confidence intervals for the distribution of cumulative emissions derived from all combinations of regional 2030 emissions that sum to the given global 2030 emissions value. For details see section 7.3.

of 2030 emissions. This effect can be seen in Figure 2, R5MAF where the CQE method exhibits a sudden drop in cumulative emissions around 4 Gt.

4.1. Temperature Limits

In Figure 4 and Table 1 we present the 2030 emissions compatible with different temperature limits for all extension methods studied. The Paris Agreement temperature limits of likely below 2°C and median 1.5°C are especially important elements for evaluating methods, because if a method is not able to reach 1.5°C or 2°C under any 2030 emissions level, then clearly the method is not suitable for tracking progress toward achieving the Paris Agreement long-term global temperature goal. Current NDCs and current policy trends are far from the 1.5°C and 2°C limits; thus, the methods also need to work for higher emissions levels, which we include in terms of likely below 3°C and likely below 4°C limits.

Comparing the implied emissions levels, we find that only two methods can find scenarios compatible with the 1.5°C limit. PDS with RCP 2.6 for just below 28 Gt CO_2 eq in 2030 and CQE for 28–34 Gt. Literature values reach from 33 (28–40) Gt (15–85% interval; Rogelj et al., 2015) to 38.8 (37.7–40) Gt (10–90% interval; UNEP, 2016). The different ranges in the studies can at least partially be explained by different assumptions. In the first study, mitigation starts in 2010, while in the second study cost-optimal mitigation only starts in 2020 with 2020 emissions that are consistent with the Cancun pledges. Both of these scenario groups are in principle included in our analysis as they do not represent a shift in climate policy after 2030. However, the AR5 Database (AR5DB) contains almost no 1.5°C scenarios. So the 1.5°C ranges for the different methods calculated here are based on the combination of especially low regional pathways for different regions. Inclusion of specific 1.5°C scenarios would widen those ranges and might enable the PWS method to reach the 1.5°C limit.

Literature ranges for the likely below 2°C limit are more consistent; 37 (32–40) Gt (15–85% interval, least cost from 2010) from Rogelj et al. (2015), 42 (31–44) Gt (20–80% interval, least cost from 2020) from UNEP (2015), and 41.8 (30.6–43.5) Gt (10–90% interval, least cost from 2010) from UNEP (2016). The CQE (30–42 Gt) and PWS (28–38 Gt) methods yield results that are close to these ranges. The AR5 and SSP databases allow much higher 2030 emissions for 2°C consistent pathways. Their distribution is best matched by the PDS method with RCP 2.6, which is designed as a 2°C scenario. The GRE method needs significantly lower 2030 emissions (20–34 Gt) to hold warming likely below 2°C. The discrepancy between the AR5DB ranges and the scenario DB based methods can be explained by looking at the likely below 3°C ranges. The AR5 database

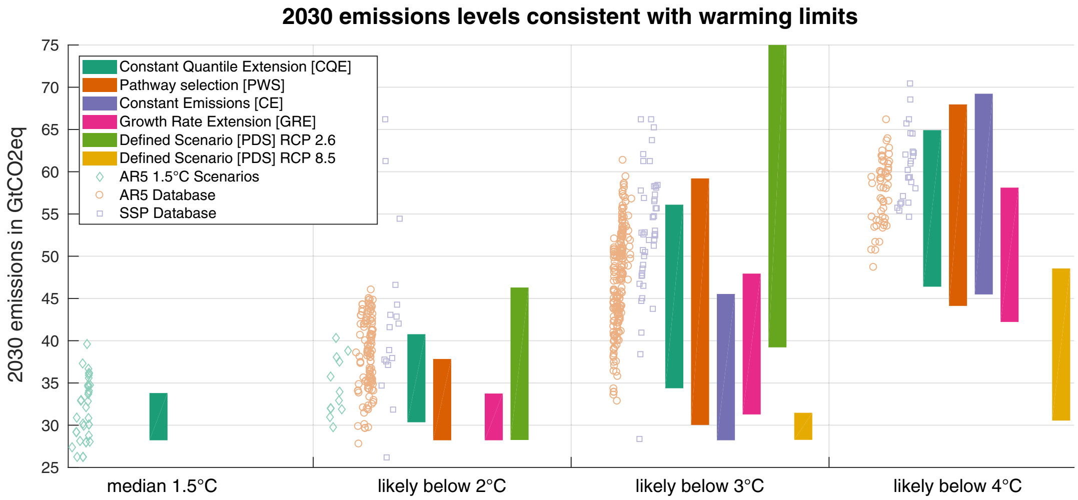

Figure 4. The 2030 emissions ranges compatible with different temperature limits for all methods. The ranges given for the methods are those of the 98% confidence range from Figure 3 and computed such that warming is held below the limit but exceed the lower limits. The scenarios are selected based on the same criterion. Some of the 1.5°C scenarios fall in our likely below 2°C category because they are at the very fringe of the 1.5°C limit and the Equal Quantile Walk has a slight bias toward higher temperatures for very low emissions scenarios (supporting information, Figure S47 and Text S7). The ranges for the different methods start at 28 Gt; thus, ranges starting at 28 Gt would likely extend to lower emissions levels if these were considered.

has a significant overlap in 2030 emissions between 2°C and 3°C scenarios. As there are several possibilities of post-2030 developments, this is not surprising. The ranges for the different methods do not come from these different future developments but from different combinations of regional emissions. The different future developments are combined, and thus, at some point of 2030 emissions, the scenarios not holding warming likely below 2°C dominate over the 2°C scenarios. The growth rate extension method (28–34 Gt) is on the low end of the AR5 range. Constant emissions and RCP 8.5 cannot reach the 2°C limit.

