ATMOSPHERIC SCIENCE

Quantifying the influence of short-term emission reductions on climate

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The COVID-19 (coronavirus disease 2019) pandemic has resulted in a marked slowdown in greenhouse gas and aerosol emissions. Although the resulting emission reductions will continue to evolve, this will presumably be temporary. Here, we provide estimates of the potential effect of such short-term emission reductions on global and regional temperature and precipitation by analyzing the response of an Earth System Model to a range of idealized near-term emission pathways not considered in available model intercomparison projects. These estimates reveal the modest impact that temporary emission reductions associated with the COVID-19 pandemic will have on global and regional climate. Our simulations suggest that the impact of carbon dioxide and aerosol emission reductions is actually a temporary enhancement in warming rate. However, our results demonstrate that even large emission reductions applied for a short duration have only a small and likely undetectable impact.

INTRODUCTION

The economic downturn associated with the COVID-19 (coronavirus disease 2019) pandemic has led to substantial emission reductions as industrial, transportation, electricity production, and other greenhouse gas intensive activities slow or stop. In China, indications (*1*, *2*) are that emissions were reduced by around 25% for a period of a couple of months, and initial estimates (*2*–*5*) are that global emission reductions in 2020 could be among the largest ever experienced, at 1.5 to 2.6 Gt of CO_2 for a reduction of 4 to 8% of 2019 emissions. Although the exact magnitude and duration of COVID-related emission reductions will not be known for some time, the expectation is that the reductions associated with COVID-19 containment will be temporary. An important question is, what are the potential climate consequences of such a temporary emission perturbation? This has been addressed in an idealized way in (*6*) but so far has not been addressed with comprehensive Earth System Models. In addition, we address the question of how large would the perturbation have to be to be noticed? Although distinct, this is complementary to the question in (*7*), which is, under a scenario of sustained emission reduction, how long would it take for the climate response to be detectable? We note that addressing these questions requires new, bespoke simulations, as those performed under currently available model intercomparison projects do not consider short-term, temporary emission reductions. We draw these results together by explicitly comparing our new perturbation results to those of sustained emission reductions consistent with achieving Paris Agreement climate goals.

RESULTS

Using the Canadian Earth System Model version 5 (CanESM5), we produced a large ensemble of simulations subject to a range of CO_2 and aerosol emission reductions over a 2-year period (see Materials and Methods for full details). In brief, we conducted four sets of 90-member ensemble simulations, each 10 years long, in which the carbon dioxide emissions were reduced in a time-varying way illustrated in Fig. 1A. Anthropogenic aerosol emissions were reduced by the same percentages. The reductions were applied to a "middle-of-the-road" Shared Socioeconomic Pathway (SSP) with radiative forcing in 2100 limited to 4.5 W m^{-2}. This scenario is denoted esmSSP2-4.5, with the prefix "esm" indicating that our simulations are emissions-driven rather than concentration-driven. The four perturbed scenarios are referred to as 10, 25, 50, and 100% reduction scenarios (the maximum percentage reduction in each case relative to the esm-SSP2-4.5 ensemble). In addition, we conducted simulations where only CO_2 emissions were reduced and where only anthropogenic aerosol emissions were reduced.

Before proceeding to our results, we note that the equilibrium climate sensitivity (ECS), defined as the amount of global-mean surface warming resulting from a doubling of atmospheric CO_2, of CanESM5 is higher than in most models of its generation (*8*). Indications are that the high ECS in CanESM5 is associated with cloud and surface albedo feedbacks, with sea ice likely playing an important role in the latter (*9*). Given the high ECS nature of CanESM5, we might expect its response to short-term greenhouse gas emission reductions to be greater than found in most other ESMs. Hence, our finding that the response to short-term emission reductions associated with COVID-19 is likely to be small and undetectable is robust.

