Climatic Change (2021) 164: 24
https://doi.org/10.1007/s10584-021-02982-9

A future perspective of historical contributions to climate change

Ragnhild B. Skeie[1] · Glen P. Peters[1] · Jan Fuglestvedt[1] · Robbie Andrew[1]

Received: 22 August 2019 / Accepted: 6 January 2021 / Published online: 28 January 2021
© The Author(s) 2021

Abstract
Countries' historical contributions to climate change have been on the agenda for more than two decades and will most likely continue to be an element in future international discussions and negotiations on climate. Previous studies have quantified the historical contributions to climate change across a range of choices and assumptions. In contrast, we quantify how historical contributions to changes in global mean surface temperature (GMST) may change in the future for a broad set of choices using the quantification of the shared socioeconomic pathways (SSPs). We calculate the contributions for five coarse geographical regions used in the SSPs. Historical emissions of long-lived gases remain important for future contributions to warming, due to their accumulation and the inertia of climate system, and historical emissions are even more important for strong mitigation scenarios. When only accounting for future emissions, from 2015 to 2100, there is surprisingly little variation in the regional contributions to GMST change between the different SSPs and different mitigation targets. The largest variability in the regional future contributions is found across the different integrated assessment models (IAMs). This suggests the characteristics of the IAMs are more important for calculated future historical contributions than variations across SSP or forcing target.

Keywords Paris Agreement · Historical contribution · Brazilian proposal · Shared socioeconomic pathways · Equity

1 Introduction

The Paris Agreement changed the role of historical responsibilities in international climate negotiations (Skeie et al. 2017). Previously, the Kyoto Protocol was designed as a top-down agreement with a total cap on emissions for the Annex B countries. While it had been

✉ Ragnhild B. Skeie
r.b.skeie@cicero.oslo.no

[1] CICERO Center for International Climate Research, Pb. 1129 Blindern, 0318 Oslo, Norway

suggested to use historical contributions to global mean temperature change to distribute emission allocations to countries in the international climate agreement (the so-called "Brazilian proposal" (UNFCCC 1997)), it was found to be difficult to use in the international negotiations (e.g., Fuglestvedt and Kallbekken 2016). The process leading to the Paris Agreement turned from designing a top-down agreement to a bottom-up agreement. Now, individual countries decide how much they are willing to reduce their emissions. The nationally determined contributions (NDCs) are national pledges that contribute to meeting the objectives of the United Nations Framework Convention on Climate Change (UNFCCC). With the Paris Agreement, historical responsibilities may again have a role to play: According to the "Lima Call for Action" (UNFCCC 2014), NDCs should be fair and ambitious (Peters et al. 2015), but it is up to parties themselves to demonstrate this, leaving open the potential use of historical contribution as an argument on the international stage and also as an element in countries' domestic discussions of negotiating positions and ambitions. Because countries are required to submit revised national contributions every 5 years, historical contribution to climate change may become even more relevant in the future. Consideration of historical contribution is also likely to play a key role in the future discussions about loss and damage (James et al. 2019; Otto et al. 2017; Skeie et al. 2017).

Relative regional and national historical contributions to global warming have changed considerably over recent decades. Estimated shares of historical contributions were quite different when "historical responsibilities" were first put on the agenda in 1997 than they are today. When considering CO_2 emissions from fossil sources from 1850, the historical contribution in 1997 was 76% for the Annex I countries, while in 2012, this share had declined to 68% (Skeie et al. 2017). There has been a rapid increase in emissions in developing countries over the past decades (Le Quéré et al. 2018), and the regional share of total greenhouse gas emission will change in the near future due to the differences in the trajectories of income, population, resources, technologies, and capacity (Riahi et al. 2017), leading also to changed historical contributions to global warming in the future (Höhne et al. 2011; Rive et al. 2006; Ward and Mahowald 2014).

A number of studies have focused on regional historical contribution to global warming for various assumptions using simple or more complex models (den Elzen et al. 2005; den Elzen et al. 2013; Höhne et al. 2011; Li et al. 2016; Matthews et al. 2014; Ward and Mahowald 2014; Wei et al. 2012). A recent study by Skeie et al. (2017) showed systematically that different adopted perspectives had a strong effect on the calculated historical contribution to global warming. Here, we take a step further and illustrate, for different perspectives, how the contributions to global mean surface temperature change may change over the coming decades and discuss other perspectives that may need to be considered. The traditional method to allocate emissions to countries is allocating the emissions occurring within the country's borders. Future flexible mechanisms and emission trading may challenge the use of traditional territorial accounting when assessing contribution to climate change, as well as carbon dioxide removal (Peters and Geden 2017). How should carbon dioxide removal be allocated between the countries involved from biomass growth, harvest, energy production and CO_2 capture, and eventual storage? For the flexible mechanisms, should the emission reduction be allocated to the country buying quotas or to the country where the emission reduction occurs?

To illustrate potential future historical contributions to global temperature change, we use the shared socioeconomic pathways (SSPs) (Riahi et al. 2017) and a simple climate model (Skeie et al. 2017). The quantified SSPs are grouped into five geographical regions, allowing the analysis of how future historical contributions are distributed across those regions. Further,

the SSPs span five socioeconomic pathways, six levels of global warming, and six integrated assessment models (IAMs), allowing a deeper analysis of how historical contributions depend on these different dimensions.

