Running head: Regional NDC contributions to climate mitigation

Climate Warming Mitigation from Nationally Determined Contributions

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ABSTRACT

Individual countries are requested to submit nationally determined contributions (NDCs) to alleviate global warming in the Paris Agreement. However, the global climate effects and regional contributions are not explicitly considered in the countries' decision-making process. In this study, we evaluate the global temperature slowdown of the NDC scenario (ΔT = 0.6°C) and attribute the global temperature slowdown to certain regions of the world with a compact earth system model. Considering reductions in CO_2, CH_4, N_2O, BC, and SO_2, the R5OECD (the Organization for Economic Co-operation and Development in 1990) and R5ASIA (Asian countries) are the top two contributors to global warming mitigation, accounting for 39.3% and 36.8%, respectively. R5LAM (Latin

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America and the Caribbean) and R5MAF (the Middle East and Africa) followed behind, with contributions of 11.5% and 8.9%, respectively. The remaining 3.5% is attributed to R5REF (the Reforming Economies). Carbon Dioxide emission reduction is the decisive factor of regional contributions, but not the only one. Other greenhouse gases are also important, especially for R5MAF. The contribution of short-lived aerosols is small but significant, notably SO_2 reduction in R5ASIA. We argue that additional species beyond CO_2 need to be considered, including short-lived pollutants, when planning a route to mitigate climate change. It needs to be emphasized that there is still a gap to achieve the Paris Agreement 2-degree target with current NDC efforts, let alone the ambitious 1.5-degree target. All countries need to pursue stricter reduction policies for a more sustainable world.

Key words: climate mitigation, nationally determined contributions, attribution, regional contribution, integrated assessment models

Article Highlights:

- Compared with a no climate policy scenario, the NDC scenario shows a slowed global warming of 0.6℃ by the end of the century, although there is still a gap when considering the Paris Agreement target.
- R5OECD and R5ASIA are the top two contributors to global warming mitigation, accounting for 39.3% and 36.8% on average, respectively.
- CO_2 reduction is the decisive factor of regional contributions to climate mitigation, while non-CO_2 reductions are small but significant.

1. Introduction

Anthropogenic activities have been the main driving force behind climate change, and the impact of global warming on human society and natural systems is increasing (IPCC 2014). The Paris Climate Agreement has set a target of 2℃ above the preindustrial level while also pursuing a 1.5℃ target (UNFCCC 2015). Mitigating global climate change requires domestic emission reduction policies. Individual countries are supposed to submit nationally determined contributions (NDCs) to achieve these global climate goals (UNFCCC 2015).

NDCs are bottom-up commitments, not top-down allocations such as the Kyoto Protocol, which mainly consider their own ambitions and feasibility. Other countries' emission reductions or global climate effects are not necessarily considered. It is meaningful to quantify the regional contributions to global climate change mitigation. Previous literature has conducted some research on regional contributions. Regional carbon emission reductions are the most intuitive evaluation indicator and are widely used [e.g., (Roelfsema et al., 2020)]. Some studies also use emissions metrics (Denison et al., 2019). Historical emissions of long-lived gases remain important for future contributions to global warming and play an important role in strong mitigation scenarios (Skeie et al., 2021). Mitigating non-CO_2 emissions such as SLCFs is also critical for meeting the Paris Agreement ambitions and sustainable development goals (Lund et al., 2020). However, there is currently no literature that absolutely attributes the slowdown of temperature rise to national emission reductions. This study aims to calculate the relative contributions by region to climate mitigation, providing a perspective on the emission reduction impact of the NDC scenario compared with the no climate policy (NP) scenarios.

Thus, this study first estimates the global temperature slowdown and then attributes this response to particular world regions. Section 2 describes the data and methods, including scenario datasets, OSACR v3.1 model, simulation framework and attribution method, and uncertainty analysis. Section 3 describes the climate mitigation of the NDC scenario relative to the NP scenario. Section 4 attributes climate mitigation to regional emission reductions. Finally, section 5 presents discussions and conclusions.

2. Data and methods

2.1 Scenario datasets

The CD-LINKS project (Linking Climate and Development Policies - Leveraging International Networks and Knowledge Sharing) is an international collaborative project that brings together research from integrated assessment modeling and explores the complex interplay between climate action and development through global and national perspectives (http://www.cd-links.org/). This study uses emission scenario datasets from the CD-LINKS project to drive a simple climate model. We downloaded CD-LINKS scenario datasets from IMAC 1.5°C Scenario Explorer hosted by IIASA (Huppmann, Rogelj et al., 2018), available at http://data.ene.iiasa.ac.at/iamc-1.5c-explorer. Emissions of five species are considered in this study: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), black carbon (BC), and sulfur dioxide (SO_2). A set of consistent national and global low-carbon development pathways that take current national policies and nationally determined contributions (NDCs) is developed in the CD-LINKS project as an entry point for short-term climate action and then transition to long-term goals of 1.5 °C and 2°C as defined by the Paris Agreement (Roelfsema, van Soest et al., 2020). The CD-LINKS scenarios were originally developed in late 2017.

The NP scenario and NDC scenario are the two scenarios at the core of this paper. Emissions in the NDC scenario relative to the NP scenario are considered mitigation, and the differences in global mean surface temperature (GMST) and atmospheric CO_2 are the intended targets to be attributed. The 2-degree scenario (each country implements its current implemented policies until 2020 and starts with cost-effective implementation to achieve the 2-degree target between 2020 and 2030 with high probability) and the 1.5-degree scenario (each country implements current implemented policies until 2020 and starts with cost-effective implementation to achieve the 1.5-degree target between 2020 and 2030 with high probability) are also simulated as supporting data to show the mitigation gaps of climate goals and current NDC. Detailed information on the scenario definitions can be found at http://data.ene.iiasa.ac.at/iamc-1.5c-explorer. For each scenario, data from the five integrated assessment models (IAMs) are available: AIM/CGE 2.1, IMAGE 3.0.1, MESSAGEix-GLOBIOM 1.0, REMIND-MAgPIE 1.7-3.0, and WITCH-GLOBIOM 4.0. These IAMs differ at the national and sectoral integration levels, and they simulate climate policy decisions in different ways. Therefore, there are differences in the emission data calculated by these IAMs.

In this study, the world is divided into five regions, the same as the shared socioeconomic pathways (SSP) database (Riahi et al., 2017). The five regions are abbreviated as the Organization for Economic Co-operation and Development in 1990 (R5OECD), Asian countries (R5ASIA), Latin America and the Caribbean (R5LAM), the Middle East and Africa (R5MAF), and the Reforming Economies (R5REF).