For the likely below 3°C limit and the likely below 4°C limit, the two scenario database based methods resemble the distribution of the underlying scenario DB. The constant emissions extension and growth rate extension are on the low end for 3°C. CE is in line with the 4°C range, while GRE is a bit on the low side. PDS with RCP 8.5 is far outside the AR5 range for 3°C and below the 3°C, while PDS with RCP 2.6 stays likely below 3°C for the whole studied range.

As an indicator for the broader sensitivity we investigated the minimal (at 28 Gt in 2030) and maximal (at 80 Gt in 2030) median temperatures, where a wider temperature range (Table 1) indicates a higher overall sensitivity of the method. The PDS method reaches 1.5–2.4°C for RCP 2.6 and 2.6–5.6°C for RCP 8.5 (median). Thus, it is not capable of calculating realistic temperatures for both high and low 2030 emissions (for results with additional scenarios, see supporting information, Text S1 and Figures S16 and S17). The growth rate extension method leads to a warming from 1.6 to 6.3°C and is consistently higher than the AR5 ranges except for the very low end of 2030 emissions and thus overestimates end of century warming, especially for high 2030 emissions (Figure 3). The pathway selection is rather on the high end for 2030 emissions below 55 Gt and on the low end for 2030 emissions above 65 Gt (range 1.7–4.7°C). This behavior stems from the selection of a fixed quantity of pathways to determine the median, leading to boundary pathways relatively far away from the boundaries of the scenario database. The CQE method shows a low bias below 35 Gt (but is in line with the 1.5°C scenarios), a slightly high bias from 40–60 Gt and a low bias above 65 Gt but in general resembles the AR5 scenario distribution better than the other methods. The range is 1.3–5.1°C. A pathway extension with constant emissions can neither resemble temperatures for low nor high 2030 emissions and has a range limited to 2.1–4.0°C.

4.2. NDC Results

Table 2 shows the projected warming for NDC emissions from the NDC fact sheets (Meinshausen & Alexander, 2016) and the CAT (Rocha et al., 2016) as well as the CAT current trends pathways. In section 7.4 we present the NDC emissions levels and explain how we calculated the temperatures. The simpler methods identify

Table 1
Summary of Results for Different Extension Methods

Pathway extension method	Temperature range (median)		2030 emissions compliant with temperature limits (in Gt CO_2 eq)				Can be biased	Monotonic
	Minimum	Maximum	1.5°C (md)	l.b. 2°C	l.b. 3°C	l.b. 4°C		
Constant quantile extension	1.3°C	5.1°C	<28–34	30–41	36–56	46–65	Partial[a]	Yes
Pathway selection	1.7°C	4.7°C	-	<28–38	30–59	44–68	Partial[a]	No
Constant emissions	2.1°C	4.0°C	-	-	<28–46	45–69	No	Yes
Growth rate extension	1.6°C	6.3°C	-	<28–34	31–48	42–58	Partial[a]	Yes
Predefined scenario RCP 2.6	1.5°C	2.4°C	<28	28–46	39–80+	-	Yes	Yes
Predefined scenario RCP 8.5	2.6°C	5.6°C	-	-	28–31	31–49	Yes	Yes

Note. The minimal temperature given is for 28 Gt CO_2 eq in 2030 and the maximal temperature for 80 Gt CO_2 eq. Lower and higher 2030 emissions could yield lower and higher temperatures than the range stated here. The ranges given for each method are those of the 98% confidence range for Figure 3 and computed such that warming is held below the given limit but exceeds the lower limits. The ranges for the different methods start at 28 Gt; thus, ranges starting at 28 Gt would likely extend to lower emissions levels if these were considered. md = median; l.b. = likely below; RCP = Representative Concentration Pathways.
[a]These methods can be biased, at least for a given 2030 emissions range, but not as strongly and globally as the PDS method.

only small variations between the different NDC and trend assessments: the constant emissions extension projects 2.9°C (low NDC cases) to 3.2°C (high trend case) of median warming, demonstrating the low sensitivity of this method to changes in short-term emissions trajectories. The results for the defined scenario extension method illustrate the strong influence of the chosen scenario; RCP 2.6 leads to a median warming of 1.9–2.0°C for all cases, with temperatures staying likely below 2.3°C in the highest case. Using this pathway extension method would indicate that at least the 2°C part of the Paris LTTG is just a few tenths of a degree away from pledged emissions and even current emissions trends. However, when using RCP 8.5 the picture is completely different. Median warming lies between 3.9 and 4.3°C, a world with potentially devastating impacts (The World Bank, 2012). The growth rate extension method has more variation (3.1–3.8°C) but is consistently warmer than the two scenario DB based methods, which is consistent with the overall results presented in Figure 3. The scenario DB based methods, CQE and PWS, show a similar but not identical behavior. PWS consistently projects lower temperatures than CQE with the largest difference of 0.3°C for the CAT high NDC and low trend cases. Figure 2 shows that while the two methods show similar regional response functions, there are differences, which can be substantial where the response functions are steep (e.g., Asia between 25 and 30 Gt CO_2 eq and R5MAF around 9 Gt CO_2 eq).