2 Method

We follow the method used in Skeie et al. (2017), using a simple climate model and emission inventories to calculate regional contributions to global mean surface temperature (GMST) change. The results are presented as relative contribution to GMST change, where the total is the sum of each individual region contribution to GMST change. In addition to historical emission inventories, we use SSPs to illustrate and discuss the future perspective of historical contribution to global warming (Fig. 1). A main point in Skeie et al. (2017) was that various scientific and policy choices influence the calculations of historical contributions for individual countries, and Skeie et al. (2017) quantified the effects of different choices. In this study, we limit our analysis to three different *start years* (1850: pre-industrial, 1992: UN Framework Convention on Climate Change (UNFCCC), and 2015: the Paris Agreement) and two *sets of components* (CO2FF: CO_2 from fossil fuel combustion and cement production and KP: Kyoto Protocol gases, which in principle means CO2FF, CO_2 from land-use change (LUC), CH_4 and N_2O as the impacts of SF_6, PFC and HFCs on calculated relative contributions are negligible (Skeie et al. 2017)) using regional territorial-based emissions and GMST as indicators of climate change. There are several other methodological choices that can be made that will influence the results (Skeie et al. 2017); however, to make the analysis tractable, we focus on a limited number of key dimensions.

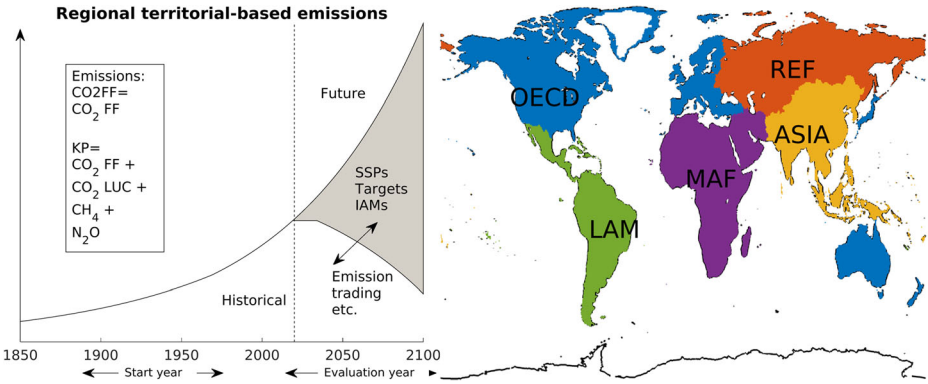

Fig. 1 Schematic overview of the setup of the simulation. The regional historical and future emissions considered are grouped into two sets of components, CO2FF and KP. A wide range of future scenarios is considered, generated by different IAMs, considering different SSPs and with different mitigation targets. The calculations of relative contribution to global mean surface temperature change are performed with different start years and results presented for different evaluation years. The historical relative contributions to global mean surface temperature change are calculated based on the traditional territorial-based emissions, but emission trading might confound the traditional territorial emission accounting. The five regions considered in this study are indicated by colors and abbreviation in the map. The regions are the OECD, countries from the Reforming Economies of Eastern Europe and the Former Soviet Union (REF), ASIA, the Middle East and Africa (MAF), and Latin America and the Caribbean (LAM)

2.1 Model

The CICERO Simple climate model (SCM) consists of an energy balance/upwelling diffusion model (Schlesinger et al. 1992) and a carbon cycle model (Joos et al. 1996) as well as simplified calculations from emissions via concentrations or directly to forcing. A detailed description of the model is presented by Skeie et al. (2017). A recent study showed that methane forcing is significantly stronger than previously thought (Etminan et al. 2016), and new expressions of CO_2, CH_4, and N_2O radiative forcing presented in that study are now implemented in the SCM. For CO_2 and N_2O, the change is minimal; however, for methane, the revision is significant, with 25% stronger forcing than presented in the IPCC Fifth Assessment Report (Myhre et al. 2013). The indirect aerosol forcing is now linearly scaled with SO_2 emissions, as studies indicate that the total global effect is linear (Kretzschmar et al. 2017) rather than logarithmic as previously specified in the model. A set of model parameters with an inferred effective climate sensitivity of 2.0 °C and the corresponding aerosol forcing from Skeie et al. (2018) is used. Because the main focus of this study is changes in the relative contribution to GMST change, uncertainties in model version are of limited importance due to cancelations of the climate system response uncertainties when relative contributions are calculated.

2.2 Setup

The future emissions scenarios used in this study are from the SSP V2.0 database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about) (Riahi et al. 2017). These scenarios are available for the following five geographical regions: OECD (defined as the OECD members in 1990 and EU member states and candidates), REF (countries from the Reforming Economies of Eastern Europe and the Former Soviet Union), ASIA (most Asian countries with the exception of the Middle East, Japan, and Former Soviet Union states), MAF (the Middle East and Africa), and LAM (Latin America and the Caribbean) (Fig. 1). We could not perform the analysis at the country level since scenario emissions are not available at this level.

There are in total 127 scenarios grouped into six radiative forcing levels (FLs) or mitigation targets (FL1.9: 1.9 Wm^{-2}, FL2.6: 2.6 Wm^{-2}, FL3.4: 3.4 Wm^{-2}, FL4.5: 4.5 Wm^{-2}, FL6.0: 6.0 Wm^{-2}, and BASELINE) as well as five shared socioeconomic pathways (SSPs). We use the term "forcing levels" as in the literature (O'Neill et al. 2016; Riahi et al. 2017) to distinguish from the specific representative concentration pathways (RCPs) as used in the IPCC Fifth Assessment Report. The five pathways are SSP1: sustainability, SSP2: middle of the road, SSP3: regional rivalry, SSP4: inequality, and SSP5: rapid growth (O'Neill et al. 2014). Each SSP and forcing level has been implemented across multiple IAMs. With six IAMs, six FLs, and five SSPs, there are in theory 180 scenarios, but not all IAMs tried every SSP and FL combination and some IAMs were unable to meet the highest and lowest forcing levels for some SSPs (Rogelj et al. 2018). In total, there are 127 scenarios distributed across different forcing levels: FL1.9: 13, FL2.6: 19, FL3.4: 25, FL4.5: 25, FL6.0: 19, and BASELINE: 26. The results from calculations of contributions are presented according to the (i) forcing level, (ii) SSP, and (iii) IAM used to generate the scenario emissions.