2.2 OSCAR v3.1 model

OSCAR v3.1 is used in this study to simulate and attribute climate change mitigation from the NDCs. OSCAR v3.1 is a reduced-complexity Earth system model that contains all the components needed to simulate climate change, including modules such as the carbon cycle, tropospheric and stratospheric chemistry, aerosols, and climate response (Gasser, Ciais et al., 2017, Gasser, Kechiar et al., 2018, Gasser, Crepin et al., 2020). OSCAR v3.1 is available at https://github.com/tgasser/OSCAR/tree/v3.1. In addition, OSCAR is built as an emulator with parameters calibrated by more complex models or observations, such as CMIP5, WETCHIMIP, ACCMIP, and TRENDY, making it capable of emulating the sensitivity of models of superior complexity (Gasser et al., 2017). The model is driven by emission datasets of greenhouse gases and aerosol precursors, which calculate the corresponding changes in atmospheric concentrations before predicting radiation forcing and climate change. OSCAR has widely been used in projections and attributions in climate change communities (Ciais et al., 2013; Gasser et al., 2018), especially for regional climate contributions (Li et al., 2016; Fu et al., 2021). In this study, we use OSCAR v3.1 to simulate future GMST and atmospheric CO_2 changes in different scenarios and to attribute the contributions of climate mitigation to different regions.

2.3 Simulation framework and attribution method

The temperature mitigation (ΔT) between the NDC and NP scenarios represents the objective of this study, which reflects the climate change mitigation of NDC emission reductions relative to the no climate policy scenario. The temperature difference between the experiments in the NDC and NP scenarios is regarded as warming mitigation and is attributed to various regions of the world. First, we run a base simulation to obtain the temperature mitigation. The OSCAR model is driven by the NP scenario and NDC scenario data from CD-LINKS to simulate the global temperature in the two scenarios before calculating the temperature mitigation ($\Delta_{base}T = T_{NP} - T_{NDC} = \mathrm{OSCAR}(E_{NP,globe}) - \mathrm{OSCAR}(E_{NDC,globe})$).

To attribute the temperature slowing specific to the regions, the 'normalized marginal attribution method' is used in this study. Applying the normalized marginal attribution method is advised by the United Nations Framework Convention on Climate Change (UNFCCC) to solve nonlinear climate attribution problems (UNFCCC 2002). One study discussed seven attribution methods and concluded that the normalized marginal attribution method is one of the two most suitable for climate attribution (Trudinger and Enting, 2005). The normalized marginal attribution method evaluates the contributions of individual regions proportional to their marginal effects and constrains the total of individual contributions equal to the global effect. In many early studies, this method attributed climate changes to processes or specific regions (Ciais et al., 2013; Li et al., 2016; Fu et al., 2020; Fu et al., 2021).

To implement the normalized marginal method in this study, we ran the basic simulation, and changed the regional emissions mitigation of each region (noted as r_i) by a small fraction ε as input for each simulation and repeatedly calculated temperature mitigation ($\Delta_{r_i}T$). The mathematical expression is $\Delta_{r_i}T = T_{NP} - T_{\mathrm{NDC},r_i-\varepsilon} = \mathrm{OSCAR}(E_{NP,globe}) - \mathrm{OSCAR}\left(E_{NDC,globe} + \varepsilon(E_{NP,r_i} - E_{NDC,r_i})\right)$. The purpose of these marginal experiments is to calculate the marginal effect of emission reduction in each region. Then, the marginal effects are normalized to calculate the relative contributions of each region $\alpha_i = \frac{\Delta_{\text{base}}T - \Delta_{r_i}T}{\sum_{j=1}^{m} \Delta_{\text{base}}T - \Delta_{r_i}T}$ and the absolute contributions are calculated by $\alpha_i \Delta_{\text{base}}T$ following the normalization marginal method. The ε value is 0.1%, similar to early studies that applied the OSCAR model, while several studies found that the results are insensitive to ε values (UNFCCC 2002, Trudinger and Enting, 2005).

2.4 Uncertainty analysis

This study considers the uncertainties from two aspects: the model parameters and the scenario data. For parameter uncertainties, all simulations are run under a Monte Carlo ensemble (n = 3000). Parameters are randomly drawn from the pool available in OSCAR v.3.1. OSCAR has approximately 200 parameters, which play a role in the carbon cycle module, tropospheric and stratospheric chemistry, aerosols, climate response, etc. They are listed in the OSACR model manual (https://github.com/tgasser/OSCAR/blob/v3.1/MANUAL.pdf). As an emulator, different configurations of OSCAR emulate different models of higher complexity, so the Monte Carlo ensemble shows the model uncertainties. For scenario data, the CD-LINKS dataset contains scenario data from five different IAMs. Data from different IAMs have large variances, so we show both the average and the standard deviation of the results as well as the results for each IAM separately.

3. Climate mitigation from NDCs

As mentioned in section 2.3, this study focuses on the difference in climate effects between NDC and NP scenarios. Their carbon dioxide emissions are shown in red and orange in Fig. 1. In the NP scenarios, R5ASIA and R5OECD emit significantly more CO_2 than other regions, followed by R5MAF, while the CO_2 emissions of R5LAM and R5REF remain low for an extended time. Compared with the NP scenario, R5ASIA and R5OECD have the most prominent contributions to CO_2 emission reduction, with cumulative emission reductions of 123.01 PgC and 106.89 PgC, respectively. The reductions of R5REF are rather small, which can also be seen in Fig. 2. The ranges of CO_2 emissions under both the NP and NDC scenarios show significant growth after 2030. Although the ranges of CO_2 emissions are affected by the simulation results of different IAMs, the ranges of CO_2 mitigation are mainly derived from the variance of the NDC scenario. The other two scenarios (the 2-degree and 1.5-degree) are also shown in Fig. 1. These two ideal scenarios are significantly different from the NP and NDC scenarios. The carbon emissions scenario shows an overall downward trend, gradually reaching carbon neutrality in the future. The 2-degree scenario achieves carbon neutrality in 2062–78, while the 1.5-degree scenario achieves carbon neutrality ten to twenty years earlier than the 2-degree scenario. This is similar to the result of Soest et al. (2021), who reported the realization of carbon neutrality by 2065–80 (2-degree) and 2045–60 (1.5-degree). Obviously, to achieve the climate goals of the Paris Agreement, it is not sufficient to rely solely on the existing NDCs.

