Evaluating China's role in achieving the 1.5°C target of the Paris Agreement

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Abstract: Now that many large emitting countries have set goals for reaching zero emissions in this century at the COP26, it is important to clarify the role of each country in achieving the 1.5°C target of the Paris Agreement. Here, we evaluated China's role by calculating the global temperature impacts caused by different national emission pathways to zero emissions in the future. Our results showed that China's contribution to global warming in 2050 is 0.17°C on average, with a range of 0.1°C to 0.22°C. Specifically, the peak contributions of these pathways vary from 0.1°C to 0.23°C, with the years reached distributing between 2036 and 2065. The large difference in peak temperature arises from the differences in emission pathways of carbon dioxide (CO_2), methane (CH_4), and sulfur dioxide (SO_2). We further analyzed the effect of the different mix of CO_2 and CH_4 mitigation trajectories from China's pathways on the global mean temperature. We found that near-term CH_4 mitigation reduces the peak temperature in the mid-century, whereas it plays a less important role in determining the end-of-the-century contribution to reaching the global temperature warming goal of 1.5°C. The most effective way to shave the peak temperature would be early CH_4 mitigation action, further contributing to reducing the temperature overshoot along the way toward the 1.5°C target.
Keywords: Climate change, China, climate change mitigation, greenhouse gas emissions, methane, Paris Agreement, 1.5°C target, emissions scenarios

1. Introduction

Climate change can seriously damage natural ecosystems, the economy, and social systems (IPCC 2014). To avoid severe climate impacts, the Paris Agreement stipulates the goals of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels (UNFCCC 2015). Keeping the warming below 1.5°C can permit us to avoid a fraction of the damages that may occur around the 2°C target (IPCC 2018, Hoegh-Guldberg *et al* 2019). For example, the probability of extreme precipitation in China occurring under 1.5°C can be reduced by 33% compared with the limit of 2°C (Li *et al* 2018). Moreover, tens of billions of dollars in economic losses caused by drought can be saved (Su *et al* 2018). On the other hand, the IPCC's latest report indicated that global surface temperature was already 1.09°C higher in 2011–2020 than in 1850–1900 (IPCC 2021). It further indicates at least a 50% chance of exceeding the 1.5°C warming level before 2040 under all scenarios considered (IPCC 2021).

The Paris Agreement requests countries to reduce emissions according to their national climate governance goals (van den Berg *et al* 2020). Compared to the 2°C target, the 1.5°C target requires countries to strengthen further their respective Nationally Determined Contributions (NDCs). For example, accelerating the implementation of renewable technology policies and improving energy efficiency are needed for countries with high greenhouse gas emissions (GHGs) (Roelfsema *et al* 2020). China, a country with massive carbon dioxide (CO_2) emissions at present, plays an essential role in global efforts to mitigate climate change (Jackson *et al* 2017). The Chinese government has pledged to peak their CO_2 emissions before 2030 and achieve carbon neutrality before 2060 (NDRC 2015, UNFCCC 2021). We assumed that China's net zero applies only to CO_2, though there is still a debate whether carbon neutrality is for CO_2 or GHGs (Thomas *et al* 2021, Zhao *et al* 2022, He *et al* 2022).

Plenty of studies have explored pathways to achieve the 2°C target (Rogelj *et al* 2016, Wollenberg *et al* 2016, Tokimatsu *et al* 2017, Wang and Chen 2019). Recent studies are more focused on the 1.5°C target and differences in the implications of the 2°C and 1.5°C targets (Su *et al* 2017, Shi *et al* 2018, Rogelj *et al* 2018, Vrontisi *et al* 2018, Tanaka and O'Neill 2018, IPCC 2018, Jiang *et al* 2018, Denison *et al* 2019, Pedde 2019, Warszawski *et al* 2021, Brutschin *et al* 2021, Duan *et al* 2021, Zheng *et al* 2021). Integrated Assessment Models (IAM) are a modeling approach to assessing climate policies (Nordhaus 1992), and multi-model analyses using different IAMs have become a well-established approach in climate research, mainly for estimating the costs of mitigation. Multi-model analysis allows understanding the differences in emission pathways, providing a basis for robust policy recommendations (Duan *et al* 2019, Warszawski *et al* 2021).

We evaluate the climate responses to China's emission reduction pathways generated by IAMs under the 1.5°C target. While different emission pathways for China have been proposed (Luderer *et al* 2018; Vrontisi *et al* 2018, Duan *et al* 2021), little attention has been paid to the effects of China's pathways on global warming, except for Chen *et al* (2021). The Chen study looked into the global temperature effect of China's carbon neutrality target. We analyzed here the contribution of China to 1.5°C target global emission pathways, which require deeper mitigation in addition to just meeting carbon neutrality. The Chen study accounted for the effect from CO_2 emission abatement. This study considers the effect from GHGs and air pollutants, even though the net zero condition is assumed to apply to CO_2 only. In particular, we examine how the mitigation strategies of CO_2 and CH_4 emissions shape the China's contributions toward the 1.5°C target.

2. Methodology

To calculate the temperature responses to emission pathways, we use a simple climate model Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate model (ACC2) (Tanaka *et al* 2007, Tanaka *et al* 2018) developed on the basis of earlier work (Hooss *et al* 2001, Bruckner *et al* 2003). The model comprises four modules: namely, atmospheric chemistry, carbon cycle, climate, and economy modules. ACC2 can be used as a simple IAM with an economy module to calculate the cost of mitigation and even optimize it (Tanaka *et al* 2021). Here, this study uses ACC2 as a simple earth system model without the economy module. The performance of this model was cross-compared with those of other simple climate models (Nicholls *et al* 2020). Our model describes CO_2, CH_4, N_2O, as well as many other short-lived and long-lived gases, air pollutants, and aerosols. The physical climate module is an energy balance and heat diffusion model DOECLIM (Kriegler 2005). The carbon cycle module is a box model comprising three ocean boxes, a coupled atmosphere-mixed layer box, and four land boxes. With rising atmospheric CO_2 concentration, the ocean CO_2 uptake is saturated through changes in the thermodynamic equilibrium of carbonate species, and the land CO_2 uptake increases due to the CO_2 fertilization effect. Climate sensitivity is one of the major uncertain parameters that determines global average temperature changes in model calculations. It is likely in the range of 1.5°C to 4.5°C in AR5 (IPCC 2013), and it is narrowed to 2.5-4.0°C in AR6 (IPCC 2021). In our research, the climate sensitivity is assumed to be 3°C, a best estimate of equilibrium climate sensitivity (IPCC 2021). Other uncertain model parameters are calibrated based on a Bayesian approach (Tanaka *et al* 2009(a)). The model is written in GAMS and numerically solved using CONOPT3, a nonlinear optimization solver included in the GAMS software package.

