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Short Communication

The significant roles of anthropogenic aerosols on surface temperature under carbon neutrality

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A target of limiting global warming below 1.5 or 2 °C by 2100 relative to the preindustrial level was established in the *2015 Paris Agreement* to combat the climate crisis. The fast increase in human-induced CO_2 in the atmosphere has accelerated the warming during the past decades. To achieve the low-warming target, China has announced that it will endeavor to reach the carbon emission peak by 2030 and carbon neutrality by 2060 [1]. Many other regions or countries have also issued legislation or policies to accomplish carbon neutrality by the middle of this century such as the European Union, India, Canada, South Africa, etc. [2]. The achievement of the ambitious carbon neutrality in the future will require anthropogenic emissions to decrease quickly from now, which could lead to reductions in both CO_2 and aerosols [3]. However, the same trends in CO_2 and aerosols have the opposite radiative forcings. The cooling effect of declined CO_2 will be superimposed by the warming effect of declined aerosols. Meanwhile, aerosol changes could affect oceanic processes from the surface to the depth [4,5] and alter the regional pattern of surface temperature. Therefore, the roles of anthropogenic aerosols on surface temperature changes under carbon neutrality need further investigations.

In this study, we adopt an extensively applied climate model, the Community Earth System Model version 1 with the Community Atmospheric Model version 5 [6] (CESM1-CAM5; Supplementary materials), which could well simulate the observed warming over the 20th century [6]. This model contains aerosol direct and indirect effects with the inclusion of both the cloud albedo and cloud lifetime effects. The aerosol radiative forcing in CESM1-CAM5 is -1.5 W m^{-2} and within the uncertainty range at a 90% confidence level (-2.0 to -0.4 W m^{-2}) of models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) [7]. We use simulations under the Representative Concentration Pathways 2.6 (RCP2.6), which is the only scenario near the low-warming target in CMIP5 future projections [3]. According to the released all-forcing simulations under RCP2.6 (rcp26), we conduct fixed-aerosol simulations (rcpFA26) over the 21st century in which anthropogenic aerosol emissions are fixed at the 2005 levels (Supplementary materials). The climate effects of the projected decrease in anthropogenic aerosols could be derived from the difference between these two simulations (rcp26-rcpFA26).

Under RCP2.6, the anthropogenic aerosols decrease since the beginning of the 21st century as shown by the change of aerosol optical depth (Fig. 1a), after a large reduction in anthropogenic emissions especially SO_2 [3]. However, CO_2 concentration increases before it starts to decrease after 2050 (Fig. 1a) due to the difficulties in carbon reduction technologies that could not be tackled. In rcp26, the increased CO_2 and decreased aerosols shall generate consistent warming effects and cause a large increase in global mean surface temperature before 2050 (0.031 °C a^{-1}; Fig. 1b, black). After 2050, despite the decline in CO_2, the decrease in anthropogenic aerosols will continue to produce a warming effect, which will enable the surface temperature to rise with a speed slower than that before 2050 (0.006 °C a^{-1}; Fig. 1b, black). However, in rcpFA26, the surface temperature is primarily driven by CO_2 and shows a slight cooling trend (-0.002 °C a^{-1}) after peaking at 2060 (Fig. 1b, green) without the extra warming from anthropogenic aerosols. The 10-year delay of temperature changes in response to CO_2 forcing is consistent with the previous studies [8]. The persistent net warming effect of anthropogenic aerosols