Despite also being based on the CQE method, the published CAT assessment, Rocha et al. (2016) is not consistent with the temperature values for the CQE method presented here. This is because the CAT assessment uses different assumptions and methodologies for land use and bunkers data include 2050 emissions targets and use a different harmonization of the AR5DB. In the supporting information (Text S6) we explain the differences in more detail.

4.3. Monotonicity

Figure 2 illustrates that all methods, except for the pathway selection, respond monotonically to increasing 2030 emissions. The pathway selection method suffers especially from the use of emissions including land use, as some models use land use for fast mitigation in some regions leading to low 2030 emissions that increase again in later years, leading to higher cumulative emissions. The most extreme cases have been excluded, but the effect is still visible (supporting information, Figures S32 and S33). The CAT used the method in 2014 on emissions excluding land use, where the problem is less pronounced, but still relevant as scenarios for fossil fuel and industrial emissions also cross each other which destroys the correspondence of 2030 emissions to cumulative emissions. The CQE method does not follow individual scenarios and is inherently monotonic.

4.4. Modeling Uncertainty

The methods studied here are of very different complexity. We cannot provide a full uncertainty analysis for the two scenario database based methods but will present some key factors.

The simplest method regarding modeling uncertainty is the constant emissions extension. Once this method has been selected there is no uncertainty, neither from parameters (there are none), nor from the model itself. The PDS method is similarly simple with the major difference that a scenario can be chosen. The impact of this

Table 2
The 2100 Global Mean Temperature Rise Projected Under Different Methodologies for NDC and Current Trend 2030 Emissions

	NDC fact sheets		Climate Action Tracker			
Pathway extension method	NDC low	NDC high	NDC low	NDC high	Trend low	Trend high
Constant quantile extension	2.4°C (2.8°C)	3.2°C (3.6°C)	2.4°C (2.7°C)	2.8°C (3.1°C)	2.9°C (3.3°C)	3.2°C (3.7°C)
Pathway selection	2.3°C (2.6°C)	3.1°C (3.5°C)	2.3°C (2.6°C)	2.5°C (2.8°C)	2.6°C (3.0°C)	3.1°C (3.6°C)
Constant emissions	2.9°C (3.3°C)	3.1°C (3.6°C)	2.9°C (3.3°C)	3.0°C (3.4°C)	3.1°C (3.5°C)	3.2°C (3.6°C)
Growth rate extension	3.1°C (3.5°C)	3.7°C (4.2°C)	3.1°C (3.5°C)	3.4°C (3.8°C)	3.5°C (3.9°C)	3.8°C (4.3°C)
Predefined scenario RCP 2.6	1.9°C (2.1°C)	2.0°C (2.3°C)	1.9°C (2.1°C)	2.0°C (2.2°C)	2.0°C (2.2.°C)	2.0°C (2.3°C)
Predefined scenario RCP 8.5	3.9°C (4.4°C)	4.3°C (4.8°C)	3.9°C (4.4°C)	4.1°C (4.6°C)	4.1°C (4.7°C)	4.3°C (4.9°C)

Note. The values are median warming; values in parentheses are "likely below" warming. NDC = Nationally Determined Contributions; RCP = Representative Concentration Pathways.

choice is substantial: using all four RCPs leads to temperature uncertainties from 1.1 to 3.2°C for the studied range (supporting information, Text S1 and Figures S16 and S17). The uncertainty is measured as the difference between the maximal and minimal temperatures when using different scenarios and a given 2030 emissions level. The growth rate extension also has one free parameter, the convergence year. Varying the convergence year between 2050 and 2100 leads to temperature differences from 0.3 to 1.6°C for the studied 2030 emissions range of 28–80 Gt CO_2 eq (supporting information, Text S2 and Figures S18 and S19).

The scenario DB based methods (CQE and PWS) can only perform as well as the underlying database; thus, the selection of scenarios to include in that database is an important parameter. If only scenarios with strong mitigation are included, low temperatures will be reached, while baseline scenarios will yield high temperaturesno matter what the 2030 emissions are. By choosing the AR5 database, we base our analysis on a large set of scenarios from different modeling groups, for different climate targets, and with several parameter choices, such as available technologies and policy regimes. The database built from the IAM implementations of the RCP greenhouse gases (GHG) concentration scenarios (van Vuuren et al., 2011) and SSP scenarios (O'Neill et al., 2013; van Vuuren et al., 2014), the SSPDB (IIASA, 2016; Riahi et al., 2016) could be used as a test case, but this analysis is out of the scope of this paper. However, we investigate the effect of the preprocessing of the scenario database on the results. To contrast results for the two methods, we discuss them in parallel. We compare the default parametrization with two variants in harmonization ((1) second step of harmonization in 2014 and (2) single harmonization step in 2010), one variant in scenario filtering (using the whole AR5DB), and one variant in scenario binning (using no binning). for details see supporting information Texts S3 and S4. Harmonization, especially the selection of harmonization year, affects both methods. CQE shows differences in the NDC assessments of up to 0.3°C and the PWS method of up to 0.5°C, with a high variation of impact between the studied NDC and current trend assessments. Using scenario binning and filtering has a very small effect on the CQE method (< 0.1°C) but impacts the PWS method significantly for some cases, the most extreme being the low CAT current trends case, which is 0.7°C lower without scenario filtering than with filtering. The effect is especially visible when regional emissions are at a level with a steep increase in cumulative emissions (see also Figure 2). Different options in scenario database processing move the position of this slope in terms of 2030 emissions and strongly influence results if emissions are in that area for a region. This slope is steeper for PWS than for CQE and the movement stronger; thus, the uncertainty introduced by scenario DB processing parameters is much higher for the PWS method than for the CQE method. For details on the variants we refer to the supporting information (Texts S3 and S4). The regional effects can be observed in the supporting information in Figures S22 and S26 and the global results are presented in the supporting information in Figures S23 and S27.