We aim to evaluate China's role in IAM-based global pathways toward the 1.5°C target by investigating the effects of China's emission reductions on global mean temperature changes. To this end, we collected emission pathways for the 1.5°C target that explicitly resolve China. The database of the ADVANCE project (Luderer *et al* 2018; Vrontisi *et al* 2018) meets our requirements, which is a set of global climate policy pathways for various purposes, including the 1.5°C target. Note that we did not consider the pathways of IMACLIM and GEM, as their historical CO_2 emissions significantly differ from China's actual CO_2 emissions, especially the former, due to the lack of the CO_2 emissions of land use emissions and industrial processes (Luderer *et al* 2018). Though Duan *et al* (2021) also generated several pathways with domestic IAM models to first examine the pathways of 1.5°C warming limit for China, they mainly presented CO_2 emissions for the period of 2015-2050. As a result, we obtained a total of 24 China's emission pathways from the ADVANCE database. Though all pathways aim at the 1.5°C target, there are differences in the carbon price level, the time to take mitigation action, and the carbon budget. We adopted the four categories of the ADVANCE project (Luderer *et al* 2018, Vrontisi *et al* 2018) (Table 1) to classify the pathways.

Table 1. Categories and definitions of pathways adopted from the ADVANCE project

Category	Label	Definition
2020_1.5°C-2100	S1	Mitigation efforts strengthened with globally uniform carbon price after 2020 to limit cumulative 2011-2100 CO_2 emissions to 400 $GtCO_2$
2030_1.5°C -2100	S2	After implementing the NDCs without strengthening until 2030, the carbon budgets from the 2020_1.5°C -2100 scenario are adopted
2030_Price1.5°C	S3	After implementing the NDCs without strengthening until 2030, carbon price trajectories from the 2020_1.5°C -2100 scenario are adopted
2030_3xPrice1.5°C	S4	Implementing a 3-fold carbon price relative to the 2020_1.5°C -2100 scenario

GHGs, air pollutants, and aerosols considered in our study are shown in Table 2. These include energy-related emissions (e.g., energy and industrial processes) and non-energy-related emissions (e.g., agriculture, forestry, and land-use sector). Emission pathways were linearly interpolated into yearly data for our temperature calculations. It is important to emphasize that the outcome of analysis such as ours is sensitive to the period of emissions considered (e.g., Skeie *et al* 2017). The emissions scenarios we collected start in 2005 and end up in 2100. Thus, it should be kept in mind that we considered the temperature effect of emissions only from 2005.

Table 2. Summary of the IAMs considered in our study

Model	Label	Source	Period	Interval	GHGs and air pollutants considered for China	Reported pathway	Climate module
AIM/CGE V.2	AIM	NIES, Japan Kyoto-University, Japan	2005-2100	5-year	CO_2, CH_4, N_2O, CO, HFC, NO_x, PFC, SF_6, SO_2, VOC	S1, S3, S4	MAGICC
GCAM4.2_ ADVANCEWP6	GCAM	PNNL & JGCRI, USA	2005-2100	5-year	CO_2, CH_4, N_2O, SO_2	S1, S2, S3, S4	Hector v2.0
IMAGE 3.0	IMAGE	UU, Netherlands PBL, Netherlands	2005-2100	5-year	CO_2, CH_4, N_2O, CO, HFC, NO_x, PFC, SF_6, SO_2, VOC	S1, S3, S4	MAGICC
MESSAGE-GLOBIOM_1.0	MESSAGE	IIASA, Austria	2005-2100	10-year	CO_2, CH_4, N_2O, CO, HFC, NO_x, SF_6, SO_2, VOC	S1, S3, S4	MAGICC
POLES ADVANCE	POLES	EC-JRC, Belgium	2005-2100	5-year	CO_2, CH_4, N_2O, HFC, PFC, SF_6	S1, S2, S3, S4	MAGICC
REMIND V1.7	REMIND	PIK, Germany	2005-2100	Before 2050: 5-year After 2050: 10-year	CO_2, CH_4, N_2O, HFC, NO_x, PFC, SF_6, SO_2	S1, S2, S3, S4	MAGICC

WITCH	WITCH	RFF-CMCC EIEE, Italy	2005-2100	5-year	CO_2, CH_4, N_2O, CO, HFC, NO_x, PFC, SF_6, SO_2, VOC	S1, S3, S4	MAGICC/ Internal climate module

