ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
21 April 2021

REVISED
10 June 2021

ACCEPTED FOR PUBLICATION
18 June 2021

PUBLISHED
2 July 2021

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

LETTER

Long-term temperature and sea-level rise stabilization before and beyond 2100: Estimating the additional climate mitigation contribution from China's recent 2060 carbon neutrality pledge

Jiewei Chen[1,2], **Huijuan Cui**[1,2,*], **Yangyang Xu**[3,*] and **Quansheng Ge**[1,2]

[1] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, People's Republic of China
[2] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[3] Department of Atmospheric Sciences, College of Geosciences, Texas A&M University, College Station, TX 77843-3150, United States of America
[*] Authors to whom any correspondence should be addressed.

E-mail: cuihj@igsnrr.ac.cn and yangyang.xu@tamu.edu

Keywords: carbon neutrality, temperature rise, sea-level rise, Paris agreement

Abstract

As the largest emitter in the world, China recently pledged to reach a carbon peak before 2030 and carbon neutrality before 2060, which could accelerate the progress of mitigating negative climate change effects. In this study, we used the Minimum Complexity Earth Simulator and a semi-empirical statistical model to quantify the global mean temperature and sea-level rise (SLR) response under a suite of emission pathways that are constructed to cover various carbon peak and carbon neutrality years in China. The results show that China will require a carbon emission reduction rate of no less than 6%/year and a growth rate of more than 10%/year for carbon capture capacity to achieve carbon neutrality by 2060. Carbon peak years and peak emissions contribute significantly to mitigating climate change in the near term, while carbon neutrality years are more influential in the long term. Mitigation due to recent China's pledge alone will contribute a 0.16 °C–0.21 °C avoided warming at 2100 and also lessen the cumulative warming above 1.5 °C level. When accompanied by coordinated international efforts to reach global carbon neutrality before 2070, the 2 °C target can be achieved. However, the 1.5 °C target requires additional efforts, such as global scale adoption of negative emission technology for CO_2, as well as a deep cut in non-CO_2 GHG emissions. Collectively, the efforts of adopting negative emission technolgy and curbing all greenhouse gas emissions will reduce global warming by 0.9 °C −1.2 °C at 2100, and also reduce SLR by 49–59 cm in 2200, compared to a baseline mitigation pathway already aiming at 2 °C. Our findings suggest that while China's ambitious carbon-neutral pledge contributes to Paris Agreement's targets, additional major efforts will be needed, such as reaching an earlier and lower CO_2 emission peak, developing negative emission technology for CO_2, and cutting other non-CO_2 GHGs such as N_2O, CH_4, O_3, and HFCs.

1. Introduction

The Paris Agreement adopted in 2015 set the goal to hold 'the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels' (UNFCCC 2017). To achieve this goal, every participating country was required to plan climate action in the form of 'nationally determined contributions' (NDCs). However, even under the current NDC plans, greenhouse gas (GHG) emissions will continue to rise to 56 $GtCO_2eq\ yr^{-1}$ by 2030, which will lead to a global mean temperature rise of 2.6 °C–3.1 °C by the end of the century, potentially even exceeding 4 °C (Fawcett *et al* 2015, Rogelj *et al* 2016, Xu and Ramanathan 2017, Wei *et al* 2018). To meet the 2 °C and 1.5 °C goals of the Paris Agreement, the current NDCs must be boosted with additional GHG emission reductions of 15 $GtCO_2eq\ yr^{-1}$ and 32 $GtCO_2eq\ yr^{-1}$ by 2030,

© 2021 The Author(s). Published by IOP Publishing Ltd

respectively (Höhne *et al* 2020, Olhoff and Chistensen 2020, Schaeffer *et al* 2020).

Furthermore, it has become clear that reaching carbon neutrality by the mid-century is essential to achieve the goal of 1.5 °C (IPCC 2018). Therefore, several countries have begun to make zero-emission commitments. Developed countries, including those in the European Union (EU), Japan, the Republic of Korea, and Canada, have announced goals of carbon neutrality by 2050 (European Union 2020, Vaughan 2020, Yonhap News 2020, Jinyi 2021). China, the largest developing country and currently the largest carbon emitter, has also recently proposed a plan to reaching carbon neutrality by 2060 (Xinhuanet 2020). Since President Xi's surprising announcement, China has begun promoting top-down planning (Xinhuanet 2021) that includes an overhaul of its energy system associated with massive investment.

There are two ways to achieve net-zero carbon emissions: reducing gross emissions and increasing negative emissions (Wang and Zhang 2020). Emission reduction involves several aspects, including major and rapid changes in energy supply, massive low-carbon transitions with the development of the carbon market, changes in consumption end-use for energy saving. Negative emission technologies broadly include land-based solutions, such as enhancing agricultural and forestry carbon sinks through soil management and afforestation, but also carbon capture utilization and storage (CCUS) for industrial facilities, such as biomass energy carbon capture and storage and direct air carbon capture. Among them, CCUS has a large potential emission reduction of approximately 3 GtC yr^{-1} to 10 GtC yr^{-1} (Smith *et al* 2016, Mac Dowell *et al* 2017), but is still in the early stages with very limited capacity. Specifically, China's CCUS is at about 0.001 GtC in 2020 (Cai and Li 2020). To keep the 1.5 °C goals alive, an accelerated scale-up of CCUS is necessary (van Vuuren *et al* 2018, IPCC 2018, Jiang 2018, Detz and van der Zwaan 2019, Hanna *et al* 2021).

Because of the high cost of mitigation (particularly the upfront investment), it is worth demonstrating what climate benefits the proposed carbon neutrality commitment from China would contribute, especially given the uncertainty associated with the pathways towards 2060. This was the purpose of this study. In particular, we aim to understand how different carbon peak years (CPYs) and carbon neutrality years (CNYs) will affect the global temperature rise in this century. Although projected temperature rise can be linearly approximated by cumulative CO_2 emissions (Wang *et al* 2012, Knutti *et al* 2017, Arora *et al* 2020), more accurate quantification of the role of all GHG species requires climate model simulations (such as in van Vuuren *et al* (2011), Ricke and Caldeira (2014), IPCC (2018), Tong *et al* (2019)). In addition to global mean temperature, sea-level rise (SLR) also has profound adaptation implications. SLR can be estimated using an empirical linear relationship that is mainly tied to historical warming, but also the warming rate during a specific period (Vermeer and Rahmstorf 2009, Rahmstorf *et al* 2012, Hu *et al* 2013). For reference, if the global temperature rises by 2 °C, the global sea level will rise 46–55 cm during this century (relative to 2000) and there will be a lower SLR of 40–48 cm if temperatures rise is limited to 1.5 °C (Mengel *et al* 2016, 2018, Rasmussen *et al* 2018).

Overall, it remains unclear whether the newly pledged carbon neutrality commitment could hold temperature rise to below 2 °C or even 1.5 °C and how the corresponding SLR would respond in this and the next century. To assess the climate impact of China's 2060 carbon neutrality pledge, this study designed a series of idealized carbon neutral pathways with different CPYs and CNYs. Then, we used the minimum complexity Earth simulator (MiCES) to estimate the temperature rise, which feeds into a semi-empirical statistical model to project the SLR under the various carbon-neutral pathways. Moreover, the mitigation benefits of new 2060 pledges as well as coordinated international reductions are presented in a comprehensive suite of metrics, including avoided warming, peak warming year, peak warming level, year of reaching 1.5 °C, number of years exceeding 1.5 °C, cumulative warming amounts exceeding 1.5 °C, warming reversal rates towards 2100, and avoided SLR in this and the next century.