In addition to CO_2, the pathways of CH_4, N_2O, BC, and SO_2 are also considered in this study and used to drive the model. The cumulative reduction (for CO_2, CH_4, and N_2O) or annual reductions (for BC and SO_2) are shown in Fig. 2**.** Their emissions can be seen in Fig. S1**.** The region with the largest N_2O emission reductions is the R5OECD, with an average of 19.59 TgN. R5OECD, R5ASIA, and R5LAM contribute significantly to CH_4 emission reductions, with average emission reductions reaching 1975.36 TgC, 1627.76 TgC, and 1309.02 TgC, respectively. The critical regions for BC emission reduction are R5ASIA and R5LAM, both reaching approximately 0.02 TgC. SO_2 is mainly reduced in R5ASIA, with an average of 0.57 TgS, accounting for more than 50% of global emission reductions. Notably, some data from specific IAMs show that the NDC scenario has larger regional emissions of some species than the NP scenario. For example, the emission reductions in R5REF obtained by the WITCH-GLOBIOM 4.0 simulation are small negative values except for CH_4. The emission reduction of BC in R5OECD obtained by IMAGE 3.0.1 simulation is –0.31 TgC, which is quite different from the results of other IAMs. There may be some inconsistency in how clean air policies are assumed in the IAMs. The uncertainty of IAMs is considerable, although they are less important to climate change than CO_2.

The increase in temperature and atmospheric CO_2 relative to preindustrial times (~1850) is simulated by OSCAR v3.1, driven by the CO_2, CH_4, N_2O, BC, and SO_2 scenario datasets from CD-LINKS (Fig. 3 and Table 1). The average of the five IAMs shows that the global CO_2 change relative to 1850 will reach 531.9±128.4 ppm in the NP scenario and 425.1±111.1 ppm in the NDC scenario in 2100. Adherence to NDC policy can avoid an increase of nearly 110 ppm in atmospheric CO2. Table 1 shows the increase in atmospheric CO_2 (ΔCO_2) simulated using scenario datasets from five IAMs. For the NP scenario, AIM/CGE 2.1 and IMAGE 3.0.1 result in an increase of approximately 500 ppm, while MESSAGEix-GLOBIOM 1.0, REMIND-MAgPIE 1.7-3.0, and WITCH-GLOBIOM 4.0 result in an increase of approximately 550 ppm. For the NDC scenario, the results are also different; that is, AIM/CGE 2.1 and REMIND-MAgPIE 1.7-3.0 optimistically yield less than 400 ppm, while MESSAGEix-GLOBIOM 1.0 results are almost as high as 500 ppm. Comparing the effects of NP and NDC, the estimation of atmospheric CO_2 mitigation ranges from 56.05 ppm (MESSAGEEix-GLOBIOM 1.0) to 151.34 ppm (REMIND-

MAgPIE 1.7-3.0). The range of ΔCO_2 for the NP scenario is 54.56 ppm, and that for the NDC scenario is 116.68 ppm. The range of CO_2 mitigation calculated by the five IAMs is 95.29 ppm, significantly higher than that for the NP scenario. Therefore, the range of CO_2 mitigation is mainly derived from the variance of the NDC scenario from IAMs.

The temperature increases in the four scenarios are also simulated (Fig. 3b). If no climate policy is implemented, the temperature will rise by 4.1°C±0.9°C relative to the preindustrial level. With NDC implemented, the temperature increase is controlled at 3.5°C±0.8°C. Although there is still a large gap between the NDC scenario and the goals of the Paris Agreement, significant mitigations (0.6°C on average) are achieved, which is the core focus of this article. The temperature in the NP scenario simulated by all IAMs is significantly larger than that in the NDC scenario. The temperature mitigations are calculated as the difference between the NP and NDC emission scenarios from the same IAM (Fig. 3b**)**, ranging from 0.3 °C–0.8 °C. To enhance the reliability of the results, we also calculate the transient climate response to cumulative carbon emissions (TCRE) in Fig. S2, which ranges from 1.54 °C–1.94 ℃/PgC, close to the estimates from the existing literature (Matthews, Gillett et al., 2009, Leduc, Matthews et al., 2016).

4. The contributions to temperature mitigation

Furthermore, we attribute the temperature mitigation to regions according to the normalized marginal attribution method, in which relative contributions are proportional to the marginal climate effect of regional emission reductions. If only CO_2 reduction is considered in the attribution, R5OECD and R5ASIA are the top two contributors, each accounting for more than 40% of the temperature mitigation on average (Fig. 4). The three IAMs conclude that R5OECD is the largest contributor, while the other two IAMs are more confident about R5ASIA (Table 2). R5LAM accounts for 10.9% of the temperature mitigation, on average, and is the third-largest contributor. The remaining temperature mitigation is attributed to R5REF and R5MAF, and their contributions are very small (no more than 5% on average).

Considering additional climate forcings, the relative contribution of temperature mitigation has changed. Considering all GHG reductions, R5MAF becomes much more important, accounting for an average of 8.9%. This is because the global CH_4 and N_2O reduction proportion of R5MAF is greater than that for CO_2 (Fig. 2). Correspondingly, the share of R5ASIA dropped by approximately six percentage points, while the shares of R5OECD, R5LAM, and R5REF showed little change. In addition, we also included aerosols (BC and SO_2) in the attribution. Although there are significant changes between aerosol-included attribution (‘GHGs+BC’, ‘GHGs+SO_2’, and ‘all’ in Table 2) and aerosol-excluded attribution (‘GHGs’ in Table 2), they are very small. This is because GHGs have a long atmospheric lifetime, and cumulative emissions determine their climate effects. In contrast, the climate effects of short-lived aerosols are essentially determined by the current year’s emissions. Since the attribution is conducted for a long period (2014–2100), GHGs are much more important than aerosols in the mitigation attribution.

Considering ‘all’ climate forcers in this study (CO_2, CH_4, N_2O, BC, and SO_2), R5OECD and R5ASIA represent the two major contributors to global warming mitigation, accounting for 39.3% and 36.8%, respectively. R5LAM and R5MAF followed R5OECD and R5ASIA, contributing 11.5% and 8.9%, respectively. R5REF only contributed 3.5%. The relative contributions depend on regional emission reductions but are not limited solely to CO_2 emission reductions. Figure 5 shows that the regional contributions to climate mitigation are positively correlated with the CO_2 emission reductions but are not completely linear. This is attributed to non-CO_2 climate forcing and the nonlinear processes of the climate system. The reductions in other GHGs and SO_2 are also worthy of attention, especially in certain regions, e.g., CH_4 in R5MAF and SO_2 in R5ASIA.

5. Conclusion and discussion

This study first assessed the regional contributions to the world's climate mitigation. According to our estimation, R5OECD and R5ASIA make similar contributions, covering almost three-quarters of climate change mitigation. At the same time, R5OECD and R5ASIA are the largest emitters of greenhouse gases and aerosols. The emission reduction actions of major emitters are essential to curb global climate change. R5LAM and R5MAF are of the second tier, each contributing approximately 10%. R5REF is a less critical contributor to slowing down warming, only 3.5%.