3. Results

3.1. Global and China's emission pathways

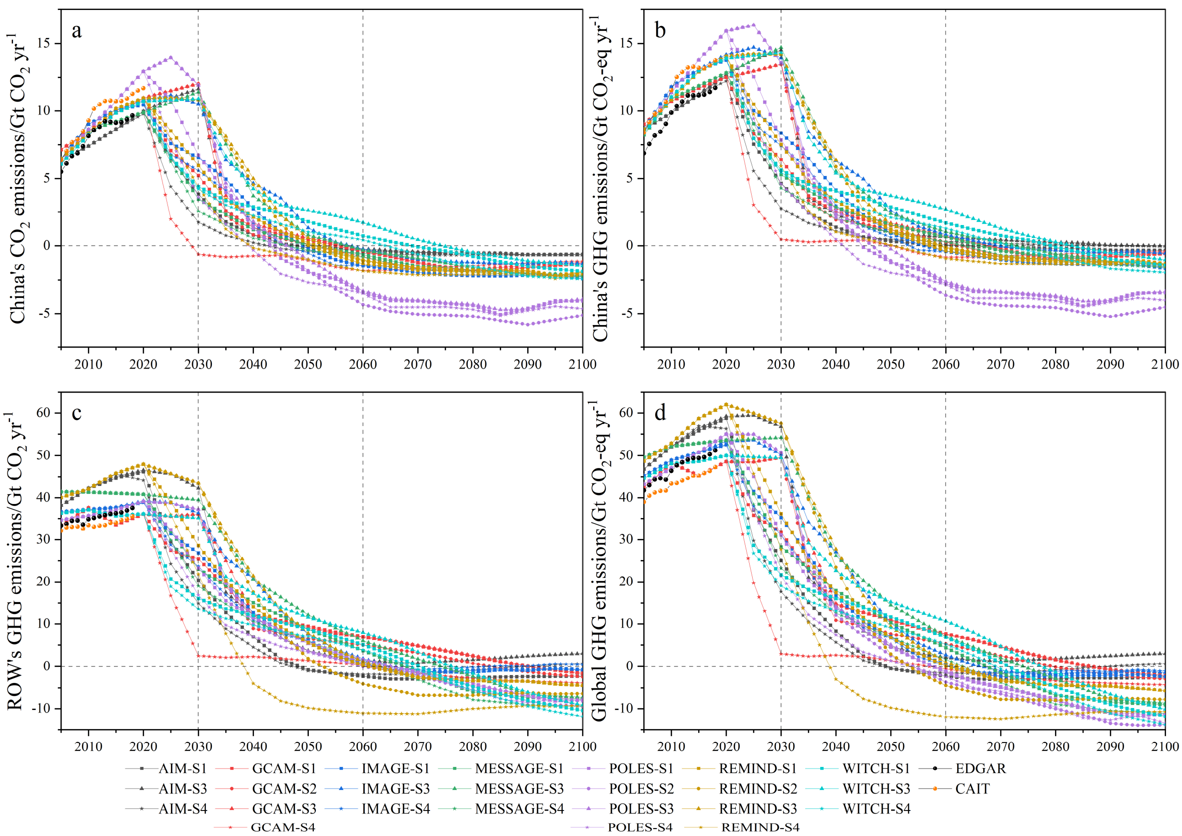
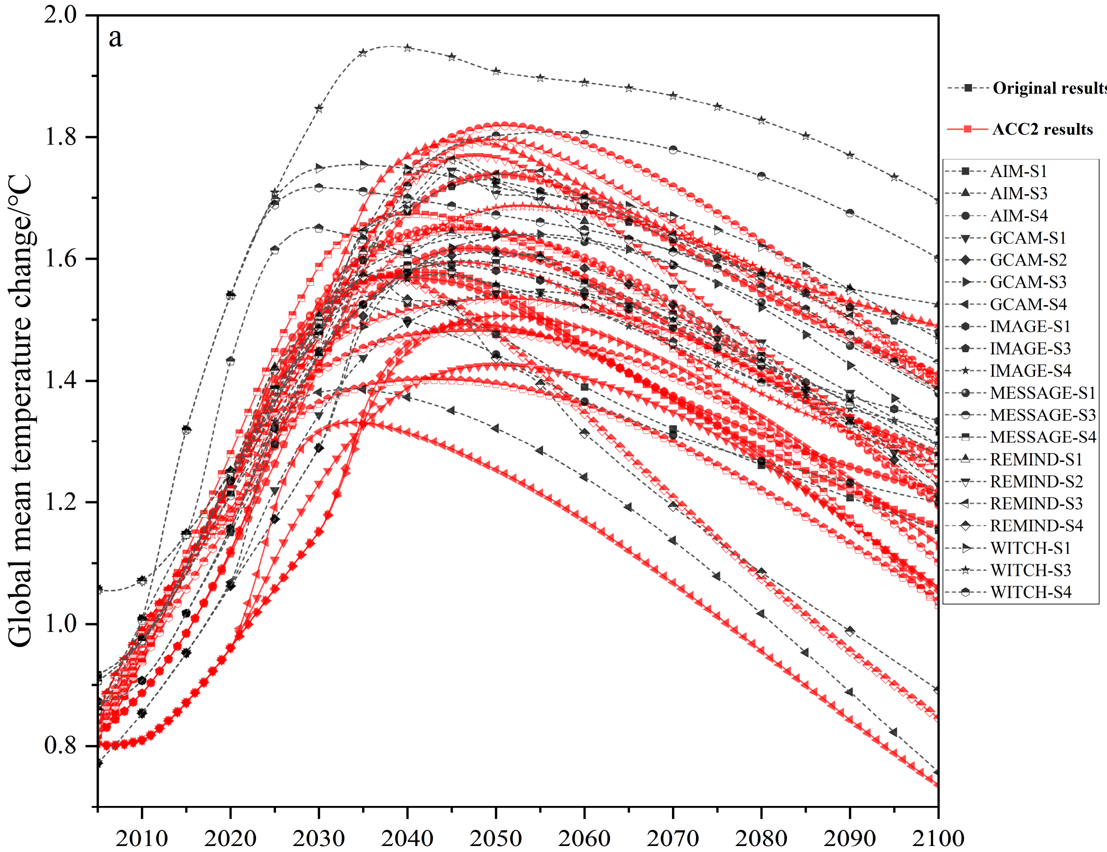


Figure 1. Original data of Global and China's emission pathways analyzed in our study. **(a)** China's CO_2 emission pathways under the 1.5°C target; **(b)** China's GHG emission pathways under the 1.5°C target with GWP100 metric; **(c)** and **(d)** Rest of the world (ROW) and Global GHG emission pathways under the 1.5°C target with GWP100 metric. We consider Kyoto gases as GHGs in this figure. Historical emission data from CAIT (2020) and EDGAR(Crippa *et al* 2020) are shown here.

To understand China's role in climate change mitigation, we first look into the levels of emission pathways. Figure 1 shows China's CO_2 emission pathways, China's GHG emission pathways, and Global GHG emission pathways. Emissions of non-CO_2 GHGs are translated into CO_2-equivalent emissions, with the 100-year Global Warming Potential (GWP100) metric being the conversion factor (UNFCCC 2018). While various issues have been discussed associated with GWP100 (O'Neill 2000, Shine 2009, Tanaka *et al* 2010; Myhre *et al* 2013, Allen *et al* 2021), we use this metric for our analysis, following the decision taken by Parties to the Paris Agreement (UNFCCC 2018).

Under all pathways, China's CO_2 emissions peak before 2030. The pathway with the highest peak CO_2 emissions is POLES, with approximately 16.3 $GtCO_2$ by 2025. The pathway with the lowest peak CO_2 emissions and earliest peak date is from AIM-S4, which gives 12.2 $GtCO_2$ in 2020. Since CO_2 is the dominant GHG emitted from China, the trends of CO_2-equivalent (GWP100 basis) emissions largely follow those of CO_2. In addition, these pathways show that China will achieve net zero CO_2 emissions before 2060, except those from WITCH. The CO_2 emissions of POLES are significantly lower than others after 2060. We further found that more than half of the pathways considered do not achieve net zero GHG emissions. If net zero GHG emissions are achieved, this happens one to two decades after net zero CO_2 emissions being achieved, as also found by Tanaka and O'Neill (2018) and van Soest *et al* (2021). WITCH-S3 is the last scenario to reach net zero CO_2 emissions (in 2075), and it then arrives at net zero GHG emissions in 2084.