For the CQE method we also investigate parameters for the calculation of the quantile distribution. For the emissions region of the NDCs and current trends, none of the parameters has a noteworthy influence. However, for very high and low emissions there is one problematic variation of the quantile calculation which introduces high uncertainty (0.5°C) and thus should not be used (supporting information, Text S3 and Figures S24 and S25).

For the PWS method we study different options of calculating the final pathway: the default option is to calculate a weighted median from the selected scenarios. Other options assessed are to use the middle of the 10–90% interval of the selected pathways, to determine a representative pathway as an actual pathway from the scenario database which is closest to the middle of the range, and to use the average of all selected pathways (supporting information, Text S4). They lead to variations of up to 0.5°C for the NDC cases (supporting information, Figures S28 and S29).

Finally, we also investigated the influence of the NDC pathway modeling on the methods for a simple test case. The short-term pathways used in this study are linear pathways from historical 2014 emissions to the prescribed 2030 emissions. As a test case, we constructed pathways that have a "peak in 2020" shape (supporting information, Text S5). By construction of the methods, this has no influence on either the CE or PDS methods. Our parametrization of the CQE method is also insensitive to the pre-2030 pathway evolution (supporting information, Figures S24 and S25). For the GRE method, high end temperatures are strongly increased, while for very low 2030 emissions, temperatures are slightly decreased. The effect is < 0.1°C for 2030 emissions around those of the NDC and current trend pathways (supporting information, Text S2 and Figures S18 and S19). For PWS, the effect is larger (up to 0.5°C) and varies in both sign and magnitude (supporting information, Figures S26 and S27).

Uncertainties that we do not cover here include the influence of variations in historical emissions, the 2030 emissions resulting from the NDC assessment on the temperatures, and uncertainties from the scenario selection process in the PWS method.

4.5. Biases

The final criterion for assessment of the methods is if they can be biased by parameter choices. From what has been said above, it is clear that the defined scenario method is highly influenced by the choice of the scenario: when choosing RCP 2.6 the temperature projection will be likely below 2.7°C, even for 80 Gt CO_2 eq in 2030, while with RCP 8.5 this temperature will be surpassed for the whole range of studied 2030 emissions. The constant emissions extension cannot be biased. The growth rate extension can be modified by choosing convergence years for the growth rate. This could also be used to more closely resemble the AR5 scenario distribution. However, this can only be used to tune the methods' sensitivity, which can change results especially in low and high 2030 emissions cases, and not to introduce an overall high or low bias (supporting information, Text S2 and Figures S18 and S19).

The two scenario database-based methods respond very differently to parameter choices. CQE is very stable except for the harmonization. Harmonizing in 2014 instead of 2010 consistently lowers the projected temperatures for all NDC trend cases (supporting information, Figures S22 and S23). The PWS method also strongly responds to scenario database filtering (supporting information, Figures S26 and S27). Including 2030 delayed action scenarios consistently lowers temperatures but does not comply with the assumption of continued level of effort. Therefore, the effect on the temperatures is not problematic. The different options to calculate the final emissions scenario can also be used to affect the temperature outcome. The weighted median option used in this study produces low temperatures compared to other options (supporting information, Text S4 and Figures S28 and S29). Thus, the PWS method has several parameters which can be used to bias the method for the whole range of 2030 emissions. The CQE method is stable with respect to the tested parameters except for the harmonization year. It is therefore important to keep the harmonization year constant when tracking progress in climate commitments.

5. Limitations

The AR5 scenario database underlying the CQE and PWS methods has the advantage of comprising several different models and scenario assumptions. However, it also has a few drawbacks that hamper its use for our purpose.

1. A database harmonized to historical emissions would be optimal for our analysis. The AR5 database however is not harmonized to the same historical emissions, and, in the case of land use data, harmonization is difficult to impossible as some scenarios have positive and others negative historical emissions for some regions. We therefore have to work with unharmonized land use emissions.
2. The dependence on a scenario database limits the analysis to parameter ranges covered by the scenarios in the database. This limitation hinders the assessment of compatibility with the 1.5°C temperature limit, because the AR5 database contains only a handful of 1.5°C scenarios. Currently, NDCs and emissions trends are far from being consistent with 1.5°C pathways; therefore, the practical relevance to assessments of current NDCs is limited. However, the issue should be addressed in the future. A recent multimodel study

expands the SSP scenario database with scenarios that reach an end of century radiative forcing of 1.9W/m^2 and restrict end of century median warming to below 1.5°C (Rogelj et al., 2018). Inclusion of these scenarios could enable the CQE and PWS methods to successfully identify 1.5°C compatible NDCs.

