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Perspective

Critical climate issues toward carbon neutrality targets

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ABSTRACT

In 2020, China announced the "emission peak, carbon neutrality" policy, that is, China aims to have CO2 emissions peak before 2030 and achieve carbon neutrality before 2060. The scenario of carbon neutrality will be significantly distinguished from the scenario we experienced since the industrial revolution. However, instrumental data are unavailable in the future carbon-neutral scenario. Earth system models and climate dynamics theory are needed to comprehend and project the climate change. In this paper, we illustrate our perspective of the issues related to "emission peak, carbon neutrality", including climate dynamics, climate-carbon feedback, interaction between China and global climate and carbon emissions and solutions, etc. We highlight that climate change has profoundly affected human production and life. The frequent occurrence of extreme weather disasters in recent years, together with the impact of epidemics, make the future "carbon peak & carbon-neutral" scenario more complex. There is whopping uncertainty but also a massive challenge to the scientific community. Thus, carbon neutrality is closely related to domestic production and lives, and there is little time left for planning. We believe that we will make a breakthrough in climate dynamics in the context of carbon neutrality with our joint efforts, which will serve our country's carbon emission policy at different stages.

1. Introduction

On September 22, 2020, Chinese President Xi Jin-Ping solemnly announced that "China will scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures, aiming to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060" at the General Debate of the 74th Session of the United Nations General Assembly. The so-called carbon neutrality means a state of net-zero carbon dioxide emissions. This ritual commitment shows the responsibility of China as a global superpower to follow a "green, low-carbon, high-quality" development path. Our series of deployments to address climate change and carbon neutrality will have far-reaching impacts on the energy structure, industrial structure, and socioeconomic development of China and even the world. It will also have considerable effects on technological progress and global governance. The ultimate goal of carbon neutrality is to unify international countries to jointly achieve the temperature target of the Paris Agreement, i.e., to control the global average temperature rise within 2 °C and to strive for only 1.5 °C above preindustrial levels. Different from the traditional carbon emission scenarios [1], the Paris Agreement established the first scenario in which temperature is regarded as a target to constrain climate change, pushing a new direction of climate research. Achievement of the target would require a decrease in atmospheric CO_2 concentration [2,3]. However, the World Climate Research Programme (WCRP) stated in 2018 that "the scientific community lacks consensus on the climate effects of CO_2 removal" and launched the Carbon Dioxide Removal Model Comparison Program [4]; as of 2021, the data were still renewing, and relevant studies were few.

Climate change is closely related to human society. Current global warming, mainly caused by the massive emissions of greenhouse gases, especially carbon dioxide, has dramatically affected human production and life. Despite a continuous increase in CO_2 since the 20th century, the global average temperature has shown a stepwise increase, including warming in the early 20th century, cooling in the mid-20th century, rapid warming in the late 20th century, and a hiatus in the early 21st century [5–7], underpinned by the nonmonotonic evolution of surface temperature [8,9]. During the period of warming, global temperature change followed the familiar "temperature–CO_2" relationship, but dur-

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ing the hiatus period, i.e., the early 21st century, the relationship was decoupled. This implies that the relationship between CO_2 concentration and surface temperature, which is of most concern to humans, is not linear and may involve complex dynamic feedbacks. Previous studies have suggested that the coupled and decoupled "temperature–CO_2" relationship can be due to the different time-scale responses of the climate system to anthropogenic activities, such as a slow response due to the large heat capacity of the ocean to anthropogenic radiative forcing [10–13]. On the other hand, the internal variability of the climate system, such as the cold phase of the Pacific Decadal Oscillation (PDO), may offset the warming effect of human activities [5,6]. In the future, under the scenario of "emission peak" and "carbon neutrality," our ultimate goal is to limit the rise of global surface temperature. Our control of carbon emissions will finally act on climate change. The management of CO_2 concentration is only a method, not the ultimate goal. Therefore, a scientific understanding of the "temperature–CO_2" relationship (especially around some key turning points) is essential for planning and coping with climate change in the coming decades.

