nature portfolio

Peer Review File

Air quality improvement masks global cooling from CO_2 reductions under China's carbon neutrality policies for half a century

Corresponding Author: Bin Zhao

Parts of this Peer Review File have been redacted as indicated to remove third-party material.

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The submitted manuscript conducts a simulation study on the response of global warming to China's carbon neutrality and air pollutant reduction strategies. Such research is helpful in the perspective of both science communities and societal managements. However, I must say that the level of novelty that this study brings does not seem sufficient to me for publication in Nature Communications, as it stands now.
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Line 49, the sentence is suggested to change as "as one of the large annual emitters of CO2 and air pollutants …"
Line 98: as the author mentioned, the research should also incorporate CH4 and N2O into the simulations, as a series of GHG reduction actions are expected to come into play for China. Therefore, the results are also expected to be significantly impacted. I think the GCAM should be able to generate CH4 and N2O emissions along with the CO2 reductions. It is also referred to as the paper of Li et al., 2022 (https://www.nature.com/articles/s41467-022-33047-9).
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Line 165: Seen from Fig. 1A, China's air pollutant burden will decline to its minimum by ~2045. As the author acknowledges the short lifetime of air pollutants, why the resultant warming could last to ~2075?
Lines 178-216: Seen from the title, the paper mainly focused on temperature, the analyses on precipitation seem unnecessary. This also applies to part text in Lines 217-263. More important, although I am not the expert in the field of aerosol-precipitation interactions, I believe precipitation process is more complicated than temperature. The current research does not show strong evidence of the response of precipitation to aerosol.
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Lines 480-488: it is still not clear how the BAU scenario is settled. It is suggested to give a figure showing the CO2 emission dynamic from 2014/2020 to 2060/2100 in the Extended Data Figure or supplementary materials. This is important for the readers to have a clear picture on CO2 emission in the China's carbon neutrality scenario. This also applies to the air pollutant dynamics in Lines 489-517.
Lines 518-526: As the remarkably potential warming effects of air pollutant reductions are seen from the current research, it is strongly suggested to further conduct additional sensitivity scenarios to separate the individual impacts of five pollutant (SO2, NOx, BC, OC, VOCs). I understand this will cost lots of computations, but I think this is really helpful for identifying which pollutant contributes most to the warming. Such doing also facilitates the authors to compare the separated results to

the IPCC reports. This also supports further evidence to explain why air pollutant reductions could lead to warming for a half-century as shown in the Figure 4B.
Line 527-529: Why the SSP2-4.5 are selected as the initial conditions.
Line 480-542: This section has to be concise and shorter.
Line 543-564: In this section, Model evaluations, the authors have to validate the models' ability in simulating the response of temperature to air pollutants in the historical period – although I am not sure if this feasibly done. But this is critically important for the current research. As validated in the present form, it is insufficient to demonstrate the reliability of future projections.
Extended Data Fig. 1: Compared to relative percentage change, there absolute values are more informative. Of course, displaying both (absolute and relative change) may be best.
Extended Data Fig. 2: The paper should explain why the change in CO2 reduction may cause to the changes in the surface albedo, although this can be easily understood from air pollutant reduction.
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Extended Data Fig. 10: It is known that sulfate aerosols are largely responsible for cooling effect. From the Fig. 10A, the CESM2 significantly underestimated the sulfate aerosol concentration. As the regression slope is not shown, it looks that the slope ranges from 0.2 to 0.4. What does this imply? The simulated warming effects could be further amplified given considering the underestimated sulfate aerosols from the model?
In addition, the observed maximum sulfate aerosols is 15 ug/m3 in Beijing-Tianjin-Hebei, a representatively high air pollutant region. This sounds good. Therefore, I suggest that the authors give a figure showing the spatial distribution of current (2020) and future map of sulfate concentrations. So that the readers could have a picture of what a magnitude of sulfate concentrations should decline in terms of "Beautiful China" scenario.

Reviewer #2

(Remarks to the Author)

[Editorial Note: Please see attached PDF at the end of the file]

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Thanks for addressing my concerns, and I have no further comments.

Reviewer #2

(Remarks to the Author)
The authors have made substantial revisions to address my comments to my satisfaction.

Having said that, I'd point the following two recent studies that are highly relevant, as they provide more quantitative estimation of long-term changes in both fine-mode aerosols (dominated by anthropogenic sources) and radiative forcing at the top of the atmosphere. Such information would serve as observation-based evidence of the same trend of aerosol and aerosol radiative forcing in recent decades to support/complement the future model-simulated trends:

Loeb, N., et al., 2025, Emerging hemispheric asymmetry of Earth's radiation, PNAS, https://doi.org/10.1073/pnas.2511595122.
Yan, X., et al., 2022, A global land aerosol fine-mode fraction dataset (2001-2020) retrieved from MODIS using hybrid physical and deep learning approaches, Earth Syst. Sci. Data, 14, 1193-1213, doi:10.5194/essd-14-1193-2022.

Reviewer #1 (Remarks to the Author):

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The authors incorporate temperature and precipitation into the current manuscript, and policy implications as well. The manuscript looks multiple topics but none are strongly demonstrated. – see specific questions in detail. It is suggested to reconsider one main topic as the key of the paper to narrate the story, rather a mixture.

It is suggested to conduct additional sensitivity scenarios to separate the individual impacts of five pollutant (SO2, NOx, BC, OC, VOCs). This is important in my point. – see specific questions in detail.

We thank the referee for recognizing the meaning of this work. We also appreciate the referee's constructive comments which are very helpful for improving the quality of the paper. We have provided point-by-point responses below and have revised the manuscript accordingly.

This study is novel in its research question, comprehensive methodology, and, most importantly, its insightful yet unexpected findings. Most previous studies on the climate impacts of decarbonization and clean-air policies have considered global policies as a whole. This work is the first to study the global climate impacts of China's carbon neutrality and clean-air ("Beautiful China") policies together over a realistic timescale. To achieve this, we use a comprehensive and fully coupled Earth system model and recently updated future anthropogenic emission scenarios to conduct long-term, transient ensemble simulations that account for dynamic oceans, biogeochemical systems, and chemistry-climate interactions; the simulations represent time-varying radiative forcing in a realistic manner. It has been widely recognized that achieving carbon neutrality will significantly lower the global surface temperature. This study reveals that, for an unexpectedly long time through ~2070, China's air pollutant reductions can cause a large global surface temperature increase that almost fully offsets the cooling from concurrent CO_2 emission reduction. This novel finding contrasts with previous studies that suggested that the global or U.S. decarbonization policies would immediately contribute to temperature decreases before 2030 or 2035. Another innovative finding is that, despite the globally offsetting impacts of air pollutant and CO_2 reductions, they lead to sharply contrasting temperature and precipitation changes in two hemispheres, along with a northward shift of the intertropical convergence zone. The inevitable and persistent warming effect of air pollutant reductions has important implications for Global South countries, underscoring the need for bolder actions toward earlier carbon neutrality, deeper methane reductions, and negative carbon emissions.

As suggested, we have also revised the paper to focus on temperature and have moved much of the analysis of precipitation to the Supplementary Information. Moreover, we have conducted additional sensitivity experiments to separate the climate impacts of the emission reductions of individual air pollutants. Below the referee's comments are presented in blue text, our responses are written in black text, and quotations from our manuscript are presented in italic type.

Specific questions:

In Abstract, the authors should show those key quantitative and mechanistic results from the simulations to further consolidate scientific issues of the paper.

Following the reviewer's comment, we have revised the Abstract to emphasize the quantitative and mechanistic results. Below is the revised part of the Abstract:

"*We find that, for an unexpectedly long time through ~2070, China's air pollutant reductions can cause a large global surface temperature increase* ***(0.12 ± 0.09 K for 2050–2070)*** *that almost fully offsets the cooling from concurrent CO_2 emission reduction* ***(0.16 ± 0.05 K for 2050–2070)****, compared to a business-as-usual scenario.* ***The air pollutant-induced temperature increase is mainly attributed to the emission reductions of SO_2 and organic matter.*** *Moreover, the combined reduction of air pollutants and CO_2 creates a striking contrast in temperature and precipitation changes between the two hemispheres, along with a northward shift of the intertropical convergence zone for 2050–2070,* ***because of the stronger aerosol-induced heating in the Northern Hemisphere****.*" (Line 31 – 39)

Line 49, the sentence is suggested to change as "as one of the large annual emitters of CO2 and air pollutants …"

Revision has been made. (Line 51 – 52)

Line 98: as the author mentioned, the research should also incorporate CH4 and N2O into the simulations, as a series of GHG reduction actions are expected to come into play for China. Therefore, the results are also expected to be significantly impacted. I think the GCAM should be able to generate CH4 and N2O emissions along with the CO2 reductions. It is also referred to as the paper of Li et al., 2022 (https://www.nature.com/articles/s41467-022-33047-9).

The objective of this study is to assess the climate impacts of China's carbon neutrality and "Beautiful China" policies, both of which are pivotal environmental strategies for the coming decades. Since the carbon neutrality strategy specifies emission targets only for CO_2, and China has not yet established clear targets for non-CO_2 greenhouse gases such as CH_4, N_2O, and fluorinated gases, we have not considered non-CO_2 greenhouse gas control measures in this study.

It should also be noted that the carbon neutrality and "Beautiful China" strategies may have synergistic or offsetting effects on non-CO_2 greenhouse gas emissions. However, non-CO_2 greenhouse gases have relatively weak source overlaps with CO_2 and most air pollutants. The energy sector, which accounts for the vast majority of CO_2 emissions and a large portion of air pollutant emissions, contributes only about 20% of non-CO_2 greenhouse gases[1]. Agriculture contributes about 30% of non-CO_2 greenhouse gases and a large share of NH_3 emissions[1], yet the synergies and trade-offs between the two remain highly uncertain[2,3]. Other major sources of non-CO_2 greenhouse gases, including specific industrial processes (adipic acid, nitric acid, electrolytic aluminum, HFCs, etc.), waste disposal, and refrigerants, are only weakly linked to CO_2 and air pollutant emissions[1]. For these reasons, we did not consider the synergies or trade-offs of carbon neutrality and the "Beautiful China" strategies with respect to non-CO_2 greenhouse gas emissions, and we recommend that future research be conducted to further address this issue.

We have included the above discussion in the revised manuscript (Line 66 – 82 of the Supplementary Information).