3. The AR5DB scenarios do not explicitly use the assumption of a continuation of climate policy at a similar level of effort, which is the basis of our scenario extensions. We implement this assumption by averaging over different future developments and by excluding scenarios which explicitly do not share this assumption, such as the P3 and P4 "Delay 2030" policy scenarios of the AR5DB. This leads to an uncertainty in the extended pathway and consequently the temperature projection.
4. AR5DB scenarios are generated using global models that often assume global cost-optimal solutions. The NDC pathways, however, are determined on a regional basis and the current NDCs differ strongly by region. They are thus not in line with global cost-optimal 2030 emissions.
5. The AR5DB contains several scenarios with strong mitigation and several baseline scenarios. However, the middle range of scenarios is scarcely populated (van Ruijven, 2016) (see also supporting information, Figures S31–S36).

The methods could be improved by using a scenario database tailored toward the use for scenario extension. It is unlikely that such a database will be generated because of the amount of work involved and the limited user group. However, some aspects, such as harmonized historical emissions (ideally with an uncertainty range used by all models), lower mitigation scenarios, and scenarios that do not assume global cost-optimal mitigation, would also benefit other uses of the database and could be implemented. The new SSP IAM scenario database (IIASA, 2016; Riahi et al., 2016) already takes some steps in this direction. For a more detailed analysis of the IAM scenarios we refer to Jeffery et al. (2018).

6. Conclusions

The simpler methods (CE, PDS, and GRE) have great advantages regarding transparency. It is just easier to communicate that emissions are kept constant than that the quantile in a scenario database is kept constant, especially to an audience that does not necessarily know what a quantile is. But, apart from their transparency, the simpler methods have not much to offer. Constant emissions and predefined scenarios cannot reproduce temperatures consistent with a wider range of 2030 emissions and are therefore not suitable to analyze the temperature implications of NDCs or current policies. The growth extension can be tuned to some extent but would require region dependent convergence years for best results, which would reduce transparency. Characteristics of the scenario literature that go beyond a simple 2030 emissions to cumulative emissions curve cannot be modeled.

The scenario based methods (PWS and CQE) generally reflect the distribution of the AR5 scenario database more closely and are a substantial improvement on the simpler methods. A further advantage of the scenario database based methods is that they can be used to project temperatures under restrictions on future development, for example, technological restrictions such as no availability of carbon capture and storage technologies, or nuclear energy. However, the PWS method suffers from severe nonmonotonicity when using emissions including land use. As several NDCs include land use, it is problematic if a method cannot be used for emissions including land use. Therefore, the CQE method is not only the method that most closely matches the ranges laid out by the scenario literature but also has the advantage of monotonicity over the PWS method which also resembles the scenario database relatively well. The main downside of the CQE method is that the scenarios generated are of purely numerical nature, despite the use of a scenario database.

The NDC analysis shows that scenario DB-based methods have the potential to model global mean temperature rise for various short-term emissions trajectories in line with the IAM literature. However, uncertainties are present and parametrization will affect the results. Uncertainties in methods are problematic when they can bias the method toward low or high temperatures. For both PWS and CQE, the harmonization of the scenario database has a significant influence on the temperatures and should therefore be carefully selected. The PWS method has further parameters with significant impact, which need to be carefully chosen, argued for, and made transparent, including their effect on the temperature.

However, uncertainties in themselves are not a problem but rather a good sign because methods that project 70 years of greenhouse gas emissions from a 2014 to 2030 trend should have high uncertainties. The AR5 scenario database has not been designed with this application in mind and introduces further uncertainties through variations of future policy assumptions. But even with a perfect modeling of continued climate political effort, future socioeconomic dynamics are unclear and can lead to substantially different emissions scenarios (Riahi et al., 2016; Rogelj et al., 2017). The pathway extension methods assessed in this paper provide a useful reference framework and tool set to measure progress that can be applied to new scenarios and new political commitments. Global socioeconomic and political development will ultimately determine the effectiveness of those pledges on limiting warming.

7. Methods

7.1. Pathway Extension Methods

7.1.1. Constant Quantile Extension

The Constant Quantile Extension is based on the idea to keep the relative effort of an emissions pathway within a database of scenarios constant over time. As a proxy for the relative effort we use the position (the quantile) of the pathway within the database. From the end of the near-term scenario this quantile is kept constant such that there is always the same number of pathways above and below the extended pathway. In this study we use the AR5 scenario database as a basis, and we filter and harmonize the database as described in section 7.2.

From the filtered and harmonized scenarios (see section 7.2) we calculate quantiles on a yearly basis using MATLAB's (The Mathworks Inc., 2017) ksdensity function with kernel bandwidth of 0.3 times the default bandwidth to smooth the scenario distribution before calculating the quantiles (see supporting information, Figures S20 and S21 for the influence of this parameter). During the calculation we use a weighting to alleviate the effect of multiple scenarios with similar parameters. We group scenarios by model, climate category, and technological category. All scenarios which coincide in all three parameters are grouped and weighted by $1/n$ where n is the number of scenarios in the group.

To extend a given pathway, the quantile of the scenario emissions in the last scenario year is determined. As the quantile distribution is discrete, emissions will, in general, lie between two quantiles. In this case, we interpolate linearly between the two quantiles to determine the emissions for all years until 2100. If the emission in the last scenario year lies outside the quantile range, we use the upper and lower bounds and do not extrapolate for higher and lower emissions.