Our estimation of the regional contributions to climate mitigation is based on the deviation of the NP and NDC scenarios. This means that regional emission reductions determine future emission reduction contributions. Although, to a certain extent, high-emitting regions are more likely to contribute to greater emission reductions and cooling contributions, such as R5ASIA, while low-emitting regions, such as R5REF, are less likely to do so. However, this does not mean that larger emissions correspond to larger contributions. For example, the CD-LINKS dataset shows that CO_2 emissions in the R5MAF will rise in the future, becoming the world's second-largest emitter by 2100. However, the contribution of R5MAF to temperature mitigation is very small at 8.03%, a contribution that only surpasses the R5REF's contribution and is disproportionate to its emissions. Such results indicate that R5MAF has room to optimize the energy structure and develop stricter climate policies to control the climate. At the same time, technical assistance from developed countries and regions may help reduce R5MAF emissions due to historical responsibilities. It is not inappropriate to simply think that the greater the contribution in this study, the more commendable it is.

We noticed that the scenario data significantly determine the evaluation results, and the scenario data of different IAMs vary greatly. In the CD-LINKS datasets, there are significant variances in the five IAMs, with the opposite sign possibly being found in some regions and species. There is a great deal of uncertainty in the process of translating national policy documents into future global emission forecast data. Different possible evolutions of NDC assumptions, which have resulted in estimated emissions ranging from 47 to 63 $TgCO_2$ yr^{-1} in 2030, have a significant impact on the feasibility and cost of predicting future global warming (Rogelj et al., 2017). We argue that the reliability and consistency of IAM datasets are vital for future scenario projection and attribution analysis.

Apart from the data differences caused by different IAMs, the gap between NDC and climate goals should be noted. The fact is that most existing emission reduction programs exceed the 2°C target set out in the Paris Agreement. In other words, current actions are not sufficient to achieve the goals of sustainable development (Sörgel et al., 2021). In addition, even if NDCs are assumed to be achieved, there is still a wide range of future possibilities because of the definition of the long-term carbon budget (Riahi et al., 2021). However, this does not mean that NDCs cannot be evaluated. Instead, we need to assess currently proposed NDCs with a clearer picture. Only when we have a clearer understanding of the contributions, gaps, and uncertainties of NDCs, can we plan and evaluate more ambitious policies and pathways. The legacy of excessive temperatures and the feasibility of limiting warming to 1.5°C or less are central to the post-Paris Agreement scientific agenda (Schleussner et al., 2016).

At present, 157 Paris Agreement Parties (representing 156 countries) have submitted their new or updated NDCs (Climate Watch, 2020). According to the recent NDC synthesis report released by the UNFCCC, new or updated NDCs are expected to result in 3.5% and 11.3% lower emission levels in 2025 and 2030, respectively, compared to the first NDCs, (UNFCCC, 2021). It is worth simulating the temperature mitigation and relative contributions of different regions under the updated NDC scenario. Unfortunately, the newest emission scenario pathway datasets of countries are still unavailable. We believe that the introduction of carbon-neutral policies will result in contribution increases for the current major carbon emitters, such as China (in R5ASIA), the United States, and the European Union (in R5OECD), both in absolute and relative aspects.

Meanwhile, the results of this paper can still be valuable as a reference for reflecting upon the necessary ambition to achieve the Paris goals and for discovering how countries can leverage their climate goals to achieve their sustainable development objectives. Of course, we strongly recommend evaluating the relative contributions under the updated NDCs when the newest datasets are available. Different countries give different peak carbon or carbon-neutral times, which affects their relative contributions.

We argue that all countries should introduce more ambitious emission reduction plans as soon as possible based on the current NDCs, and more international technical assistance to developing countries is needed to achieve a low-carbon world. These considerations represent important directions for climate policy research.

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Table 1. Future CO_2 increase (ΔCO_2) and temperature changes (ΔT) relative to 1850 in 2100.

Model	NP	NDC	2-degree	1.5-degree
Future CO_2 increase ΔCO_2 (ppm)				
AIM/CGE 2.1	502.20±122.34	380.78±93.59	132.61±30.85	94.89±22.57
IMAGE 3.0.1	504.66±118.69	426.50±102.01	143.03±35.40	93.31±23.09
MESSAGEix-GLOBIOM 1.0	553.51±126.24	497.46±117.21	122.43±33.05	82.85±22.42
REMIND-MAgPIE 1.7-3.0	542.64±132.83	391.30±100.34	124.01±32.08	84.63±22.56
WITCH-GLOBIOM 4.0	556.76±130.53	430.10±102.42	121.36±28.68	83.96±20.79
average	531.89±128.42	425.07±111.14	128.69±33.12	87.93±22.29
Future temperature changes ΔT (℃)				
AIM/CGE 2.1	4.10±0.92	3.52±0.81	1.91±0.51	1.57±0.45
IMAGE 3.0.1	3.91±0.89	3.49±0.80	1.96±0.53	1.62±0.45
MESSAGEix-GLOBIOM 1.0	4.01±0.90	3.74±0.85	1.79±0.51	1.43±0.43
REMIND-MAgPIE 1.7-3.0	4.20±0.95	3.40±0.80	1.89±0.52	1.59±0.45
WITCH-GLOBIOM 4.0	4.00±0.90	3.35±0.78	1.61±0.45	1.32±0.40
average	4.05±0.92	3.50±0.82	1.83±0.52	1.51±0.44

Table 2. The contributions of regional NDC to climate change mitigation (%).

Model	Region	CO_2	GHGs	GHGs+BC	GHGs+SO_2	all
AIM/CGE 2.1	ASIA	31.3	27.8	27.4	28.3	27.9
	LAM	7.0	7.8	7.8	7.8	7.8
	REF	4.0	3.8	3.8	3.8	3.8
	OECD	51.2	51.6	51.9	51.2	51.4
	MAF	6.4	9.0	9.1	9.1	9.2
IMAGE 3.0.1	ASIA	31.0	28.4	28.5	27.1	27.2
	LAM	18.1	16.8	16.7	17.4	17.4
	REF	2.3	4.9	4.8	4.8	4.8
	OECD	36.8	34.6	34.3	36.0	35.7
	MAF	11.9	15.4	15.7	14.7	15.0
MESSAGEix-GLOBIOM 1.0	ASIA	37.1	31.7	31.4	31.6	31.4
	LAM	11.0	11.8	12.0	11.8	12.1
	REF	0.5	2.1	2.0	2.2	2.1
	OECD	51.1	52.7	52.5	52.6	52.4
	MAF	0.2	1.8	1.9	1.8	2.0
REMIND-MAgPIE 1.7-3.0	ASIA	45.8	41.3	41.4	41.1	41.2
	LAM	10.6	11.4	11.4	11.5	11.5
	REF	1.1	3.3	3.3	3.4	3.4
	OECD	40.2	36.0	35.8	36.1	36.0
	MAF	2.4	7.9	8.0	7.9	8.0
WITCH-GLOBIOM 4.0	ASIA	69.5	56.6	56.6	56.2	56.2
	LAM	7.8	8.9	8.9	9.0	9.0
	REF	-1.6	3.2	3.2	3.4	3.4
	OECD	22.4	20.9	20.9	21.0	21.0
	MAF	1.9	10.4	10.3	10.4	10.4