Two sets of components are included; *only CO_2 fossil fuel* and the group of the main *Kyoto Protocol components* total CO_2, N_2O, and CH_4. Short-lived components including aerosols are not included to make the analysis more tractable. Our previous study showed that the relative contributions from the different countries did not change strongly from the Kyoto Protocol component results if short-lived warming and cooling components were included (Skeie et al. 2017).

To calculate the climate impact of each region, we first run the SCM with all anthropogenic emissions included and then run the SCM with emissions from each region removed one-by-one, and the change in GMST is calculated as the difference between global (control) and regional (perturbed) run. There are different approaches to account for the non-linearities in the climate response as discussed in Trudinger and Enting (2005), and here, the emission perturbations are scaled down to 10%. The relative contribution to GMST change is given in relation to the sum of each individual region's contribution to GMST change; hence, the contribution from all regions adds to 100%. The background scenarios used in the SCM for the control are one of the four RCPs (van Vuuren et al. 2011), chosen based on the total forcing in 2100 for each of the SSP scenarios: RCP2.6: < 3.6 Wm^{-2}, RCP4.5: 3.6 to 5.2 Wm^{-2}, RCP6.0: 5.2 to 7.3 Wm^{-2}, and RCP8.5: > 7.3 Wm^{-2}.

In this study, we have chosen to use three different start years: 1850, 1992, and 2015 (corresponding to pre-industrial period, signing of UNFCCC, and the Paris Agreement). The model is run with emission perturbation from the start year until 2100 and we focus on five evaluation years, 1992, 2015, 2030, 2065, and 2100.

The historical emissions used in this study are from Le Quéré et al. (2018) for CO_2 (fossil fuels and cement), Hoesly et al. (2018) for methane, and EDGARv432 (Janssens-Maenhout et al. 2019) from 1970 to 2012 scaled backward using emission data from MATCH (Höhne et al. 2011) for N_2O. Historical emissions for CO_2 from land-use change are taken from Houghton and Nassikas (2017). There are uncertainties in the historical emission estimates, especially for CO_2 emissions from land-use change (Le Quéré et al. 2018). This will especially influence results using 1850 as start year when land-use change emissions are included. Results using 1992 as start year are obviously less influenced by historical emissions, and 2015 as start year uses only (future) scenario data. The focus of this paper is on the future developments and contributions, but we are aware of the uncertainties in the historical emissions and their impacts on the calculated regional relative contributions for early start years. The historical emissions are aggregated to the five chosen regions.

The regional emissions in the last year of the historical inventory generally do not match the scenario emissions for the same year. The differences between the historical inventory and the scenario emissions are as follows: (1) different historical emission inventories are generally used by each IAM and (2) the scenarios are often started in 2010 or 2015 and thus diverge from historical emissions, which are up to a more recent year. It should also be noted that uncertainties in the current anthropogenic emissions of CH_4 and N_2O are substantial (Saunois et al. 2020; Tian et al. 2020), particularly for land-use-related CO_2 emissions (Friedlingstein et al. 2019). We have chosen to linearly interpolate the regional emissions between the end year of the historical inventory (N_2O: 2012, CH_4: 2014, CO_2 FF: 2017, CO_2 LUC: 2015) and year 2020 of the scenario (see supporting Fig. S1–S4) as our focus is future contribution to warming and we want to avoid unnecessarily manipulating the original scenarios. Other methods to harmonize historical emissions and scenarios exist (Gidden et al. 2018; Rogelj et al. 2011). Different methods of harmonization will lead to slightly different results, but since we focus on the future period (post-2015), this issue is minimized. The most problematic variable is CO_2 LUC, where the regional emissions can even have the opposite sign to the historical emissions in some scenarios (see supporting Fig. S5). A reasonable transition from the historical regional emissions to the scenario emissions is hence difficult, and for this reason, no harmonization on a regional scale is performed for CO_2 LUC in the Coupled Model Intercomparison Project Phase 6 (Gidden et al. 2019).

3 Results

We will first consider the effect on the calculated relative contribution to GMST change for the choice of different evaluation years for the two sets of emission components (Fig. 2). Then, for the same set of emission components, the impact of the choice of start year is illustrated (Fig. 3). Further, the regional historical contribution (pre-2015) and the future contribution (post-2015) to GMST change in 2100 are compared across all mitigation targets and SSPs (Fig. 4). Finally, we will explore and compare the effects of SSPs, mitigation targets, and IAMs on the regional relative contribution to GMST change in 2100 (Fig. 5).

In 1992, when the climate convention was signed, the main contributing region to global mean temperature change was the OECD, with approximately 70% for start year 1850 and CO2FF (Fig. 2a). Since then, the emissions have increased rapidly in other regions (Fig. S1), and the relative contribution to GMST change from OECD is reduced for later evaluation years up to and including 2065 (Fig. 2a), regardless of assumed start year except start year 2015 (Fig. S11a, S12a). For evaluation year 2100, the relative contribution for OECD is larger than in 2065 for some scenarios with strong mitigation. In these scenarios, there is a large amount of carbon dioxide removal in the second half of the twenty-first century (Fig. S1). The carbon dioxide removal from bioenergy with carbon capture and storage (BECCS) is allocated to CO2FF, while afforestation is included in the CO2LUC emissions in the SSP database. The contribution from Asia has the opposite behavior, with increasing contribution for later evaluation years and with similar relative contribution for evaluation year 2065 and 2100 (Fig. 2a). For MAF, the relative contribution increases for later evaluation years, also from 2065 to 2100 (Fig. 2a). For the evaluation years 2065 and 2100, the relative contribution to GMST change for ASIA and OECD is similar for the weakest mitigation targets, but for stronger mitigation scenarios, the OECD has larger contribution than ASIA (Fig. 2a).