Line 115: five ensembles are claimed here, but in Line 529, it is said that the model is performed with three ensembles. These superficial mistakes should not occur.

We apologize for this oversight. We have changed "three ensemble members" in Line 529 to "five ensemble members". (Line 529 – 530)

Line 165: Seen from Fig. 1A, China's air pollutant burden will decline to its minimum by ~2045. As the author acknowledges the short lifetime of air pollutants, why the resultant warming could last to ~2075?

As shown in Fig. 5B, the global temperature increase driven by the air pollutant reductions under the CNCN policies relative to BAU intensifies until around 2055–2060 and then levels off. This stabilization occurs later than the point at which $PM_{2.5}$ burden reductions roughly plateau (2045–2050), largely due to the ocean's thermal inertia and its slow uptake of heat.
We have added the explanation to the revised manuscript (Line 247 – 249).

Lines 178-216: Seen from the title, the paper mainly focused on temperature, the analyses on precipitation seem unnecessary. This also applies to part text in Lines 217-263. More important, although I am not the expert in the field of aerosol-precipitation interactions, I believe precipitation process is more complicated than temperature. The current research does not show strong evidence of the response of precipitation to aerosol.

Following the referee's suggestion, we have revised the paper to focus on temperature and have moved much of the analysis of precipitation to the Supplementary Information (Line 23 – 63).

Lines 264-296: As a carbon-climate-aerosol research paper, such a lengthy of policy implications seems a redundant content.

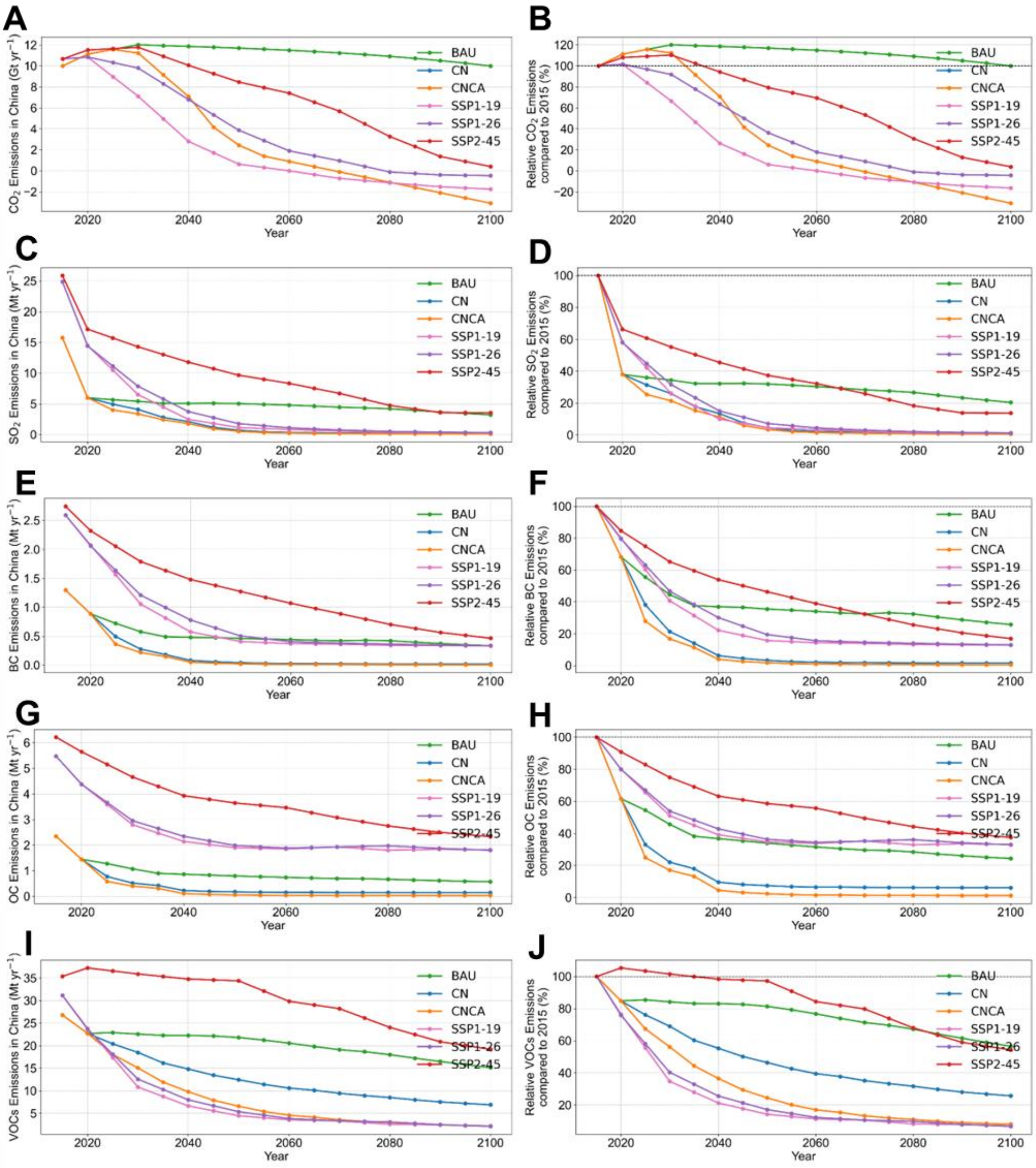
We have condensed the policy implication section to highlight the central points (Line 283 – 311 in the revised manuscript). Although this study primarily focuses on the scientific investigation of the climate impacts of CO_2 and pollutant emission reductions, the scenarios developed herein also carry clear policy relevance. The results offer valuable implications for future policy formulation, which represent a meaningful aspect of the study's overall contribution.

Lines 438-479: CESM is well known in the communities, and this section can be largely reduced.

We have shortened this section according to the referee's suggestion (Line 466 – 500 in the revised manuscript).

Lines 480-488: it is still not clear how the BAU scenario is settled. It is suggested to give a figure showing the CO2 emission dynamic from 2014/2020 to 2060/2100 in the Extended Data Figure or supplementary materials. This is important for the readers to have a clear picture on CO2 emission in the China's carbon neutrality scenario. This also applies to the air pollutant dynamics in Lines 489-517.

We have illustrated the emission trends of CO_2 and air pollutants from 2015 to 2100 in Extended Data Fig. 1 (shown below). The discussions of those trends are provided on Line 504 – 507.



Extended Data Fig. 1. National emissions of CO_2 and major air pollutants in China for 2015–2100 under the BAU and CNCA scenarios and an intermediate scenario (CN) where the carbon neutrality target is implemented but no additional clean air policies are considered. Also shown are emissions in China under different SSPs for comparison. Panels (A, C, E, G, I) show absolute emissions, while panels (B, D, F, H, J) show relative changes compared with 2015. (A, B) CO_2, (C, D) SO_2, (E, F) black carbon (BC), (G, H) organic carbon (OC), and (I, J) volatile organic compounds (VOCs).

Lines 518-526: As the remarkably potential warming effects of air pollutant reductions are seen from the current research, it is strongly suggested to further conduct additional sensitivity scenarios to separate the individual impacts of five pollutant (SO2, NOx, BC, OC, VOCs). I understand this will cost lots of computations, but I think this is really helpful for identifying which pollutant contributes most to the warming. Such doing also facilitates the authors to compare the separated results to the IPCC reports. This also supports further evidence to explain why air pollutant reductions could lead to warming for a half-century as shown in the Figure 4B.

We thank the reviewer for this constructive and insightful suggestion. Following the reviewer's suggestion, we have conducted an additional set of sensitivity experiments to quantify how much the emission changes of individual air pollutants contribute to effective radiative forcing (ERF). In these experiments, the emissions of SO_2 (together with primary sulfate, the same hereafter), POM, BC, and VOCs are sequentially adjusted from their BAU levels to the CNCA levels, with each experiment differing from the previous one by the change of a single pollutant. Therefore, by taking the difference between each pair of adjacent experiments, we can quantify the contribution of each pollutant to ERF.

Because fully coupled transient simulations are computationally prohibitive for multiple scenarios, we conduct these experiments with the atmosphere-only configuration. Specifically, the experiments are driven by prescribed present-day monthly sea surface temperatures and sea ice concentrations, allowing the differences between experiments to represent the ERF. The detailed experiment setups are documented in Methods (Line 540 – 553).

Figure 2C (shown below) illustrates that the global mean ERF associated with the emission reductions of SO_2, POM, BC, and VOCs are 0.045 ± 0.016 W m^{-2}, 0.046 ± 0.024 W m^{-2}, -0.018 ± 0.020 W m^{-2}, and 0.017 ± 0.023 W m^{-2}. These results clearly show that SO_2 and POM reductions are the dominant contributors to positive ERF, namely, reductions in sulfate- and POM-induced cooling drive most of the warming effect associated with air pollutant reductions. BC reductions contribute a negative ERF due to the removal of a warming agent, which partly offsets the sulfate- and POM-driven warming. VOC reductions contribute a smaller but non-negligible positive ERF, indicating that the decrease of secondary organic aerosol (SOA) also contributes to the warming effect.

We have included the discussion above in the revised manuscript (Line 153 – 163).

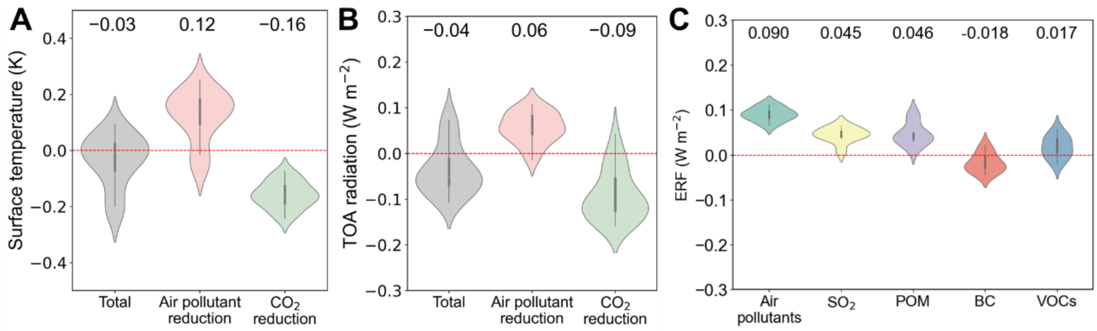


Fig. 2. Global mean differences in key climate variables under China's CNCA policies with respect to the BAU scenario for 2050–2070. (A) and **(B)** show the overall differences in **(A)** surface temperature and **(B)** top-of-atmosphere (TOA) net radiation under these policies relative to the BAU scenario (CNCA−BAU), as well as the respective differences induced by emission reductions of CO_2 (SENS−BAU) and air pollutants (CNCA−SENS). Panel **(C)** shows the Effective Radiative Forcing (ERF) due to the combined and individual emission reductions of air pollutants, including sulfur dioxide (SO_2), primary organic matter (POM), black carbon (BC), and volatile organic compounds (VOCs). Note that results in **(A)** and **(B)** are derived from fully coupled simulations while those in **(C)** are derived from atmosphere-only simulations (see Methods). Interpretation of the violin plots is the same as that in Fig. 1. The numbers on top of the violin plots

represent mean values.