2. Methods

2.1. Uncertainty of carbon neutrality pathways in China

The baseline CO_2 emissions for China and the world from 2015 to 2100 were derived from an NDC pathway developed by Huang *et al* (2020) using a Computable General Equilibrium model with optimized costs. Note this baseline scenario is already a mitigation pathway globally, which aims at holding a temperature rise under 2 °C by 2100. Thus, it should not be confused with a typical 'baseline' in the literature in which there assumes no or weak climate policy in place, such as SSP3-7.0. In this NDC pathway, CO_2 emission in China peaks in 2030 and continues to decline toward 2100, while the global emission peaks in 2040. Here, we further expand the NDC-related pathway to 2200 by holding the same reduction rate as in 2050–2100 (thick black line in figure 1).

The carbon naturality pathways in China were constructed to have two distinct components: reducing gross emissions and increasing the CCUS capacity.

Emission reduction is represented by a power function of time with a reducing rate r as follows:

$$\text{Emission} = \text{Emission}_{\text{peak}} \cdot (1-r)^{t-t_{\text{peak}}} \quad (1)$$

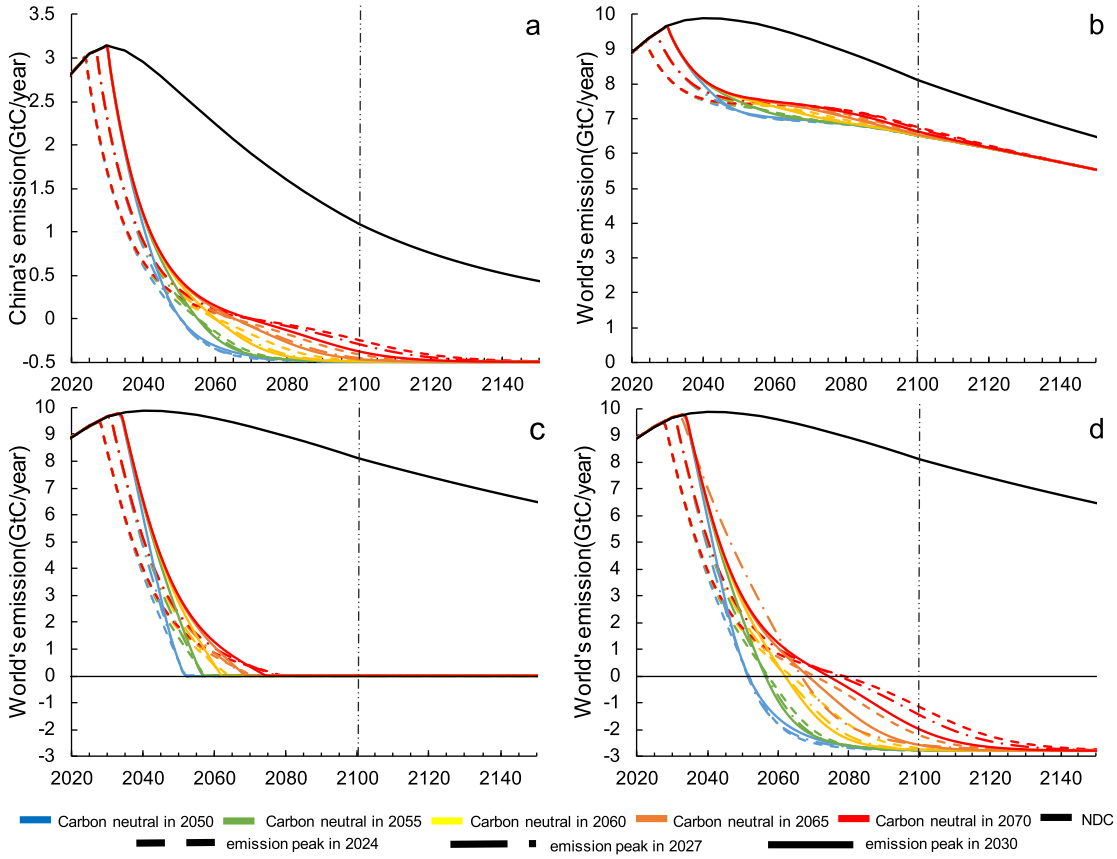

Figure 1. Carbon emissions (GtC/year) in different cases. (a) China's carbon emission, (b) global carbon emission under the China only pathway, (c) global carbon emission under the zero CO_2 pathway, and (d) global carbon emission under the negative CO_2 pathway.

where Emission is the emission of China in year t (beginning at t_{peak}), and Emission_{peak} and t_{peak} are the peak emission and corresponding year, respectively.

The growth of CCUS is represented as an S-curve function with a growth rate g, and a cap of CCUS_{limit}, as follows:

$$\frac{\text{dCCUS}}{\text{d}t} = \frac{(\text{CCUS}_{limit} - \text{CCUS}) \cdot \text{CCUS}}{\text{CCUS}_{limit}} \cdot g \qquad (2)$$

where CCUS_{limit} is set to be 0.5 GtC yr^{-1} for China according to the layout proposed by Wei *et al* (2021). As noted previously, the current CCUS capacity is very low at 0.001 GtC (Cai and Li 2020), and that is the initial condition used in this study.

To assess the impact of pathway uncertainty associated with the carbon peaking year (2024–2030) and CNY (2050–2070), a suite of pathways was constructed. The values of r and g for certain CPYs and CNYs are listed in table 1. Because CCUS is limited to 0.5 GtC yr^{-1}, only a sufficiently large r can lead to eventual carbon neutrality. Thus, the value of r was set to 6.0%/year, which is the minimum to realize carbon neutrality in 2060 or later, and 9.0%/year, which is the minimum to realize carbon neutrality in 2050, as well as faster rates, such as 10.5%/year and 12.0%/year, which were used for sensitivity exploration. The corresponding values of g were calculated based on the given r and assumed CPY in order to reach carbon neutrality at certain years. It is reasonable that a larger r would require a smaller g to achieve carbon neutrality at a certain time (e.g. 2060).

2.2. International cooperation to reach global carbon neutrality

International cooperation is required to mitigate climate change. As previously mentioned, several countries raised their own carbon-neutral targets before or shortly after China. As China is one of the world's major emitters, world emissions partially depend on China's emissions. To correlate the world emission response to China's carbon neutrality pathway obtained in the previous section, we fit the world's emissions with China's emissions using all available SSP pathway emission data (Riahi *et al* 2017) in the low emission range (China's emissions less than 3.5 GtC yr^{-1}) and obtained a quadratic function. The R^2 of the fitness is 0.94 and the root mean square error is 1.45 GtC yr^{-1}. Therefore, using this function, global emissions (fossil fuel and land use) can be approximately estimated from China's emissions. In addition, global emissions are capped by the baseline that is the NDC pathway as derived from Huang *et al* (2020).