When including the other Kyoto Protocol gases, the contribution of OECD is reduced for all evaluation years (Fig. 2b) compared to the CO2FF case (Fig. 2a), a general finding from the early study on regional historical contributions (den Elzen et al. 2005). As historical CO2FF

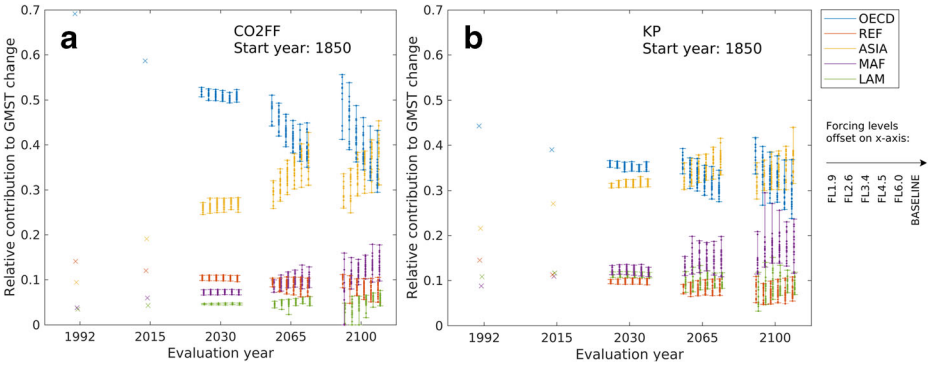

Fig. 2 Relative contribution to GMST change for different evaluation years. Regional emissions of CO2FF (**a**) and KP gases (**b**) from 1850 up to evaluation year are taken into account. The results for the different forcing levels are offset on the *x*-axis, from FL1.9 to the left to BASELINE to the right. Results for each SSP are indicated with a dot on the vertical bar spanning the maximum and minimum relative contribution to GMST change. For the historical contribution (evaluation years 1992 and 2015), the regional contributions are indicated by an *x*. The regions are the OECD, countries from the Reforming Economies of Eastern Europe and the Former Soviet Union (REF), ASIA, the Middle East and Africa (MAF), and Latin America and the Caribbean (LAM). Similar plots with start years 1992 and 2015 in the supplement (Fig. S11, S12)

emissions were dominated by OECD (Fig. S1), the regional distribution of the other emissions is more mixed (Fig. S2–S4). For 2030, the OECD contribution to GMST change is slightly larger than the contribution from ASIA, while ASIA is similar or larger for later evaluation years for all forcing targets (Fig. 2b). The contributions from LAM and MAF increase when including the other Kyoto Protocol gases, and both regions have a larger historical contribution than REF for the evaluation year 2030 for all scenarios, while in the CO2FF case, REF had the largest contribution of these three regions (Fig. 2a). It should be noted that the results for 2030 are influenced by methods used to harmonize the scenario emissions and the historical inventory. Here, we have chosen to keep the original scenario emissions post-2020 (see Section 2.2). If a uniform scaling harmonization is applied (that scales the entire pathway to match the historical emission), the spread in the results is reduced (Fig. S6). This test is only preformed for CO2FF as a reasonable transition from the historical inventory to the scenario is difficult for CO_2 LUC (see Section 2.2).

Figure 3 shows how the regional contributions to GMST change in 2100 depend on the start year (1850, 1992, 2015). For CO2FF, the earlier the start year, the smaller the contribution from ASIA and the larger the contribution from OECD (Fig. 3a), as OECD dominated the historical CO2FF emissions while ASIA currently has the largest CO2FF emissions (Fig. S1). The effect of larger contribution from developed countries for earlier start year is expected and found in previous studies (den Elzen et al. 2005; Höhne et al. 2011; Skeie et al. 2017). The contribution from MAF increases with a later start year, while REF and LAM have similar contributions for different start years. In the strongest mitigation scenario (FL1.9), scenarios make use of large-scale carbon dioxide removal (primarily afforestation and BECCS). In several of the scenarios, there are regions that contribute to cooling, with negative cumulative CO2FF emissions over the evaluation period. For these regions, we set the contribution to zero warming effect when calculating the relative contribution, implying that the regions with a positive contribution will have a larger relative contribution. Also, in the mitigation levels FL2.6 and FL3.4, there are a few scenarios where LAM and REF contribute to cooling. For start year 1850, the relative contribution to GMST change in 2100 is dependent on the mitigation target, for all regions except REF. For a strong mitigation target, there is less room

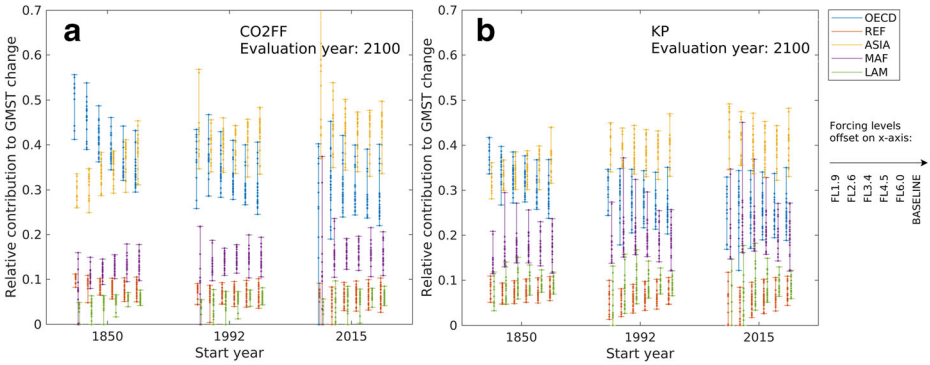

Fig. 3 Impacts of start year of emissions on the regional contribution to GMST change in 2100 for the CO2FF case (**a**) and Kyoto Protocol gases case (**b**). The results for the different forcing targets are shifted on the *x*-axis, from FL1.9 to the left to BASELINE to the right. Results for each SSP are indicated with a dot. Regions contributing to cooling are set to zero in the plot and when relative contributions are calculated. The regions are the OECD, countries from the Reforming Economies of Eastern Europe and the Former Soviet Union (REF), ASIA, the Middle East and Africa (MAF), and Latin America and the Caribbean (LAM)

for future emissions, and the relative contributions are therefore more dependent on the historical emissions. For weaker mitigation targets, the future emissions, with a different regional distribution than the historical emissions (Fig. S1), hold a larger share of the total cumulative emissions and hence influence the relative contribution in 2100 to a larger degree than for the strong mitigation targets. For a late start year, there is less variability on relative contributions between the mitigation targets, indicating relative mitigation contributions are similar across regions, perhaps because IAMs often seek cost-effective mitigation pathways.