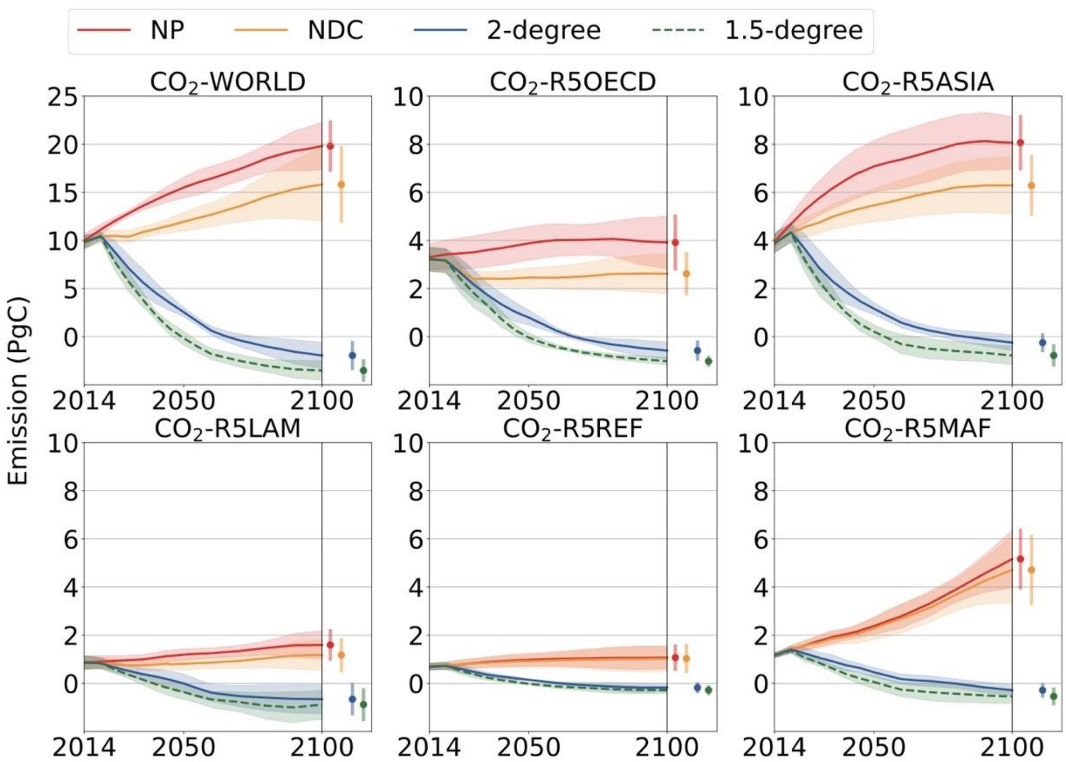

Fig. 1. CO_2 emissions of the R5 regions based on the CD-LINKS scenario dataset. Future CO_2 emissions in the R5 region under four climate scenarios. The line is the average of the results of the five emission IAMs, and the shaded areas show the range of the scenario data. 'NP', 'NDC', and '2-degree' scenarios are marked by red, orange, and solid blue lines. The '1.5-degree' scenario is marked by green dashed lines. Pathways of other species (CH_4, N_2O, BC, and SO_2) can be found in Fig. S1.

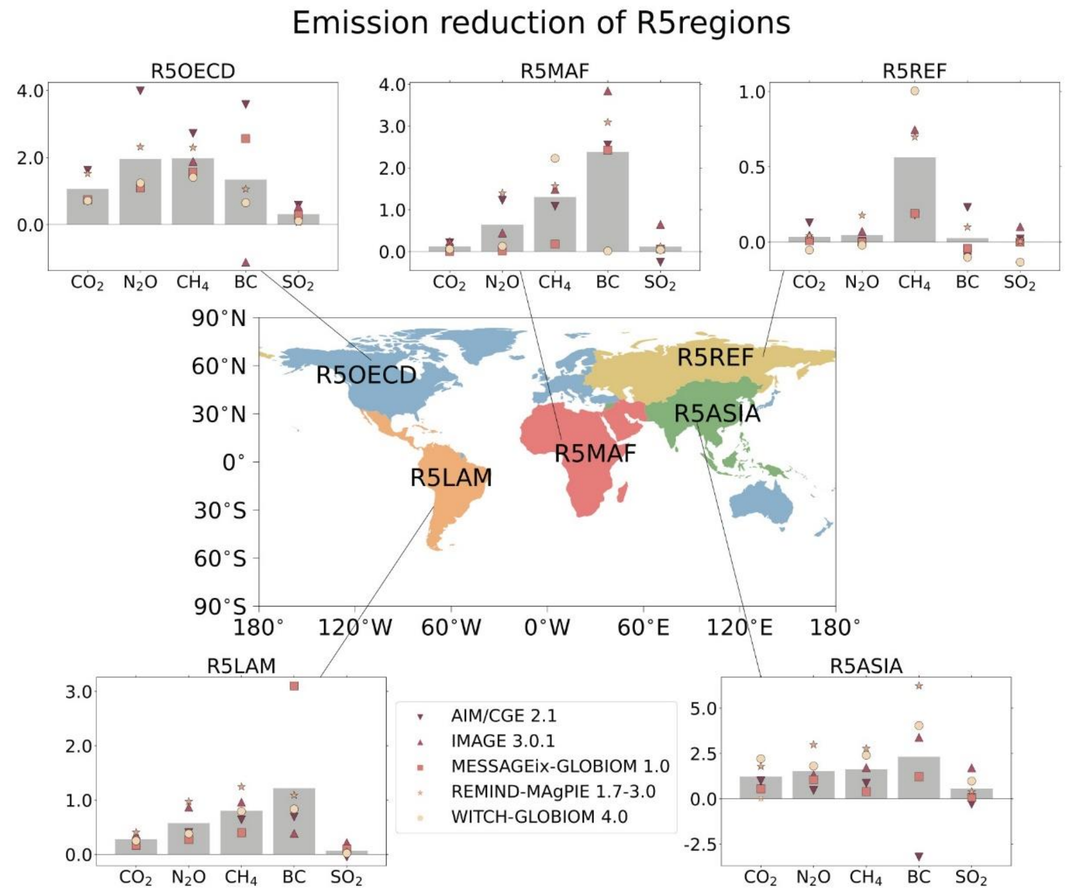

Fig. 2. The mitigation of CO_2, CH_4, N_2O, BC, and SO_2 emissions of the R5 regions based on the CD-LINKS scenario dataset. The map shows the regionalization (R5 regions) in this study. The bars around the map show emission reductions of NDC relative to NP scenarios. The cumulative reduction (for CO_2, CH_4, and N_2O) or annual reductions (for BC and SO_2) are shown here. The height of each column is a global emission difference, with the different colors representing the various R5 regions. The results are based on five IAMs are marked by different markers, and their average is shown with grey bars. The units are 100 PgC for CO_2, 10 TgN for N_2O, 1000 TgC for CH_4, 0.01 TgC for BC, and 1 TgS for SO_2 to plot the bars in one axis.