2020 was an extraordinary year with worldwide climate extremes. The sudden epidemic of COVID-19 early in the year led to a severe reduction in our productivity. As a vast industrial country, the stagnation in productivity caused a significant decrease in CO_2 and aerosol emissions. With effective epidemic prevention measures, our productivity levels began to recover at the end of the year and were coming on strong in 2021, while the emissions in the rest of the world continued to decline. COVID-19 forced us to passively experience an emission reduction. Reductions in CO_2 or aerosols may cause an asynchronous response of the ocean and atmosphere in a short period, as the response of the ocean to radiative change is slower than that of the land and atmosphere, which may cause potential ecological, environmental, and engineering safety risks. Extreme weather tends to become more frequent under global warming; for example, the record-breaking Yangtze River floods in China triggered by the strong anomalous Mei-yu event in 2020; the dust storms in northern China and thunderstorms and windy weather in southern China in early 2021; the daily rainfall of more than 100 mm in South Xinjiang in June; and the once-in-a-thousand-year event in Zhengzhou on July 20, of which the hourly rainfall exceeded 200 mm. Beyond China, these extreme weather events include the wildfires in Australia and California in 2020, the snowstorm on the eastern coast of Canada, the heatwave in India and France, the extreme cold weather in Texas in February 2021 that led to widespread, long-term power outages, the extreme precipitation in Europe in spring, etc. These extreme events resulted in tremendous damage to the production and lives of human beings. Should these severe weather and climate disasters be attributed mainly to human activities or natural variability? The actual physical processes of the "emission peak and carbon neutrality" scenario may be more complex. A better comprehension of the changes in the proportion of the climate disaster process is of high scientific and application value for predicting the intensity, area, and duration of extreme weather and climate disasters under future scenarios.

The target of carbon neutrality is an integrated and extremely complex issue that is widely associated with climate, ecology, energy, environment, society, etc. It results from interactions of multiple systems, such as land, atmosphere, ocean, and cryosphere. At present, the climate impact of carbon neutrality is still unclear, and it may be related to planning a reasonable carbon emission path to realize the optimal layout of energy, industry, the ecological environment, and other fields to achieve carbon neutrality with relatively small socioeconomic costs. To date, there are several questions that still need to be answered. How will the regional climate over China and the global climate respond to the three critical stages of the carbon neutrality target (Fig. 1), i.e., from now to the "emission peak", from the "emission peak" to "carbon neutrality," and from "carbon neutrality" to the end of this century? What will be our stance on achieving an "emission peak"? Are there feedbacks from climate change on carbon emissions or uptakes in both directions? What are the possible feedbacks? How much uncertainty is there? To address these questions, it is essential to understand the relationship between atmospheric CO_2 and temperature, i.e., to address the climate under carbon neutrality, which is now a critical task.

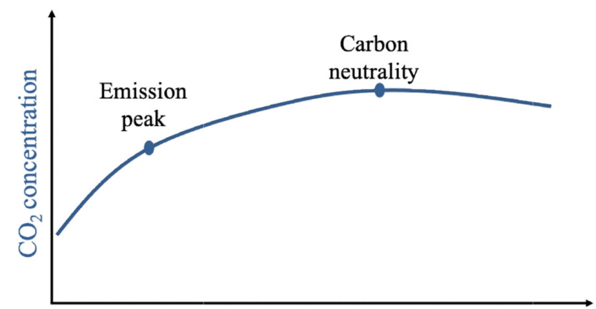

Fig. 1. Schematic diagram of the evolution of CO_2 concentration in a carbon-neutral background.