Looking at the case including the Kyoto Protocol gases (Fig. 3b), compared to CO2FF (Fig. 3a), the contribution from OECD is reduced. The contribution from MAF and LAM is increased due to the higher share of methane and land-use change CO_2 emissions from these two regions compared to the other regions (Fig. S2–S3). Compared to the CO2FF case, there is less variation across the chosen start years, because of different temporal development of CO_2 LUC emissions (Fig. S2) and inclusion of methane with its shorter lifetime, and therefore, there is no influence on the temperature response in 2100 for the early emissions. For start year 2015 (at the time of the Paris Agreement), the relative contribution to GMST change from MAF overlaps with the contribution from the OECD for the evaluation year 2100 for most of the scenarios, compared to almost no overlap if only CO2FF is included (Fig. 3a) except forcing target FL1.9.

In order to compare the historical contributions from 1850 to 2015 to the contributions from 2015 to 2100 to the temperature response in 2100, an additional set of simulations is performed, where the temperature response in 2100 is calculated due to the regional emissions for the years 1850 to 2015. This set of simulations is combined with simulations with start year 2015, so that the historical contributions in 2100 can be split into two, the contribution from 1850 to 2015 and 2015 to 2100. The results for the KP case are presented in Fig. 4 where historical (darker colors) and future contribution (lighter colors) for each region to the temperature change in 2100 are shown. A pie chart is shown for each set of mitigation targets and SSPs. As expected, the stronger the mitigation target, the smaller the contribution of 2015–2100 emissions to temperature change in 2100. For strong mitigation (e.g., FL2.6), historical OECD emissions have the largest share of contribution to GMST change in 2100 (22%), while the share is reduced to 7 to 12% (depending on SSP) for BASELINE. For weak mitigation (BASELINE), the contribution from post-2015 emissions from ASIA has the largest share of GMST change in 2100 (31 to 34% depending on SSP). Regardless of SSP or forcing level, ASIA and MAF have a much larger contribution from 2015 compared to before 2015. ASIA is the region with largest emissions in 2015 (Fig. S1–S4) for all components considered except CO_2 LUC, and it is assumed to continue to be the regions with the largest emissions over the next decades in the scenarios. ASIA's CO2FF emissions have increased rapidly over the last decades (Fig. S1), and hence, the region has a small share of the historical global emissions when compared with its current share. Currently, MAF has a small share of the historical emissions, but in all scenarios, a strong increase in both population and GDP growth is assumed (Fig. S7–S8), giving a larger share of post-2015 emissions compared to pre-2015 in all scenarios. The other three regions, OECD, REF, and LAM, have a more equal contribution before and after 2015, but with a larger share of pre-2015 emissions for strong mitigation and larger share of post-2015 emissions for weak mitigation.

Notable changes in the regional contributions across forcing target for each SSP are seen, especially when the regional contributions are split into post- and pre-2015 contributions (Fig. 4, across the rows). However, for a given mitigation target, there is no clear pattern of change in the regional contribution for the different SSPs (Fig. 4, down the columns). We will now

investigate the surprisingly little difference in regional variations across the SSPs. As we saw in Fig. 3, there was also little variability in the relative contributions between the mitigation targets for late start year, which indicated the models produce similar relative mitigation levels across regions. To remove the influence and inertia from the earlier historical period up until 2015, we focus on the regional contribution to GMST change in 2100 for emissions occurring in the period 2015 to 2100. We add a third dimension when presenting the results, the IAMs used to generate the scenario emissions.

The results for KP are presented in three different ways, including the three dimensions SSPs, forcing levels, and IAMs (Fig. 5). A first observation is that there is no clear or obvious trend in any of the three dimensions. This suggests that the SSPs do not have sufficient detail to differentiate historical contribution for these geographical regions, though SSP3 shows a more distinct difference in the regional contribution from ASIA and OECD. For example, SSP1 and SSP5 have lower inequality compared to SSP3 and SSP4, but this does not translate to macrolevel differences in how the regions may develop or implicitly allocate mitigation obligations. The similar variations across forcing targets indicate that mitigation follows the