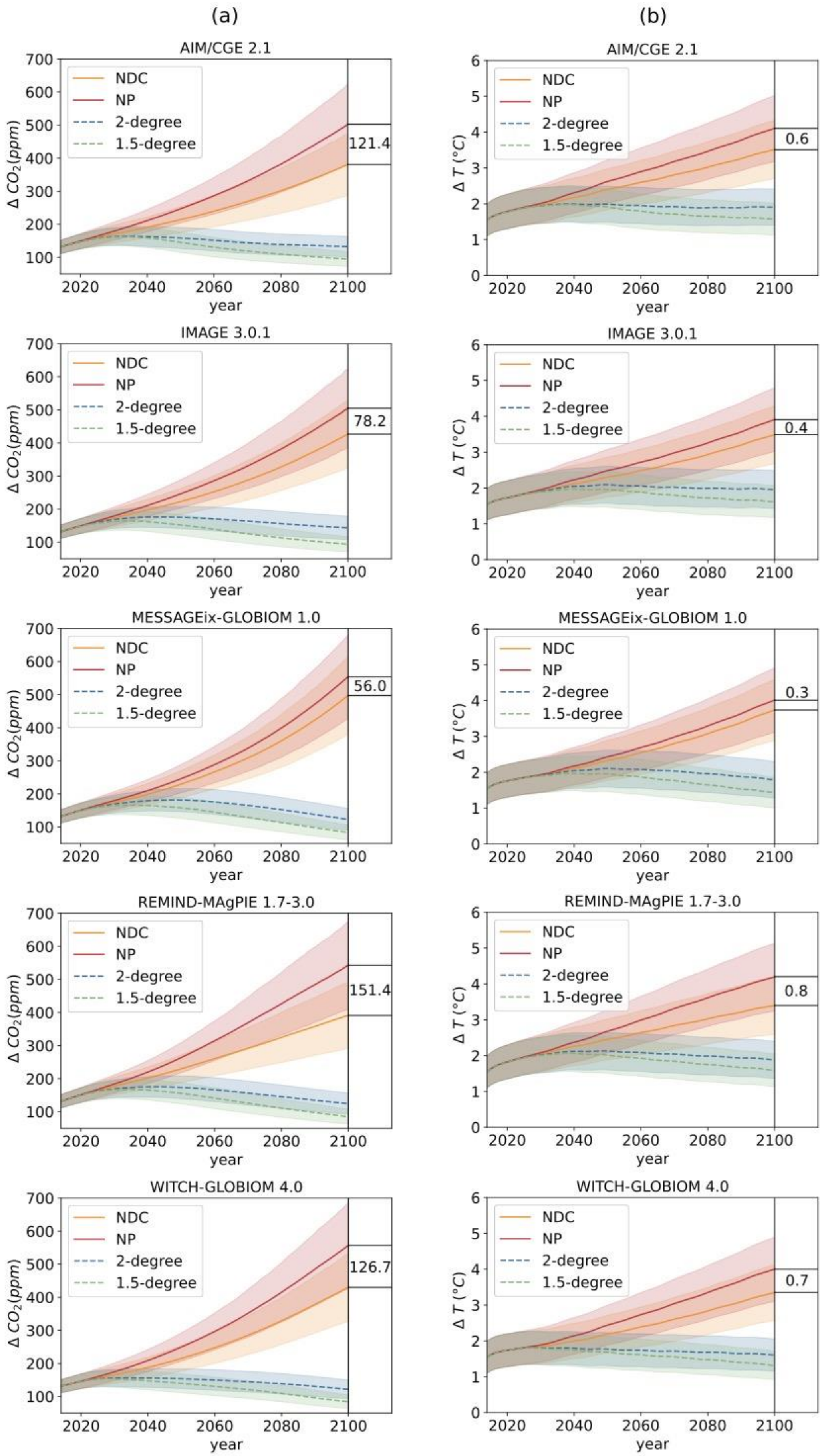
(a)
(b)
AIM/CGE 2.1
IMAGE 3.0.1
MESSAGEix-GLOBIOM 1.0
REMIND-MAgPIE 1.7-3.0
WITCH-GLOBIOM 4.0
NDC
NP
2-degree
1.5-degree
Δ CO2(ppm)
Δ T (°C)
year
121.4
78.2
56.0
151.4
126.7
0.6
0.4
0.3
0.8
0.7

Fig. 3. Atmospheric CO_2 increase (ΔCO_2) and temperature change (ΔT) relative to preindustrial (1850) simulations for scenarios. (a) The simulation of ΔCO_2 based on emission data from the five IAMs. The mitigation of ΔCO_2 induced by NDC relative to NP is marked and valued in the figures. ΔCO_2 in the 2-degree and 1.5-degree scenarios are also shown in the figures for comparison. (b) The same as (a), but for ΔT. The mitigation of temperature increases is the core concern of this study and is attributed to regions in this study.