3.2. Global mean temperature projections



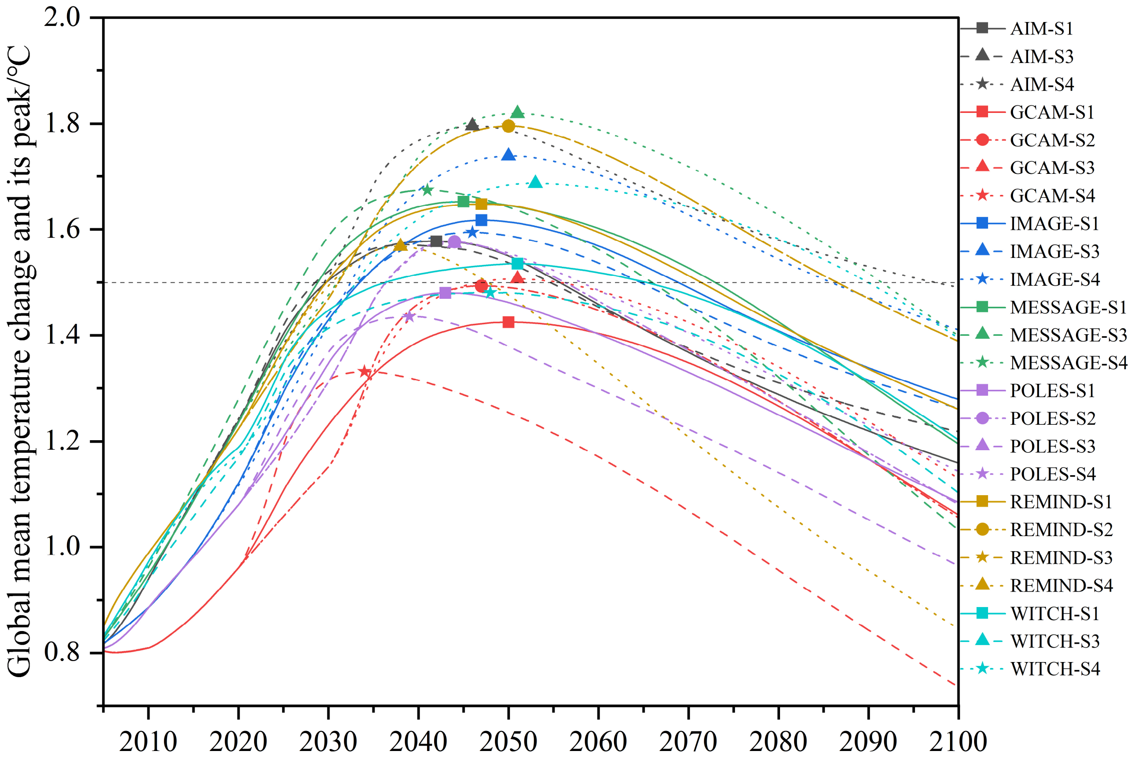
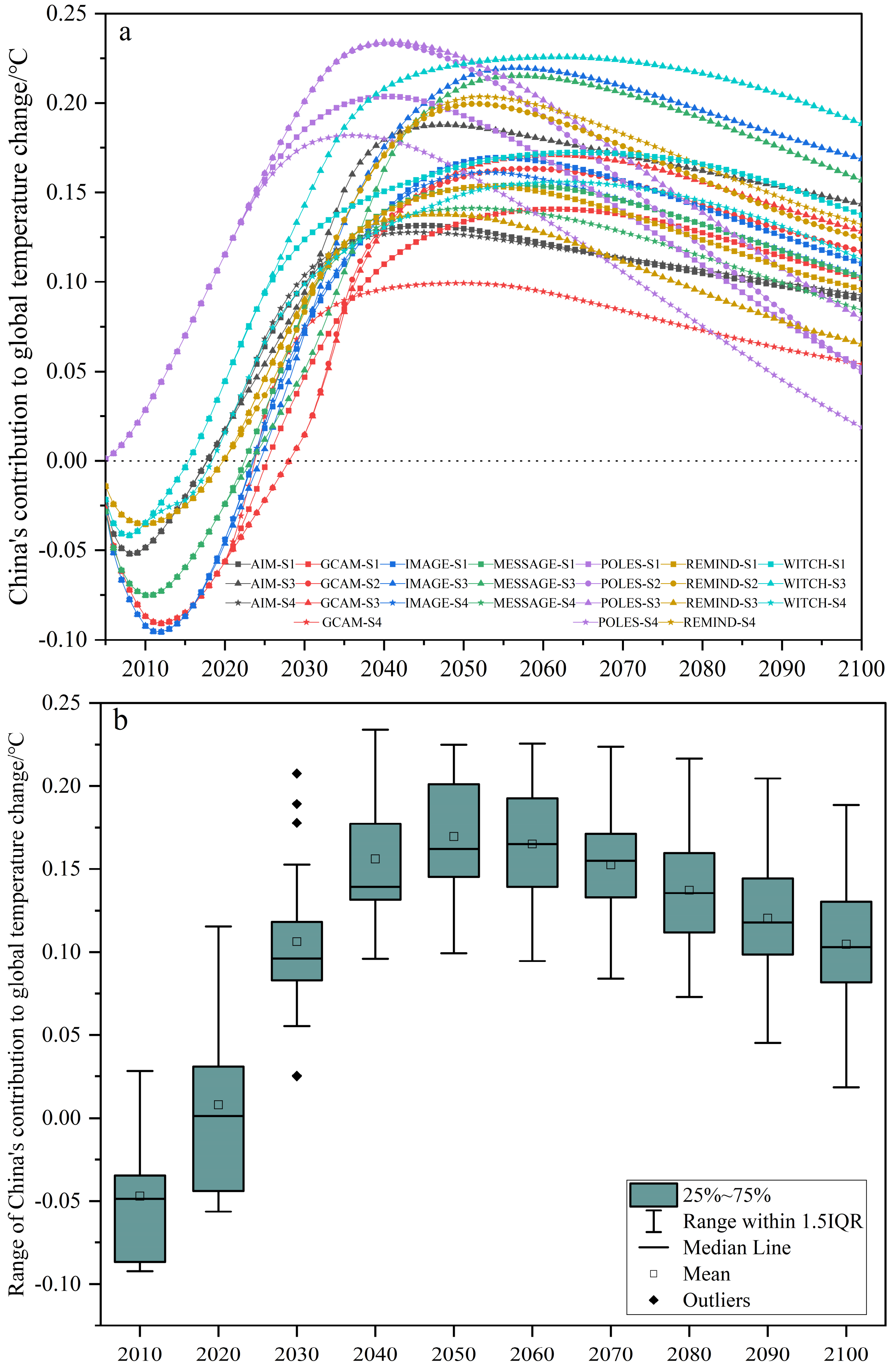


Figure 2. Global mean temperature projections of the emission pathways aiming at the 1.5°C target. **(a)** Global mean temperature projections obtained from the original databases (i.e., ADVANCE project) (black dotted lines) are compared with those calculated by ACC2 using the emission pathways in the databases (solid red lines). See Table 2 for temperature calculation methods of the original databases. Note that only a subset of the IAMs report temperature results in the original databases; **(b)** Global mean temperature projections are calculated using ACC2 for the emission pathways in the original database, with peak temperatures indicated as stars.