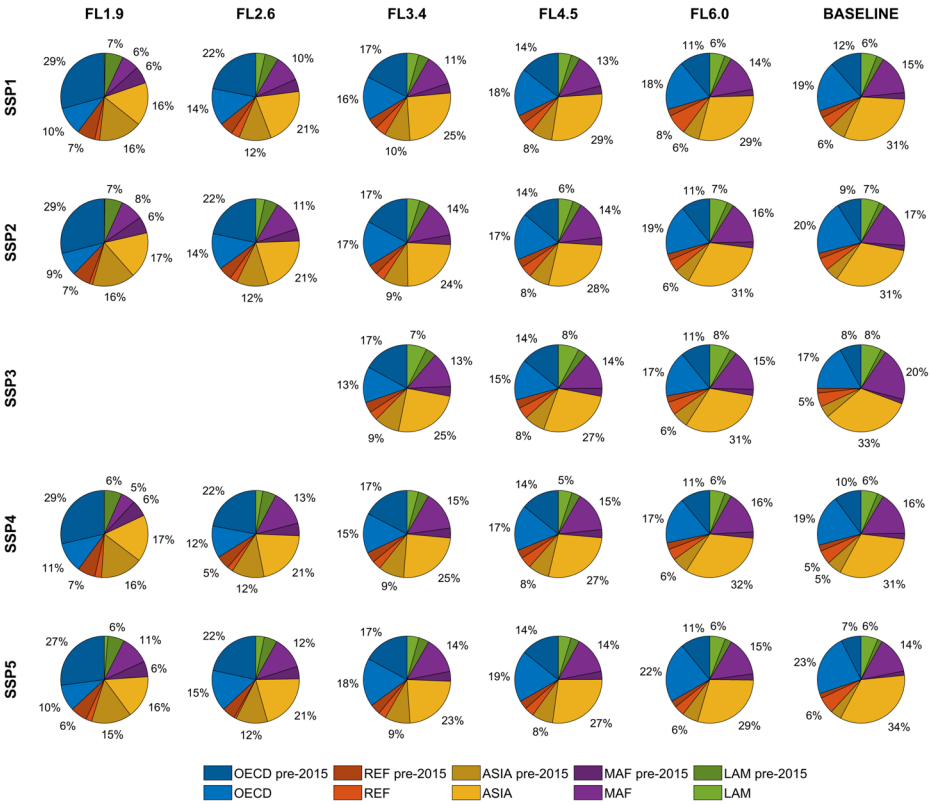

Fig. 4 Relative contribution to GMST change in 2100 from different regions and time periods for KP. Dark colors indicate regional contribution due to emissions in the period 1850 to 2015, while lighter colors indicate regional contribution due to emissions over the period 2015 to 2100. Contributions are plotted for each mitigation and SSP. The median temperature response in 2100 is used for this figure. The regions are the OECD, countries from the Reforming Economies of Eastern Europe and the Former Soviet Union (REF), ASIA, the Middle East and Africa (MAF), and Latin America and the Caribbean (LAM). A similar figure for CO2FF in the supplement (Fig. S9)

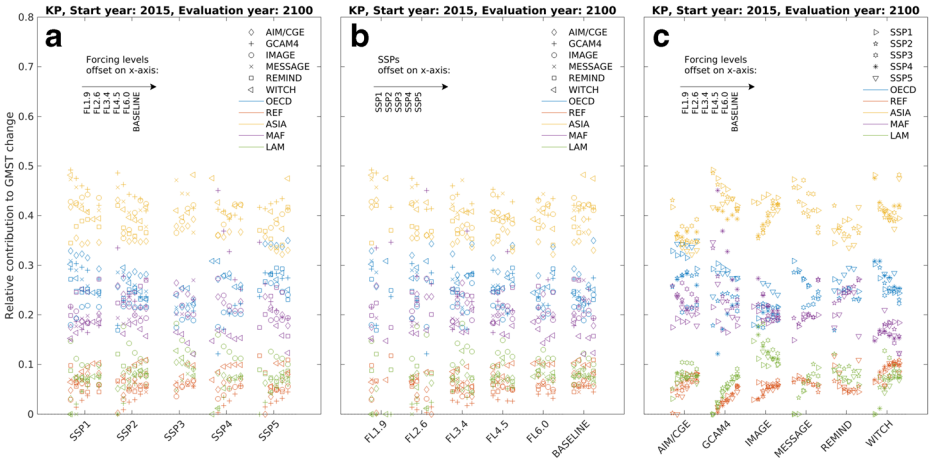

Fig. 5 Relative contribution to GMST change in 2100 for regional emissions of Kyoto Protocol gases with start year 2015. The results are presented in three different ways, with SSPs on the *x*-axis with minor offset on the *x*-axis for the forcing targets (**a**), with forcing targets on the *x*-axis with minor shift on the *x*-axis for the SSPs (**b**), and with IAMs on the *x*-axis and minor shift in the *x*-axis for the SSPs (**c**). The regions are the OECD, countries from the Reforming Economies of Eastern Europe and the Former Soviet Union (REF), ASIA, the Middle East and Africa (MAF), and Latin America and the Caribbean (LAM). A similar figure for regional emissions of CO2FF in the supplement (Fig. S10)

same allocation rules, regardless of SSP or IAM. Since the same distribution occurs under reference and deep mitigation scenarios, and across SSPs, it may indicate that the cost-effective mitigation in IAMs is essentially equivalent to grandfathering (allocating according to the current distribution of emissions).

While the SSPs are designed to include aspects of inequality, that does not translate into historical contributions. There are two key reasons for this. First, the SSPs apply to the whole world, and different SSPs are not mixed across regions. For example, in an SSP3 Regional Rivalry world, all regions have the same assumptions, likewise for all other SSPs. Second, IAMs are solved in a cost-optimizing way, meaning they reduce emissions where it is cheapest. While some of the SSPs introduce climate policy at a different rate (Riahi et al. 2017), this fragmentation quickly dissipates by 2040. Effectively, the SSPs were not designed specifically to introduce equity dimensions into stringent mitigation, and thus, it would not be expected that a large variation occurs in historical responsibility for a given SSP with no, weak, or strong mitigation. It should be noted that not all IAMs were able to resolve some of the lowest forcing levels for all SSPs (Rogelj et al. 2018), meaning there may be different models in each SSP-FL subgroup. However, we do not see a variation between the SSPs at higher forcing levels either where all models are included, suggesting that scenario bias across IAMs or SSPs is not a factor.