Line 527-529: Why the SSP2-4.5 are selected as the initial conditions.

The SSP2-4.5 scenario represents a medium pathway within the range of future forcing trajectories, and is generally regarded as a plausible outcome under moderate policies. Because our focus is on the impacts of China's carbon neutrality and clean air policies, we use different emission estimates with and without considering these policies for China, while holding other factors—including initial conditions and emissions outside China—consistent with the medium SSP2-4.5 case, which we consider to best reflect the most likely future emission trajectory.
We have included the above explanation in the revised manuscript (Line 535－537).

Line 480-542: This section has to be concise and shorter.

Following the reviewer's suggestion, we have substantially shortened the description of emission scenarios, since the key points of the scenarios have been described in the main text. Please see Line 501－510 for the revised text.

Line 543-564: In this section, Model evaluations, the authors have to validate the models' ability in simulating the response of temperature to air pollutants in the historical period – although I am not sure if this feasibly done. But this is critically important for the current research. As validated in the present form, it is insufficient to demonstrate the reliability of future projections.

We thank the reviewer for pointing out the importance of evaluating the model's ability to simulate the temperature response to air pollutants in the historical period. We agree that such evaluation is critical for proving the reliability of our future projections.

First, CESM2 performs well in reproducing the overall evolution of global historical temperature in the 20th century. As shown in Fig. R1, compared with observational datasets such as HADCRU4.5, GISTEMP and NOAAGlobalTemp, CESM2 successfully captures key multi-decadal evolution of global mean surface temperature change, including the early warming from 1920－1940, the mid-century warming hiatus from 1940－1970, and the accelerated warming after the 1970s[4].

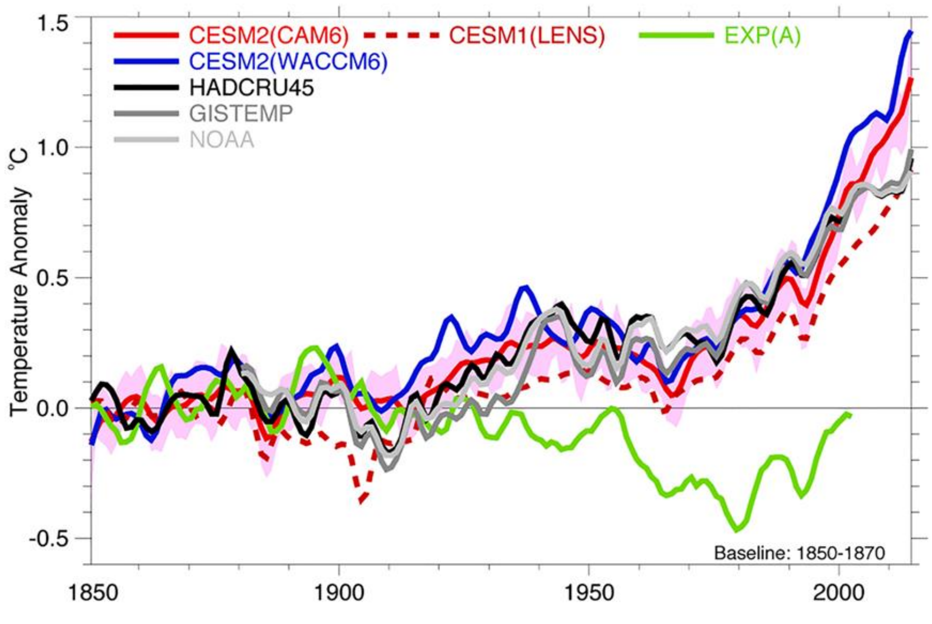


Fig. R1. Time series of global mean surface temperature anomalies during the historical period from observations and CESM simulations. Observations include HADCRUT4.5, GISTEMP, and NOAAGlobalTemp. Model results include CESM2(CAM6), CESM2(WACCM6), and CESM1(LENS) ensemble simulations. Anomalies are relative to the 1850–1870 mean, and shaded areas indicate ensemble spreads. This figure is adapted from Fig. 7 of Danabasoglu et al.[4].

Building on this, we further examine CESM2's ability to simulate the separate responses to greenhouse gases (GHG) and aerosols—two key forcing factors. Although their individual contributions cannot be directly verified through observations, we can indirectly assess the model by analyzing their roles in different historical phases of global temperature change. From the CESM2 single forcing large ensemble experiments, which isolate historical climate forcings (such as GHG and aerosols), the model reveals the independent effect of each forcing (Fig. R2)[5]. The results show that under GHG-only forcing, the model simulates a continuous warming trend, consistent with the physical understanding of GHG as the main driver of warming. Under anthropogenic aerosol-only forcing, the model produces a clear cooling signal, with the strongest cooling in the mid-20th century, gradually weakening afterward due to the decrease in aerosol loading. When both GHG warming and aerosol cooling are combined, CESM2 successfully reproduces the phased characteristics of historical temperature change, i.e., mid-20th-century warming hiatus and accelerated warming in the late 20th century. This indicates that aerosols contributed significantly to the mid-century warming slowdown, while the continued strengthening of GHG impact and the weakening of aerosol impact drove later temperature rise. These results also align with previous attribution studies[6]. This suggests that CESM2 can not only reproduce the overall historical temperature curve but also capture the separate effects of GHG and aerosols on temperature change from a physical mechanism perspective.

[*REDACTED*]

Fig. R2. [*REDACTED*]. This figure is adapted from Fig. 2a of Simpson et al.5.

Additionally, the effective radiative forcing of GHG and aerosols simulated by CESM2 falls within the range of the CMIP6 multi-model ensemble (Fig. R3)[7], further supporting the reasonableness of its forcing representations.

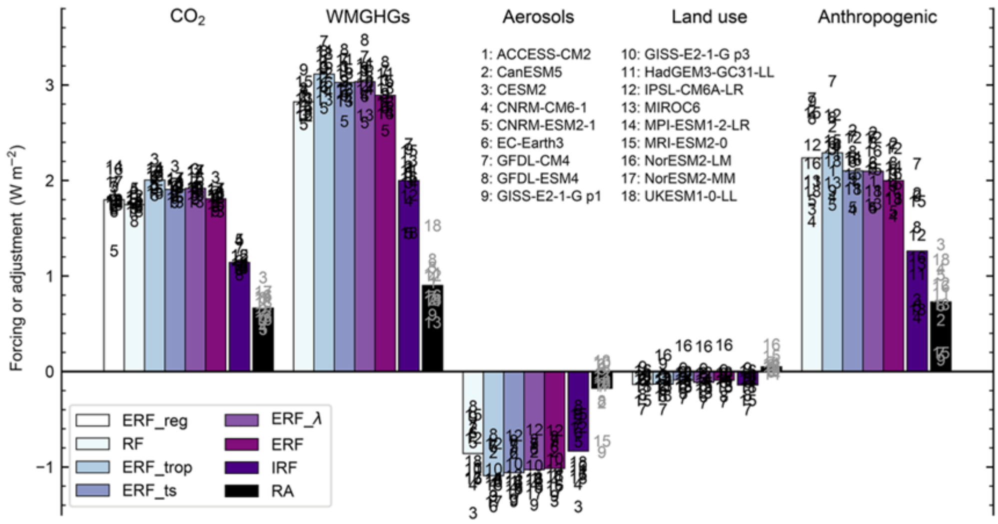
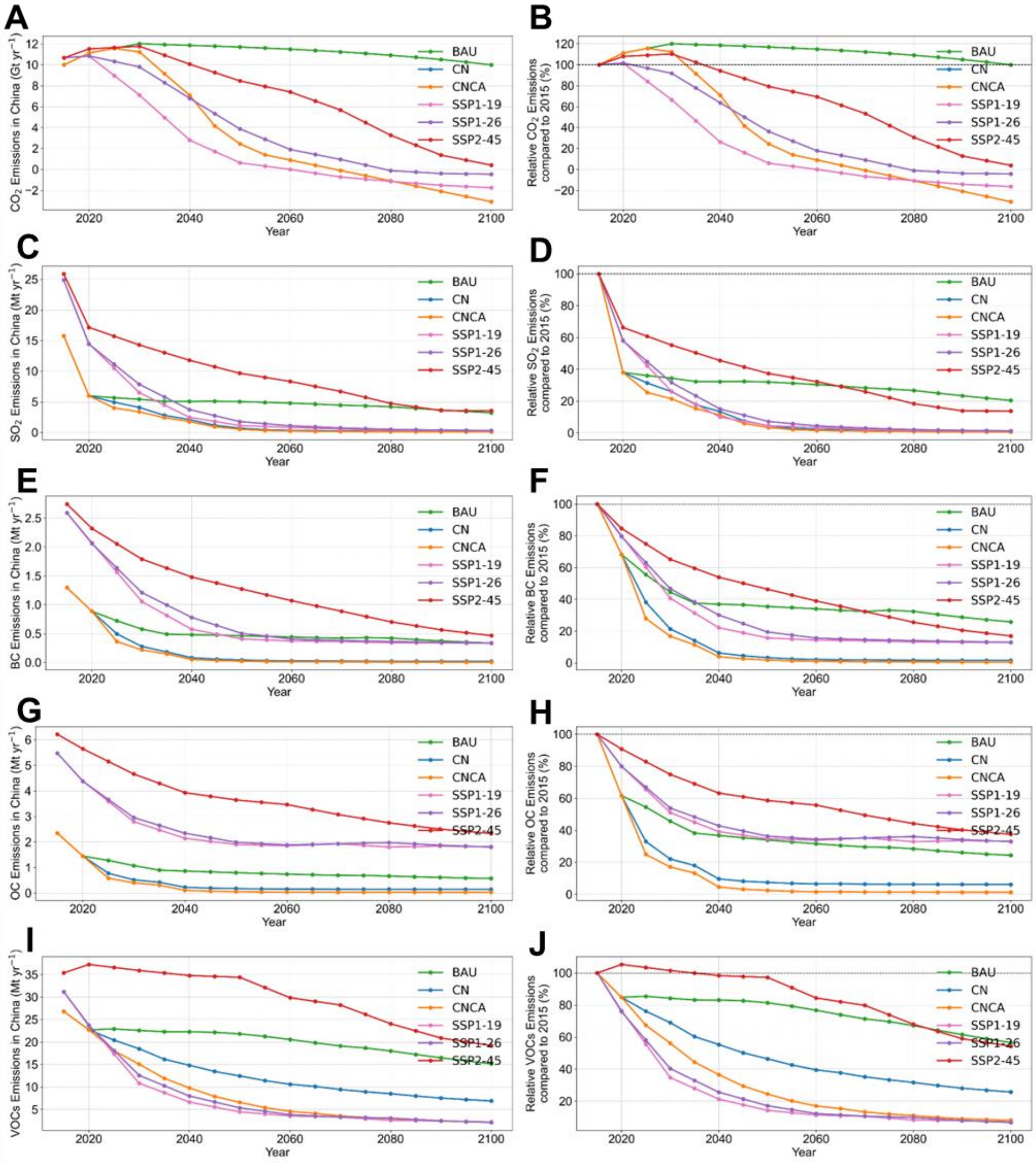