The original database contains global mean temperature projections for most of the emission pathways used in this study, which can be compared with corresponding temperature projections from ACC2. The results (figure 2(a) and Supplementary figure S1) show that temperature outcomes of ACC2 agree reasonably well with respective original projections, except a few cases of WITCH. We, therefore, use ACC2 to examine the temperature implications of emission pathways in the analysis that follows. This approach allows evaluating the temperature implications of emissions pathways based on the same methodological framework.

Figure 2(b) shows a considerable range in the global mean temperature pathways calculated from ACC2. The temperature peaks lie between 1.33°C (GCAM-S4) and 1.82°C (MESSAGE-S3), and the year that reaches peak temperatures varies from 2034 (GCAM-S4) to 2053 (WITCH-S3). All pathways eventually come to the 1.5°C level by 2100, with the AIM-S3 scenario achieving it at last (in 2098). Most of these pathways show an overshoot above the 1.5°C target, a finding consistent with IPCC (2018). There are six pathways that keep the global mean temperature change below 1.5°C all the time while none of the S3 scenarios achieve the 1.5°C target without overshoot.

3.3. Effects of China's emissions on the global mean temperature


a
China's contribution to global temperature change/°C
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
AIM-S1
GCAM-S1
IMAGE-S1
MESSAGE-S1
POLES-S1
REMIND-S1
WITCH-S1
AIM-S3
GCAM-S2
IMAGE-S3
MESSAGE-S3
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AIM-S4
GCAM-S3
IMAGE-S4
MESSAGE-S4
POLES-S3
REMIND-S3
WITCH-S4
GCAM-S4
POLES-S4
REMIND-S4
b
Range of China's contribution to global temperature change/°C
25%~75%
Range within 1.5IQR
Median Line
Mean
Outliers

Figure 3. Effects of China's emissions since 2005 on the global mean temperature. **(a)** Global mean temperature change arising from China's emissions of each scenario, **(b)** distribution characteristics of global warming contributions from China's emissions.

Now we focus on emissions from China and explore how they influence the global mean temperature. We use the emissions of all countries except China from the AIM-S1 scenario, which is roughly in the middle of the ensemble (figure 1(c) and (d)), as a baseline. We then add China's emissions from each IAM on the baseline and calculate the temperature change. The difference in warming between the two temperature time series for each IAM is shown in figure 3. The way how China will influence the global mean temperature is highly dependent on pathways (figure 3(a)). Overall, China's temperature contributions are negative until around 2025 (2028 at the latest), with several pathways being an exception, and then turn positive thereafter. Pathways from POLES, among others, are such examples, with the highest contribution at about 0.234°C in 2041. Negative contributions in early periods are caused by the cooling effect of air pollutants (Andreae *et al* 2005, Tanaka and Raddatz 2011).

Figure 3(b) shows that the highest value of China to the global mean temperature from the mean of these IAM pathways is as high as 0.170°C [0.099,0.223] in mid-century (in 2051), dropping to 0.105°C [0.019, 0.188] by the end of this century (square brackets indicate the range of pathways). Meanwhile, the peak contributions of these pathways vary from 0.099°C to 0.234°C, and the years reached are distributed between 2036 and 2065. In contrast, Chen *et al* (2021) estimated that China's carbon neutrality can reduce global warming by 0.16-0.21°C in 2100. The difference in the estimates of the end-of-the-century temperature contribution between the two studies can be explained in the following. The Chen study considered China's carbon neutrality pathways based only on CO_2 emissions from 2020 onwards. In contrast, our study deals with 1.5°C pathways involving deeper mitigation than that required for carbon neutrality and considers GHG emissions since 2005. While our emissions starting in 2005 should lead to an increase in China's contribution to the global mean temperature, this effect was overcompensated by net negative CO_2 emissions after carbon neutrality, resulting in a lower China's temperature contribution at the end of the century than the estimate of the Chen study. The difference between the two studies also appears in China's temperature contribution in mid-century primarily because of CH_4 considered in our study, as discussed in the next section.