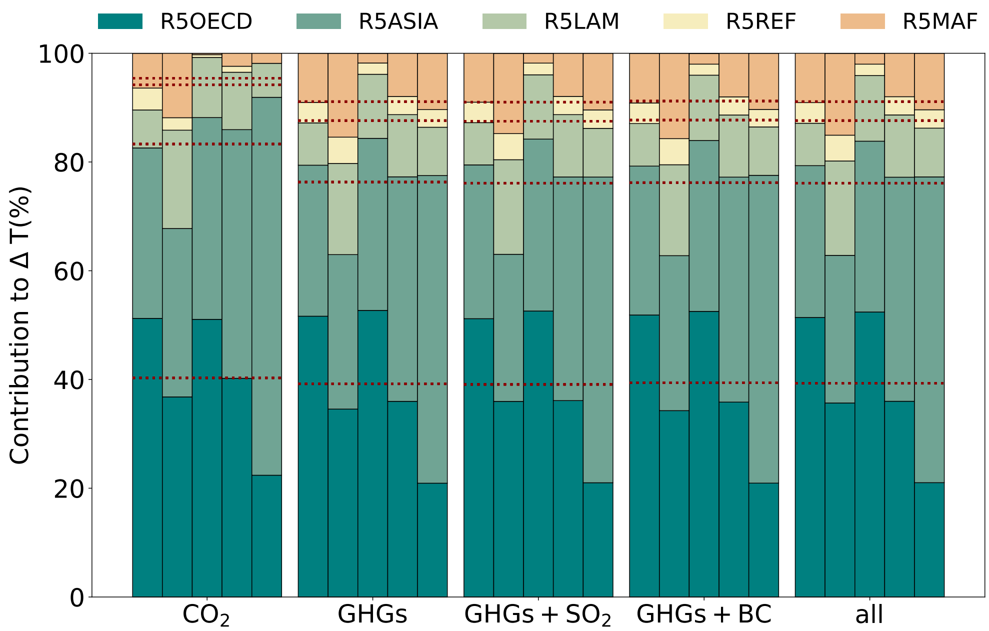

Fig. 4. The relative contributions of regions to climate mitigations with different climate forcers included. Each column represents the global climate mitigations (100%), with relative contributions from the R5 regions marked by different colors. ‘CO_2’, ‘GHGs’, ’GHGs + SO_2’, ’GHGs + BC’, and ’all’ labeled at the axis indicate which climate forcings are considered. GHGs refer to CO_2, CH_4, and N_2O, and ‘all’ refers to GHGs, BC, and SO_2. The close-together columns represent results based on different IAMs, with the model average indicated by the red dashed lines. The five IAMs are AIM/CGE 2.1, IMAGE 3.0.1, MESSAGEix-GLOBIOM 1.0, REMIND-MAgPIE 1.7-3.0, and WITCH-GLOBIOM 4.0 (from left to right).

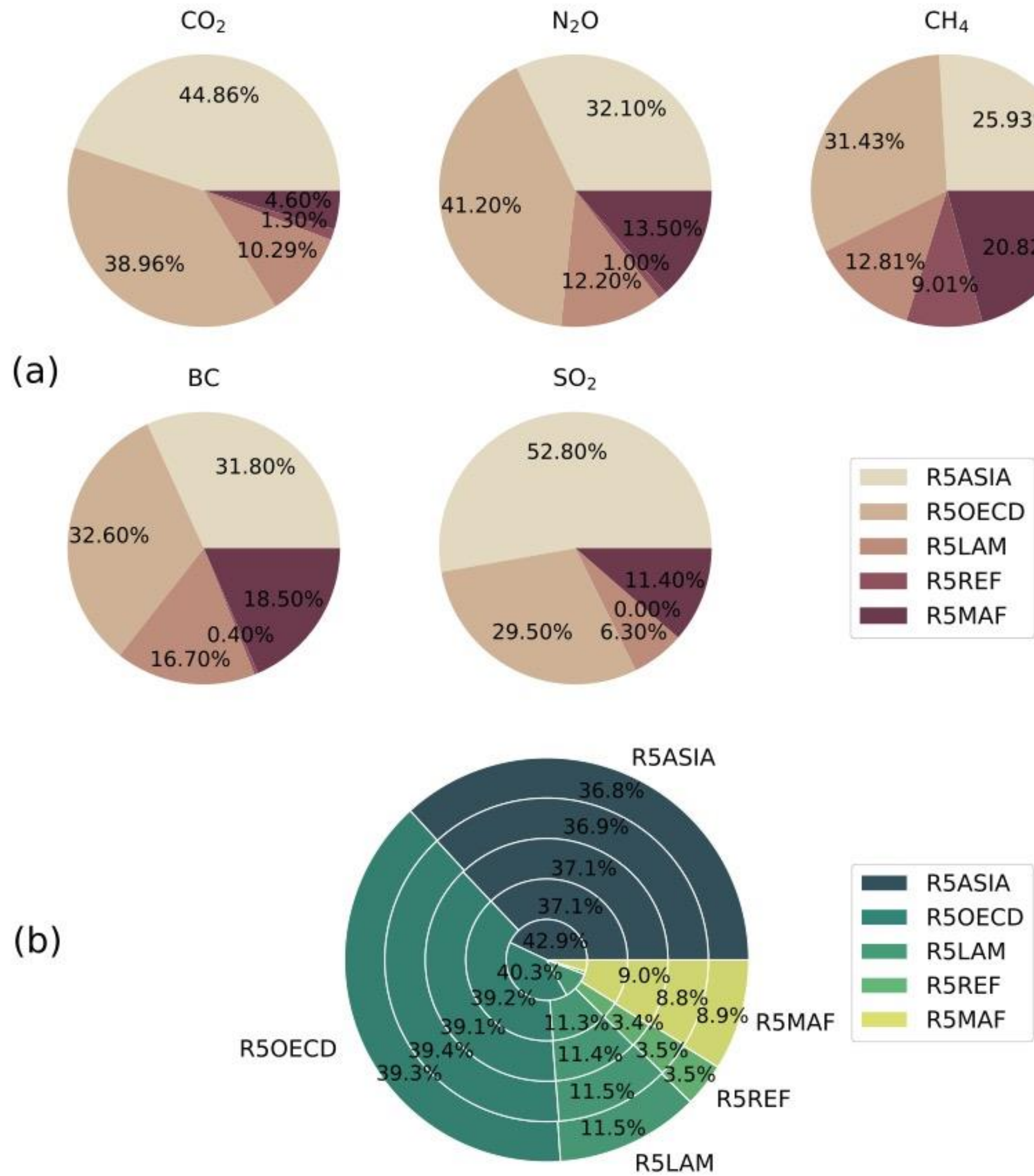

Fig. 5. Pie charts for regional emission reductions and induced climate warming mitigations. (a) Pie charts for regional reductions in CO_2, CH_4, N_2O, BC, and SO_2. (b) The nested pie chart in the center of this figure shows the regional relative contributions when calculated with different amounts of substances considered. The center part of the nested pie chart shows the relative contributions calculated with only CO_2 considered.

The second layer, from the inside to the outside, considers CH_4 and N_2O in addition to CO_2 (abbreviated as GHGs in this study). The third layer considers GHGs and BC, and the fourth layer considers GHGs and SO_2. The outermost layer considers GHGs, BC, and SO_2, referred to as ‘all’ in this study.