Fig. R3. Comparison of effective radiative forcing (ERF) estimates from CMIP models for major forcing agents, including CO_2 and anthropogenic aerosols. Each point represents an individual model from the RFMIP experiments, and model spread illustrates inter-model uncertainty in historical forcing. This figure is adapted from Fig. 1 of Smith et al.[7].

In summary, CESM2 accurately reproduces the historical temperature trend and reasonably represents the effects of GHGs and aerosols, both individually and jointly. This strengthens our confidence in its ability to provide reliable projections of future climate impacts driven by evolving aerosols and GHGs. We have added the above points related to CESM's fidelity in the revised manuscript (Line 566 – 571, 590 – 610).

Extended Data Fig. 1: Compared to relative percentage change, there absolute values are more informative. Of course, displaying both (absolute and relative change) may be best.

We have revised the figure to display both absolute and relative changes in air pollutant emissions.



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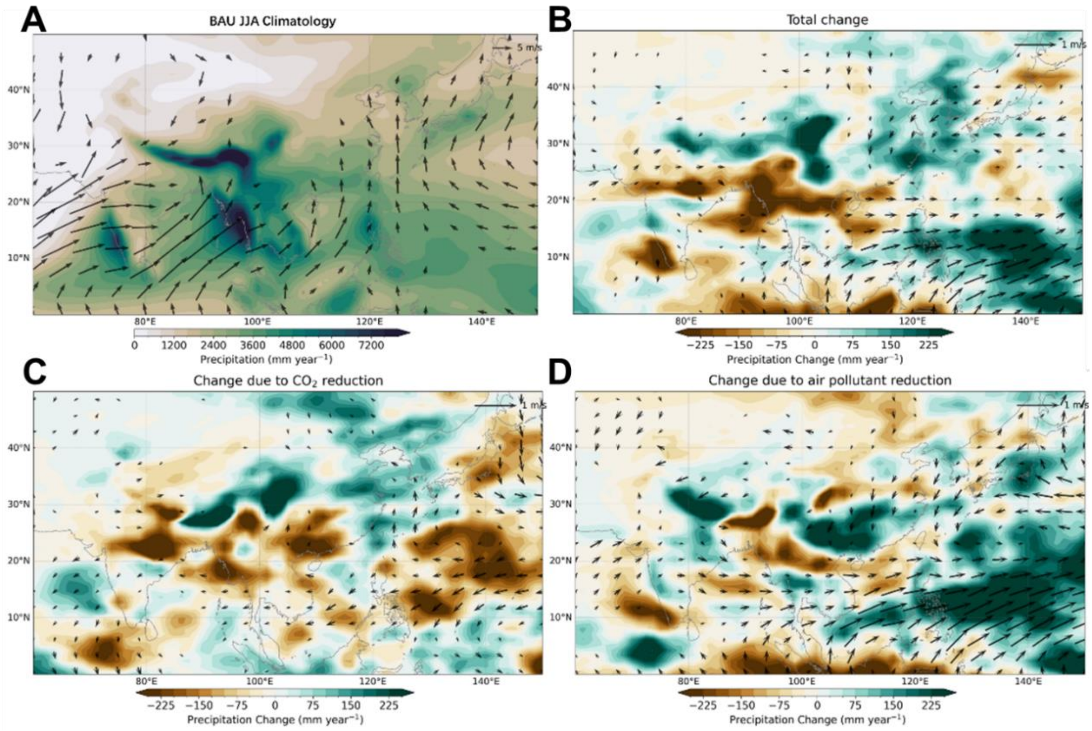
Extended Data Fig. 2: The paper should explain why the change in CO2 reduction may cause to the changes in the surface albedo, although this can be easily understood from air pollutant reduction.

This is because CO_2 reduction causes a global surface temperature decrease, which generally slows down sea ice melting and increases surface albedo over the Arctic. This ultimately creates a positive feedback involving surface temperature, sea ice melting, surface albedo, and incoming energy surplus/deficit over the Arctic, leading to the "polar amplification" of temperature change[8,9].
We have added this explanation to the revised manuscript (Line 181 – 185).

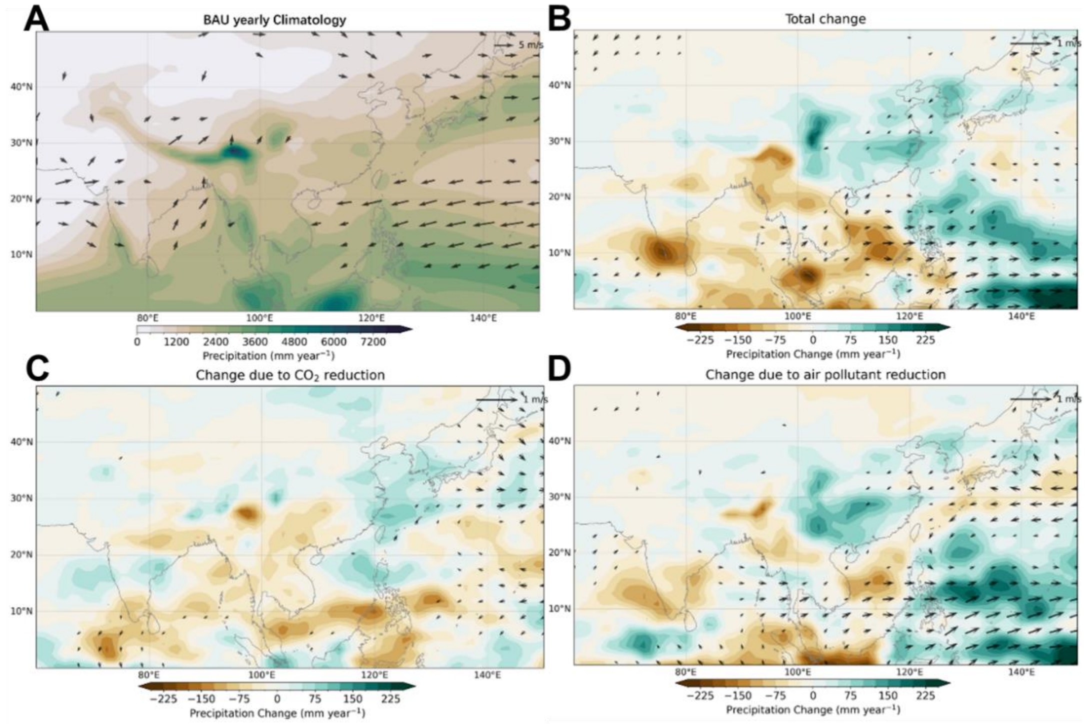
Extended Data Fig. 8: The unit in the Fig. 8A (m/year) is inconsistent with the text in the caption (mm/year). The unit format A/B in Fig. 8 (also in Figs, 5, 7, 9) is inconsistent with that format like A B^(-1) in other figures (Figs. 2, 4, 10). In addition, it is not clear the changes in precipitation in 8B-D is annual total change or just JJA change because the Fig.8A displayed the JJA precipitation. Regardless of JJA or annual changes in precipitation, a change of negative or positive 225 mm/year in precipitation is quite large. Such simulated magnitude of precipitation change in the paper is also significantly larger than the report from the Refence 5 (at least twice of that) (Yang et al., 2023. Sci Bulletin) The paper should explain and discuss the underlying mechanism, and interpret if this is reasonable – I am not in the field of aerosol-precipitation interaction research.

We apologize for the mistake. We have changed the unit in Extended Data Fig. 8A (now Extended Data Fig. 13A) to mm $year^{-1}$. We have also standardized the unit format in all figures to A B^{-1}. Moreover, we have clarified in the figure caption that the precipitation or precipitation changes presented in all panels are JJA values. The revised figure is given below.



Extended Data Fig. 13. Differences in JJA (June–July–August) mean precipitation and wind field in East Asia due to CNCA policies relative to BAU for 2050–2070. (A) Climatological mean precipitation (mm/year) and 1000hPa wind field averaged under BAU; **(B)** Total differences due to CNCA policies (CNCA−BAU); **(C)** Differences due to CO_2 reduction (SENS−BAU); **(D)** Differences due to air pollutant reductions (CNCA−SENS). Arrows indicate 1000hPa wind field, and blue (brown) shading indicates increased (decreased) precipitation in mm $year^{-1}$.

The magnitude of precipitation change is larger than those from Yang et al.[10] because they showed annual mean precipitation change instead. Below we also show the annual mean precipitation change from our simulation results, which is broadly consistent with the magnitude in Yang et al.[10].