While the future time evolution of emission reductions associated with the current pandemic is unknown, reductions over a 2-year period are a reasonable first guess. Reduced emissions on this time scale result in a small reduction in ensemble-mean surface CO_2 concentration as shown in Fig. 1B. To judge the detectability of a response in surface CO_2 concentration, we consider the range of anomalies across the 90 ensemble members. A reduction is potentially detectable if and when the 10 to 90% range of anomalies across the ensemble members does not encompass zero. These ranges are shown for the 25 and 100% reductions scenarios in Fig. 1B and for all of the reduction scenarios in fig. S1. We conclude that, for the 25% and greater emissions reduction cases, there is a detectable decrease in surface CO_2 over the 2-year period the emission reductions are applied. Furthermore, for the 50 and 100% emissions reduction cases, the decrease in surface CO_2 remains detectable to the end of the decade. To put these changes into context, we also consider the surface CO_2 concentration changes in scenarios designed

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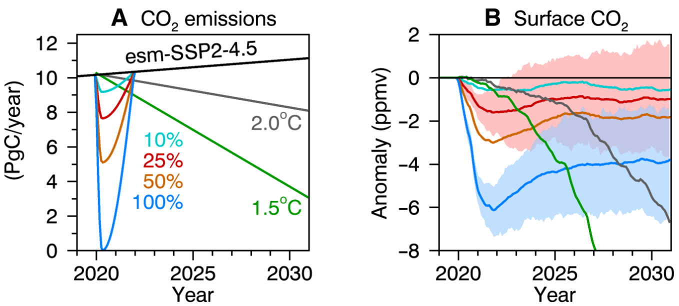

Fig. 1. Global average CO_2 emissions and surface concentration. (**A**) Global average CO_2 emission reduction profiles with peak reductions of 10, 25, 50, and 100% relative to the esm-SSP2-4.5 forcing scenario. Also shown are linear emission reductions consistent with limiting global warming to 1.5° and 2.0°C relative to preindustrial. (**B**) Global average surface CO_2 concentration anomalies relative to the esm-SSP2-4.5 forcing scenario. Curves are 90-member ensemble means. Shadings on the 25 and 100% reduction cases are 10 to 90% ranges across 90 ensemble members. The 10 to 90% ranges for all of the reduction scenarios are shown in fig. S1. Ppmv, parts per million in volume.

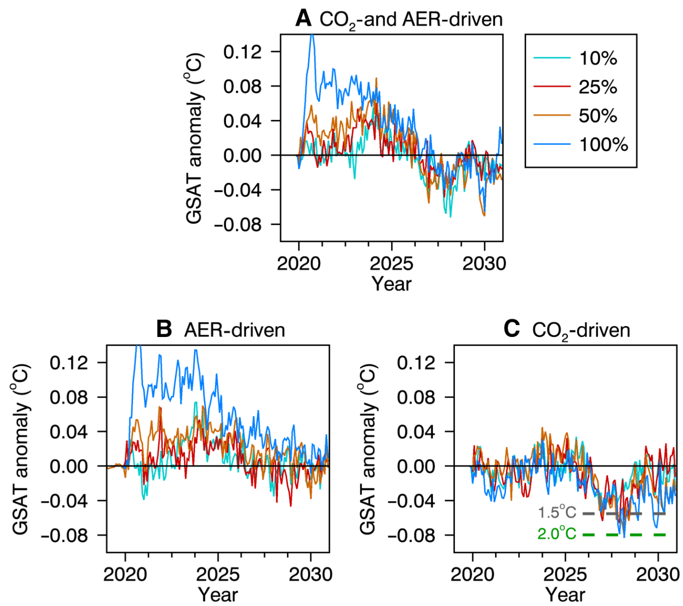

Fig. 2. Global average surface temperature anomalies. (**A**) CO_2- and aerosol (AER) emission–driven runs. (**B**) As in (A) but in AER emission–driven runs. (**C**) As in (A) but in CO_2 emission–driven runs. Anomalies are relative to the esm-SSP2-4.5 forcing scenario. Curves are 90-member ensemble means. In (C), the gray and green horizontal dashed lines are averages over 2026 to 2031 in the 1.5° and 2.0°C emission scenarios, respectively. Ensemble means and their 90% confidence intervals for anomalies averaged over 2020–2022 and 2026–2030 are shown tables S1 and S2, respectively.

to keep global warming below 1.5° and 2°C relative to preindustrial (*10*). By the end of the decade under these scenarios, the reductions in surface CO_2 concentration are detectable (fig. S2) and exceed those associated with even the most extreme temporary emission reductions (Fig. 1B), reflecting the cumulative nature of CO_2 emission reductions under these long-term scenarios.