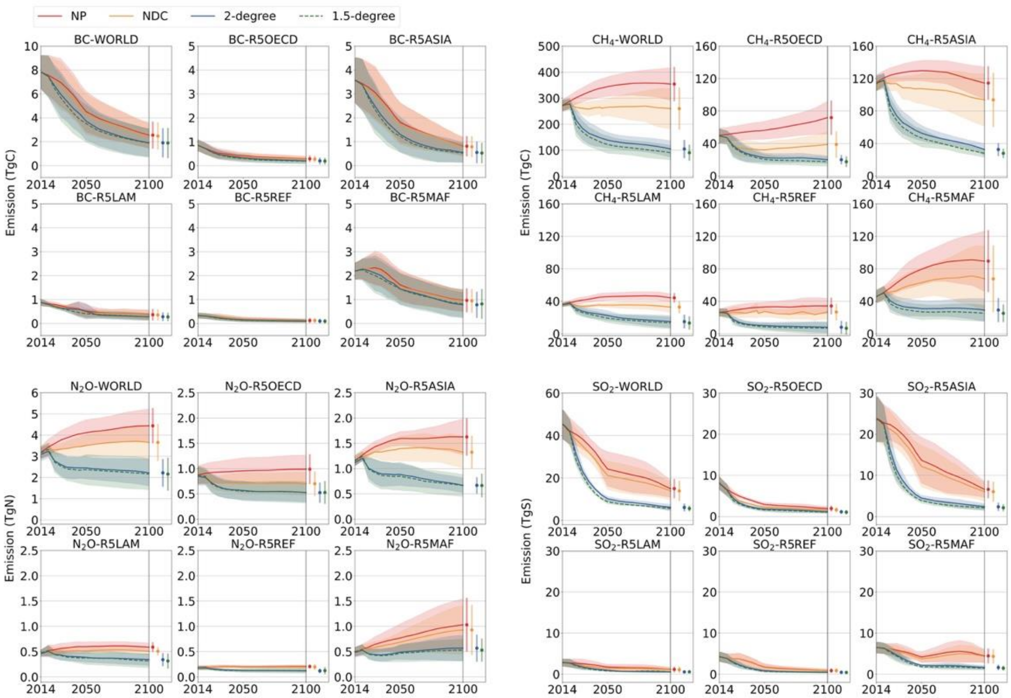

Fig.S1. CH_4, N_2O, BC, and SO_2 emissions of the R5regions based on the CD-LINKS scenario dataset. Future CH_4, N_2O, BC, and SO_2 emissions in the R5 region in four climate scenarios. The line is the average of the results of the five emission IAM and the shade shows the range of the scenario data. 'NP', 'NDC', and '2-degree' scenarios are marked by red, orange, and blue solid lines. '1.5-degree' scenario is marked by green dashed lines.

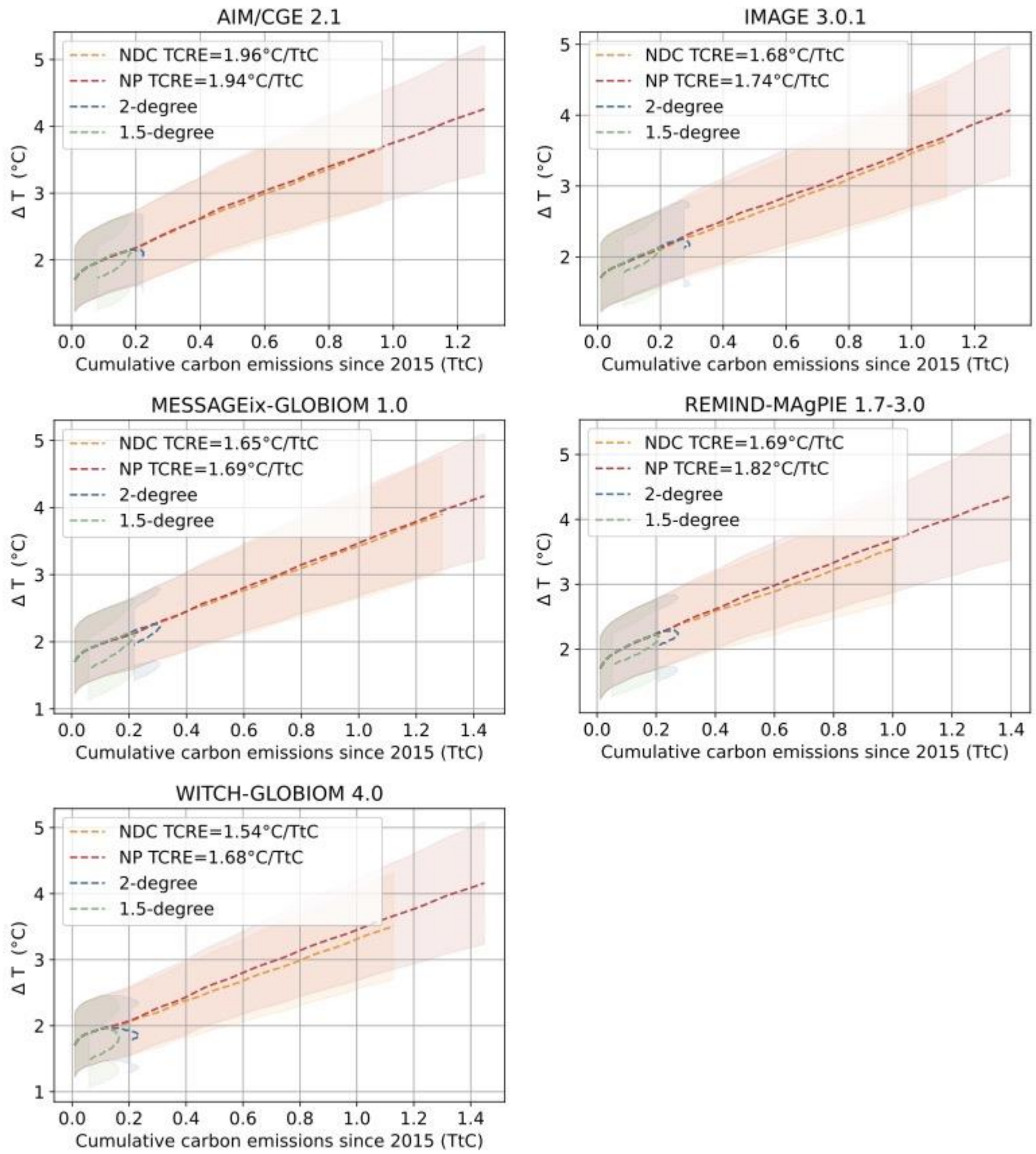

Fig.S2. The transient climate response to cumulative carbon emissions (TCRE) in this study. The lines are the average of the results of 3000 simulations and the shades show the range of the simulated data. 'NP', 'NDC', '2-degree' and '1.5-degree' scenarios are marked by red, orange, blue and green dashed lines. We calculate the TCRE for NDC scenario and NP scenario as the slope. Considering the negative emissions of the 2-degree and 1.5-degree scenarios, we do not calculate the TCRE for these two scenarios.