In the supporting information (Text S3 and Figures S20–S25) we present results for methodological variations and different parameter choices.

7.1.2. Pathway selection

Similarly to the CQE method, the pathway selection is based on the AR5 scenario database. The database is harmonized and filtered as described in section 7.2. To extend a scenario, we calculate a distance of the scenario to all scenarios in the database for the years 2015–2030. This distance is calculated as the root mean square distance. The 8% of scenarios with the least distance are selected to define the range for the extension scenarios. From this range we calculate a weighted median with the weighting as in the CQE case but only applied to the selected scenarios. Selecting a single pathway would lead to strong nonmonotonicity as scenarios with a similar development in the short term can have very different future developments. This would produce a large uncertainty in the method; thus, we select multiple pathways to obtain a more robust extension method. When the method was introduced for the CAT in 2014, a so-called representative pathway was used that was determined as the pathway with the least distance to the middle of the 80% range of the selected scenarios. The weighted median is used here instead to allow scenario weighting and to create a smoother relationship between cumulative emissions and the 2030 emission level of the NDC pathway. Results for the representative pathway are presented in the supporting information (Text S4 and Figures S28 and S29). The supporting information also includes information on the influence of variation in the scenario database preparation (Text S4 and Figures S26 and S27).

A fixed percentage of pathways is used instead of selecting all pathways within a fixed relative distance of the NDC pathway, because the distances vary very much and the same value could lead to selecting no scenario in one case and over 100 scenarios in another case.

7.1.3. Predefined Scenario

A linear trend is calculated from the last $n = 10$ years of the NDC scenario and used to calculate a 2031 emissions level. The PDS is then scaled uniformly on a per region basis to match this 2031 emissions level.

In the supporting information (Text S1 and Figures S16 and S17) we show results for additional extension scenarios.

7.1.4. Constant Emissions (CE)

A linear trend is calculated from the last $n = 10$ years of the scenario. The 2031 value of this linear trend is then used as a constant emissions level for the rest of the century.

7.1.5. Growth Rate Extension (GRE)

A linear trend is calculated from the last $n = 10$ years of the short-term scenario. The trend values for the first (y_{t-n+1}) and the last (y_t) year of this period are calculated and used to calculate the initial growth rate g_i

$$g_i = \sqrt[n]{E_{y_t}/E_{y_{t-n+1}}}, \tag{1}$$

where E_y are the emissions in year y. We then construct a linear growth pathway with $g_{y_t} = g_i$ and $g_{y_{\text{end}}} = 1$. The emissions are calculated via

$$E_y = E_{y_t} \cdot \prod_{z=y_{t+1}}^{y} g_z. \tag{2}$$

In the supporting information (Text S2 and Figures S18 and S19) we study the method for different values of y_{end}; our standard value for y_{end} is 2100.

7.2. Preparation of the Scenario Database

Not all of the scenarios in the AR5DB can be used for the pathway extension methods described here. To calculate temperatures, we need emission from all gases and sectors; thus, we only take scenarios from the full-gas, full-sector models (Global Change Assessment Model (GCAM), Integrated Model to Assess the Global Environment (IMAGE), Model for Estimating the Regional and Global Effects of Greenhouse Gas Reductions (MERGE), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), Regionalized Model of Investments and Development (REMIND), and World Induced Technical Change Hybrid (WITCH)). We work on the level of the RC5 regions and therefore remove scenarios that do not resolve these regions. This is done on a regional level such that a scenario can be used for all regions it contains. While we allow negative emissions, we do remove scenarios that have negative emissions exceeding 20 Gt per year (AR5 N2 category). We also remove the GCAM EMF27 mitigation scenarios and the GCAM LIMITS 450 ppm and 500 ppm scenarios as they show negative total emissions for R5LAM and / or R5MAF before 2040 with emissions rising afterward, which is problematic for the pathway extension methods and contrary to the idea of continuation of climate policy at a similar level of ambition. Scenarios which assume a sudden increase in climate policy ambition after 2030 (AR5DB policy categories P3 and P4) are also removed. Figures S31–S40 in the supporting information illustrate the scenario filtering.

All remaining scenarios are harmonized using a two-step method. To account for different region definitions and historical emissions used during scenario generation, we harmonize the emissions (excluding land use) in 2005 to historical emissions (PRIMAP-hist + CDIAC for international transport) with a constant factor (i.e., the whole scenario is multiplied by a factor such that 2005 emissions coincide with historical emissions). In a second step, we harmonized to 2010 emissions with a harmonization factor linearly approaching 1 in 2050. Some scenarios start in 2010 only. In that case we harmonize with a constant factor in 2010 making the second harmonization step unnecessary. The effect of harmonization on the scenario database is illustrated in Figures S41–S46 in the supporting information.

Land use data are not harmonized because of the high variability of 2005/2010 emissions in the scenario database. Historical land use emissions data have high uncertainty and emissions estimates depend strongly on the methodology used, and the activities and land areas included. Thus, the variability is high between different sources for historical land use emissions data and the historical sources used by the models that contributed to the AR5DB are not harmonized. Different scenarios in the AR5DB even have positive and negative emissions for the same region.