The most significant difference across the three dimensions seems to be the IAMs, indicating that the IAM used to generate emissions pathways is more important for calculated future contributions than the SSP or forcing target. When holding the IAM constant (Fig. 5c), it also reveals more structure across SSP and forcing target. AIM/GGE and REMIND clearly lead to lower contributions from ASIA; IMAGE has a lower contribution for OECD and a larger contribution from LAM and WITCH and a lower contribution for MAF compared to the other IAMs. GCAM clearly shows variation across forcing target for REF and LAM, and

MESSAGE for LAM, with larger contributions for larger forcing targets. GCAM has lower contribution for ASIA with SSP4 and significantly higher contribution for MAF compared to the rest of the SSPs. A closer inspection across the IAMs reveals different sub-patterns across SSPs and forcing levels. Within each of the IAMs, there may be particular aspects that drive these patterns, but it is beyond the scope of this paper to be able to analyze those aspects.

4 Conclusion

We estimated the future contributions to GMST change using emission scenarios spanning five geographical regions, five shared socioeconomic pathways (SSPs), six radiative forcing levels, and six IAMs and investigated causes of variations across these selections. We find that the period 1850 to 2015 is important for future contributions, due to the inertia effects of long-lived greenhouse gases accumulating in the atmosphere (CO_2 and N_2O), and increasingly more important for strong mitigation scenarios (e.g., 1.5 and 2 °C) due to less room for future emissions. Since the SSPs incorporate a broad range of socioeconomic characteristics that affect the challenges to mitigation and adaptation, it could be expected that the future contributions vary by SSP. We found that from 2015 to 2100, there is surprisingly little variation across SSPs and forcing levels to the regional contributions to GMST change. This suggests that mitigation occurs at similar rates in the different regions for a given mitigation scenario, which is expected as a consequence of the cost-effective pathways followed in most IAMs (mitigation occurs where it is cheapest). If the scenarios were set up with a stronger equity dimension, for example, by having much earlier and deeper mitigation in wealthier countries, then more variations may be seen. The calculations were performed for five large geographical regions, and it may be that much more variation would be found at a disaggregated level. Larger variations are found across IAMs, but the pattern varies across IAMs for SSP and forcing targets. This indicates that the choice of IAM is more important for calculated future contributions than either SSP or forcing target.

We considered emission scenarios for five large geographical regions to illustrate future historical contributions to GMST change. On a more detailed country level, additional complications may arise. First, contributions based on the traditional accounting of territorial emissions may become complicated in the future if flexibility mechanisms are increasingly used. The Paris Agreement has provisions for the use of flexibility mechanisms (e.g., emission trading), but it still remains unclear as to what extent the flexibility mechanisms will be used in the future (UNFCCC 2018). Second, most mitigation scenarios use carbon dioxide removal (particularly afforestation and BECCS), and at the regional and country level, this eventually leads to negative contributions to climate change. Particularly at the detailed country level, how to deal with carbon dioxide removal may lead to additional allocation challenges.

The scenarios we used span a range of possible futures up to 2100, and we have used these to illustrate future regional contributions to climate change. Although the countries have submitted NDCs, we do not know if they will be fulfilled or what role flexible mechanisms may play. Countries have only specified commitments until 2025 or 2030 (Gütschow et al. 2018), but the NDCs can be strengthened and will eventually be extended post-2030. The NDCs are required to be fair and ambitious (Peters et al. 2015), and historical contributions could play a role in helping to assess if an NDC is fair and ambitious. The politically contentious issue of countries' historical contributions to climate change will no doubt be brought on the agenda in the future, both when countries strengthen their NDCs and possibly in loss and damage discussions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-021-02982-9.

Acknowledgments This work was funded by the Norwegian Ministry of Foreign Affairs.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

den Elzen M et al (2005) Analysing countries' contribution to climate change: scientific and policy-related choices. Environ Sci Pol 8:614–636. https://doi.org/10.1016/j.envsci.2005.06.007

den Elzen MJ, Olivier JJ, Höhne N, Janssens-Maenhout G (2013) Countries' contributions to climate change: effect of accounting for all greenhouse gases, recent trends, basic needs and technological progress. Clim Chang 121:397–412. https://doi.org/10.1007/s10584-013-0865-6

Etminan M, Myhre G, Highwood EJ, Shine KP (2016) Radiative forcing of carbon dioxide, methane, and nitrous oxide: a significant revision of the methane radiative forcing. Geophys Res Lett 43:12,614–612,623. https://doi.org/10.1002/2016GL071930

Friedlingstein P et al (2019) Global Carbon Budget 2019. Earth Syst Sci Data 11:1783–1838. https://doi.org/10.5194/essd-11-1783-2019

Fuglestvedt JS, Kallbekken S (2016) Climate responsibility: fair shares? Nat Clim Chang 6:19–20. https://doi.org/10.1038/nclimate2791

Gidden MJ, Fujimori S, van den Berg M, Klein D, Smith SJ, van Vuuren DP (2018) Riahi K, A methodology and implementation of automated emissions harmonization for use in integrated assessment models environmental modelling & software. 105:187–200. https://doi.org/10.1016/j.envsoft.2018.04.002

Gidden MJ et al (2019) Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. Geosci Model Dev 12:1443–1475. https://doi.org/10.5194/gmd-12-1443-2019

Gütschow J, Jeffery ML, Schaeffer M, Hare B (2018) Extending near-term emissions scenarios to assess warming implications of Paris Agreement NDCs Earth's future. 6:1242–1259. https://doi.org/10.1002/2017EF000781

Hoesly RM et al (2018) Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). Geosci Model Dev 11:369–408. https://doi.org/10.5194/gmd-11-369-2018

Höhne N et al (2011) Contributions of individual countries' emissions to climate change and their uncertainty. Clim Chang 106:359–391. https://doi.org/10.1007/s10584-010-9930-6

Houghton RA, Nassikas AA (2017) Global and regional fluxes of carbon from land use and land cover change 1850–2015. Global Biogeochem Cy 31:456–472. https://doi.org/10.1002/2016GB005546