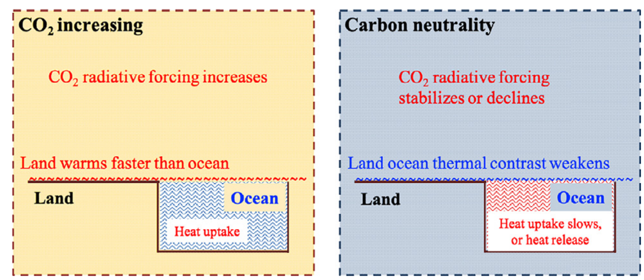

Fig. 2. Diagrams of climate-dynamical processes at different stages of atmospheric CO_2 concentration change. (a) During rising stages, CO_2 radiative forcing is the main driving force of the climate system. Due to the small heat capacity, land warms rapidly with the increasing of CO_2 radiative forcing; the ocean's response is slow owing to its large heat capacity. The thermal difference between land and ocean increases, which enhances monsoon circulation. (b) After carbon neutrality, CO_2 radiative forcing stabilizes or decreases, while the ocean is still slowly absorbing heat and warming. The land-ocean thermal contrast diminishes, weakening the monsoon circulation; if the CO_2 concentration decreases dramatically, the deep ocean will release heat upward to decelerate the cooling of the sea and land surface.

2. Understanding climate dynamics under carbon neutrality

During the historical period, researchers have conducted climate analysis with instrumental data, which, however, are unavailable in the future carbon-neutral scenario. Earth system models and climate dynamics theory are needed to comprehend and project climate change.

Under a carbon-neutral scenario, accurate prediction of climate–carbon feedbacks and the hazards of weather and climate highly depends on the precise projection of the future climate. The scenario of carbon neutrality will be significantly distinguished from the scenario we have experienced since the industrial revolution. Additionally, the corresponding climate dynamics are different from the well-known stages during which CO_2 is rising. Before neutrality, the CO_2 concentration will continue to increase, and radiative forcing during this period will be the leading factor in global warming, dominated by the rapid responses of the climate system (especially land and mixed-layer oceans). The heating effect due to the greenhouse gas (GHG) effect notably (approximately 90%) enters the ocean, which acts as a "heat reservoir" [1,14]. After carbon neutrality, GHGs will stabilize or decline. The slow responses of the climate system (the slow absorption or release of heat from the deep ocean) will gradually increase. The "heat reservoir" effect may resist the cooling effect led by the decline in CO_2 concentration or slowly warm the global surface when the CO_2 concentration stabilizes. Supposing that the CO_2 concentration decreases too rapidly, the ocean may even overwhelm GHGs and become the driver of global climate change, as shown in Fig. 2.

China features a typical monsoon climate. The thermal contrast between land and ocean plays an essential role in forming the East Asian monsoon [15]. Before carbon neutralization, the land warms more rapidly than the ocean, strengthening the thermal contrast and favoring the continued enhancement of the East Asian summer monsoon. After carbon neutralization, the ocean may still warm or cool slowly due to its thermal inertia, leading to a weaker thermal contrast and weakening the East Asian summer monsoon [16,17]. All of the above factors may have impacts on the climate in China.

Multiple studies have suggested that the El Niño–Southern Oscillation (ENSO) amplitude will strengthen, and extreme El Niño events will continue to increase during the carbon-neutral stage [18,19]. During extreme El Niño events (e.g., the 2015–2016 super El Niño event), the carbon emissions from the biosphere will increase due to high temperatures and droughts in the tropics [20]. The response in the oceans under global warming may alter the uptake and storage of CO_2, which can impact the realization of carbon neutrality. For example, the North Atlantic Ocean is one of the major global carbon sinks. Due to deep convection in the sinking branch of the AMOC, a large amount of carbon is sequestered in the deep North Atlantic; therefore, a weakening of the AMOC will reduce its carbon storage capacity [21], thus affecting the atmospheric carbon concentration. In addition, under the low-carbon emissions scenario, the North Atlantic Ocean would potentially gradually replace the Southern Ocean as the focus of global ocean heat uptake due to the weakening of the Atlantic Meridional Overturning Circulation (AMOC) [22]. Under the carbon neutrality goal, future anthropogenic aerosol emissions will continue to decrease. The subsequent warming effect will be superimposed on the cooling effect caused by CO_2 reduction, resulting in an increase in surface warming and a decrease in the rate of temperature decline, thus prolonging the time needed to achieve the Paris Agreement's low-temperature rise target [23]. Therefore, when designing specific pathways to achieve carbon neutrality, the critical climate impacts of anthropogenic aerosols need to be considered.