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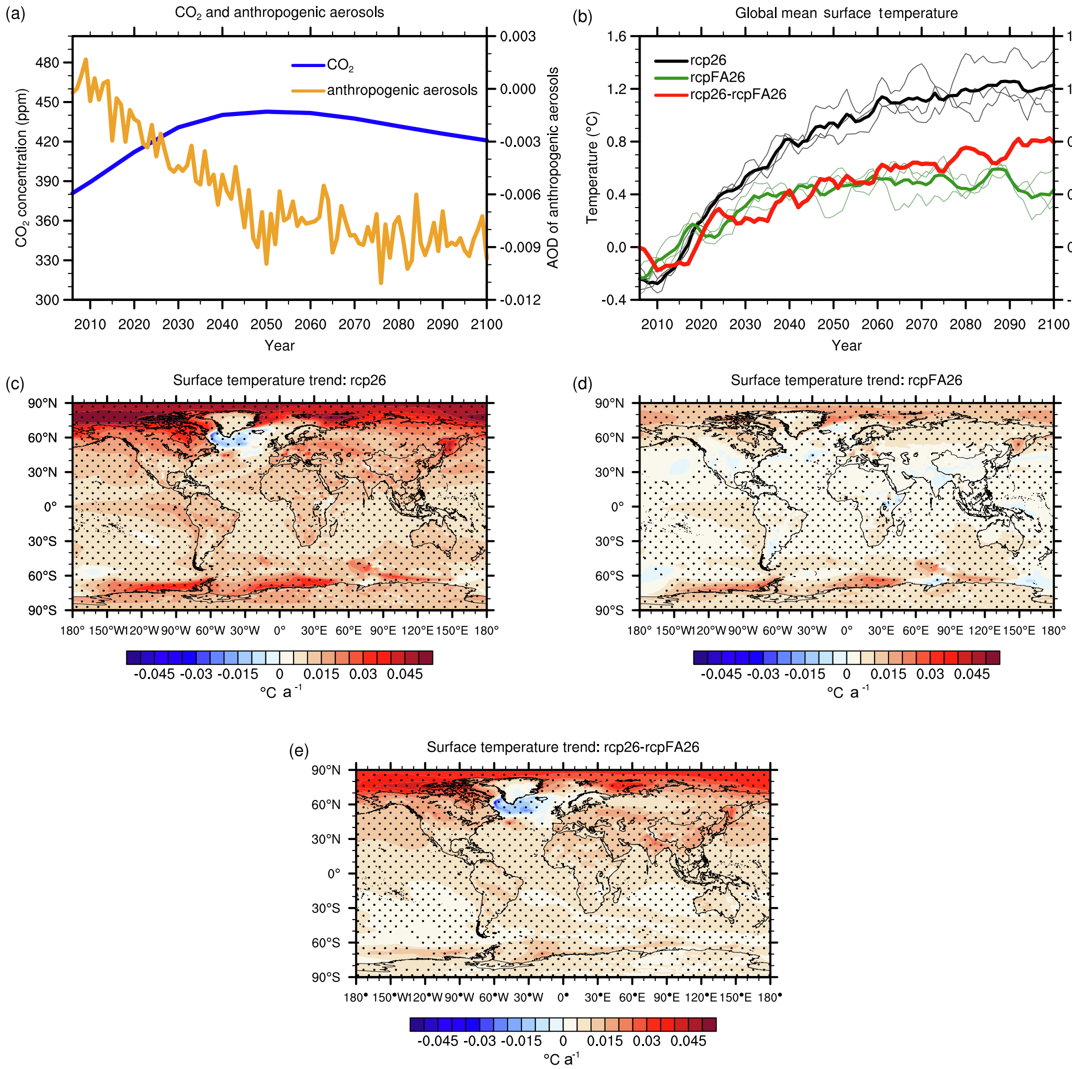

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Fig. 1. Changes in atmospheric CO_2 and anthropogenic aerosols as well as the response of surface temperature under RCP2.6 in CESM1-CAM5. (a) CO_2 concentration (blue) and aerosol optical depth (AOD) at 500 nm of anthropogenic aerosols (orange) in the 21st century. (b) Time series of global mean surface temperature anomalies (relative to 2006–2025 mean) in rcp26 (black), rcpFA26 (green), and their difference rcp26-rcpFA26 (red). Thin lines denote the results in three ensemble members. Long-term trends of surface temperature over 2006–2100 in (c) rcp26, (d) rcpFA26, and (e) their difference rcp26-rcpFA26. Trends in (c–e) are the results of the ensemble mean. Stippling indicates where SST trends are statistically significant at the 95% confidence level based on the Student's *t*-test.