Table 1. Fifteen pathways to reach net-zero in China. Note that the emission reduction rate and CCUS applications growth rate correspond to different CPYs and CNYs.

Targeted CNY	Assumed CPY	Assumed emission reduction rate *r*	Required CCUS growth rate *g*
		9.0%	22.0%
	2024	10.5%	19.5%
		12.0%	17.5%
		9.0%	25.0%
2050	2027	10.5%	21.5%
		12.0%	19.5%
		9.0%	30.0%
	2030	10.5%	24.5%
		12.0%	21.5%
		9.0%	16.5%
	2024	10.5%	14.5%
		12.0%	12.5%
		9.0%	18.0%
2055	2027	10.5%	16.0%
		12.0%	14.0%
		9.0%	20.0%
	2030	10.5%	17.5%
		12.0%	15.5%
		6.0%	18.0%
	2024	9.0%	12.5%
		12.0%	9.0%
		6.0%	19.5%
2060	2027	9.0%	14.0%
		12.0%	10.0%
		6.0%	24.0%
	2030	9.0%	15.0%
		12.0%	11.5%
		6.0%	14.5%
	2024	9.0%	10.0%
		12.0%	6.5%
		6.0%	15.5%
2065	2027	9.0%	11.0%
		12.0%	7.5%
		6.0%	16.5%
	2030	9.0%	11.5%
		12.0%	8.5%
		6.0%	11.5%
	2024	9.0%	8.0%
		12.0%	4.5%
		6.0%	12.5%
2070	2027	9.0%	8.5%
		12.0%	5.5%
		6.0%	13.5%
	2030	9.0%	9.5%
		12.0%	6.0%

Considering the technical limitations and the political will to reduce emissions, we considered four cases of decarbonization pathways from 2015 to 2200:

Case A) China-only pathway. The rest of the world stays with the baseline-mitigation emissions, and China's emissions reach carbon neutrality and negative. This is a hypothetical case to quantify the added value of enhanced pledges from China.

Case B) Global zero CO_2 pathway. In addition to Case A, the rest of the world also reduces carbon emissions to zero, but without going negative.

Case C) Global negative CO_2 pathway. In addition to Case B, the rest of the world reaches negative carbon emissions between 2050 and 2070.

Case D) Global zero GHG pathway. This case uses the same carbon emission as Case C, but also considers non-CO_2 GHGs following the RCP4.5 emissions to 2050 (e.g. the peaks of CH_4 and N_2O are 2030 and 2040, respectively), and then declines linearly to zero in 2100, as opposed to the remaining 2.5 GtCeq in RCP4.5.

Table 2. Key parameters in the MiCES.

Parameter	Description and unit	Value
λ	Climate sensitivity $K(Wm^{-2})^{-1}$	2.78
κ_l	Land surface heat capacity $(Ka^{-1})^{-1}$ Wm^{-2}	23.5
κ_o	Ocean heat capacity $(Ka^{-1})^{-1}$ Wm^{-2}	145.5
Do	Atmosphere–ocean diffusion coefficient Wm^{-2} K^{-1}	0.19
β_l	Biosphere CO_2 fertilization parameter Pg ppm^{-1}	2.27
β_o	Ocean carbon diffusion parameter Pg ppm^{-1}	4.92
γ_l	Biosphere temperature response Pg K^{-1}	−50.8
γ_o	Ocean carbon solubility response Pg K^{-1}	−1.52

2.3. Calculation of temperature rise

The MiCES is used to simulate climate change from 1850 to 2200 caused by global GHG and aerosol emissions (Sanderson *et al* 2017). It is a simplified climate model based on the energy and carbon budget of the Earth's system. In this model, the Earth system is divided into four parts: land, atmosphere, surface ocean, and deep ocean, wherein carbon and heat transfer between these parts can achieve dynamic equilibrium.

In total, the model contains 37 parameters, which can be divided into two categories: heat and carbon transfer parameters and chemical parameters. Herein, we used parameter sets optimized by Chen *et al* (2020), who investigated the sensitivity of the parameters and found that seven parameters related to heat and carbon transfer were the most sensitive among the 37 parameters. Chen *et al* (2020) optimized the parameters by fitting the most sensitive parameters with the observed emission and temperature rise within their uncertainty range. For example, the most important parameter, the equilibrium climate sensitivity, starts with the 1 °C–6 °C range and is set to 4 °C in the original model. After the optimization, this parameter is recalibrated to 2.8 °C in the updated model used in this study, which is close to the central values documented in recent IPCC reports. The settings of key parameters are summarized in table 2 for references and reproducibility. Note climate sensitivity is one of the major causes of uncertainty, we use the 2.3 °C−4.7 °C (the 5%–95% bound range) by Sherwood *et al* (2020) for the uncertainty range calculation.

The historical (up to 2014) global CO_2 emissions come from the PRIMAP-hist dataset (Gütschow *et al* 2016), which combines several published datasets to provide a GHG emission pathway for both globally and individual countries. The historical CO_2 pathway was merged with constructed CO_2 pathways for 2015–2200 (section 2.2). The radiative effect of non-CO_2 GHGs on the climate was included using an individual chemical module, not the carbon cycle model. We considered other non-CO_2 GHGs listed by the Kyoto Protocol (as well as sulfate that represents the aerosol's cooling effects). We adopt non-CO_2 projections in RCP4.5 (www.iiasa.acat/web-apps/tnt/RcpDb) because the CO_2 emissions in RCP4.5 are the closest to the baseline selected here. These non-CO_2 emissions are considered in all cases.

2.4. Calculation of SLR

The SLR was calculated using a semi-empirical statistical model proposed by Vermeer and Rahmstorf (2009):

$$\frac{dSLR}{dt} = a \cdot (T - T_0) + b \cdot \frac{dT}{dt} \quad (3)$$

where T and SLR are the temperature rise and SLR at time t, respectively, and T_0 is the base temperature at which sea level is in equilibrium with climate. The coefficient estimates for the model were based on the fit of the observed global temperature and SLR (NOAA 2020, 2021). The 1850–2014 period was considered the historical period used to calibrate the model, generating the optimized coefficients of $a = 0.25$ cm yr^{-1} K^{-1}, $b = -0.25$ cm K^{-1}, and $T_0 = -0.43$ K. Note that these coefficients are slightly different from those used in Hu *et al* (2013), which may be because of the different observation data used for training.