Although the scientific community has some preliminary understanding of the above processes, some difficulties appear in research:

(1) Uncertainty in atmospheric CO_2 concentrations in the future. The future pathway of CO_2 concentration is a result of net carbon emissions from countries all over the world. At present, although most countries have proposed related carbon neutral policies, there is still much uncertainty regarding the pathway of CO_2 emissions as well as its concentration. This increases the difficulty of climate prediction.

(2) Uncertainty of numerical simulation. The Earth system model is an ideal tool to carry out climate prediction in the carbon neutrality scenario. Many physical processes in the Earth system model are simplified, and the details of weather and climate processes are not fully described, which introduce simulation biases. Moreover, the lack of observation data and knowledge of some regional climate phenomena makes it difficult to judge whether the presentation in the Earth system model is reasonable. This uncertainty may affect other regional climate phenomena.

(3) The influence of internal climate variability. In addition to human activities, the climate is also influenced by internal climate variability. For example, during the first decade of the 21st century, atmospheric CO_2 continued to rise, but global temperature displayed a hiatus due to the cooling of the eastern Pacific Ocean [5]. Considering that in numerical simulation experiments, internal climate variability is stochastic, it is a challenge to force out the variability. This makes climate prediction more difficult.

In general, the scientific understanding of climate dynamics under carbon-neutral scenarios is insufficient. The impact of these dynamic processes on East Asia and the global climate is less understood. In addition, the precise quantification of the climate–carbon feedbacks under future climate relies on a deeper understanding of climate dynamics and a more accurate prediction of climate change under a carbon-neutral scenario. Therefore, we need to conduct independent research and systematically understand the climate dynamic processes under carbon neutrality scenarios, as well as their impacts on climate change in China and the globe. A deep understanding of these issues may enable us to accurately and scientifically project the risk of climate in China and the world under the influence of carbon-neutral policies, the climate conditions in critical areas of carbon sources and sinks, and the climate–carbon feedback before and after carbon neutrality. It provides scientific support to the rational layout of energy, industry, ecology, and the environment in China and makes carbon neutrality better and more stable.

3. Quantitative analyses of climate–carbon feedback

At present, while there has been some relevant research on carbon–climate feedback, there is still considerable uncertainty in the climate–carbon-cycle model results that still need to be further developed [24–26]. In the field of climatology, recent studies have primarily focused on one-way impacts, i.e., carbon emissions on climate change, while in fact, the carbon cycle and climate are interactive. The IPCC Fifth Assessment Report (IPCC AR5) concludes that there is positive feedback between the carbon cycle and climate: under the future scenario, global warming may weaken the carbon sink of ecosystems, leading to higher CO_2 concentrations in the atmosphere and further reinforcing global warming. The above understanding provides some implications: (1) If we ignore the weakening of the carbon sink under global warming, the timing of carbon neutrality achievement may be delayed. (2) If the atmospheric CO_2 concentration does not decrease enough after carbon neutrality, the global temperature may rise slowly and continue to weaken the global carbon sink. Therefore, all countries cannot evade the efforts to control carbon emissions.

However, there is uncertainty in understanding some key parameters in the climate–carbon feedback (e.g., feedback strength, critical thresholds, and spatial distribution), which significantly constrains the planning of carbon-emission reduction. Supposing that we do not have an accurate understanding of the climate–carbon feedback; then we may fail to achieve the optimal deployment of the development of energy, industry, ecological environment and other fields in China. It may bring additional socioeconomic losses. Therefore, there is an urgent need to conduct research on the carbon cycle and climate feedback. In addition, in recent years, the WCRP updated the "Grand Challenges" on climate research, in which carbon–climate feedback was listed as one of the seven challenges. This implies the importance of climate–carbon feedback.

4. Interaction between China/global climate and carbon emissions

CO_2 can mix in the atmosphere and affect the climate through changes in its concentration on a global scale. That is, the climate change of each country is not solely determined by the net carbon emissions within the territory of each country but depends on the net carbon emissions on Earth. Therefore, on the issue of climate change and carbon emissions, all countries on the worldwide scale are not isolated but are closely linked communities [1,27-29], as shown in Fig. 3.