leads to an increase in the surface temperature throughout the entire century (0.010 °C a^{-1}) as demonstrated by the simulation difference rcp26-rcpFA26 (Fig. 1b, red). The long-term evolution in the time series of global mean surface temperature is consistent with the temperature trend over 2006–2100 in spatial maps (Fig. 1c–e). The aerosol forcing makes more contributions to the total changes in the surface temperature relative to other forcings (mainly CO_2). This is evident in the Northern Hemisphere, especially Asia, Europe, and North America, which are the major sources of aerosol emissions (Fig. S1 online). The surface temperature does not vary consistently over the globe. The greatest warming occurs over the Arctic (Fig. 1c). In the case of declining aerosols, the Arctic temperature amplification is primarily due to the strong positive feedback between sea-ice-albedo and temperature [9] as well as an increase in horizontal energy transported to the Arctic region [10]. In contrast, a significant surface cooling dominated by the anthropogenic aerosol effects appears in the subpolar North Atlantic (Fig. 1c, e). This distinctive cooling occurring in a warming environment has been referred to as the North Atlantic warming hole and is related to variations in deep ocean circulations in the Atlantic basin [11], which is mainly the Atlantic Meridional Overturning Circulation (AMOC).

Under the net effect of decreased anthropogenic aerosols, the long-term (2006–2100) surface cooling trend over the subpolar North Atlantic (Fig. 1e) mostly comes from the second half-century, as indicated by the times series of the regionally averaged (50°–70°N, 60°–10°W) sea surface temperature (SST) in rcp26-rcpFA26 (Fig. 2c, red). The decreasing anthropogenic aerosols trigger a weakening AMOC at the beginning of the century (Figs. 2a (red) and S2 online). The initial weakening of the AMOC is possibly related to changes in atmospheric circulation [4]. The decline of aerosols reduces sea level pressure gradient, weakens surface winds over the North Atlantic, reduces surface latent and sensible heat fluxes, and ultimately leads to a decrease in surface density flux [4]. In turn, the deep convection weakens and the AMOC slows down. The weakened AMOC induces a reduction in northward ocean heat transport in the Atlantic (Fig. 2b, red). Less heat is transported from the tropics to high latitudes. As time goes by, a large SST cooling trend over the subpolar North Atlantic will emerge after 2050 (Fig. 2c, red). The SST fluctuations in the first half-cen-