3. Results and discussion

3.1. Emission pathways

Figure 1 shows emissions of different proposed pathways. China's emission pathway decreased from the Chinese NDC baseline (Huang *et al* 2020) after the assumed CPYs of 2024, 2027, and 2030, and reached neutrality between 2050 and 2070 (figure 1(a)). As the CCUS limit was set to 0.5 GtC yr^{-1}, negative emissions will remain constant when they reach the lower bound. Correspondingly, the world's carbon emissions under three different pathways (figures 1(b)–(d)) have the same peak emissions of 9.3 GtC, 9.5 GtC, and 9.7 GtC in 2024, 2027, and 2030, respectively. Under the only China pathway (as a hypothetical case to isolate the contribution from China's recent pledge alone), 123–160 GtC less carbon will be emitted than that of the baseline NDC during this century (2015–2100). However, the world will not achieve net-zero emissions. Conversely, under Case B (global zero CO_2, figure 1(c)), there is a large decrease in carbon emissions reaching zero around 2050–2070, causing a cumulative difference of 370 GtC to 420 GtC

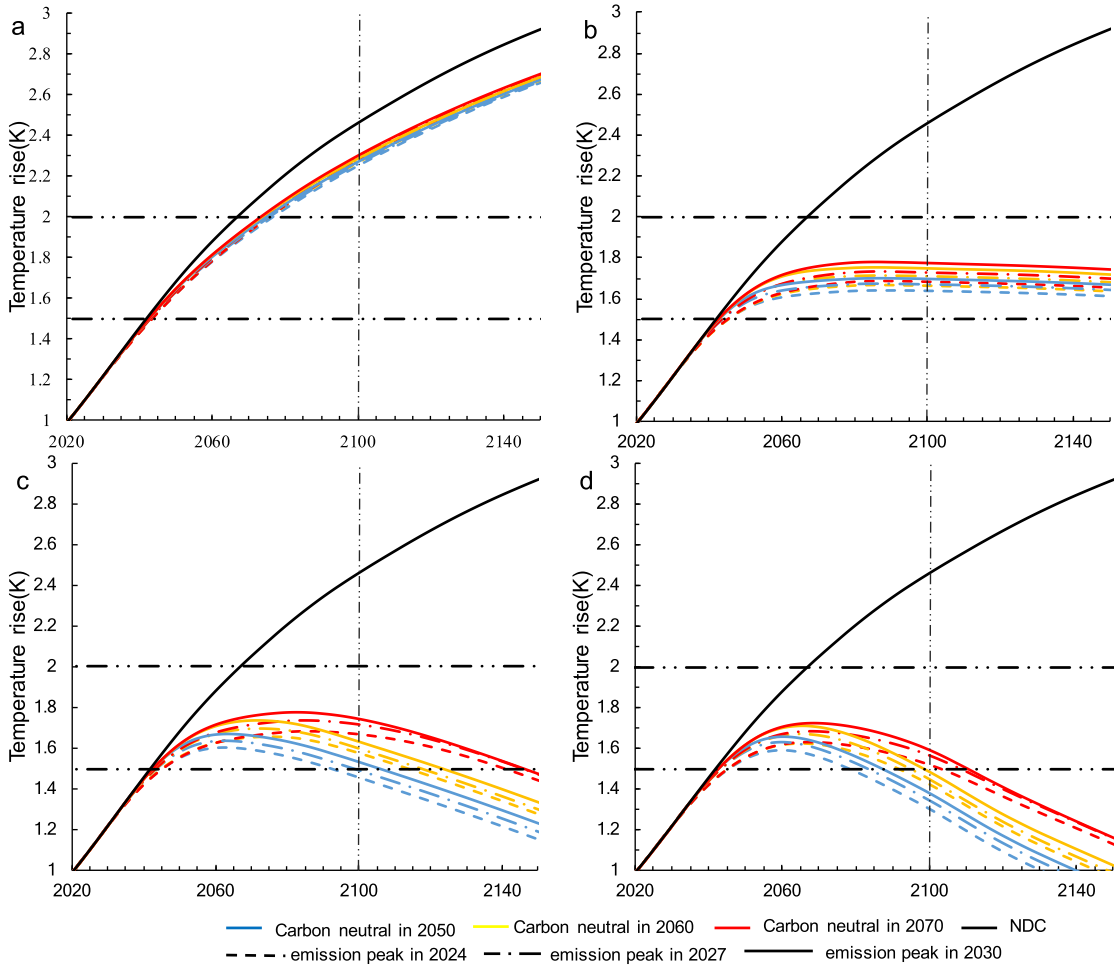

Figure 2. Temperature rises (2020–2150) for (a) Case A: China only pathway, (b) Case B: zero CO_2 pathway, (c) Case C: negative CO_2 pathway, and (d) Case D: zero GHG pathway.

during this century. Under Case C (the negative CO_2 pathway), the emission pathway is the same as in Case B. However, emissions will further decrease to approximately -3 GtC yr^{-1} after this time (proportional to the imposed cap of 0.5 GtC yr^{-1} for China), resulting in 30–100 GtC fewer carbon emissions, as compared with Case B (global zero CO_2) during this century.

Based on the simple scaling approach, we estimate that global carbon neutrality will be achieved 2–9 years after China's carbon neutrality, and also, earlier carbon neutrality in China will result in a shorter delay. For example, China reaching carbon neutrality in 2050 will lead the world to neutrality in 2052; however, if China reaches carbon neutrality in 2070, global carbon neutrality will be delayed to 2075–2079. To illustrate the sensitivity of timing of policy implementation, we also find that the uncertainty of CNYs (i.e. 2050–2070) have a stronger impact on the cumulative emission with a 35 GtC difference under the zero CO_2 pathway and with a 130 GtC difference under the negative CO_2 pathway (within this century). In contrast, the near-term CPYs (i.e. 2024–2030) only caused a 40 GtC difference under the negative CO_2 pathway and a 50 GtC difference under the zero CO_2 pathway.

3.2. Temperature rise under different pathways

Compared with the global baseline (black line in figure 1(b)), China's carbon neutrality will help reduce the global temperature rise from 2.46 °C (uncertainty range 2.06 °C–4.01 °C) to 2.25 °C–2.30 °C (uncertainty range 1.89 °C–3.75 °C) by 2100 (figure 2(a)). That is, the contribution from China's recent pledge alone will reduce warming by 0.16 °C–0.21 °C, contributing approximately 17%–22% to the Paris Agreement's 1.5 °C goals (relative to the 0.96 °C gaps between the NDC's projection to 1.5 °C). This is consistent with a recent estimate that China achieving carbon neutrality would lower global warming by approximately 0.2 °C–0.3 °C (Climate Action Tracker 2020). A range of benefits comes from the uncertainty associated with the decarbonization pathway, but it can be seen in figure 2(a), an earlier carbon neutralization year would lead to greater avoided warming.

With global efforts to achieve carbon neutrality in the 2nd half of this century, all three other cases (global zero CO_2, globally negative CO_2, and global

zero GHG) can successfully hold the temperature rise below 2 °C (figures 2(b)–(d)), which is consistent with previous studies (Rogelj *et al* 2015, 2019, Salvia *et al* 2021). However, stabilizing the temperature below 1.5 °C is more difficult (horizontal dash line in figure 2), which is discussed in detail next.

Under the global zero CO_2 pathway (Case B in figure 2(b)), the global temperature would slowly decrease after peaking by 1.64 °C–1.78 °C (uncertainty range 1.37 °C–3.03 °C) around 2087 and would remain nearly constant until the end of the century and beyond. Under this pathway, the warming peak year (around 2087) remains the same for all CNYs. That is because CO_2 emissions will continue to be zero after carbon neutrality, so the warming peak is mostly dependent on the non-CO_2 emission and the sensitivity of the earth system. Meanwhile, under the global negative CO_2 pathway (Case C), global temperature will rise, peaking by 1.6 °C–1.8 °C (uncertainty range 1.35 °C–2.92 °C) between 2062 and 2085, which is approximately 15 years later than the CNY, before it will decrease to a rise of 1.5 °C–1.8 °C (uncertainty range 1.21 °C–2.95 °C) in 2100 at a rate of 0.02–0.05 °C/decade. The temperature overshoot is stronger in Case D, under the zero GHG pathway. Specifically, temperatures will reach peaks earlier (at 2060–2067) by 1.6 °C–1.7 °C (uncertainty range 1.34 °C–2.77 °C), in which the peak time varies with CNY, and may achieve a peak temperature before carbon neutrality as non-CO_2 emissions are lower under the zero GHG pathway. After the peak level, the temperature would then decrease to 1.3 °C–1.6 °C (uncertainty range 1.08 °C–2.71 °C) in 2100 and maintain the declining trend into the 22nd century at a rate of 0.07–0.10 °C/decade.