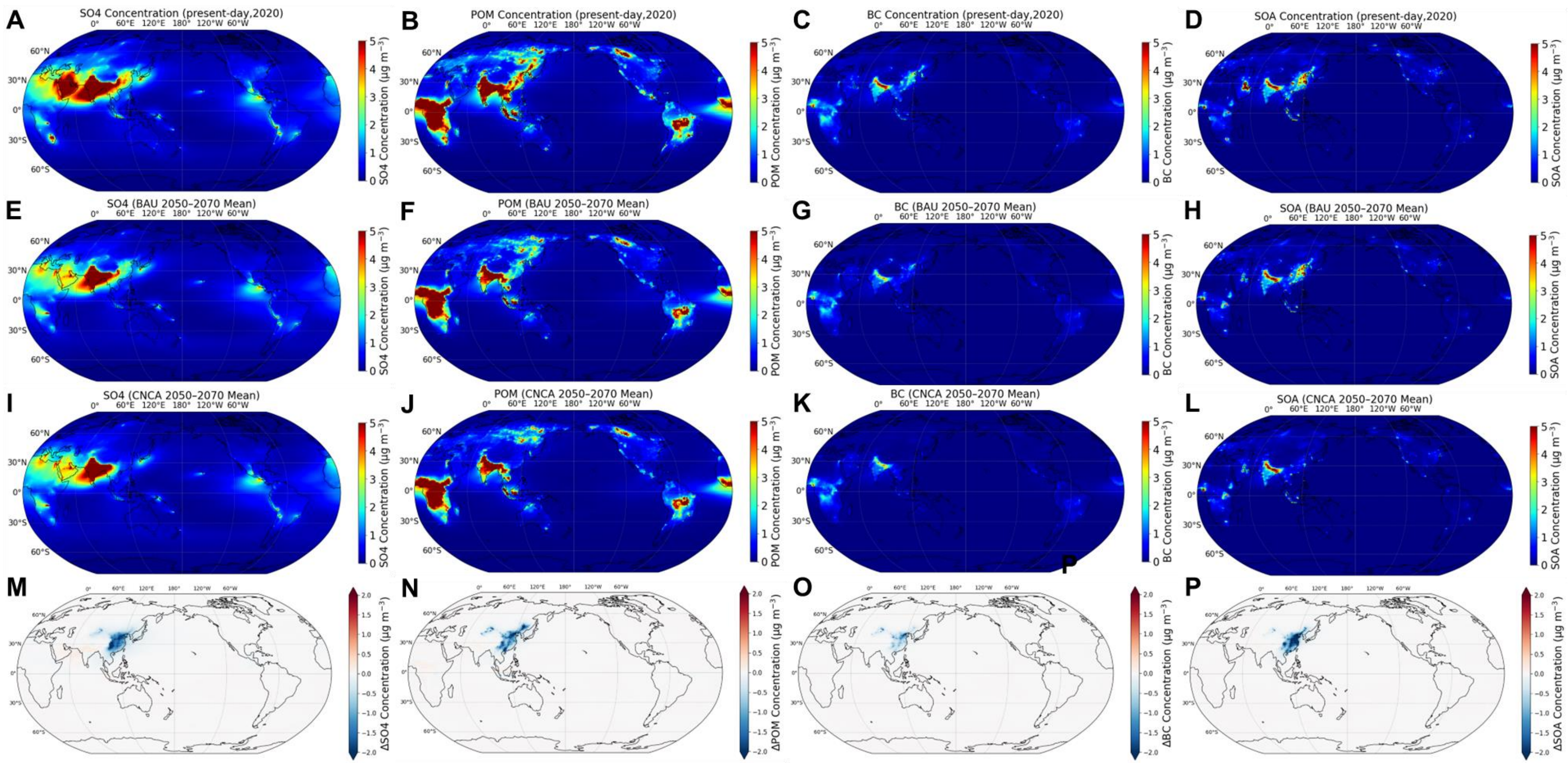
Extended Data Fig. 14. The same as Extended Data Fig. 13 but for annual mean precipitation.

Extended Data Fig. 10: It is known that sulfate aerosols are largely responsible for cooling effect. From the Fig. 10A, the CESM2 significantly underestimated the sulfate aerosol concentration. As the regression slope is not shown, it looks that the slope ranges from 0.2 to 0.4. What does this imply? The simulated warming effects could be further amplified given considering the underestimated sulfate aerosols from the model?

Yes. Our model evaluation indicates that sulfate concentrations are underestimated by 46% on average (Extended Data Fig. 8A). The warming effects due to air pollutant reductions could indeed be stronger than our current simulation results. Accordingly, the global surface temperature increase from China's air pollutant reductions may offset the cooling from China's CO_2 reduction for an even longer time. We have added an explicit discussion of such a model discrepancy on Line 586 – 589.

In addition, the observed maximum sulfate aerosols is 15 ug/m3 in Beijing-Tianjin-Hebei, a representatively high air pollutant region. This sounds good. Therefore, I suggest that the authors give a figure showing the spatial distribution of current (2020) and future map of sulfate concentrations. So that the readers could have a picture of what a magnitude of sulfate concentrations should decline in terms of "Beautiful China" scenario.

Following the reviewer's comment, we have updated Extended Data Fig. 2 (shown below) to include current (2020) and future (BAU and CNCA) mean concentrations of different aerosol components.



Extended Data Fig. 2. Spatial distribution of concentrations and concentration differences for four $PM_{2.5}$ components (sulfate, POM, BC, and SOA) across present day (2020) and BAU/CNCA scenarios (2050 – 2070 mean). (A – D) Present day concentrations: (A) sulfate, (B) POM, (C) BC, and (D) SOA; (E – H) BAU scenario concentrations: (E) sulfate, (F) POM, (G) BC, and (H) SOA; (I – L) CNCA scenario concentrations: (I) sulfate, (J) POM, (K) BC, and (L) SOA; (M – P) CNCA−BAU concentration differences: (M) sulfate, (N) POM, (O) BC, and (P) SOA.

Reviewer #2 (Remarks to the Author): see attached PDF

To combat global warming, countries around the world have set targets to achieve carbon neutrality. While the year of achieving this target varies from country to country with developed countries somewhat earlier than developing ones. It has been widely recognized that achieving carbon neutrality will significantly lower the global surface temperature. This study is groundbreaking to demonstrate that this is far being the case for such a big country as China whose carbon emission is closely tied with aerosol loading. As the two most prominent anthropogenic forcing agents, reduction in carbon emission is also accompanied with decrease in aerosol loading. The two have opposite effects on the earth's climate to offset each other. Besides realizing the goal of carbon neutrality in 2060, China is also pursuing the "Beautiful China" agenda by 2050. Unlike well-mixed CO2 with long lifetime, aerosols are highly inhomogeneous with much shorter lifetime. This makes the projection of resulting changes in global surface temperature more complex and unpredictable. As such, there have been a large range in the estimates of global mean temperature changes contributed by China's carbon neutrality, and clean air initiatives. Running the CESM2 model "over a realistic policy-relevant timescales", they reached a seemingly stunning finding that China will have virtually nil contribution to lower global mean temperature by 2070, 10 years after it achieves its neutrality target. This is in stark contrast with the significant effect of cooling by carbon neutrality achieved by US, or any other countries of low aerosols at present. Such a finding is thus of very important policy implication for China, likely for most developing countries, to take quicker and bolder actions in reducing emissions of both greenhouse gases and aerosols. Overall, the paper is well written, the approach is sound, and the finding is important. I'd thus recommend it for publication after the following comments are addressed.

We thank the reviewer for recognizing the merit of our paper. We also appreciate the reviewers' valuable suggestions, which have helped us improve the manuscript. We have carefully revised the manuscript according to these comments. The reviewers' comments are in blue, our responses are in black, and the quotations from our manuscript are in italics.

Major comments:

1. The principle of the finding is totally understandable, although may sound surprising at first. The real challenge is the magnitude and temporal evolution. As the study is totally based on model simulations, the results are as good as the model and input quantities are. It's thus key to demonstrate their fidelities in dealing with both forcing terms, especially in tackling aerosol and GHG effects. In general, the GHG effects are well-understood with low uncertainties. In contrast, the aerosol climate effects are much less certain, especially concerning the aerosol-radiation-interaction (ARI) and aerosol-cloud interactions (ACI). I'd thus recommend the authors to elaborate more how the two effects are accounted for in the CESM2, and how well is the model in simulating temperature changes in the past, especially the roles of GHGs and aerosols.

To demonstrate the fidelity of the CESM2 model, we first examined its performance in simulating historical temperature changes. As shown in Fig. R1, compared with observational datasets such as HADCRUT and GISTEMP, CESM2 successfully reproduces multi-decadal evolution of global mean surface temperature change in the 20th century, including the early warming from 1920 – 1940, the mid-century warming hiatus from 1940 – 1970, and the accelerated warming after the 1970s[4].

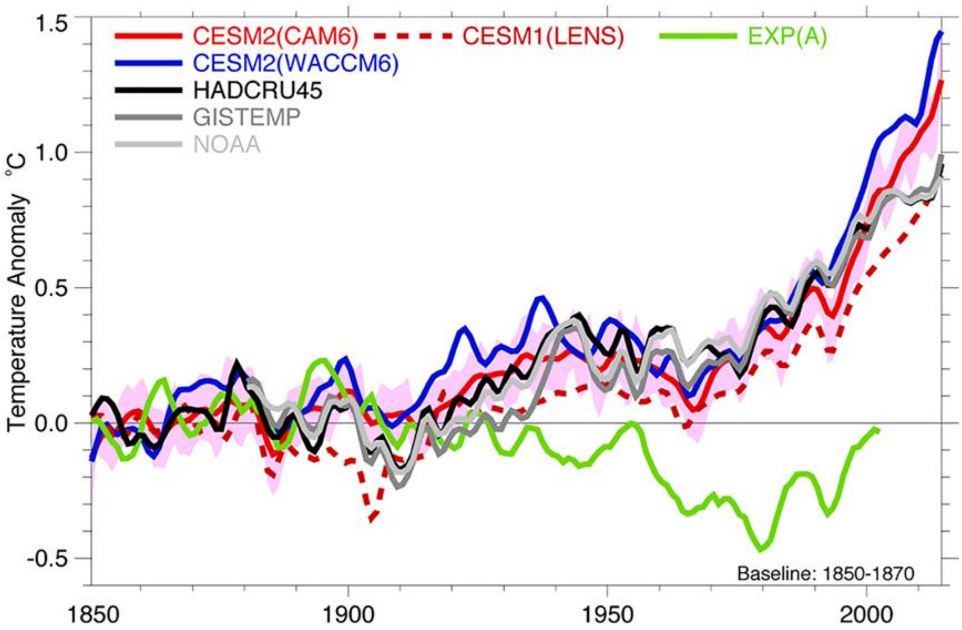


Fig. R1. Time series of global mean surface temperature anomalies during the historical period from observations and CESM simulations. Observations include HADCRUT4.5, GISTEMP, and NOAAGlobalTemp. Model results include CESM2(CAM6), CESM2(WACCM6), and CESM1(LENS) ensemble simulations. Anomalies are relative to the 1850–1870 mean, and shaded areas indicate ensemble spreads. This figure is adapted from Fig. 7 of Danabasoglu et al.[4].