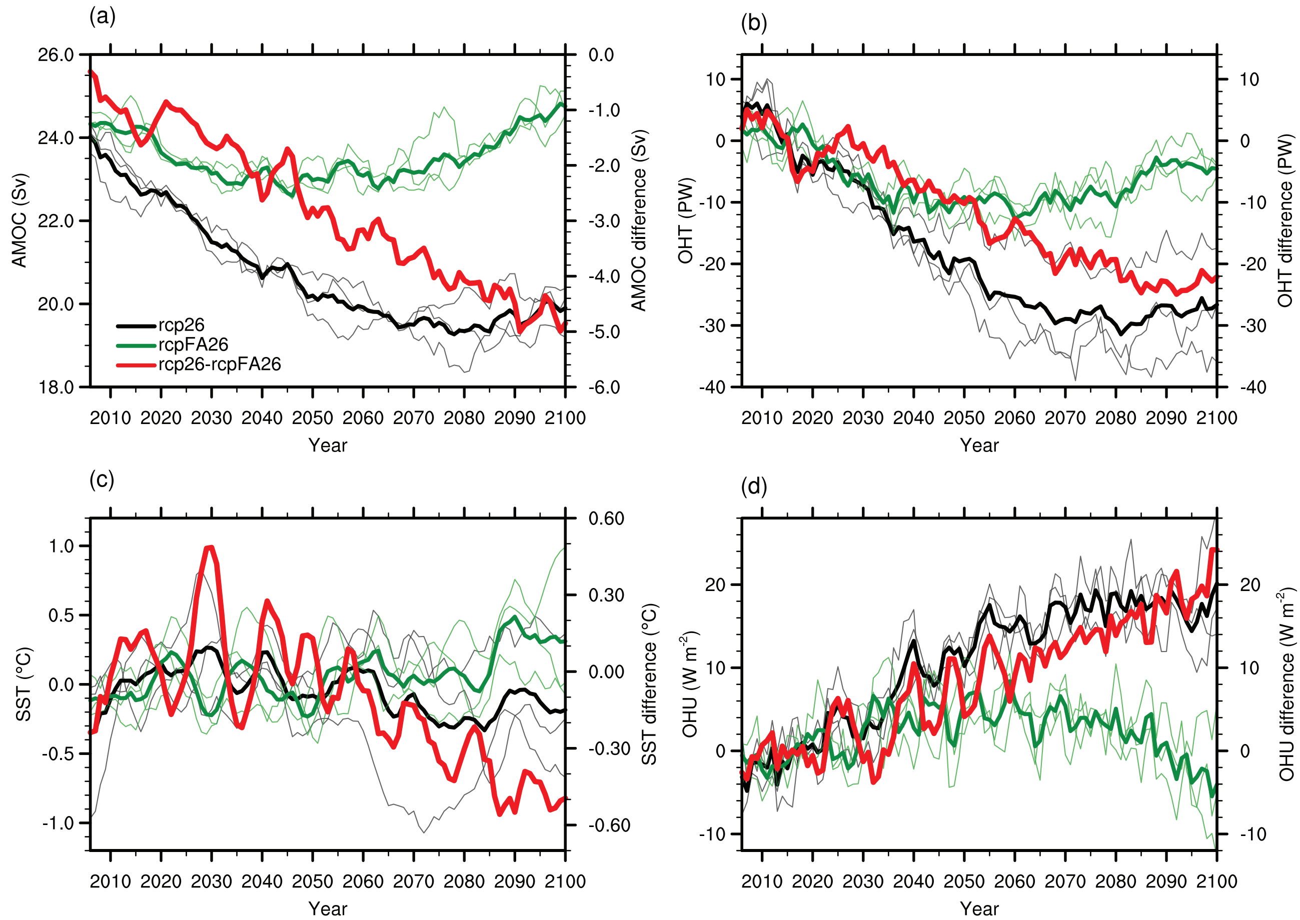

Fig. 2. Evolutions of oceanic processes in the Atlantic under RCP2.6 in CESM1-CAM5. Time series of (a) the AMOC index, (b) total ocean heat transport (OHT) anomalies in the Atlantic, (c) SST anomalies, and (d) ocean heat uptake (OHU) anomalies in the subpolar North Atlantic (50°–70°N, 60°–10°W) in rcp26 (black), rcpFA26 (green), and their difference rcp26-rcpFA26 (red; right *Y*-axis). Thin lines denote the results in three ensemble members. Thick lines denote the results of the ensemble mean. Anomalies are relative to the 2006–2025 mean.

tury might be associated with the competing roles between the direct warming effect of decreased aerosols and the AMOC-induced heat loss. In the second half of the century, the direct warming weakens as the aerosol reduction slows down (Fig. 1a) and the continuous weakening of the AMOC dominates the SST decline in the subpolar North Atlantic. The continuous AMOC weakening after 2050 under declining aerosols mainly results from a continuous increase of surface freshwater flux in the subpolar North Atlantic [5]. The surface freshwater flux increase is possibly controlled by a reduction in surface evaporation due to the cooling of local SST [5]. The SST decline further causes an increase in ocean heat uptake on the surface through the turbulent heat flux feedback [12] in the subpolar North Atlantic (Fig. 2d, red). The variations of ocean heat uptake in the first half of the century might be a comprehensive result of oscillating SST and direct warming effects of aerosols.