In fig. S3, we show anomalies of total atmospheric mass of sulfate aerosol, SO_4, for each of the emissions reduction scenarios. In contrast to surface CO_2 concentration, the decrease in SO_4 is short-lived, with global values returning to the esmSSP2-4.5 level within 2 years. We also note that the SO_4 reductions are detectable in the 25, 50, and 100% emissions reduction scenarios.

The ensemble-mean global surface air temperature (GSAT) response to the perturbed CO_2 and aerosol forcing is shown in Fig. 2A. Here, we note that the ensemble-mean differences averaged over the first 3 years of the simulations are statistically significant at the 90% level in the 50 and 100% emissions reduction scenarios but not for the 10 and 25% cases (table S1). Perhaps counterintuitively, the net effect of the temporary emission reduction in CO_2 and aerosols is a temporary increase in warming rate. That is, the ongoing ensemble-mean temperature increase in the perturbed case is larger than in the unperturbed case, particularly for the first few years. That said, while the ensemble-mean increase is statistically significant in the 50 and 100% emissions reduction scenarios, the increase is undetectable in any individual realization for all scenarios (table S1). The implication is the GSAT response to plausible emission reductions associated with the COVID-19 pandemic will not be discernible in the observational record.

The net warming response in Fig. 1B can be understood by looking at Fig. 2 (B and C), which shows the results of additional simulations in which either aerosol emissions or CO_2 emissions are perturbed individually, respectively. The response to a 2-year CO_2-only perturbation is a cooling anomaly that persists, whereas the response to a corresponding aerosol perturbation is a warming anomaly that declines to near zero over the course of the simulations. We note that global mean temperature increase is associated with cumulative CO_2 emissions (*11*) and, therefore, even a temporary reduction in emissions has an effect on the carbon budget associated with temperature stabilization goals, such as those in the Paris agreement. However, if the emission reduction is temporary, it merely delays slightly the time at which a particular temperature threshold is passed (e.g., 25% reduction for 1-year results in a 3-month delay). We also note that by the end of the decade, the surface temperature anomalies associated with the CO_2 emissions scenarios designed to stay below 1.5° and 2.0°C warming relative to preindustrial are larger than the anomalies associated with the 100% CO_2 emissions reduction scenario (Fig. 2C and table S2). Last, in Fig. 2C, we see a decadal time scale fluctuation in the anomalies of GSAT that is common across the CO_2 emission reduction scenarios. While this suggests a mode of variability triggered by the abrupt emission reductions, it is important to stress that the fluctuation lies within the range of statistical uncertainty.

It must be noted that in all cases considered here, surface CO_2 concentration continues to rise, on average, and the temporary reduction in emissions only leads to an offset relative to the background increase. The persistent concentration anomaly (due to the long lifetime of CO_2 in the atmosphere) alters global radiative forcing and so acts to reduce (but not reverse) the rate of warming. Sulfate, black carbon, and organic aerosols, by contrast, have a relatively short atmospheric lifetime (see fig. S3), and so their burden is reduced only temporarily while emissions are reduced.