3.4. Effects of emissions from individual gases and aerosols on global mean temperature

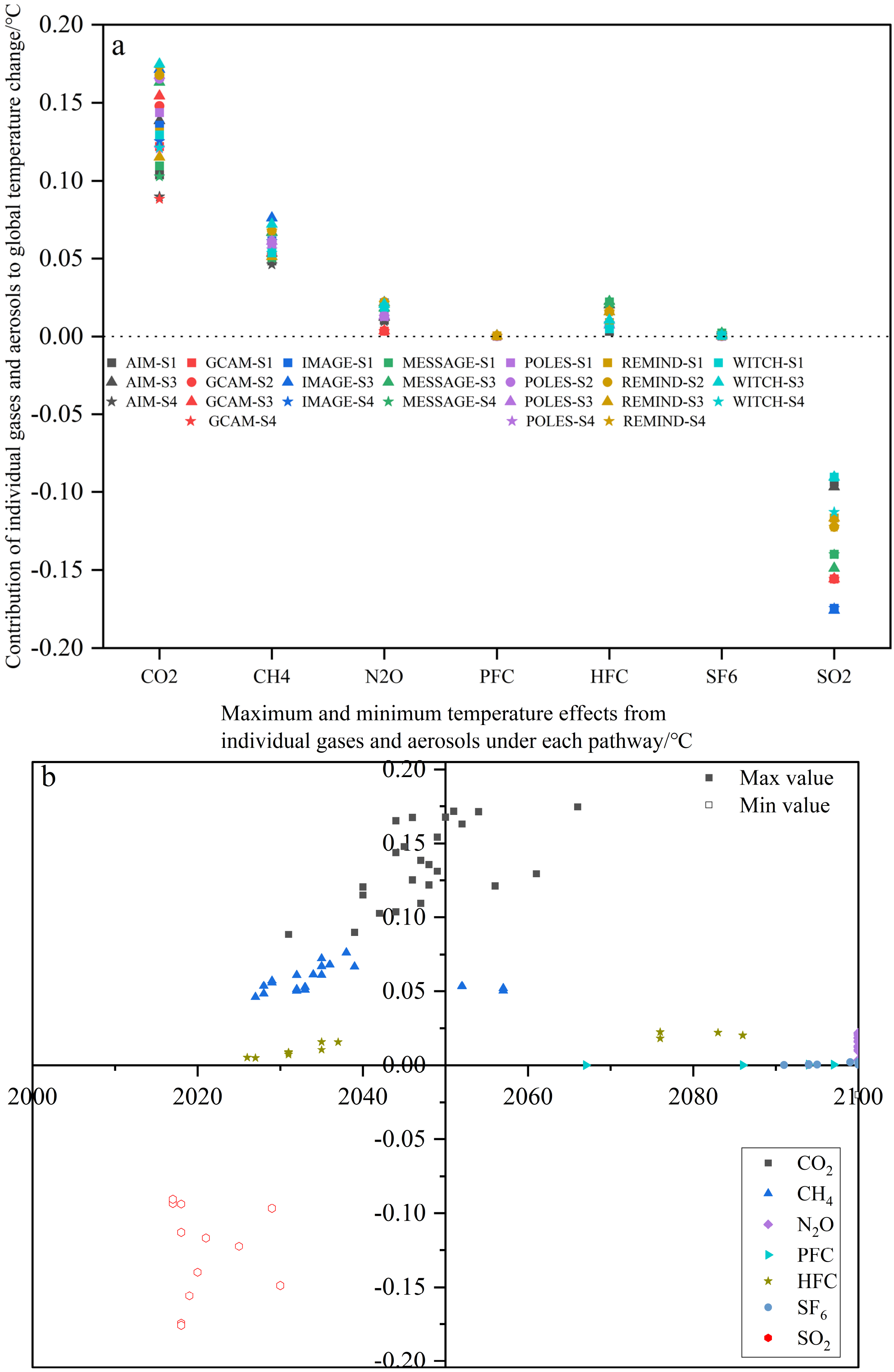

Figure 4. China's contribution to the global mean temperature from individual GHGs and air pollutants. **(a)** Maximum gas-by-gas contributions (in absolute terms) of China's emissions to the global mean

temperature, **(b)** Temporal distribution of the maximum and minimum of gas-by-gas contributions (filled and open symbols, respectively).

We further analyze the effect of individual gases and aerosol precursors emitted by China on the global mean temperature. Our analysis considers Kyoto gases, as well as SO_2, which has strong cooling effects. Note that other air pollutants such as NOx, CO, and VOC are not considered here because they are not part of Kyoto gases and are not primarily crucial in the analysis here in terms of the effect on global warming through their influence on CH_4 and ozone (Prather 2007). We found that climate forcers that are important for China's temperature contributions are CO_2, CH_4, and SO_2 (figure 4(a) and Supplementary figure S2), although the contribution from SO_2 is in the opposite direction. The peak contribution from CO_2 is by far the largest, followed by that from CH_4. The peak contributions from N_2O and HFC are smaller than those from CO_2 and CH_4, but they can occur later in this century or beyond.

Different GHGs and air pollutants influence the temperature in different ways (figure 4(b)). The years of peak contribution of CO_2 occur between 2040 and 2060. Those of CH_4 and SO_2 happen earlier (in around 2030s and 2020s, respectively), reflecting the short-lived nature of these components and the early mitigation efforts assumed in the emission pathways (the moderate scatter of the points in figure 3(b) shows that IAMs are broadly consistent with each other in the pathways of emissions of each species). The temperature impact from N_2O increases over time, indicating the long-lived nature of this gas and the difficulty in abating its emissions.

3.5. China's CH_4 mitigation

The results of the previous section suggest that both CO_2 and CH_4 play an important role in determining the temperature warming contribution of China's emissions. These two gases are the most important long-lived and short-lived climate forcers, respectively, that have led to the current warming (IPCC 2021). It was shown that ratios of CO_2 and CH_4 emissions would influence global mean temperature projections (Denison *et al* 2019). Any pledge or target expressed as GHGs is therefore ambiguous in terms of how this might mean for the global mean temperature (Tanaka and O'Neill 2018, Fuglestvedt *et al* 2018, Allen *et al* 2021). Here we explore how the proportions of these two gases can affect China's contributions to the global mean temperature by developing scenarios dedicated to this question, with particular attention to the role of different CH_4 mitigation in meeting the 1.5°C target.

During COP26 in November 2021, the U.S. and the E.U. pledged to reduce anthropogenic CH_4 emissions by 30% by 2030 compared with 2020 levels (U.S. and E.U. 2021). Many countries followed suit, although China and India did not indicate participation in this pledge. Ocko *et al* (2021) showed that global CH_4 emissions could be cut by 57% in 2030 based on existing technologies, while Höglund-Isaksson *et al* (2020) gave the maximum technically feasible reduction potential (MRP) of 54% in 2050 compared to 2015 levels. Given these political pledges and mitigation assessments, we set up the following scenarios, called China's CH_4 mitigation scenarios (Table 3 and figure 5).

Table 3. Details of China's CH_4 mitigation scenarios. Except for the 1.5°C consistent scenario, we linearly extrapolate the 30% CH_4 & MRP scenario after 2050 to the point where it meets the 1.5°C consistent scenario. In other words, all scenarios other than the 1.5°C consistent scenario are assumed to follow the 30% CH_4 & MRP scenario after 2050 until these scenarios merge with the 1.5°C consistent scenario.

Scenario	Insight	Definition
1.5°C consistent	It shows that China will follow the 1.5°C emission reduction pathway	Following the average emission pathway obtained from the pathways aiming at the 1.5°C target discussed earlier (Table 1)
30% CH_4 & MRP	It represents a case in which China will follow the 2030 CH_4 pledge together with many other countries and then decrease the rate of CH_4 emission reduction while still achieving the MRP target by 2050	Reducing CH_4 emissions by 30% by 2030 relative to 2020 levels and then following the MRP until 2050
1.5°C consistent & MRP	It assumes that China will take decisive efforts to keep up with the 1.5°C target until 2030 and then relax the efforts while still achieving the MRP target by 2050	Keeping CH_4 emissions consistent with that of the 1.5°C consistent pathway before 2030 and then aiming toward the MRP target by 2050
MRP-only	It gives a situation that China will only consider the MRP target as their policy priority	Mitigating CH_4 emissions towards the 2050 MRP target after 2020, without considering the 2030 pledge of 30% CH_4 reductions.
Constant CH_4 until 2030	It portrays a situation in which China will keep the same level of CH_4 emissions before 2030	Keeping CH_4 emissions in line with 2020 levels before 2030 and then mitigating CH_4 emissions toward the MRP until 2050