China has developed a long-term plan to achieve carbon neutrality, which will significantly contribute to global climate mitigation and carbon reduction. Based on the understanding of carbon–climate feedbacks and climate dynamics under the "carbon neutrality" scenario, this makes it possible to estimate the contribution of China's carbon neutrality policy to global warming mitigation, climate disasters, and ecological carbon sinks. On the other hand, other countries might also influence the domestic carbon emissions in China. Imagine an extreme scenario under which our country achieves carbon neutrality while the net CO_2 emissions of other countries are positive. Then, the CO_2 concentration still rises, leading to a higher-than-expected temperature increase in our country, further weakening the (ecosystem) carbon sink and destroying

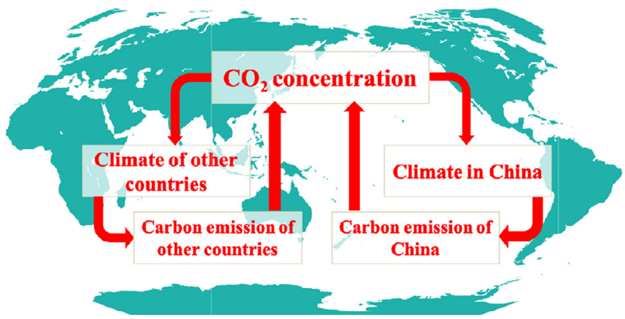

Fig. 3. Relationship between China and other countries in terms of net carbon emissions and climate.

the carbon-neutral state of China. Considering this, we can also rely on the further study of climate–carbon feedback and climate dynamics to assess the impact of carbon emissions from other countries on our carbon-neutral status. These two aspects are important issues to be considered in climate diplomacy.

Based on an in-depth understanding of the carbon–climate feedback and carbon-neutral climate dynamics, it is feasible to conduct a study on the interaction among China's carbon neutrality, global climate, and carbon emissions with the aid of sophisticated Earth system models. Conducting research in this area and quantifying the contribution of China's carbon neutral policies to global climate and carbon emissions helps increase China's discourse power in climate diplomacy. Moreover, assessing the impacts of carbon emissions of other countries on climate and carbon emissions in China and timely adjusting China's deployment in the fields of energy, industry, ecology, and the environment prudently favor the achievement of carbon-neutral goals.

5. Solutions to scientific problems associated with carbon neutrality

The major political plan of carbon neutrality gives rise to a series of scientific problems. Future human-induced GHG change is a physical problem and a complex problem involving politics, society, and the economy. Anthropogenic perturbations can result in impacts and consequences that threaten the security of the Earth system. Due to the complexity of the Earth system and the nature of nonlinear responses, changes in the relationship between humans and nature in the short term will inevitably cause significant uncertainty in the prediction of the future environment. Thus, it is worthwhile to start from the following three aspects.

(1) One solution is climate dynamic research and Earth system model development. The understanding of climate dynamics under carbon neutrality relies on the theoretical study of climate dynamics and Earth system models. The Earth system model is the only dynamic tool that we use to predict the future. Climate dynamics studies can be used to validate Earth system models and jointly contribute to accurate estimates of climate–carbon feedbacks together with models. With a proper understanding of carbon-neutral climate dynamics and the key quantitative indicators of the climate–carbon feedback, we can use them to assess the interactions between China and the globe on climate and carbon emissions.

(2) The second solution is to develop multidisciplinary theoretical research, emphasizing the interactions of multiple systems of the Earth, including the atmosphere–ocean, atmosphere–land, and other multilayer interactions, as well as the two-way feedback of climate and carbon. Carbon neutrality is not only a scientific issue but also a complex sociological topic. It is important to focus on the intersection of social sciences (e.g., economics and international relations) with climatology. Currently, the promotion of interdisciplinary research is an inevitable trend in the development of Earth sciences. The understanding of carbon neutrality is also accompanied by the rapid development of computer technology, which provides computing power for large numerical calculations.