While most of the 15 constructed pathways under the negative CO_2 pathway (Case C) can consistently bend the warming curve past 2100 and eventually bring it back to be under 1.5 °C, to meet the target of limiting the temperature under the 1.5 °C level in 2100, the more ambitious emission ramp-down pathways are required. Among the 15 constructed pathways, only the three most aggressive ones: World's carbon emission peaks in 2024–2027, instead of 2030, and reaches carbon neutrality around 2050; and carbon peaks in 2024 and reaches neutrality before 2058, have the chance to keep the temperature rise under 1.5 °C in 2100 with the aid of coordinated global efforts.

We also emphasize that when supplemented with non-CO_2 GHG neutrality before the end of the century (Case D), which is even more ambitious than cutting the non-CO_2 GHG emissions to 1.4 GtCeq as in SSP1-1.9, it is possible to keep the temperature rise under 1.5 °C in 2100 under more lenient carbon neutrality conditions. Specifically, it would require that World reaches carbon neutrality before 2065 and has an emission peak before 2030, or reaches carbon neutrality in 2070 and has an earlier and lower emission peak in 2024 (figure 2(d)).

In contrast, in the absence of sustained net-negative carbon emissions and zero emissions of non-CO_2 GHGs (Case B), even if the world achieves carbon neutrality as early as 2050, the 1.5 °C targets will barely be achieved (figure 2(b)). This suggests that even with the reduction of human influence, the climate system stays near a steady-state, maintaining the temperature rise for a long time (figure 2(b)), which is consistent with the results of the Zero Emissions Commitment Model Intercomparison Project, which showed that further temperature rise remains close to zero after reaching carbon neutrality (Jones *et al* 2019, MacDougall *et al* 2020).

The benefit of pursuing both negative CO_2 emissions and aggressive non-CO_2 GHG cuts does not end in 2100. Figure 2 shows that both the negative CO_2 and zero GHG pathways have cooler temperatures in 2150 than in 2050, while the zero CO_2 pathway remains stable in 2150. Indeed, the projected warming reversal rate in 2100 is 0.02–0.05 °C/decade under the negative CO_2 pathway and 0.07–0.1 °C/decade under the zero GHG pathway, much larger than the 0.003 °C/decade rates in the zero CO_2 pathway (a quasi stabilization).

Figure 3 shows the temperature rises in 2050, 2100, and 2150 depending on different CPYs and CNYs. It can be seen that temperature rise would increase with delayed CPYs and CNYs, especially by 2100 (figure 3). In particular, 20 years earlier in the CNY will lead to a sizable 0.2 °C temperature increase in 2100 under the negative CO_2 and zero GHG pathways and 0.04 °C–0.07 °C under the zero CO_2 pathway. Meanwhile, 6 years of delay in CPY will cause an approximately 0.07 °C–0.09 °C increase in temperature in 2100. This indicates that earlier emission peaks will lead to lower temperature rises, reducing the burden of mitigation later, as suggested by many previous studies (Tong *et al* 2019, Olhoff and Chistensen 2020).

In particular, for the near-term period (period to mid-century), CPYs caused a greater difference in temperature rise than CNYs. We find that a 6 year difference of CPY avoided approximately 0.05 °C–0.07 °C warming in 2050, while a 20 year difference of CNY caused a negligible 0.01 °C. However, in the long-term, CPYs and CNYs caused approximately the same difference in temperature rise in 2100 and 2150, realizing an approximately 0.06 °C–0.09 °C difference for the 6 year range of CPY explored here (2024–2030) and a 0.04 °C–0.08 °C difference for the 20 year range of CNY explored here (2050–2070). Furthermore, CNYs show a greater influence of approximately 0.2 °C–0.3 °C in 2150 in both the negative CO_2 pathway and zero GHG pathway than in the zero CO_2 pathway, which is consistent with the results of the cumulative carbon difference caused by different pathways (section 3.1), because earlier neutrality

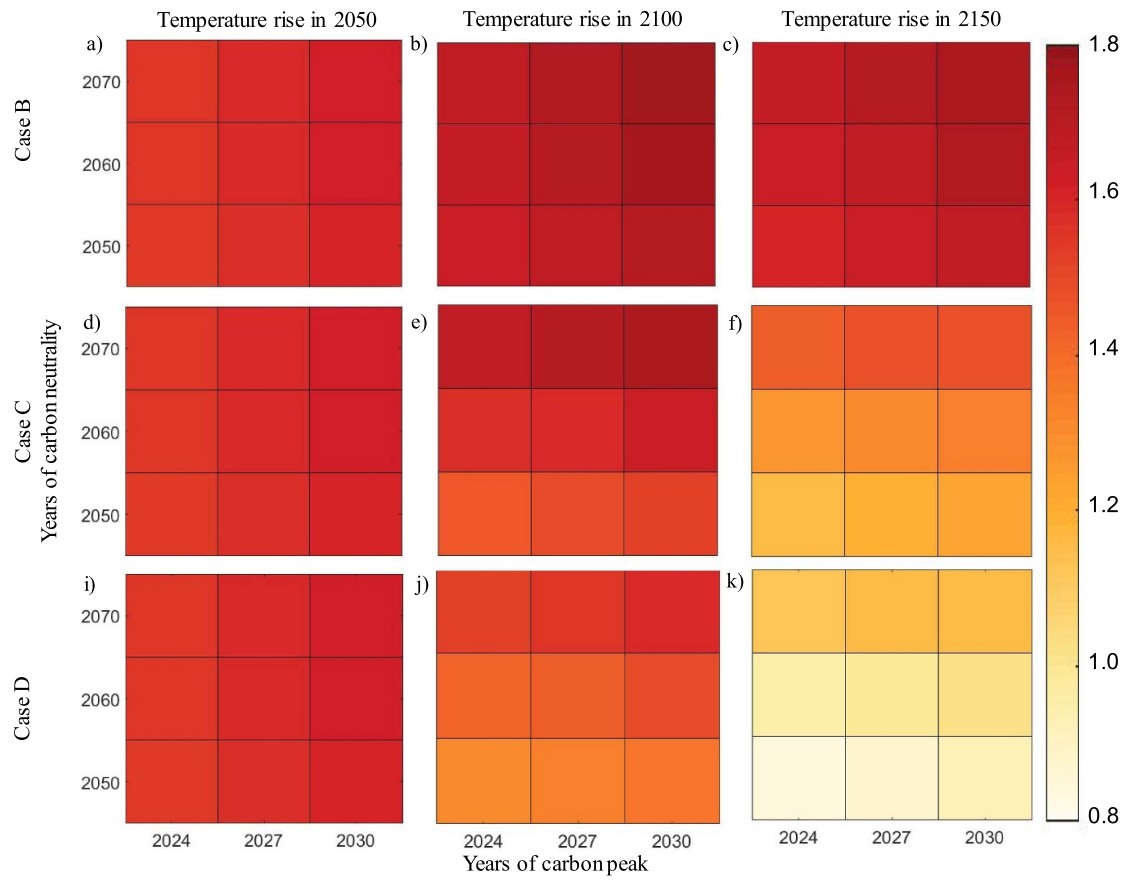

Figure 3. Temperature rises for (a)–(c) Case B: zero CO_2 pathway, (d)–(f) Case C: negative CO_2 pathway, and (g)–(i) Case D: zero GHG pathway in 2050, 2100, and 2150. *X* and *y*-axes represent years of emission peak (CPY) and carbon neutrality (CNY).