Comparing the evolutions in oceanic processes during the 21st century in rcp26 and rcpFA26 simulations (Fig. 2, black and green), we find that the extra warming effect of reduced anthropogenic aerosols in rcp26 causes a prolonged weakening in the AMOC strength (Fig. 2a, black). This subsequently leads to prolonged decreases in the Atlantic's poleward heat transport and subpolar North Atlantic SST, which in turn causes a prolonged increase in the local ocean heat uptake (Fig. 2b–d, black). However, these variables in rcpFA26 tend to recover in the second half-century, mainly following the CO_2 pathway (Fig. 2a–d, green). In addition to the reduced aerosol forcing, the North Atlantic warming hole could appear under increased CO_2 [13] via inducing a largely weakened AMOC. The warming hole in rcpFA26 is not obvious (Fig. 1d) due to the recovery of the AMOC (Fig. 2a) dominated by CO_2 changes.

In summary, the concentrations of CO_2 and aerosols in the atmosphere will decrease at the same time because anthropogenic emissions are significantly cut down to fulfill the carbon neutrality and low-warming target. The extra warming effect produced by the reduction in anthropogenic aerosols synchronizes with the cooling effect induced by CO_2 decrease. Thus, the reduced aerosols will allow global surface temperature to keep rising for an unexpected long period rather than gradually decline as the CO_2 decreases. In the 21st century, compared with the consistent long-term warming trends elsewhere, there is a long-term cooling trend of surface temperature in the subpolar North Atlantic, which leads to a large increase in local ocean heat uptake. This is primarily related to a weakening in the AMOC and a decrease in northward ocean heat transports throughout the century under the forcing of declining aerosols, which causes a substantial cooling in SST over the subpolar North Atlantic in the last decades of the century.

The response in oceans to changes in aerosol forcing could last long (e.g., decades or centuries) due to the slow adjustments of oceanic processes. In addition to modulating long-term climate change, changes in oceans could also affect the uptake and storage of atmospheric CO_2, which would influence carbon neutrality [1] over a long period. The North Atlantic is a major atmospheric CO_2 sink because the deep convection branch of the AMOC [14] leads to the deep storage of carbon, thus a weakened AMOC would result in increased carbon concentration in the atmosphere. Beyond the CESM1 simulations under RCP2.6 scenario, the latest CESM2 model and the updated low-emission scenario SSP1-2.6 in the framework of CMIP6 could be applied in the next step of the study. One caveat in this study is the potential model dependence of the aerosol-induced climate responses. The current climate models differ in aerosol schemes [7], deep convection sites [15], parameterization, etc. The findings from the CESM model need to be compared with those in other climate models.

Our study indicates that future decreases in anthropogenic aerosols could amplify the warming maximum and slow down the cooling rate due to CO_2 reduction, thereby extending the time required to reach the low-warming target. Despite the 1.5 °C/2 °C temperature goal set in the *Paris Agreement*, the zero-emission pathways in practice are subject to various possibilities. The specific future emissions are different among countries due to their different policies [2]. The carbon emission peak and emission reduction rate could be distinct from those under RCP2.6. Hence, future climate change under carbon neutrality could have some biases against that projected under RCP2.6. Nevertheless, the significant roles played by anthropogenic aerosols on the spatiotemporal evolution of surface temperature need to be considered in designing the specific pathway of carbon neutrality.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Gang Huang and Xiaofan Ma conceived the research. Xiaofan Ma performed model simulations, prepared figures, and led the writing of the manuscript. Junji Cao contributed to the discussion and explanation of the results.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2021.10.022.

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