The spatial patterns of temperature and precipitation response over the first 3 years in the 100% emissions reduction scenario are shown in Fig. 3. Correspondingly, fig. S4 shows the zonal average responses for the 25, 50, and 100% emission reduction scenarios. Carbon dioxide is well mixed and so a percentage CO_2 emissions reduction leads to a temperature response that has, as expected, rather little spatial structure, mostly reflecting internal variability. The aerosol-forced temperature response, by contrast, has a spatial structure that corresponds to the pattern of aerosol transport and

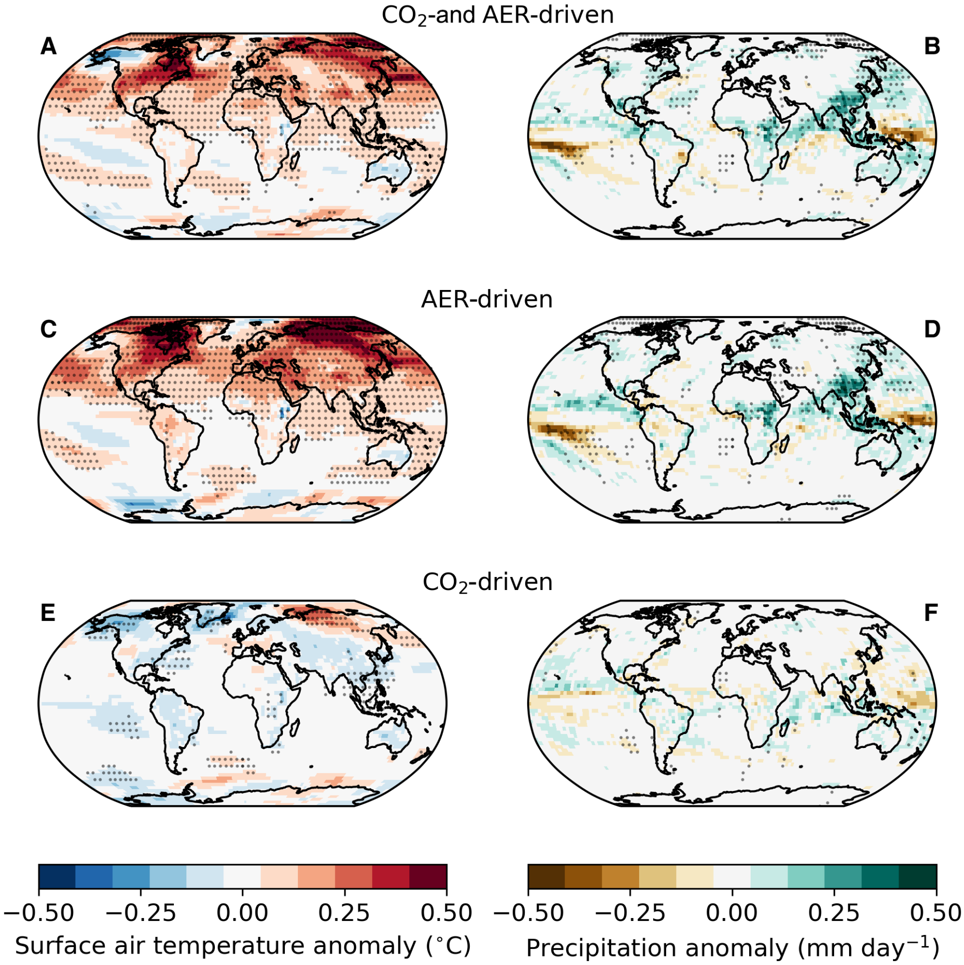

Fig. 3. Surface air temperature and precipitation anomalies. Anomalies are averages over the 36-month period from January 2020 to December 2022 and are based on peak emission reductions of 100%. (**A** and **B**), CO_2- and AER emission–driven runs. (**C** and **D**) AER emission–driven runs. (**E** and **F**) CO_2 emission–driven runs. Anomalies are relative to the esm-SSP2-4.5 forcing scenario. Stippling indicates ensemble-mean anomalies significant at the 90% confidence level.

burden (see fig. S5), and this pattern dominates the overall response. The largest temperature response is a region of warming over North America and Northern Eurasia. Tropical precipitation is also affected by aerosol reductions as shown in Fig. 3 and fig. S4. These patterns of aerosol-driven temperature and precipitation change are consistent with a northward shift of the intertropical convergence zone (ITCZ) as seen in observations and in model simulations (*12*). Last, we note that the northward shift of the ITCZ shown in Fig. 3 and fig. S4 mirrors the response of the ITCZ to volcanic aerosol forcing (*12*, *13*).