James RA, Jones RG, Boyd E, Young HR, Otto FEL, Huggel C, Fuglestvedt JS (2019) Attribution: how is it relevant for loss and damage policy and practice? In: Mechler R. BL, Schinko T., Surminski S., Linnerooth-Bayer J. (ed) Loss and damage from climate change. Climate risk management, policy and governance. Springer, Cham

Janssens-Maenhout G et al (2019) EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. Earth Syst Sci Data 11:959–1002. https://doi.org/10.5194/essd-11-959-2019

Joos F, Bruno M, Fink R, Siegenthaler U, Stocker TF, Lequere C (1996) An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. Tellus B 48:397–417

Kretzschmar J, Salzmann M, Mülmenstädt J, Boucher O, Quaas J (2017) Comment on "rethinking the lower bound on aerosol radiative forcing". J Clim 30:6579–6584. https://doi.org/10.1175/JCLI-D-16-0668.1

Le Quéré C et al (2018) Global Carbon Budget 2018. Earth Syst Sci Data 10:2141–2194. https://doi.org/10.5194/essd-10-2141-2018

Li B et al (2016) The contribution of China's emissions to global climate forcing. Nature 531:357–361. https://doi.org/10.1038/nature17165 http://www.nature.com/nature/journal/v531/n7594/abs/nature17165.html#supplementary-information

Matthews HD, Tanya LG, Serge K, Cassandra L, Donny S, Trevor JS (2014) National contributions to observed global warming. Environ Res Lett 9:014010

Myhre G et al (2013) Anthropogenic and natural radiative forcing. In: Stocker TF et al (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

O'Neill BC et al (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim Chang 122:387–400. https://doi.org/10.1007/s10584-013-0905-2

O'Neill BC et al (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci Model Dev 9:3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Otto FEL, Skeie RB, Fuglestvedt JS, Berntsen T, Allen MR (2017) Assigning historic responsibility for extreme weather events. Nat Clim Chang 7:757. https://doi.org/10.1038/nclimate3419

Peters GP, Geden O (2017) Catalysing a political shift from low to negative carbon. Nat Clim Chang 7:619. https://doi.org/10.1038/nclimate3369

Peters GP, Andrew RM, Solomon S, Friedlingstein P (2015) Measuring a fair and ambitious climate agreement using cumulative emissions. Environ Res Lett 10:105004. https://doi.org/10.1088/1748-9326/10/10/105004

Riahi K et al (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob Environ Chang 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rive N, Torvanger A, Fuglestvedt JS (2006) Climate agreements based on responsibility for global warming: periodic updating, policy choices, and regional costs. Glob Environ Chang 16:182–194. https://doi.org/10.1016/j.gloenvcha.2006.01.002

Rogelj J, Hare W, Chen C, Meinshausen M (2011) Discrepancies in historical emissions point to a wider 2020 gap between 2 °C benchmarks and aggregated national mitigation pledges. Environ Res Lett 6:024002. https://doi.org/10.1088/1748-9326/6/2/024002

Rogelj J et al (2018) Scenarios towards limiting global mean temperature increase below 1.5 °C. Nat Clim Chang 8:325–332. https://doi.org/10.1038/s41558-018-0091-3

Saunois M et al (2020) The Global Methane Budget 2000–2017. Earth Syst Sci Data 12:1561–1623. https://doi.org/10.5194/essd-12-1561-2020

Schlesinger ME, Jiang X, Charlson RJ (1992) Implication of anthropogenic atmospheric sulphate for the sensitivity of the climate system. In: Rosen L, Glasser R (eds) Climate change and energy policy: Proceedings of the International Conference on Global Climate Change: its mitigation through improved production and use of energy. American Institute of Physics, New York, pp 75–108

Skeie RB, Fuglestvedt J, Berntsen T, Peters GP, Andrew R, Allen M, Kallbekken S (2017) Perspective has a strong effect on the calculation of historical contributions to global warming. Environ Res Lett 12:024022

Skeie RB, Berntsen T, Aldrin M, Holden M, Myhre G (2018) Climate sensitivity estimates – sensitivity to radiative forcing time series and observational data. Earth Syst Dynam 9:879–894. https://doi.org/10.5194/esd-9-879-2018

Tian H et al (2020) A comprehensive quantification of global nitrous oxide sources and sinks. Nature 586:248–256. https://doi.org/10.1038/s41586-020-2780-0

Trudinger C, Enting I (2005) Comparison of formalisms for attributing responsibility for climate change: non-linearities in the Brazilian proposal approach. Clim Chang 68:67–99. https://doi.org/10.1007/s10584-005-6012-2

UNFCCC (1997) Paper no. 1:Brazil; proposed elements of a protocol to the United Nations Framework Convention on Climate Change. Bonn: United Nations Framework Convention on Climate Change, available at http://unfccc.int/resource/docs/1997/agbm/misc01a03.pdf

UNFCCC (2014) Report of the Conference of the Parties on its Twentieth Session, Held in Lima from 1 to 14 December 2014 (UNFCCC, 2014); http://unfccc.int/resource/docs/2014/cop20/eng/10a01.pdf

UNFCCC (2018) Report of the Conference of the Parties on its twenty-fourth session, held in Katowice from 2 to 15 December 2018 (UNFCCC,2018); https://unfccc.int/sites/default/files/resource/10.pdf

van Vuuren DP et al (2011) The representative concentration pathways: an overview. Clim Chang 109:5. https://doi.org/10.1007/s10584-011-0148-z

Ward DS, Mahowald NM (2014) Contributions of developed and developing countries to global climate forcing and surface temperature change. Environ Res Lett 9:074008

Wei T et al (2012) Developed and developing world responsibilities for historical climate change and CO_2 mitigation. PNAS 109:12911. https://doi.org/10.1073/pnas.1203282109

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.