Table 3. Sensitivity of various metrics (years when the warming cross 1.5 °C, years above 1.5 °C, cumulative warming) to the assumed carbon peak year (CPY) and carbon neutrality year (CNY) under cases C and D.

		The year when temperature cross 1.5 °C		Years above 1.5 °C		Cumulative warming above 1.5 °C (°C *decade)	
CPY	CNY	Case C	Case D	Case C	Case D	Case C	Case D
2024	2050	2046	2046	46	33	7.2	5.1
2024	2060	2046	2046	68	46	10.9	7.3
2024	2070	2046	2046	95	57	15.4	9.0
2027	2050	2044	2044	55	39	8.7	6.2
2027	2060	2044	2044	74	51	12.0	8.2
2027	2070	2044	2044	102	64	16.9	10.4
2030	2050	2043	2043	63	45	10.1	7.2
2030	2060	2043	2043	81	56	13.4	9.2
2030	2070	2043	2043	104	68	17.5	11.2

implies a larger amount of avoided cumulative emission over time.

Even for the pathways that can successfully bend the warming down below 1.5 °C at 2100 or early 22nd century, the number of years exceeding 1.5 °C is another metric to be considered. As in table 3, under both the negative CO_2 case and zero GHG cases, the temperature rise will exceed 1.5 °C at approximately the same time (2043–2046), depending on the CPY. Under the negative CO_2 pathways, there is a 46–104 year period where temperature rise is above 1.5 °C, wherein this period is only 33–68 years under the zero GHG pathway. Further, it can be seen that the CNY has a more influential role, leading to a difference of approximately 40–50 years in years above 1.5 °C under the negative CO_2 pathway and 25 years under the zero GHG pathway. In contrast, CPY only leads to a 15 year difference under the negative CO_2 pathway and a 10 year difference under the zero GHG pathway. Thus, CNYs are the main driver of the number of years exceeding the 1.5 °C. Consistently, for cumulative warming above the 1.5 °C level

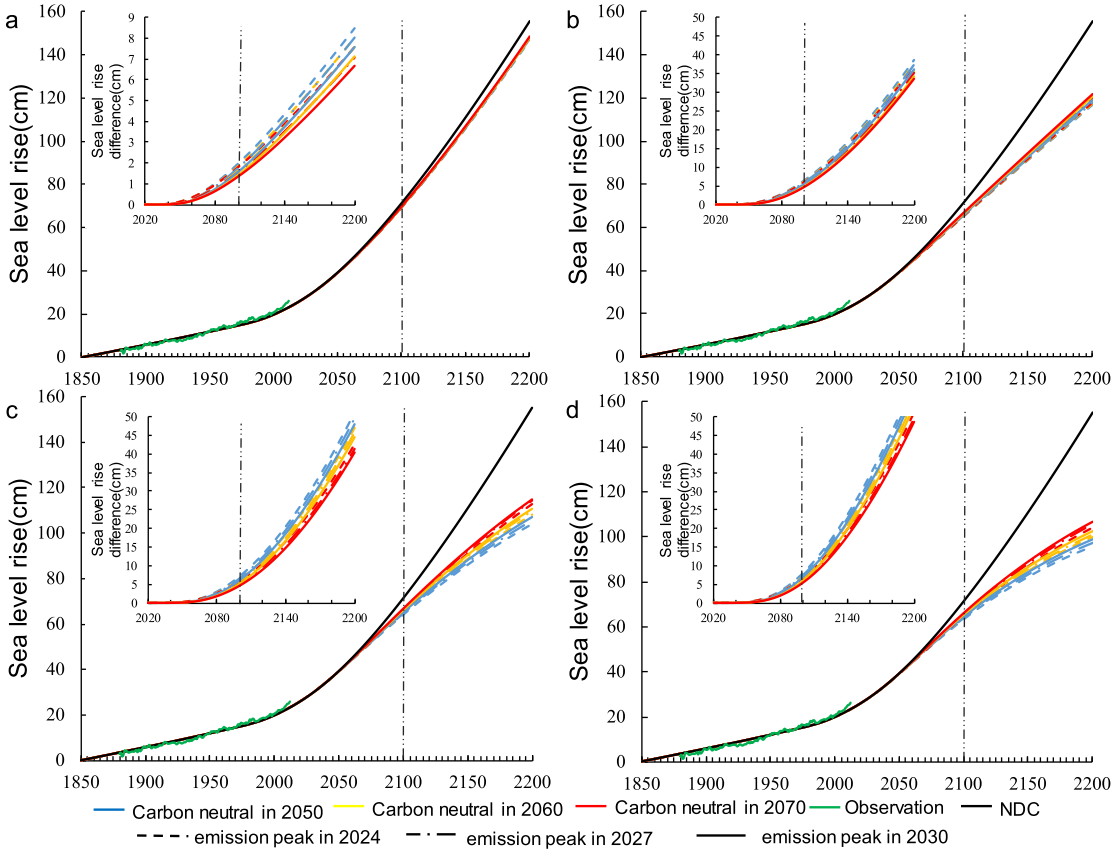

Figure 4. Sea level rises and (inserted) SLR differences from baseline for (a) only China pathway, (b) zero CO_2 pathway, (c) negative CO_2 pathway, and (d) zero GHG pathway. Green lines are the observational record.

which can be an analogy to cooling degree days, CNYs are more influential than CPYs, causing an approximately 8 °C·decade difference (between the more aggressive pathways and more relaxed decarbonization pathways), as opposed to a 3 °C·decade difference due to spreads in CPYs.

Looking beyond temperature level, we also note that with efforts to reduce non-CO_2 GHG emissions (Case D), the years above 1.5 °C and cumulative warming above 1.5 °C is reduced to only 60%–70% of that under the negative CO_2 pathway (Case C), further justifying the role of curbing the non-CO_2 GHG emission, beyond the well-demonstrated effects in reducing near-term warming rates (Ocko *et al* 2021).