Building on this, we further examine CESM2's ability to simulate the separate responses to greenhouse gases (GHG) and aerosols—two key forcing factors. Although their individual contributions cannot be directly verified through observations, we can indirectly assess the model by analyzing their roles in different historical phases of global temperature change. From the CESM2 single forcing large ensemble experiments, which isolate historical climate forcings (such as GHG and aerosols), the model reveals the independent effect of each forcing (Fig. R2)[5]. The results show that under GHG-only forcing, the model simulates a continuous warming trend, consistent with the physical understanding of GHG as the main driver of warming. Under anthropogenic aerosol-only forcing, the model produces a clear cooling signal, with the strongest cooling in the mid-20th century, gradually weakening afterward due to the decrease in aerosol loading. When both GHG warming and aerosol cooling are combined, CESM2 successfully reproduces the phased characteristics of historical temperature change, i.e., mid-20th-century warming hiatus and accelerated warming in the late 20th century. This indicates that aerosols contributed significantly to the mid-century warming slowdown, while the continued strengthening of GHG impact and the weakening of aerosol impact drove later temperature rise. These results also align with previous attribution studies[6]. This suggests that CESM2 can not only reproduce the overall historical temperature curve but also capture the separate effects of GHG and aerosols on temperature change from a physical mechanism perspective.

[*REDACTED*]

Fig. R2. [*REDACTED*]. This figure is adapted from Fig. 2a of Simpson et al.[5].

Additionally, the effective radiative forcing of GHG and aerosols simulated by CESM2 falls within the range of the CMIP6 multi-model ensemble (Fig. R3)[7], further supporting the reasonableness of its forcing representations.

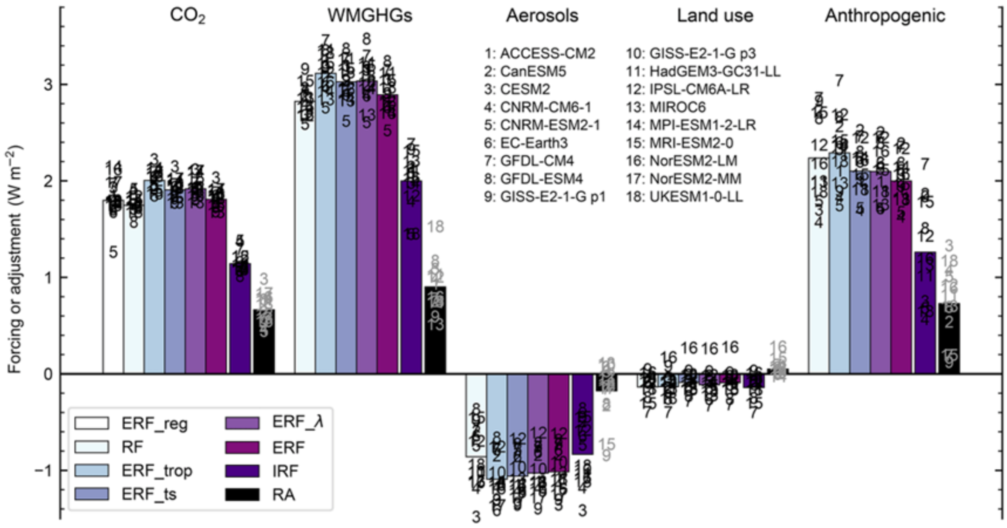


Fig. R3. Comparison of effective radiative forcing (ERF) estimates from CMIP models for major forcing agents, including CO_2 and anthropogenic aerosols. Each point represents an individual model from the RFMIP experiments, and model spread illustrates inter-model uncertainty in historical forcing. This figure is adapted from Fig. 1 of Smith et al.[7].

In summary, CESM2 accurately reproduces the historical temperature trend and reasonably represents the effects of GHGs and aerosols, both individually and jointly. This strengthens our confidence in its ability to provide reliable projections of future climate impacts driven by evolving aerosols and GHGs.

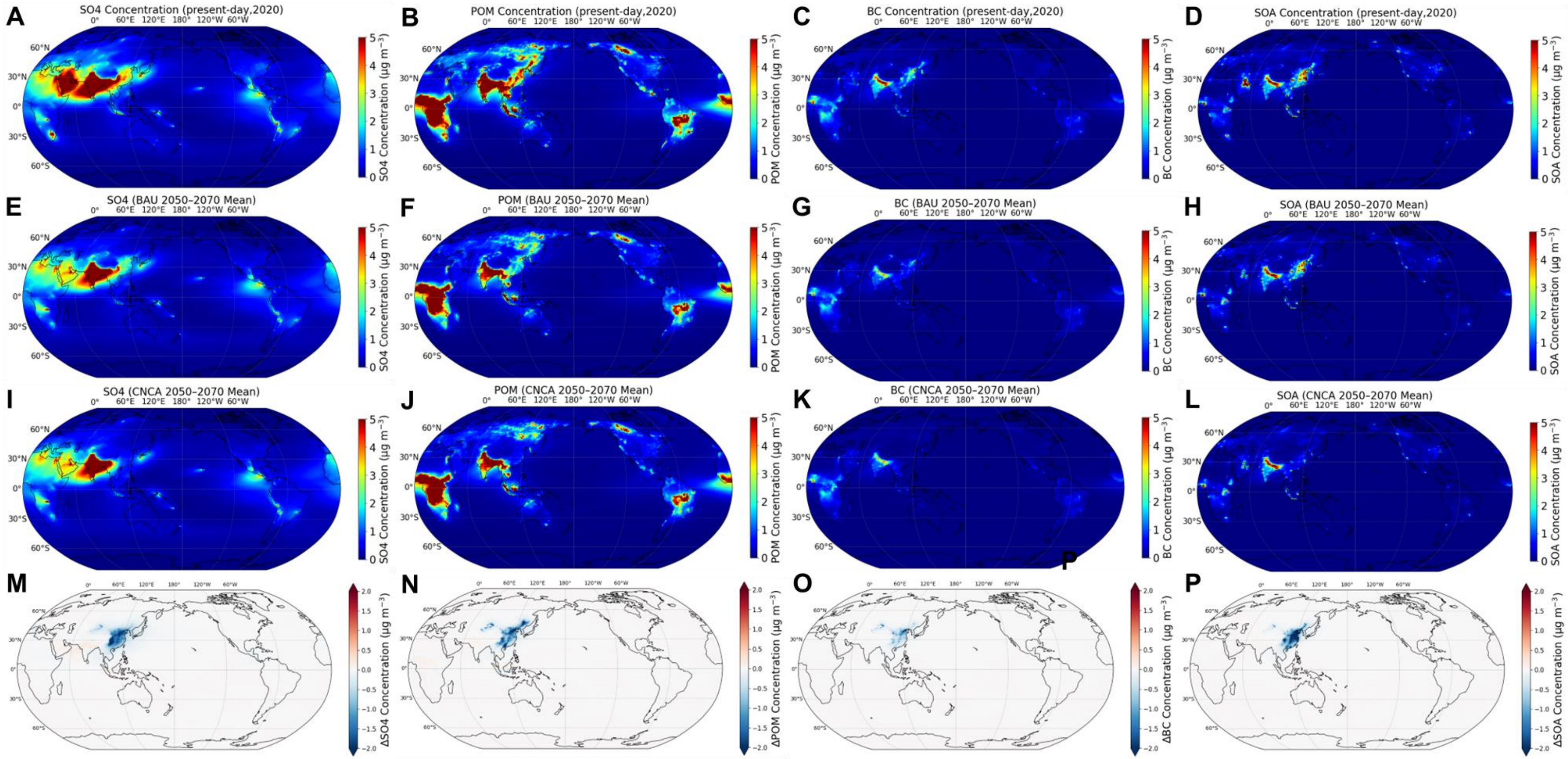
Finally, we elaborate on how the aerosol-radiation interaction (ARI) and aerosol-cloud interaction (ACI) are represented in CESM2. ARI is computed online by the Rapid Radiative Transfer Model for GCMs (RRTMG) radiation scheme[11], which is fully coupled with the four-mode Modal Aerosol Model (MAM4)[12]. MAM4 predicts both the mass and number concentrations of major aerosol species across different modes, calculates their optical properties (including scattering, absorption, and asymmetry parameters), and directly provides these properties to the radiation scheme to assess shortwave and longwave radiative effects. ACI is represented by the Morrison-Gettelman version 2 (MG2) two-moment cloud microphysics scheme[13]. In MG2, aerosol activation follows the parameterization of Abdul-Razzak and Ghan[14], which converts aerosol number concentrations into cloud droplet number concentrations. This subsequently influences both the droplet size and cloud albedo (the "first indirect effect") and the efficiency of cloud water converting into rainwater, thereby affecting cloud lifetime and precipitation processes (the "second indirect effect").

We have included the above descriptions and discussion in the revised manuscript (Line 489 – 497, Line 566 – 571, Line 590 – 610).

2. As ARI and ACI strongly depend on aerosol types. Yet, reductions in anthropogenic aerosols may vary considerably pending on specific actions taken. Little insight is given as to the government policies and their consequential implications on the proportions of different types of aerosols, especially those producing primary and secondary aerosols of different species. Their differences affect both the ARI and ACI and their feedback with the climate systems.