We chose 2010 as final harmonization year because the methods presented in this study are used to assess temperature implications of countries pledges and to track their changes. For this purpose it is important to keep the scenario database constant to allow tracking of pledges rather than scenario changes through harmonization to different historical emissions. The effect of the harmonization year on the projected warming is not negligible (supporting information, Figures S22, S23, S26, and S27). To test if the methods work if the harmonization year is not the last historical year, we used 2010.

Table 3
The 2030 Emissions for NDC and Trend Assessments

	NDC fact sheets		Climate Action Tracker			
Pathway extension method	NDC low	NDC high	NDC low	NDC high	Trend low	Trend high
Asia	24.1 (24.8)	27.9 (28.5)	23.9 (24.6)	25.1 (25.7)	24.4 (25.1)	25.5 (26.2)
Latin America	4.1 (4.2)	4.1 (4.2)	4.0 (4.2)	4.4 (4.5)	4.5 (4.7)	4.6 (4.7)
OECD	11.6 (12.4)	11.6 (12.4)	10.3 (11.1)	11.1 (11.9)	13.0 (13.9)	13.9 (14.8)
Middle East and Africa	8.4 (8.7)	8.4 (8.7)	7.3 (7.6)	8.2 (8.5)	8.6 (8.9)	8.8 (9.1)
Reforming economies	5.4 (5.5)	5.6 (5.8)	5.4 (5.6)	5.7 (5.9)	5.3 (5.4)	5.7 (5.9)
World	53.6 (55.7)	57.7 (59.7)	51.0 (53.0)	54.4 (56.4)	55.7 (57.9)	58.4 (60.7)

Note. Emissions excluding emissions from international transport are shown on the left, and emissions including bunkers are in parentheses. All values in GT CO_2 eq. OECD = Organisation for Economic Co-operation and Development.

7.3. Sensitivity Analysis

To analyze the sensitivity of the methods, we create 31 short-term scenarios for each region. The scenarios are linear pathways from 2014 historical emissions to 2030 where the 2030 emissions cover the range of 2.5% to 97.5% of the harmonized AR5DB emissions for each region. Each of the regional NDC scenarios is extended with all methods and cumulative 2011 to 2100 emissions are calculated. These results are shown directly in the regional figures (Figure 2 and similar figures in the supporting information). The global values are computed from regional values. As several combinations of regional emissions lead to the same global emissions, we obtain ranges of cumulative global emissions for a given 2030 global emissions level. To calculate the ranges, we create all combinations of regional emissions levels and sort them into 1,000 bins according to equally sized intervals of the whole 2030 emissions range of roughly 28 to 80 Gt CO_2 eq. Bins with less than 16 scenarios are merged with adjacent bins until the minimal size of 16 is reached. For each of the resulting bins we calculate a median and confidence intervals, which are the basis of Figure 3. The median is a numerical value and does not necessarily correspond to a likely distribution of regional emissions. This is illustrated by the results for NDCs and current policy projections shown in Figures 3 and 2, some of which are far from the median at the very border of the 98% interval.

7.4. NDC Analysis

The NDC values from the fact sheets (Meinshausen & Alexander, 2016) include land use emissions. For the CAT values Rocha et al. (2016) we sum land use and fossil fuel emissions. To include bunkers values in the NDCs, we use the CAT bunkers pathways for the NDC high and low and trend high and low cases. These pathways are global. We split them to the five regions using historical (2014) shares from CDIAC Boden et al. (2017). Depending on the scenario, global bunkers emissions are between 2.0 and 2.3 Gt CO_2 eq. Table 3 contains all 2030 emissions values both excluding and including bunkers.

To calculate the temperature implied by the different NDC and trend assessments, we use the set of 2030 pathways calculated for the sensitivity analysis and interpolate linearly between the temperatures implied by the two nearest 2030 emissions levels. A full calculation with an explicit NDC pathway might lead to slightly different temperatures.

7.5. Historical Data

For national emissions we use the PRIMAP-hist time series version 1.1 (Gütschow et al., 2016, 2017). We sum the national time series to the RC5 regions and complement with CO_2 from international transport from the CDIAC 2017 release (Boden et al., 2017). We have no data source for non-CO_2 emissions from international transport from which emissions can be attributed to countries or regions. As more than 99% of international transport Kyoto GHG emissions comes from CO_2, we omit the non-CO_2 emissions (Boden et al., 2017; JRC, 2013).

7.6. Relating Cumulative Emissions to Temperature Change

We use cumulative emissions as a proxy for assessing the temperature rise implied by the different extended pathways. This approach saves the large amounts of computing time that would be required run the probabilistic MAGICC setup for all individual pathways of the sensitivity analysis.