3.3. Sea level rise under different pathways

While temperature rise can be stabilized at the end of the century, sea level would continue to rise under all pathways. However, different pathways would affect the SLR because SLR is more related to cumulative temperature rise. Our results show that SLR is less sensitive than temperature rise to CPYs and CNYs within the pathways, which may be due to the large heat capacity of the ocean. Specifically, under the baseline pathway, the sea level will rise to 71 cm at the end of the century (relative to 1850) and will rise by 155 cm in 2200 (figure 4). Figure 4 shows the differences caused by the different pathways. Our results (44–45 cm in this century) are between those found by the IPCC (2018) and Rasmussen *et al* (2018), who stated that the sea level would rise by 40–48 cm under the 1.5 °C pathway. China achieving carbon neutrality between 2050 and 2070 will lead to a 1–2 cm SLR decrease in 2100 and a 6–9 cm decrease in 2200. With global efforts to reach carbon neutrality, SLR decreases can be controlled to more than 5 cm under the other three cases in 2100 but close to 50 cm in 2200. It could also be seen that the difference of SLR from the baseline is more sensitive to CNY than CPY under the negative CO_2 pathway and zero GHG pathway, which is a 10 cm difference caused by CNY and 5 cm by CPY. However, under the zero CO_2 pathway, CPY and CNY cause approximately the same difference.

The semi-empirical SLR model used here does not account for potential expected transitions in ice dynamics, which could result in substantially higher SLR (DeConto and Pollard 2016, DeConto *et al* 2021). Neglecting nonlinear physical processes, feedbacks, and threshold behavior could lead to biased conclusions based on statistical fits. However, statistical modeling of SLR could give cursory yet useful insights into whether SLR can be slowed down, despite land ice dynamics not being fully represented.

4. Conclusion

This study constructed a set of idealized China emission pathways with different carbon peak years (CPYs) and carbon neutrality years (CNY). We find that to meet the commitment of carbon neutrality by 2060, an emission reduction rate of no less than 6%/year and a high CCUS growth rate (larger than 10%/year and in some cases as large as 24%/year) are required for China. Moreover, CNYs have a stronger impact than CPYs on the difference in cumulative emissions within this century.

In sync with China's recent pledge, we also developed three sets of global emission pathways, including the zero CO_2 pathway, negative CO_2 pathway, and zero GHG pathway. The simple climate model MiCES was used to calculate the temperature rises under each idealized pathway, and the corresponding SLR was calculated using a semi-empirical statistical model. China's carbon-neutral proposal will lead to a cooler climate, as compared with a previous NDC-related baseline (in which emission will be halved from its peak towards the end of the century), by 0.16 °C–0.21 °C at 2100 and by 0.22 °C–0.26 °C in 2150. That suggests that China's pledge for reaching carbon neutrality will additionally contribute at least 17%–22% to the effort of reaching the 1.5 °C global goal.

With accompanying global efforts for carbon neutrality around 2070, the global temperature rise will be successfully kept below 2 °C (relative to pre-industrial levels). However, more aggressive efforts, such as a broad application of negative emissions technologies (NETs, more than simply offsetting the remaining portion of fossil fuel use) and a deep cut to all other non-CO_2 GHG emissions, are needed to bend the temperature curve down to less than 1.5 °C. Only limited pathways that include NETs (our Case C) can fulfill the 1.5 °C goal at 2100, including a carbon peak in 2024–2027 with carbon neutrality around 2050, or a carbon peak in 2024 with carbon neutrality before 2058. With complete GHG neutrality by the end of the century (our case D), conditions can become more lenient, such as carbon neutrality before 2060 with an emission peak before 2030, and carbon neutrality in 2065 with an emission peak in 2024.

Furthermore, the explored ranges in CPYs and CNYs lead to approximately the same difference in temperature rise in 2100 and 2150. Earlier CPYs and CNYs can avoid the warming by 0.04 °C–0.09 °C in 2100 under the zero GHG pathway. Meanwhile, CNYs are the main driver of the difference in the number of years exceeding 1.5 °C and cumulative warming above 1.5 °C. Specifically, the explored range of CNYs can lead to a large 40–50 year difference in years above 1.5 °C and an approximately 8 °C·decade difference in cumulative warming above 1.5 °C, whereas the corresponding range of CPYs causes a 10–15 year difference in years above 1.5 °C and a 3 °C·decade difference in cumulative warming.

The coordinated global efforts under the three pathways can hold SLR to under 67 cm in 2100 (compared with the baseline of 71 cm relative to pre-industrial). The benefit is much larger in the 22nd century, leading to a 40–51 cm SLR avoidance at 2200 from the baseline pathway under the negative CO_2 pathway, and an even larger differences of 49–59 cm under the zero GHG cases, which is a significant cut from the 130 cm of the projected SLR (since 2020) in the baseline case.

Overall, we conclude that while iconic goals of CNYs are crucial, taking immediate actions to reach earlier CPYs and lower emission peaks also contribute greatly to mitigating climate change, especially in the near term. Moreover, we emphasize that it is important to go beyond the net-zero of carbon. The world needs to further scale up the negative emission technology (mindful of economic and geophysical constraints) and to adopt a deep cut of non-CO_2 GHGs in order to reduce the upcoming climate risks in this and next century and eventually bring the planet back to a safe regime.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

IGSNRR authors were supported by the National Key Research and Development Program of China (Grant Number: 2017YFA0605303), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA23100401), the National Natural Science Foundation of China (41877454), the Youth Innovation Promotion Association of CAS (No. 2019053), and the Young Talents in IGSNRR, CAS (2017RC201).

ORCID iDs

Huijuan Cui https://orcid.org/0000-0002-0308-1550
Yangyang Xu https://orcid.org/0000-0001-7173-7761

References

Arora V K *et al* 2020 Carbon–concentration and carbon–climate feedbacks in CMIP6 models and their comparison to CMIP5 models *Biogeosciences* **17** 4173–222
Cai B and Li Q 2020 China status of CO_2 capture, utilization and storage (CCUS) 2019 *Chinese Academy of Environmental Planning*
Chen J *et al* 2020 An investigation of parameter sensitivity of minimum complexity Earth simulator *Atmosphere* **11** 95
Climate Action Tracker 2020 China going carbon neutral before 2060 would lower warming projections by around 0.2–0.3