We have shown in Extended Data Fig. 2 (shown below) the concentration differences in $PM_{2.5}$ major chemical components between the BAU and CNCA scenarios (CNCA−BAU). Sulfate, primary organic matter (POM), and secondary organic aerosol (SOA) make dominant contributions to $PM_{2.5}$ concentration difference, accounting for 30%, 28%, and 29%. Consequently, the effective radiative forcing (ERF) due to SO_2, POM, and VOC emission reductions is 0.045 W m^{-2}, 0.046 W m^{-2}, and 0.017 W m^{-2}, respectively, under the CNCA policies relative to BAU (Fig. 2C). Meanwhile, the ERF due to BC emission reduction is −0.018 W m^{-2}, offsetting a fraction of the positive ERF induced by SO_2, POM, and VOC reductions. All aerosol types contribute to ERF through both ARI and ACI.

We have included these results and discussion in the revised manuscript (Line 153 – 163).



Extended Data Fig. 2. Spatial distribution of concentrations and concentration differences for four $PM_{2.5}$ components (sulfate, POM, BC, and SOA) across present day (2020) and BAU/CNCA scenarios (2050 – 2070 mean). (A – D) Present day concentrations: (A) sulfate, (B) POM, (C) BC, and (D) SOA; (E – H) BAU scenario concentrations: (E) sulfate, (F) POM, (G) BC, and (H) SOA; (I – L) CNCA scenario concentrations: (I) sulfate, (J) POM, (K) BC, and (L) SOA; (M – P) CNCA−BAU concentration differences: (M) sulfate, (N) POM, (O) BC, and (P) SOA.

3. I agree that the findings presented have important policy implications. I'd hope the Chinese government does act as per the recommendation to drastically reduce air pollutants at a faster pace, especially aerosols. Please elaborate any more scenarios including the most optimistic one in pollution reduction, how the earth's climate may change and potential economic benefits to motivate the government to act. Like any government, environmental and climate policies are subject to changes in future policies. Educating policy-maker is thus essential especially for such an influential study as this one.

Beyond the carbon neutrality and clean air (CNCA) scenario described in the manuscript, we suggest that carbon neutrality should be achieved as early as possible and that negative carbon technologies be vigorously promoted in the long run, augmented by policies to rapidly reduce methane emissions. We refer to this proposed scenario as "CNCA_optimistic". Earlier achievement of carbon neutrality and the deployment of negative emission technologies lead to a much larger cumulative carbon reduction in CNCA_optimistic relative to BAU than in CNCA relative to BAU. As a result, CNCA_optimistic realizes a net cooling effect relative to BAU earlier and with greater magnitude. In addition, the rapid methane reduction under CNCA_optimistic also contributes to cooling, further advancing and amplifying the net cooling effect. At the same time, with carbon neutrality reached earlier, air pollutant levels also decline more rapidly to minimal levels. During the period when CNCA_optimistic has achieved carbon neutrality but CNCA has not yet done so, the faster reduction of air pollutants under CNCA_optimistic may induce a slightly stronger warming effect. However, this effect will soon vanish, unlike the persistent impacts of CO_2 and methane reductions, because the atmospheric lifetimes of air pollutants and aerosols are much shorter. Therefore, compared with the BAU scenario, CNCA_optimistic is projected to produce an earlier and stronger cooling effect than CNCA. Moreover, due to earlier pollutant reductions, CNCA_optimistic can deliver greater health benefits, further highlighting the benefits of this scenario.

We have included the above discussion in the revised manuscript (Line 83–100 of the Supplementary Information).

Specific comments:

L103 "where" or "when"?

We have modified this sentence to "1) a BAU scenario, defined by the climate and air pollution control policies enacted as of 2020, assumes that carbon emissions peak around 2030 and then decline slightly". (Line 105 – 107)

L111-112, why are aerosols expected to swiftly decrease after 2030. Air quality in China has improved so much that I wonder if it'd wait till then to see drastic reduction in air pollutants. To me, this has taken place, especially since 2013.

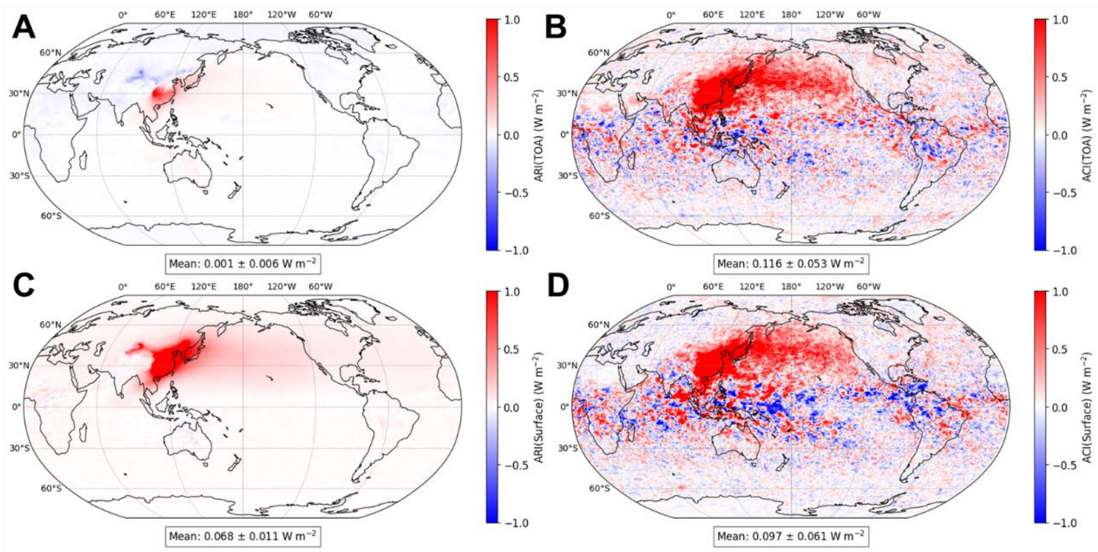
Sorry for the confusion here. On Line 111 – 112 we meant to state that CO_2 emissions increase constantly until about 2030, while emissions of major air pollutants have already decreased swiftly in the previous decade (2010–2020). Under the CNCA scenario, air pollutants emissions are projected to keep decreasing for another 2–3 decades, until about 2045–2050 (Extended Data Fig. 1). The main reason for the sustained decrease is that, as the potential of end-of-pipe control measures diminish, the emission reductions in the next 2–3 decades will be more driven by carbon neutrality policies that requires a slower, fundamental transformation of the economic-societal system.

We have revised this sentence to avoid potential confusion:

"The integrated assessment model fully accounts for China's recent development path and policies and thus realistically reproduces recent and anticipated near-future emission trends, e.g., the constantly increasing CO_2 emissions until about 2030 and the swiftly decreasing emissions of major air pollutants in the previous decade (2010–2020)." (Line 111 – 115)

L140-141, how much are the ARI and ACI, besides their combined effects? I'd suggest differentiating the two effects.

Quantifying the separate contributions of ARI and ACI to temperature changes requires conducting additional fully coupled transient sensitivity simulations for multiple ensemble members, which is computationally challenging. Here we conduct additional sensitivity experiments with the atmosphere-only configuration (see Methods) to diagnose the contribution of ARI and ACI to ERF, which is closely tied to temperature changes. Extended Data Fig. 9A,B (shown below) reveals that ARI contributes a minor fraction of the ERF, partly because the warming effect of BC and the cooling effect of other aerosol components largely offset each other. In contrast, ACI makes a dominant contribution to ERF, implying that ACI likely plays a leading role in causing the temperature changes. We have included the discussion in the revised manuscript (Line 10 – 22 of the Supplementary Information).



Extended Data Fig. 9. Spatial contribution of aerosol-radiation interaction (ARI) and aerosol-cloud interaction (ACI) to net radiative flux changes at TOA (i.e., the ERF) and at the surface induced by air pollutant reductions under China's CNCA policies. The panels are values at (A, B) TOA and (C, D) the surface due to (A, C) ARI and (B, D) ACI, derived from atmosphere-only simulations nudged towards present-day meteorology.

L149-150, if aerosol in China have such a significant effect in the Arctic, they must be transported a far distance without being totally scavenged. What's model's scavenging mechanisms and how trustworthy they are?

The CESM2 model includes state-of-the-art treatments of both the dry deposition and wet removal of aerosols, and the wet removal processes consist of stratiform in-cloud scavenging, convective in-cloud scavenging, and below-cloud scavenging, as detailed in Liu et al.[12,15]. Partly because of the scavenging, China's air pollutant emission reductions have a rather small effect on aerosol concentration in the Arctic (Extended Data Fig. 2). A likely decisive cause of the Arctic amplification is that, following either CO_2 and air pollutant reductions, energy perturbations originating at low- and mid-latitudes can propagate poleward and get amplified through a positive feedback loop involving incoming energy surplus, sea ice melting, surface albedo, and surface temperature over the Arctic[8,9,16]. The stronger Arctic amplification due to air pollutant reductions than that due to CO_2 reduction arises because the concentrated energy perturbations at northern mid-latitudes in the former case enhance poleward energy transport. We have included the above descriptions in the revised manuscript (Line 181 – 188).

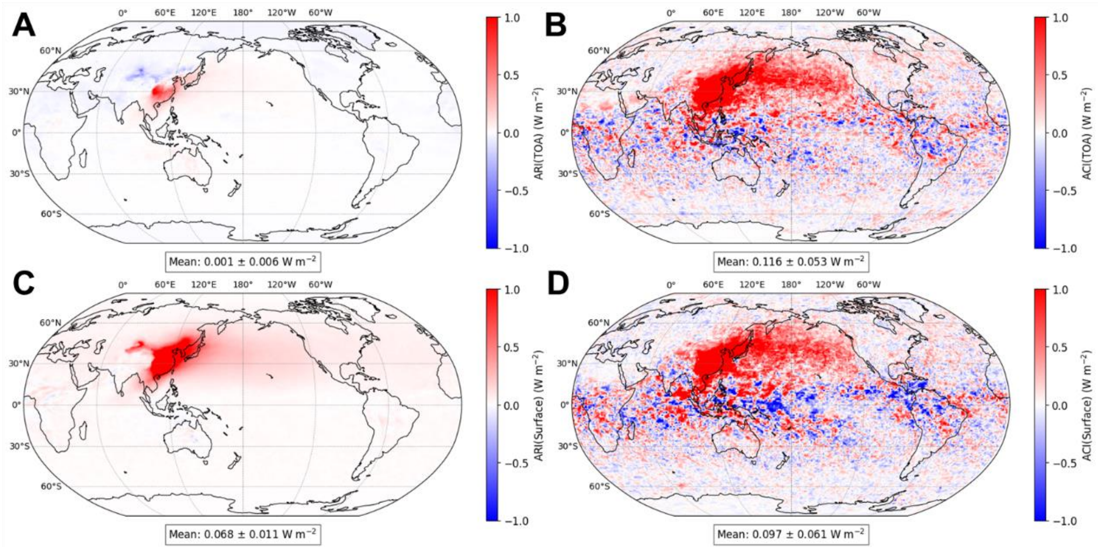
L167-170, I like this finding very much, and also curious the combined global effect, warming or cooling?