(3) The third solution is to effectively gather human resources, extensively recruit outstanding scientists in related fields, and bring into research teamwork synergy. For example, we could build large-scale computer devices to provide strong support for large-scale scientific calculations and establish carbon-neutral research centers. In particular, attention and emphasis should be placed on institutional arrangements and national scientific policies to strengthen the scientific innovation of China. For example, funding for fundamental research should be strengthened, and young researchers, especially scholars who have recently received their doctoral degrees, should be given more opportunities to explore independently, and the evaluation mechanism should not be paper-centered but should be more varied.

6. Conclusion and prospects

In the process of energy change and carbon neutrality emerging globally, greenhouse gases such as CO_2 in the atmosphere will be influenced by significant anthropogenic perturbations. Although low-carbon emissions may slow atmospheric warming, the overall trend of climate warming will continue for a long time. Achieving carbon neutrality is likely to lead to changes in global and national weather hazard patterns and potentially decrease the uncertainty of climate variability and the occurrence of climate extremes, with important implications for global security. Therefore, the feedback and response of the Earth system to anthropogenic CO_2 emissions after carbon neutrality and its impacts will be scientific issues worthy of attention in the future. Carbon neutrality is closely related to domestic production and lives, and there is little time left for planning. This set of factors has given rise to key scientific questions that need to be addressed in the context of carbon neutrality, mainly including the following:

(1) Carbon-neutral climate dynamics research (understanding the key climate dynamic processes under carbon-neutral scenarios, including the fast and slow responses of the climate system, internal climate variability, and their impacts on our domestic and global climate).

(2) Two-way feedbacks between the regional and global climate–carbon feedback (to understand the spatial distributions of the crucial quantitative indicators, such as feedback coefficients and critical thresholds and climate–carbon feedbacks in China and worldwide).

(3) The contribution of China's carbon neutrality to global climate and carbon emissions (assessing the contribution of China's carbon neutrality policy to global warming mitigation, climate disasters, ecological carbon sinks, etc. and evaluating the impact of other countries' carbon emissions on China's carbon neutrality status and route).

In summary, climate change has profoundly affected human production and life. Carbon neutrality is not a purely scientific topic but a complex and comprehensive issue. Established policies and emission reduction pathways might be highly affected by unexpected events, such as the frequent occurrence of extreme weather disasters and outbreaks of epidemics in recent years, which make the "carbon peak and carbon-neutral" scenario face great uncertainty. There is enormous uncertainty but also a massive challenge to the scientific community. However, we should believe that we will make a breakthrough in climate issues in the context of carbon neutrality with our joint efforts, which will serve our country's carbon emission policy at different stages.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest in this work.