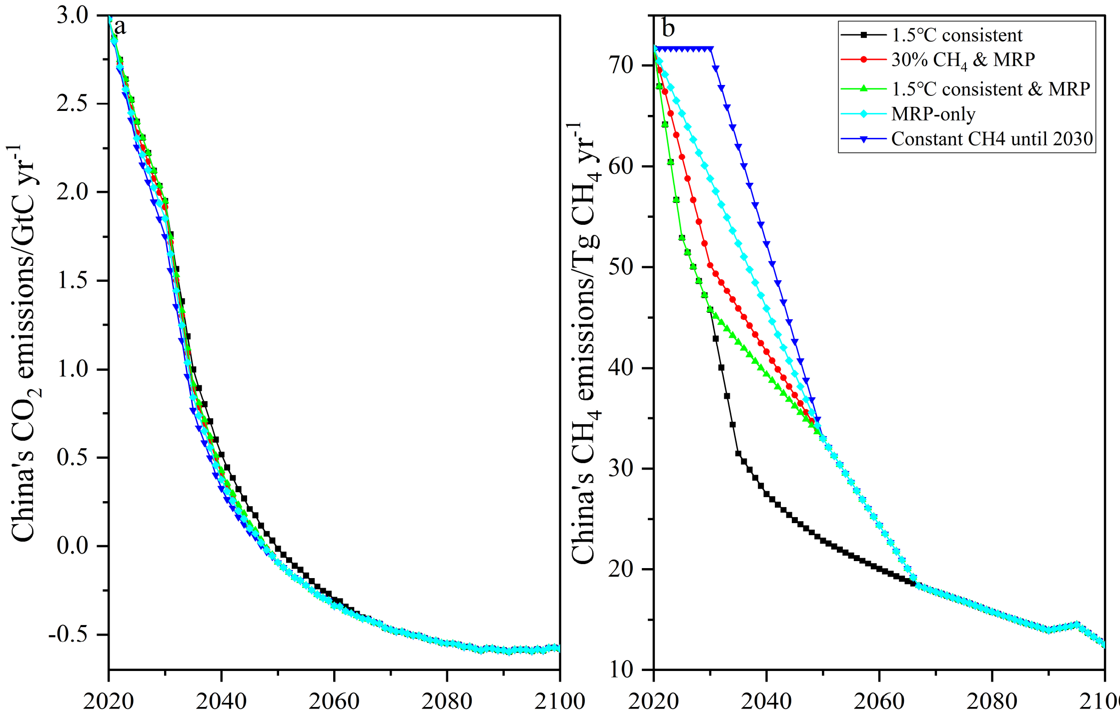

Figure 5. CO_2 and CH_4 emissions of China's CH_4 mitigation scenarios to evaluate the effect of different GHG compositions on the global mean temperature. **(a)** China's CO_2 emissions, **(b)** China's CH_4 emissions. Across all scenarios, CO_2 equivalent emissions (GWP100-basis) are hypothetically kept the same each year. In other words, the reduction of CO_2 emissions relative to the level in the 1.5°C consistent scenario each year is equivalent in absolute magnitude (GWP100-basis) to the increase in CH_4 emissions relative to that in the 1.5°C consistent scenario. See text for details.

The way how we constructed China's CH_4 mitigation scenarios is in the following. The 1.5°C consistent emission scenario, which is the average of the 24 scenarios analyzed earlier, is taken as the baseline here. We then varied the CH_4 emission pathway in the 1.5°C consistent scenario to reflect alternative cases, such as a 30% CH_4 emission reduction by 2030 relative to 2020 levels. Since the 1.5°C consistent scenario already assumes very ambitious CH_4 mitigation, we increased CH_4 emissions in all other scenarios relative to the level in the 1.5°C consistent scenario (figure 5(b)). To understand the trade-off between the abatement of CO_2 and CH_4 emissions, we further hypothetically decreased CO_2 emissions in each scenario by the amount equivalent to the reduction in CH_4 emissions relative to the level in the 1.5°C consistent scenario. In doing so, we equated CH_4 emissions on a common scale of CO_2-equivalents by using GWP100. This approach allows exploring the temperature implication of different GHG compositions for the same total GHG pathways. Although it is known that this method does not ensure the same temperature outcome (Tanaka *et al* 2009(b), Wigley 2021, Allen *et al* 2021), we applied this method because GWP100 has been adopted by Parties to the Paris Agreement for its implementation (UNFCCC 2018). Note that emissions of the rest of the world are kept the same with the levels in the 1.5°C consistent scenario.

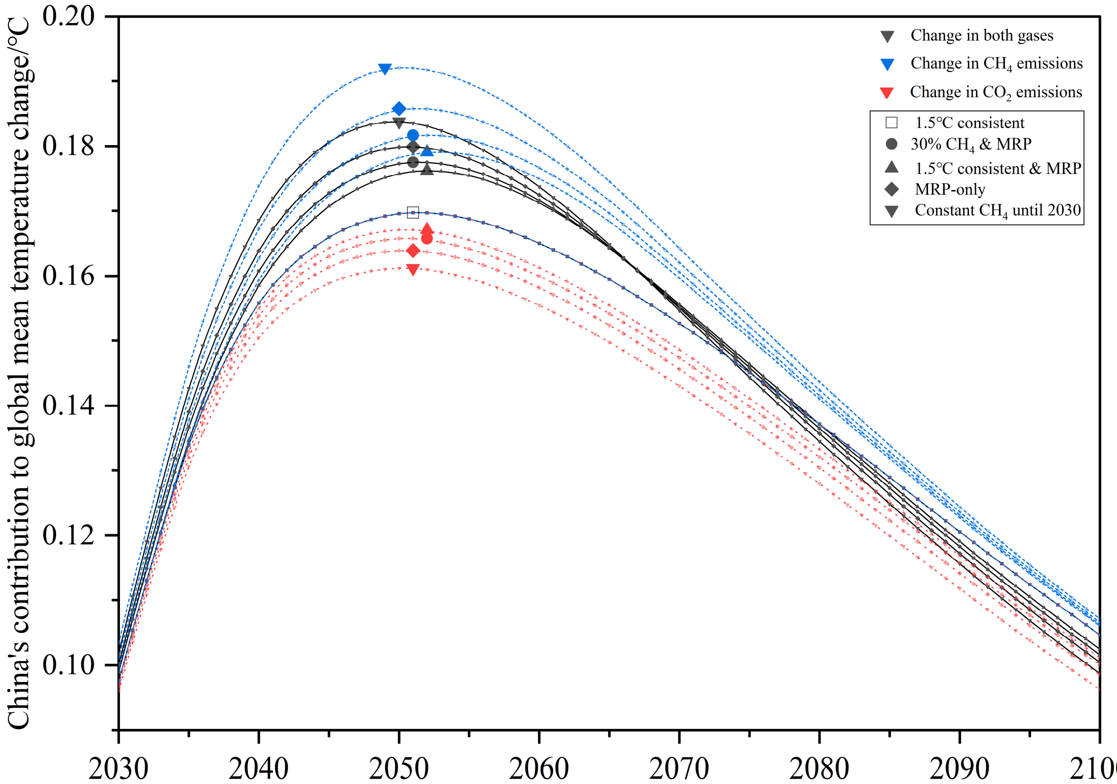

Figure 6. The difference of China's contribution to global warming under different scenarios. Different points represent different scenarios. Colors are designated according to how CO_2 and CH_4 emissions are hypothetically altered.

Large differences in temperature contributions were found in around 2050 across the scenarios playing on CH_4 emissions reductions and their trade-offs with CO_2 emissions reductions, while those in 2030 and 2100 were less pronounced (black lines of figure 6). In 2050, the temperature contribution of the Constant CH_4 until 2030 scenario becomes 0.184°C, 0.014°C higher than the 1.5°C consistent scenario. In 2100, on the contrary, the temperature contributions of all scenarios become lower than that of the 1.5°C consistent scenario.