The combined global effect is an insignificant cooling of -0.03 ± 0.09 K. We have included this information in the revised manuscript (Line 150).

L183-186, While the finding concerning changes in precipitation is intriguing, it's a long shot for any models due to much more complex ACI driven by meteorology, aerosol type and ARI, etc. I'd like to know which effect is more dominant in this finding.

Quantifying the individual contributions of ARI and ACI to the simulated precipitation changes requires additional fully coupled transient simulations for multiple ensemble members, which is computationally challenging. Meanwhile, some insights can be drawn from the ARI and ACI contributions to ERF, which are identified using additional atmosphere-only experiments (see Methods). Extended Data Fig. 9 (shown below) indicates that the net radiation flux changes at the top of the atmosphere (TOA) and at the surface due to ARI are smaller than those due to ACI. Moreover, since ACI may lead to the simulated precipitation changes not only through radiation changes but also by altering collision–coalescence efficiency, it is likely to be a key driver of the simulated precipitation responses. We have included the discussion in the revised manuscript (Line 10 – 22 of the Supplementary Information).

It is also noted that, following the first reviewer's suggestion, our revised manuscript now focuses on temperature changes and the precipitation changes are no longer the focus of this paper (mostly moved to the Supplementary Information).



Extended Data Fig. 9. Spatial contribution of aerosol-radiation interaction (ARI) and aerosol-cloud interaction (ACI) to net radiative flux changes at TOA (i.e., the ERF) and at the surface induced by air pollutant reductions under China's CNCA policies. The panels are values at (A, B) TOA and (C, D) the surface due to (A, C) ARI and (B, D) ACI, derived from atmosphere-only simulations nudged towards present-day meteorology.

L212-213, similar to the above, why "likely"? sensitivity tests may show which one is more important.

This question is similar to the last one but with a focus on the China region. Over the China region, both the fully coupled simulation results (Fig. 4) and atmosphere-only simulation results (Extended Data Fig. 9) show that the changes in clear-sky radiation at the surface and at TOA are much smaller than the changes in cloud radiative effect caused by air pollutant reductions. Thus, ACI probably dominates the precipitation changes over China. (Line 210 – 214 of the main text, Line 10 – 22 of the Supplementary Information)

L236-238, important finding, but how realistic is it, which may be supported to some extent with reference to historical records. I am sure such CESM2-based studies were done but need to be summarized.

We appreciate the reviewer's valuable comments on the realism of our global precipitation evolution results. Below, we address the reviewer's concerns from two aspects: CESM2's precipitation simulation skill and the reasonableness of its response to emission changes.

Although precipitation simulation is a challenge for all global climate models, CESM2 performs much better than its predecessor in simulating historical precipitation, providing a reliable basis for long-term projections. Its global mean bias is reduced from 0.33 mm/day in CESM1 to 0.25 mm/day, with root-mean-square error decreased by about 20%[4]. These improvements mainly come from reduced wet biases in key regions like the Indian Ocean, South Pacific Convergence Zone, and tropical Atlantic Inter-Tropical Convergence Zone (ITCZ), showing better skill in large-scale water cycle processes[4].

The separate responses of precipitation to GHG and aerosol changes cannot be directly verified against observations, but these responses in CESM2 closely follow basic atmospheric energy budget constraints. Aerosol reduction causes warming, and the atmosphere balances energy by increasing latent heat release (i.e., precipitation). CO_2 reduction causes cooling, and both energy constraints and lower moisture capacity reduce precipitation. This physical rule is widely confirmed by CMIP6 models, including CESM2, showing a very strong linear relationship between global precipitation changes and surface temperature changes[17]. IPCC AR6 (Fig. 4.42) also used CESM2 as a key model to show precipitation changes under a substantial global warming[18].

In summary, CESM2's improved historical performance and physically consistent mechanisms lend confidence to the reliability of our results, despite remaining uncertainties in precipitation projections. We have included the above evaluation in the revised manuscript (Line 102 – 120 of the Supplementary Information).

It is also noted that, in response to the first reviewer's suggestion, the revised manuscript now focuses on temperature changes, while precipitation changes are no longer a main focus and have been largely moved to the Supplementary Information.

L249-250, indeed this finding has an important policy implication. I wonder how sure if the year of transition in 2070. Is it subject to big change with respect to government policies?

The transition towards significant net cooling effects is projected to occur around 2070 under the CNCA scenario, assuming the achievement of carbon neutrality by 2060 and "Beautiful China" by 2050 following China's released policies. It is indeed subject to change with respect to governmental policies. For example, as discussed in our response to the reviewer's 3rd major comment, if China achieves carbon neutrality earlier, pursues negative carbon emissions afterwards, and promote methane reduction measures, the transition is expected to occur earlier. In contrast, if China's progress toward carbon neutrality falls short of expectations, this transition may occur later.

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Reviewer #2

The authors have made substantial revisions to address my comments to my satisfaction.

Having said that, I'd point the following two recent studies that are highly relevant, as they provide more quantitative estimation of long-term changes in both fine-mode aerosols (dominated by anthropogenic sources) and radiative forcing at the top of the atmosphere. Such information would serve as observation-based evidence of the same trend of aerosol and aerosol radiative forcing in recent decades to support/complement the future model-simulated trends:

Loeb, N., et al., 2025, Emerging hemispheric asymmetry of Earth’s radiation, PNAS, https://doi.org/10.1073/pnas.2511595122.

Yan, X., et al., 2022, A global land aerosol fine-mode fraction dataset (2001-2020) retrieved from MODIS using hybrid physical and deep learning approaches, Earth Syst. Sci. Data, 14, 1193-1213, doi:10.5194/essd-14-1193-2022.

We thank the reviewer for highlighting these highly relevant observational studies. We have now incorporated both references into the manuscript to provide observation-based context for the hemispheric asymmetry in aerosol-related radiative forcing and temperature responses. The references have been added and discussed in the revised manuscript (lines 198–201):

“This hemispheric asymmetry is consistent with recent observations of declining fine-mode aerosols globally and a greater trend in absorbed solar radiation (ASR) increase in the Northern Hemisphere relative to the Southern Hemisphere.”

Review of NC article "Air quality improvement masks global cooling from CO2 1 reductions under China's carbon neutrality for half a century" by Zhao et al.

To combat global warming, countries around the world have set targets to achieve carbon neutrality. While the year of achieving this target varies from country to country with developed countries somewhat earlier than developing ones. It has been widely recognized that achieving carbon neutrality will significantly lower the global surface temperature. This study is ground-breaking to demonstrate that this is far being the case for such a big country as China whose carbon emission is closely tied with aerosol loading. As the two most prominent anthropogenic forcing agents, reduction in carbon emission is also accompanied with decrease in aerosol loading. The two have opposite effects on the earth's climate to offset each other. Besides realizing the goal of carbon neutrality in 2060, China is also pursuing the "Beautiful China" agenda by 2050. Unlike well-mixed CO2 with long lifetime, aerosols are highly inhomogeneous with much shorter lifetime. This makes the projection of resulting changes in global surface temperature more complex and unpredictable. As such, there have been a large range in the estimates of global mean temperature changes contributed by China's carbon neutrality, and clean air initiatives. Running the CESM2 model "over a realistic policy-relevant timescales", they reached a seemingly stunning finding that China will have virtually nil contribution to lower global mean temperature by 2070, 10 years after it achieves its neutrality target. This is in stark contrast with the significant effect of cooling by carbon neutrality achieved by US, or any other countries of low aerosols at present. Such a finding is thus of very important policy implication for China, likely for most developing countries, to take quicker and bolder actions in reducing emissions of both greenhouse gases and aerosols.

Overall, the paper is well written, the approach is sound, and the finding is important. I'd thus recommend it for publication after the following comments are addressed.

Major comments:

1. The principle of the finding is totally understandable, although may sound surprising at first. The real challenge is the magnitude and temporal evolution. As the study is totally based on model simulations, the results are as good as the model and input quantities are. It's thus key to demonstrate their fidelities in dealing with both forcing terms, especially in tackling aerosol and GHG effects. In general, the GHG effects are well-understood with low uncertainties. In contrast, the aerosol climate effects are much less certain, especially concerning the aerosol-radiation-interaction (ARI) and aerosol-cloud-interactions (ACI). I'd thus recommend the authors to elaborate more how the two effects are accounted for in the CESM2, and how well is the model in simulating temperature changes in the past, especially the roles of GHGs and aerosols.
2. As ARI and ACI strongly depend on aerosol types. Yet, reductions in anthropogenic aerosols may vary considerably pending on specific actions taken. Little insight is given

as to the government policies and their consequential implications on the proportions of different types of aerosols, especially those producing primary and secondary aerosols of different species. Their differences affect both the ARI and ACI and their feedback with the climate systems.

3. I agree that the findings presented have important policy implications. I'd hope the Chinese government does act as per the recommendation to drastically reduce air pollutants at a faster pace, especially aerosols. Please elaborate any more scenarios including the most optimistic one in pollution reduction, how the earth's climate may change and potential economic benefits to motivate the government to act. Like any government, environmental and climate policies are subject to changes in future policies. Educating policy-maker is thus essential especially for such an influential study as this one.

Specific comments:

L103 "where" or "when"?

L111-112, why are aerosols expected to swiftly decrease after 2030. Air quality in China has improved so much that I wonder if it'd wait till then to see drastic reduction in air pollutants. To me, this has taken place, especially since 2013.

L140-141, how much are the ARI and ACI, besides their combined effects? I'd suggest differentiating the two effects.

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L212-213, similar to the above, why "likely" ? sensitivity tests may show which one is more important.

L236-238, important finding, but how realistic is it, which may be supported to some extent with reference to historical records. I am sure such CESM2-based studies were done but need to be summarized.

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