degrees celsius *Climate Action Tracker* (available at: https://climateactiontracker.org/press/china-carbon-neutral-before-2060-would-lower-warming-projections-by-around-2-to-3-tenths-of-a-degree/) (Accessed 23 September 2020)
DeConto R M *et al* 2021 The Paris climate agreement and future sea-level rise from Antarctica *Nature* **593** 83–9
DeConto R M and Pollard D 2016 Contribution of Antarctica to past and future sea-level rise *Nature* **531** 591–7
Detz R J and van der Zwaan B 2019 Transitioning towards negative CO_2 emissions *Energy Policy* **133** 110938
European Union 2020 Long-term low greenhouse gas emission development strategy of the EU and its Member States *UNFCCC* (available at: https://unfccc.int/documents/210328) (Accessed 06 March 2020)
Fawcett A A *et al* 2015 Can Paris pledges avert severe climate change? *Science* **350** 1168–9
Gütschow J, Jeffery M L, Gieseke R, Gebel R, Stevens D, Krapp M and Rocha M 2016 The PRIMAP-hist national historical emissions time series (1850–2017) *Earth Syst. Sci. Data* **8** 571–603
Hanna R, Abdulla A, Xu Y and Victor D G 2021 Emergency deployment of direct air capture as a response to the climate crisis *Nat. Commun.* **12** 368
Höhne N *et al* 2020 Emissions: world has four times the work or one-third of the time *Nature* **579** 25–28
Hu A, Xu Y, Tebaldi C, Washington W M and Ramanathan V 2013 Mitigation of short-lived climate pollutants slows sea-level rise *Nat. Clim. Change* **3** 730–4
Huang X, Chang S, Zheng D and Zhang X 2020 The role of BECCS in deep decarbonization of China's economy: a computable general equilibrium analysis *Energy Econ.* **92** 104968
IPCC 2018 Global warming of 1.5 °C *IPCC* accepted
Jiang K-J 2018 1.5 °C target: not a hopeless imagination *Adv. Clim. Change Res.* **9** 93–4
Jinyi H 2021 Carbon neutral, global action: France strives to be the "ecological pioneer" on the international stage *Reference News Network* (available at: www.cankaoxiaoxi.com/world/20210107/2431451.shtml)
Jones C D *et al* 2019 The Zero Emissions Commitment Model Intercomparison roject (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions *Geosci. Model Dev.* **12** 4375–85
Knutti R *et al* 2017 Beyond equilibrium climate sensitivity *Nat. Geosci.* **10** 727–36
Mac Dowell N, Fennell P S, Shah N and Maitland G C 2017 The role of CO_2 capture and utilization in mitigating climate change *Nat. Clim. Change* **7** 243–9
MacDougall A H *et al* 2020 Is there warming in the pipeline? A multi-model analysis of the zero emissions commitment from CO_2 *Biogeosciences* **17** 2987–3016
Mengel M, Levermann A, Frieler K, Robinson A, Marzeion B and Winkelmann R 2016 Future sea level rise constrained by observations and long-term commitment *Proc. Natl Acad. Sci.* **113** 2597–602
Mengel M, Nauels A, Rogelj J and Schleussner C-F 2018 Committed sea-level rise under the Paris agreement and the legacy of delayed mitigation action *Nat. Commun.* **9** 601
NOAA 2020 *National Centers for Environmental Information, NOAA Coastal Services Center Coastal Inundation Digital Elevation Model: Eureka (CA) WFO—Mendocino County* (available at: https://coast.noaa.gov/slrdata/) (Accessed 29 June 2020)
NOAA 2021 *National Centers for Environmental Information, Climate at a Glance: Global Time Series* (available at: www.ncdc.noaa.gov/cag/) (Accessed 18 April 2021)
Ocko I B, Sun T, Shindell D, Oppenheimer M, Hristov A N, Pacala S W, Mauzerall D L, Xu Y and Hamburg S P 2021 Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. *Environ. Res. Lett.* **16** 054042
Olhoff A and Chistensen J M 2020 EmissionsGap report 2020 *UNEP DTU Partnership* p 128
Rahmstorf S, Perrette M M and Vermeer M 2012 Testing the robustness of semi-empirical sea level projections *Clim. Dyn.* **39** 861–75
Rasmussen D J, Bittermann K, Buchanan M K, Kulp S, Strauss B H, Kopp R E and Oppenheimer M 2018 Extreme sea level implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd centuries *Environ. Res. Lett.* **13** 034040
Riahi K *et al* 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68
Ricke K L and Caldeira K 2014 Maximum warming occurs about one decade after a carbon dioxide emission *Environ. Res. Lett.* **9** 124002
Rogelj J, Den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K and Meinshausen M 2016 Paris agreement climate proposals need a boost to keep warming well below 2 °C *Nature* **534** 631–9
Rogelj J, Huppmann D, Krey V, Riahi K, Clarke L, Gidden M, Nicholls Z and Meinshausen M 2019 A new scenario logic for the Paris agreement long-term temperature goal *Nature* **573** 357–63
Rogelj J, Schaeffer M, Meinshausen M, Knutti R, Alcamo J, Riahi K and Hare W 2015 Zero emission targets as long-term global goals for climate protection *Environ. Res. Lett.* **10** 105007
Salvia M *et al* 2021 Will climate mitigation ambitions lead to carbon neutrality? An analysis of the local-level plans of 327 cities in the EU *Renew. Sustain. Energy Rev.* **135** 110253
Sanderson B M *et al* 2017 Community climate simulations to assess avoided impacts in 1.5 and 2 °C futures *Earth Syst. Dyn. Discuss.* **8** 827–47
Schaeffer R *et al* 2020 Comparing transformation pathways across major economies' *Clim. Change* **162** 1787–803
Sherwood S C *et al* 2020 An assessment of Earth's climate sensitivity using multiple lines of evidence *Rev. Geophys.* **58** e2019RG000678
Smith P *et al* 2016 Biophysical and economic limits to negative CO_2 emissions *Nat. Clim. Change* **6** 42–50
Tong D, Zhang Q, Zheng Y, Caldeira K, Shearer C, Hong C, Qin Y and Davis S J 2019 Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target *Nature* **572** 373–7
UNFCCC 2017 The Paris Agreement | UNFCCC (available at: http://unfccc.int/paris_agreement/items/9485.php) (Accessed 9 March 2017)
van Vuuren D P *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31
van Vuuren D P *et al* 2018 Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies *Nat. Clim. Change* **8** 391–7
Vaughan A 2020 Japan steps up climate ambition with 2050 net zero emissions goal *NewScientist* (available at: www.newscientist.com/article/2258163-japan-steps-up-climate-ambition-with-2050-net-zero-emissions-goal/) (Accessed 26 October 2020)
Vermeer M and Rahmstorf S 2009 Global sea level linked to global temperature *Proc. Natl Acad. Sci. USA* **106** 21527–32
Wang C and Zhang Y X 2020 Implementation pathway and policy system of carbon neutrality vision *Chin. J. Environ. Manage.* **12** 58–64
Wang S W *et al* 2012 Equilibrium climate sensitivity *Adv. Clim. Change Res.* **8** 232–4
Wei Y-M *et al* 2018 An integrated assessment of INDCs under shared socioeconomic pathways: an implementation of C3IAM *Nat. Hazards* **92** 585–618
Wei Y-M, Kang J-N, Liu L-C, Li Q, Wang P-T, Hou -J-J, Liang Q-M, Liao H, Huang S-F and Yu B 2021 A proposed global layout of carbon capture and storage in line with a 2 °C climate target *Nat. Clim. Change* **11** 112–8

Xinhuanet 2020 Xi Jinping delivers an important speech at the general debate of the 75th UN general assembly *Xinhuanet* (available at: www.xinhuanet.com/world/2020-09/22/c_1126527647.htm) (Accessed 22 September 2020)

Xinhuanet 2021 Xi Jinping presided over the ninth meeting of the financial and economic commission of the CPC Central Committee, emphasizing the promotion of standardized, healthy and sustainable development of the platform economy and incorporating carbon neutrality into the overall layout of ecological civilization *Xinhuanet* (available at: www.xinhuanet.com/politics/leaders/2021-03/15/c_1127214324.htm) (Accessed 15 March 2021)

Xu Y and Ramanathan V 2017 Well below 2 °C: mitigation strategies for avoiding dangerous to catastrophic climate changes *Proc. Natl Acad. Sci.* **114** 10315–23

Yonhap News 2020 Moon to declare S. Korea's carbon neutrality vision in televised event *Yonhap News Agency* (available at: https://en.yna.co.kr/view/AEN20201210007700315) (Accessed 10 December 2020)