Figure 6 also shows the effects of CO_2 and CH_4 separately (red and blue lines, respectively, of figure 6). Differences in peak warming are larger in the CH_4-only cases than in the cases changing both CO_2 and CH_4, with the largest contribution of 0.192°C in the Constant CH_4 until 2030 scenario. On the other hand, differences in peak years are only three years (2050 for the Constant CH_4 until 2030 scenario and 2053 for the 1.5°C consistent & MRP scenario). Thus, stronger near-term CH_4 mitigation in China can have a pronounced effect on reducing temperature contribution in mid-century while it may not bring earlier the peak year of China's contribution to the warming.

Furthermore, our results indicate that CH_4 has stronger effects on the near-term temperature than CO_2 does. The temperature contribution of CH_4 in 2050 under the Constant CH_4 until 2030 scenario is 0.022°C higher than that under the 1.5°C consistent scenario, while the that of CO_2 under the Constant CH_4 until 2030 scenario is 0.009°C lower than that under the 1.5°C consistent scenario. In 2100, on the contrary, the temperature difference for the scenarios for CH_4 is only 0.002°C but those for CO_2 remains the same level persistently (0.009°C).

Table 4. Temperature contributions of China's emissions with varying GHG compositions. The percentage indicates the difference from the corresponding estimate in the 1.5°C consistent scenario.

Scenarios	Unit	2030			2050			2100		
		Both gases	CO_2-only	CH_4-only	Both gases	CO_2-only	CH_4-only	Both gases	CO_2-only	CH_4-only
1.5°C consistent	°C		0.097			0.170			0.105	
30% CH_4 & MRP	**%**	1.53	-0.55	2.08	4.55	-2.26	6.81	-2.93	-4.42	1.50
1.5°C orientation & MRP	**%**	0.00	0.00	0.00	3.64	-1.47	5.11	-2.10	-3.36	1.27
MRP-only	**%**	2.69	-0.95	3.65	6.07	-3.33	9.4	-4.04	-5.87	1.83
Constant CH_4 until 2030	**%**	4.43	-1.57	6.01	8.35	-4.93	13.27	-5.71	-8.05	2.33

The trade-off between CO_2 and CH_4 can be further seen in Table 4. If we look at the pathway changing only CH_4 of the Constant CH_4 until 2030 scenario, the temperature effect of CH_4 is more pronounced in 2050 (13.27% increase) than in 2100 (2.33% increase). On the other hand, if we look to that changing only CO_2, the temperature effect of CO_2 is larger in 2100 (8.05% decrease) than in 2050 (4.93% decrease). In pathways changing both CO_2 and CH_4, the interplay of two gases becomes evident. The temperature effect from CH_4 outcompetes that of CO_2 in mid-century (8.35% increase). However, the effect from CO_2 outcompetes at the end of the century (5.71% decrease).

4. Discussion and conclusions

4.1. Significant contribution of China's mitigation to the global efforts toward the 1.5°C target

We explored how China's emissions can shape global mean temperature projections toward the 1.5°C target. The magnitude of China's contribution to the global mean temperature over time can differ significantly, even if all pathways considered are intended for the 1.5°C target. The peak of China's temperature contribution from the average of the IAM pathways to global warming in 2051 is 0.170°C with the range of 0.099°C to 0.223°C. The peak years of these pathways range from 2036 to 2065. Thereafter, China's contribution will decline to 0.105°C [0.019, 0.188] in 2100. The significant temperature contribution of China, as well as the range of contributions, highlight the importance of the course of China's mitigation actions toward the 1.5°C target.

4.2. Differences in the temperature contribution from individual gases

Emissions of CO_2, CH_4, and SO_2 play a major role in determining the temperature contribution from China. Our pathway analysis showed that peak temperature contributions of these three gases are 0.136°C [0.088, 0.175], 0.058°C [0.046, 0.076], and -0.132°C [-0.176, -0.091], respectively. The peak (negative) contribution from SO_2 occurs around 2020 in most pathways, while that from CO_2 and CH_4 can be found around 2050 and 2030, respectively. Most pathways showed the peak contribution from China's CO_2 emissions earlier than 2060, the target year of China's carbon neutrality.

Even though SO_2 brings about a short-term cooling effect, it is a source of air pollution and harmful to human health (Khaniabadi *et al* 2017). There is thus a trade-off for SO_2 abatements: while reducing the emissions of SO_2 improves air quality, it unmasks warming currently hidden by SO_2. However, the implementation of clean air policies is rapidly progressing in China (Wang *et al* 2018). With further penetration of clean air policies in China, aerosols' cooling effect will weaken, giving rise to warming (Workman *et al* 2020), which makes it important to tackle CH_4 mitigation in China, a point that has been made globally (IPCC 2021).

4.3. Impact of China's CH_4 mitigation on the global peak temperature

The significance of China's CH_4 mitigation in determining the peak temperature brings us to the question of how China should tackle CH_4 mitigation. If China leverages a shift from the Constant CH_4 until 2030 scenario (i.e., maintaining the same CH_4 emissions from 2020 until 2030) to the 1.5°C consistent scenario, China's contribution to peak temperature in 2050 will be decreased by 7.61% (i.e. the case changing both gases). Therefore, near-term CH_4 actions can reduce China's peak impact on global warming while noting that the year of peak temperature contribution is largely unaffected.

Abatement strategies on CH_4 should be determined by policy priorities. For the purpose of reducing China's temperature contribution in mid-century, taking deep near-term CH_4 mitigation is an effective policy choice; however, this is not necessarily an adequate measure if the purpose is to reduce China's contribution to the end-of-the-century temperature. Other concerns are outside the scope of this study but are relevant for such policy decisions, most notably, the CH_4 effect on air pollution through the production of tropospheric O_3.

There are many mitigation opportunities for CH_4. The energy sector, especially coal and natural gas (Tanaka *et al* 2019), accounts for 46% of the anthropogenic CH_4 emissions from China in 2019 (O'Rourke *et al* 2021). The agricultural sector is an equally important CH_4 source, although it is known to be generally more difficult to mitigate CH_4 from the agricultural sector than from the energy sector. Early CH_4 action from China can reduce the global peak temperature in mid-century, potentially contributing to reducing the temperature overshoot (Melnikova *et al* 2021) along the way toward the 1.5°C target.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files) and are available on Zenode with the doi:10.5281/zenodo.5844488

Author contributions

W.X. and K.T. conceived this study. W.X. led the study. W.X. and K.T. designed the experiment. W.X. performed the analysis. All authors analyzed the results. W.X. and K.T. drafted the manuscript, with contributions from P.C. All authors approved the manuscript.

Competing financial interests

The authors declare no competing financial interest.

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