DISCUSSION

Although the emission perturbations we apply here are hypothetical and, for the most part, likely larger than the perturbations that will ultimately be experienced, they illustrate the rather modest impact that temporary emission reductions associated with the COVID-19 pandemic will have, both on CO_2 concentration and on global temperature. If aerosol emissions decrease proportionally to CO_2 emissions as we assume, our model results suggest that, on average, the net effect of emission reductions is actually a small enhancement in warming rate. However, our results elucidate that even large emission reductions applied for a short duration have only a small and likely undetectable impact on climate. In contrast, reducing warming and ultimately stabilizing global mean temperatures (*10*) would require continuous year-upon-year reduction in emissions to net zero. The economic stimulus measures in response to the COVID-19 economic crisis could have substantial positive or negative impacts on long-term emissions (*3*) and, hence, on climate depending on whether they also consider climate goals.

MATERIALS AND METHODS

We made use of the CanESM5. This model is described in detail in (*9*) and has been used to perform simulations as part of the sixth phase of the Coupled Model Intercomparison Project [CMIP6; (*14*)]. We used as a comparison a 90-member initial condition ensemble of simulations analogous to those contributed to the Coupled Climate Carbon Cycle Model Intercomparison Project [C4MIP; (*15*)], although we used the emission-driven equivalent of the SSP2-4.5 scenario (a midrange scenario), referred to here as esm-SSP2-4.5. See (*16*) for further details on forcing scenarios. We conducted four sets of 90-member ensemble simulations, each 10 years long, in which the esm-SSP2-4.5 carbon dioxide emissions were reduced in a time-varying way illustrated in Fig. 1A. Anthropogenic aerosol emissions were reduced by the same percentages (because anthropogenic CO_2 and aerosol emissions share many of the same sources).

The four perturbed scenarios are referred to as 10, 25, 50, and 100% reduction scenarios (the maximum percentage reduction in each case relative to the esm-SSP2-4.5 ensemble) and represent a rapid onset of reductions beginning in December of either 2009, 2014, or 2019. As we are only looking at anomalies relative to the corresponding unperturbed simulation, we align all of the results to the 2019 case. Using three different start years allow for a sampling of different initial states of the climate system. Emission reductions peak in May of the following year (e.g., May 2020) and recover by the end of the next year (e.g., 2021). In all cases, the perturbations are limited to a 2-year period, and the annualized average percent reductions over the 2-year period are 6.3, 16, 32, and 63%, respectively, when reductions begin in December of 2019.

Of course, these are necessarily hypothetical emission perturbation scenarios aimed at spanning a range of reductions—the actual details will depend on how the pandemic evolves and how governments and the economy respond. As CanESM5 has specified concentrations of non-CO_2 greenhouse gases (many of which are emitted along with CO_2) that are unmodified in our simulations, the emission perturbations do not affect these and so the CO_2 emissions perturbations we apply are to be interpreted as "effective" values representing the total greenhouse gas emission reduction. As a result, the 10% perturbation is roughly consistent with the CO_2-only emission reduction suggested in (*2*–*5*), but we use a sequence of larger emission perturbations as well to more clearly visualize the qualitative aspects of the response.

The 1.5° and 2.0°C scenarios were constructed by taking the observed amount of warming in 2020, relative to preindustrial, to be 1°C. The Transient Climate Response to Cumulative Emissions of CanESM5 was then used to calculate the allowable emissions remaining to keep warming below the relevant target. Scenarios that imposed a linear ramp-down from 2020 emissions to zero emissions (required for stabilization) were constructed over a period of time such that the cumulative carbon budget was not exceeded.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/10/eabf7133/DC1

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