The relationship between cumulative emissions and global mean temperature rise is established in the following way. First, we take all scenarios from full-gas, full-sector models from the AR5 scenario database

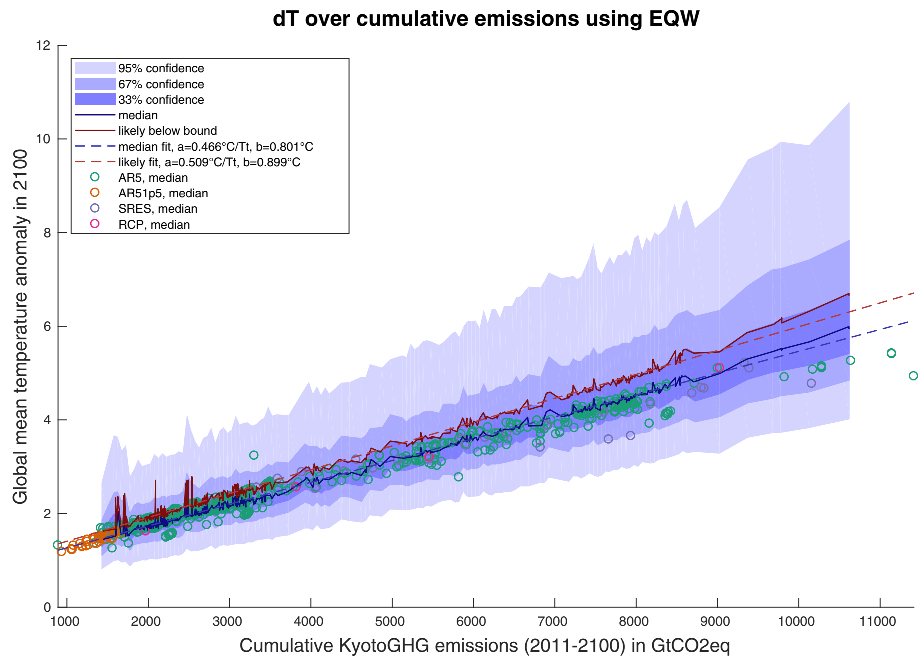

Figure 5. Probability distribution for global mean temperature rise for a given cumulative Kyoto greenhouse gas (GHG) budget using the Equal Quantile Walk (EQW). The median (blue line) and the 67th quantile (red line), which defines the bound for "likely below X" temperature increase, are almost linear. The individual marks are multigas scenarios that have not been derived using the EQW and illustrate that the linear relation is only true when using the EQW and not a direct property of the climate system. The ranges are calculated by first grouping scenarios according to their cumulative 2011 to 2100 Kyoto GHG emissions. Each group is 50 Gt CO_2 eq wide. For each group we take all 600 runs from each scenario in that group and collectively calculate the ranges.

(IIASA, 2014), except the class "N2" negative emissions scenarios and scenarios that are not defined until 2100. All remaining 686 scenarios are harmonized to historical emissions as described in section 7.2. The harmonized fossil and industrial emissions pathway for cumulative Kyoto GHGs is used together with the unharmonized land use pathway as input to the EQW.

We then compute the temperature rise (median and "likely below") using the historically constrained probabilistic setup for the reduced complexity climate model MAGICC (Meinshausen et al., 2009, 2011) using the same model version and parameters as used for the CAT (Climate Action Tracker, 2015) and the UNEP Emissions Gap Report (UNEP, 2015; climate sensitivity distribution from Rogelj, Meinshausen, & Knutti, 2012; historical reference period in accordance with IPCC, 2013; see supporting information, Text S9). For each individual scenario, we also calculate the cumulative 2011 to 2100 Kyoto GHG emissions. Figure 5 shows the resulting relation between cumulative emissions and temperature rise. Results for all individual runs are presented in Figure S48 in the supporting information. Using the EQW method to obtain multi gas emissions pathways, we obtain an almost linear relation between cumulative emissions and median warming. The same holds for the 67th Quantile which defines the temperature which are likely (in IPCC terms) not surpassed. The deviation from the median for individual scenarios are likely due to large negative land use emissions, as they are much smaller if a fixed land use pathway is used (supporting information, Figure S49). However, it is important to note that this linear relation is a property of the equal quantile walk and not of the climate system (nor a modeling artifact of MAGICC) To illustrate this, we ran several independent multi gas scenarios through the same probabilistic MAGICC setup. They are shown as individual marks in Figure 5 and do not all fall on the median line of the EQW multigas pathways. The reason is that general multigas pathways can have very different emission profiles for the individual gases while having the same aggregate Kyoto GHG emissions. EQW pathways with similar Kyoto GHG pathways have similar pathways for all individual gases. Furthermore, the EQW is based on 40 SRES and 14 post-SRES scenarios Meinshausen et al. (2006) which assume different gas mixes and pollutant emissions than current scenarios. We correct for the continuing high sulfur emissions from fossil fuel burning (Schaeffer et al., 2015), but for other gases the EQW reproduces the gas mix of the older scenarios (supporting information, Text S8).

To calculate median temperature rise from cumulative emissions, we use a linear fit to the median values for the individual scenarios. We also use a linear fit to the 67th quantile to calculate the highest temperature rise that will not be surpassed with a likely probability. We obtain

$$T_{\text{md}} = E_{\text{cum}} 0.466^{\circ}\text{C}/\text{TtCO}_2\text{eq} + 0.801^{\circ}\text{C}, \tag{3}$$

for median warming, and

$$T_{\text{lb}} = E_{\text{cum}} 0.509^{\circ}\text{C}/\text{TtCO}_2\text{eq} + 0.899^{\circ}\text{C} \tag{4}$$

for the likely below limit. The analysis with a fixed land use pathway (supporting information, Figure S49) gives results with a deviation of less than 1% for the inclination and less than 8% (about 0.05°C) for the offset. The cumulative emissions to temperature relation is therefore robust with respect to the use of different scenario sets.

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