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References

[1] IPCC, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, USA, 2013, p. 1535. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)].
[2] B.M. Sanderson, B.C. O'Neill, C. Tebaldi, What would it take to achieve the Paris temperature targets? Geophys. Res. Lett. 43 (2016) 7133–7142.
[3] B.M. Sanderson, Y. Xu, C. Tebaldi, et al., Community climate simulations to assess avoided impacts in 1.5 and 2 degrees C futures, Earth Sys. Dyna. 8 (3) (2017) 827–847.
[4] D.P. Keller, L. Andrew, S. Vivian, et al., The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6, Geosci. Model Dev. 11 (2018) 1133–1160.
[5] Y. Kosaka, S.-P. Xie, Recent global-warming hiatus tied to equatorial Pacific surface cooling, Nature 501 (2013) 403–407.
[6] Y. Kosaka, S.-P. Xie, The tropical pacific as a key pacemaker of the variable rates of global warming, Nat. Geosci. 9 (9) (2016) 669–673.
[7] S.-L. Yao, J.-J. Luo, G. Huang, et al., Distinct global warming rates tied to multiple ocean surface temperature changes, Nat. Clim.Change 7 (2017) 486–491.
[8] F. Ji, Z. Wu, J. Huang, et al., Evolution of land surface air temperature trend, Nat. Clim. Change 4 (6) (2014) 462–466.
[9] Z. Xu, F. Ji, B. Liu, et al., Long-term evolution of global sea surface temperature trend, Int. J. Climatol. 41 (9) (2021) 4494–4508.
[10] T. Andrews, P.M. Forster, O. Boucher, et al., Precipitation, radiative forcing and global temperature change, Geophys. Res. Lett. 37 (2010) L14701.
[11] G. Bala, K. Caldeira, R. Nemani, Fast versus slow response in climate change: implications for the global hydrological cycle, Climate Dyn 35 (2010) 423–434.
[12] I.M. Held, M. Winton, K. Takahashi, et al., Probing the fast and slow components of global warming by returning abruptly to preindustrial forcing, J. Climate 23 (2010) 2418–2427.
[13] S.M. Long, S.-P. Xie, X.-T. Zheng, et al., Fast and slow responses to global warming: sea surface temperature and precipitation patterns, J. Climate 27 (2014) 285–299.
[14] L. Cheng, J. Abraham, J. Zhu, et al., Record-setting ocean warmth continued in 2019, Adv. Atmos. Sci. 37 (2020) 137–142.
[15] B. Wang, Q. Ding, Global monsoon: dominant mode of annual variation in the tropics, Dyn. Atmos. Oceans 44 (3–4) (2008) 165–183.
[16] Y. Kamae, M. Watanabe, M. Kimoto, et al., Summertime land-sea thermal contrast and atmospheric circulation over East Asia in a warming climate-Part II: Importance of CO_2-induced continental warming, Climate Dyn 43 (2014) 2569–2583.
[17] X.Q. Li, M.F. Ting, Understanding the Asian summer monsoon response to greenhouse warming: the relative roles of direct radiative forcing and sea surface temperature change, Climate Dyn 49 (2017) 2863–2880.
[18] M. Ohba, J. Tsutsui, D. Nohara, Statistical Parameterization Expressing ENSO Variability and Reversibility in Response to CO2 Concentration Changes, J. Climate 27 (2014) 398–410.
[19] G.J. Wang, W. Cai, B. Gan, et al., Continued increase of extreme El Nino frequency long after 1.5 degrees C warming stabilization, Nat. Clim. Change 7 (2017) 568–572.
[20] J. Liu, K.W. Bowman, D.S. Schimel, et al., Contrasting carbon cycle responses of the tropical continents to the 2015–16 El Niño, Science 358 (2017) eaam5690.
[21] M. Srokosz, M. Baringer, H. Bryden, et al., Past, present, and future changes in the Atlantic meridional overturning circulation, Bull. Am. Meteorol. Soc. 93 (11) (2012) 1663–1676.
[22] X. Ma, W. Liu, R.J. Allen, et al., Dependence of regional ocean heat uptake on anthropogenic warming scenarios, Sci. Adv. 6 (2020) eabc0303.
[23] X. Ma, G. Huang, J. Cao, The significant roles of anthropogenic aerosols on the climate system under carbon neutrality, Sci. Bull. (2021) In Press.
[24] Y. Malhi, J.T. Roberts, R.A. Betts, et al., Climate change, deforestation, and the fate of the amazon, Science 319 (2008) 169–172.
[25] J.P. Dunne, J.G. John, A.J. Adcroft, et al., Gfdl's esm2 global coupled climate—carbon earth system models. Part I: physical formulation and baseline simulation characteristics, J. Climate 25 (19) (2012) 6646–6665.
[26] P.M. Cox, D. Pearson, B.B. Booth, et al., Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability, Nature 494 (7437) (2013) 341–344.
[27] P.M. Cox, R.A. Betts, C.D. Jones, et al., Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, Nature 408 (2000) 184–187.
[28] H.D. Matthews, A.J. Weaver, K.J. Meissner, Terrestrial carbon cycle dynamics under recent and future climate change, J. Climate 18 (2005) 1609–1628.
[29] N. Zeng, H.F. Qian, E. Munoz, et al., How strong is carbon cycle-climate feedback under global warming? Geophys. Res. Lett. 31 (20) (2004) 183–213.

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